THE NON-DESTRUCTIVE TESTING OF SPOTWELDS IN ALCLAD ALUMINUM ALLOY SHEETS

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In Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy

California Institute of Technology
Pasadena, California

1944

SUMMARY

This thesis presents the results of an investigation of non-destructive test methods for spotwelds in aluminum alloy sheets. The purposes of the research were:

(a) to investigate proposed non-destructive test methods for spotwelds in aluminum alloys,

(b) to determine the feasibility of such tests,

(c) to develop suitable methods for practical application and

(d) to test each useful method for reliability and accuracy on a large number of industrially made spotwelds.

Investigation was made of approximately thirty proposed non-destructive methods of testing spotwelds, including electric current conduction tests, eddy current tests, thermal tests, sonic and vibration tests, material property tests, penetrator tests, X-ray tests, and mechanical proof tests. Preliminary tests and analysis of the requirements of a suitable non-destructive test indicated that penetrator, electrical, and X-ray methods showed the most promise. Extensive developments of each of these methods were carried out, and each test method was tried on groups of several hundreds of industrially made spotwelds. The reliability and accuracy with which weld size, strength, and quality were predicted by each test were determined.

It was found that, in terms of reliability and accuracy,

the most promising non-destructive test method is the radiographic inspection of spotwelds. From spotweld radiographs made with the proper technique, it is possible to interpret weld structure, size, geometry, and strength, as well as to detect defects such as cracking, porosity, inclusions, expulsion of metal at the faying plane, extensive segregation of eutectic, inadequate or excessive nugget penetration, excessively large heat-affected zones, excessive tip skid, and mis-shapen nuggets.

The most promising non-radiographic tests were found to be the ring penetrator (mechanical) test and the ring electrode (electrical) test. The ring penetrator test is sensitive to spotweld nugget size and shape. The ring electrode test is sensitive to the total bonded area at the faying plane of the spotweld. Both tests are subject to wide error if the test probes are not centered accurately over the weld.

On production spotwelds, the penetrator, electrical, and radiographic non-destructive tests each measure spotweld static shear strength with reliability and accuracy well above the requirements of practical industrial spotweld inspection.

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I - INTRODUCTION

This thesis presents the results of an investigation of non-destructive test methods for spotwelds in aluminum alloy sheets.

The purposes of the research were:

To investigate proposed non-destructive test methods for spotwelds in aluminum alloy sheets, to determine the feasibility of such tests, to recommend and develop those methods found suitable for reduction to practical application and to test each useful method for reliability and accuracy on thousands of industrially made welds.

The need for practical non-destructive tests for spotwelds in aluminum alloy sheet is recognized in the aircraft industry. Present industrial process control and visual inspection procedures are inadequate to guarantee that all spotwelds made in aluminum alloy sheets for aircraft will meet minimum strength requirements. Consequently, spotwelding of aluminum alloys in aircraft applications has been limited, for the most part, to secondary or unstressed structures. The fabrication advantages of spotwelding are yet to be realized for a large part of aircraft construction involving primary or stressed structures which are critical in the operation of the aircraft. Until adequate process control, monitoring of the welding process, or reliable non-destructive tests are provided to guarantee weld quality, the spotwelding of primary aircraft structures tends to be delayed. When designers and inspectors are shown undeniable proof that weld quality is adequate, the spotwelding of primary aircraft structures may be expected. A reliable non-destructive test for spotwelds would provide this proof of adequate weld quality.

The applications visualized for practical non-destructive tests for spotwelds include routine production tests on some or all welds of certain vital aircraft structures, and occasional check tests on weld quality at any point in the aircraft fabrication process. For the routine production tests, the equipment must be capable of rapid testing; for the incidental check tests, portable equipment is desired. For all applications, absolute reliability is required.

II - THE PROBLEM OF NON-DESTRUCTIVE TESTING OF SPOTWELDS IN ALCLAD ALUMINUM ALLOY SHEETS

To indicate the nature and scope of the problem involved in developing non-destructive tests for spotwelds, there are now listed:

(a) the requirements of an acceptable test,

(b) spotweld properties and nomenclature,

(c) factors contributing to weld shear strength and quality,

(d) weld types to be discriminated, and

(e) quantitative measurements needed to measure weld quality.

A. Requirements of an Acceptable Non-Destructive Spotweld Test

The non-destructive spotweld test must be reliable and should be practical, fast, efficient, and economical both in labor and equipment. It should be suitable for production testing and for occasional inspection checks on questionable welds at any point in the fabrication process. It should detect bad welds regardless of their cause.

To be more specific, the test must be:

1. Reliable -- It should discriminate mormal welds, (static shear strengths 25% to 125% above

the minimum acceptable strength) from welds with less than the minimum acceptable strength, with complete reliability. To obtain this reliability, the method should predict spotweld static shear strength within plus or minus 20% of actual weld strength, and more accurately if possible, throughout the range of strengths from one-half the minimum acceptable strengths to the highest strength obtained under normal production conditions in acceptable welds.*

2. Practical -- It must be such that it can be used reliably by semi-skilled personnel under normal production conditions.

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* A reasonable maximum accuracy to be expected from a non-destructive spotweld test is that test indications should measure weld strength as closely as nugget diameter (which could be observed by destructively sectioning the weld) correlates with weld strength. Any non-destructive test which approaches this standard should be considered successful, for the relation between nugget diameter and weld strength is generally recognized as the most significant relation between a single weld parameter and the static shear strength of the weld.

3. <u>Fast</u> -- Because of the large number of welds to be tested, a production testing device should preferably operate in a few seconds and be capable of being quickly transferred and positioned for testing. For this reason, its location with respect to the weld nugget should preferably not be too critical.

4. <u>Immediate in Response</u> -- In production testing, it would be desirable to have an immediate indication of weld strength, to avoid delay and unnecesary identification of specific welds under test.

5. <u>Independent of Weld Location</u> -- Test results should not be invalidated by the proximity of other welds, or of corners, slots or edges in the sheet, or of large masses of metal.

6. <u>Independent of Ambient Conditions and of Surface Conditions of Welded Sheets</u> -- Since weld testing may be done on production lines within buildings or out-of-doors, test results must not be affected by temperature, noise, vibration, dirt, humidity or other test conditions dependent upon location. Sheet surfaces must not require excessive

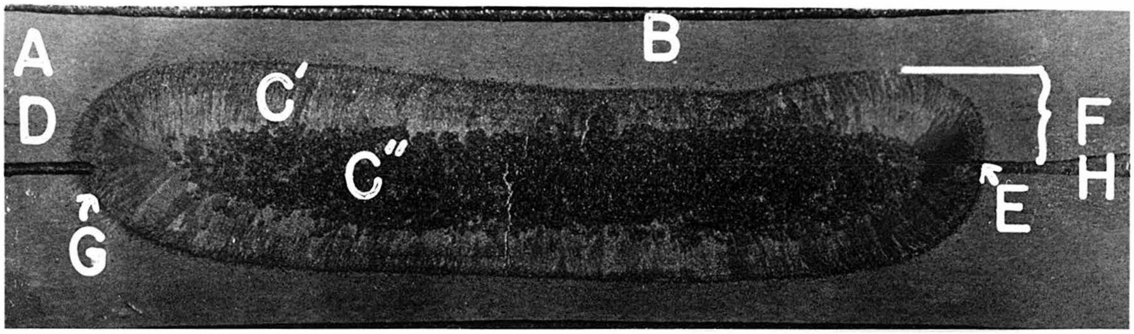
preparation, nor should surface conditions resulting from normal production processes invalidate the test.

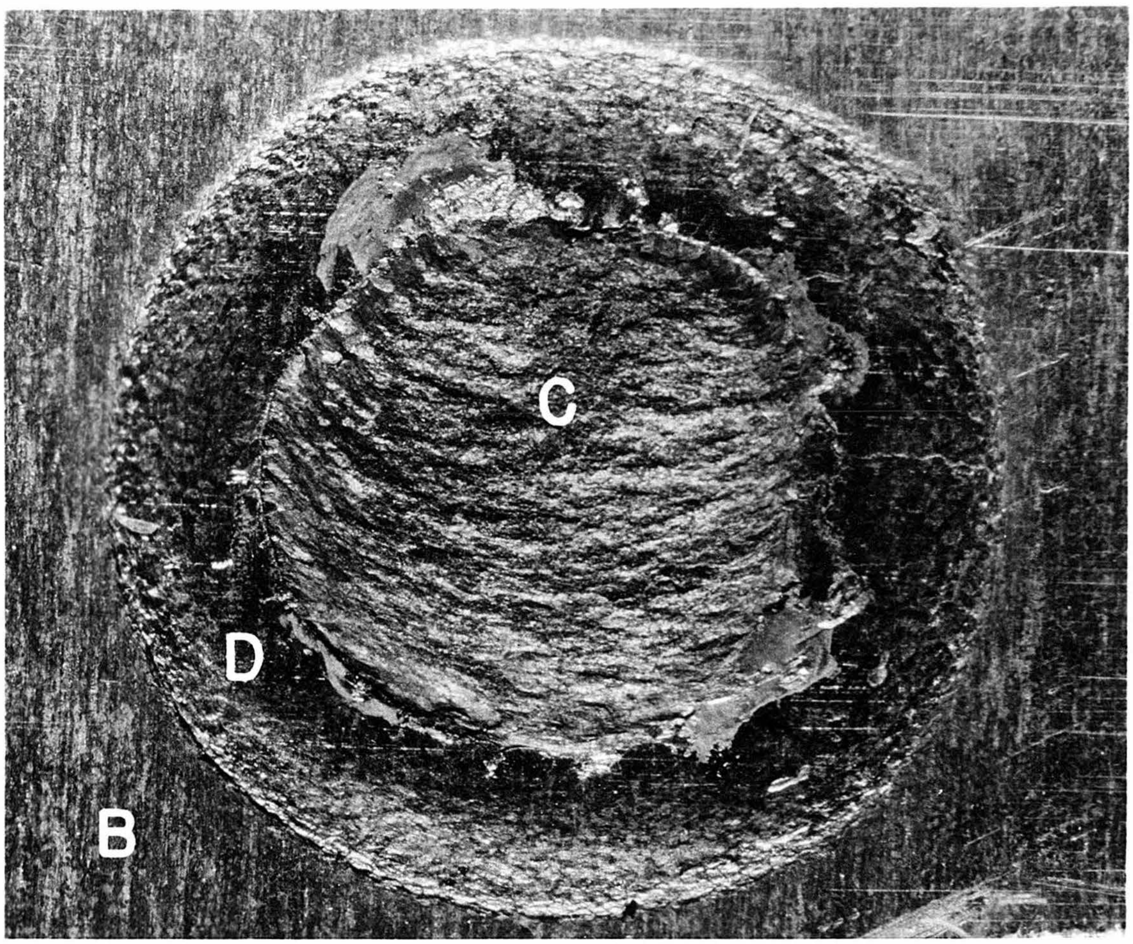
7. Non-destructive -- The weld must not be damaged by the test, nor should the Alclad layer be broken nor the sheet or part be distorted by the test.

In addition, it would be highly desirable (but not necessary) that the test equipment be portable and that it require access to only one side of the welded sheets. If used on fabricated pieces, it would be advantageous if the portion of the tester to be brought to the weld were small, weighing only a few pounds at most, and were easy to move and set accurately in position. (For production testing of small parts before further assembly, the work might be brought to a fixed testing machine). Although 95% of the spotwelds in aircraft are accessible from both sides of the work at some point in the fabrication process, a testing unit operating from only one side of the sheet would be very advantageous, provided reliability of measurement were not sacrificed to obtain this advantage.

B. Weld Properties and Nomenclature

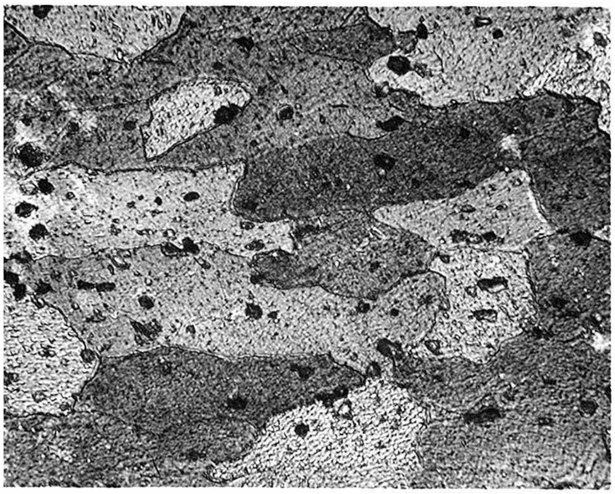
Figure 1 shows photomacrographs of both cross-section



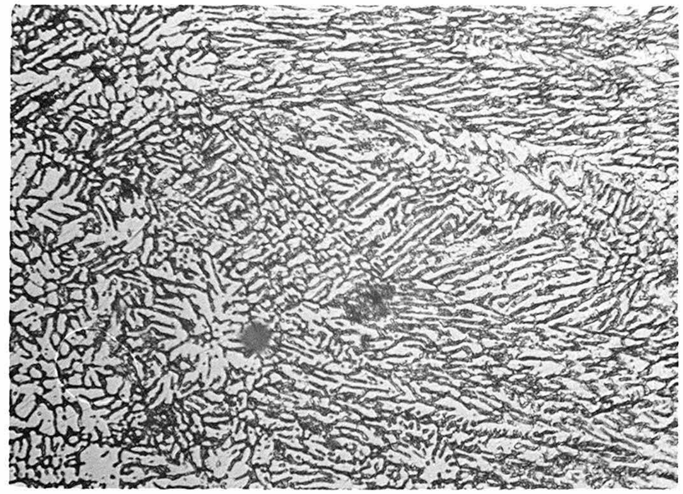


CROSS SECTION AND FAYING PLANE OF A TYPICAL SPOTWELD IN 24 ST ALUMINUM ALLOY, SHOWING SIGNIFICANT REGIONS OF WELD; (A) PARENT MATERIAL, (B) ALCLAD LAYER, (C) CAST ALLOY NUGGET, INCLUDING (C^{I}) DENDRITIC ZONE AND (C^{II}) EQUIAXED ZONE, (D) CORONA, (E) ALCLAD INCLUSION, (F) PENETRATION, (G) HEAT AFFECTED ZONE AND (H) FAYING PLANE. 20X.

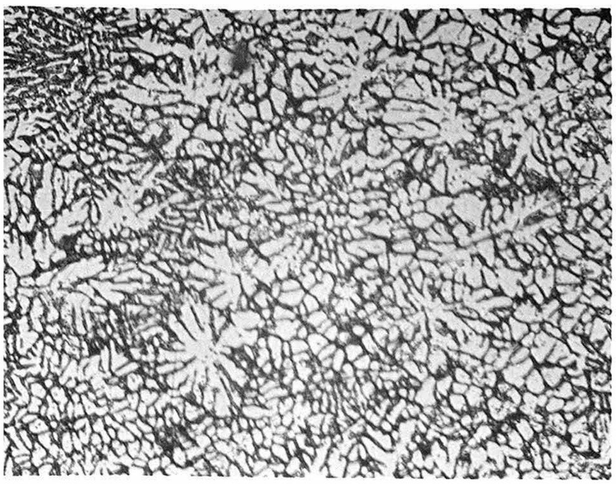
FIG. 1



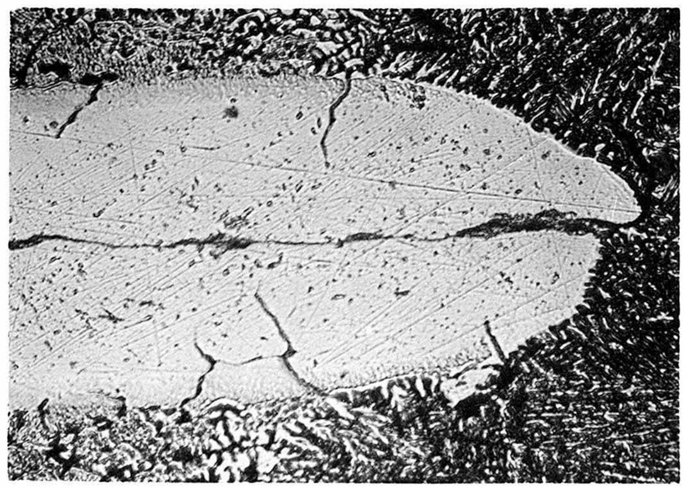
A). PARENT MATERIAL, 24ST ALUMINUM
LLOY. 500X.



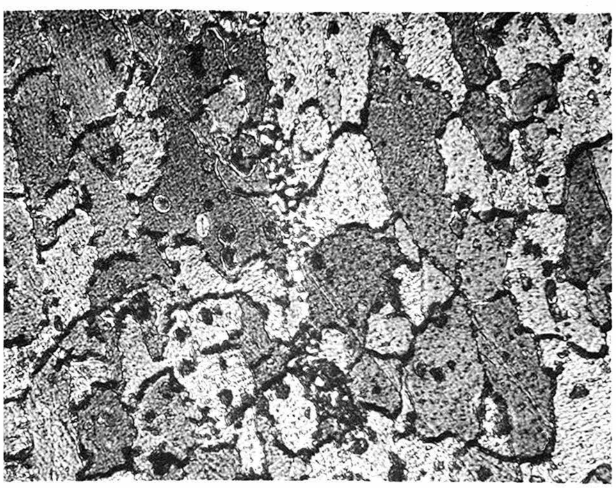
(C^{I}). DENDRITIC ZONE OF NUGGET. 500X.



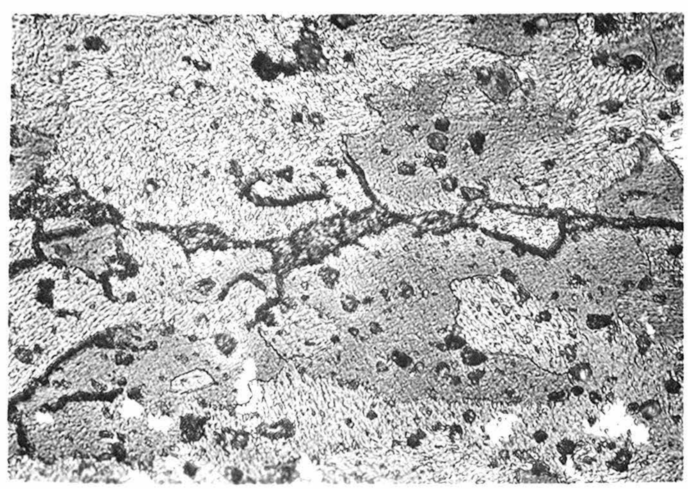
C^{II}). EQUIAXED ZONE OF NUGGET. 500X.



(E). ALCLAD INCLUSION INTO NUGGET. 500X.



. HEAT AFFECTED ZONE SHOWING IN-
IENT MELTING AT THE GRAIN BOUNDARIES.
X.



(G^{I}). HEAT AFFECTED ZONE SHOWING EUTECTIC "STRINGER" OR "INTRUSION INTO THE GRAIN BOUNDARIES". 500X.

and faying surface and photomicrographs of significant regions, of a typical spotweld in Alclad 24ST aluminum alloy sheet. The following nomenclature, which will be used throughout this thesis, refers to this figure.

1. The parent sheet (A) is the 24ST aluminum alloy sheet in the region outside the weld proper which has not been affected in any manner by the welding process. This alloy is composed of 4.5% copper, 0.6% manganese, and 1.5% magnesium, with aluminum and normal impurities making up the balance. (Ref. #1) Ingots are rolled into sheets which are subsequently tempered by heating to 920°F in an air furnace or in a molten nitrate bath and then quenched with minimum time delay into cold water. Aging at room temperature follows. The 24ST (tempered) alloy develops about 41,000 psi. shearing strength, while 24SO (annealed) alloy develops only 18,000 psi. The incipient melting temperature of this 24S alloy is only 936°F. (Ref. #2)

2. The Alclad layer (B) is a thin layer (approximately 5% of the parent sheet thickness) of commercially pure aluminum bonded to each surface of the parent sheet. Its prime purpose is to protect the parent sheet against corrosion. It is important that

the welding operation should not impair the protection provided by this coating. This commercially pure aluminum develops about 9500 psi. in shear and has a melting point of about 1200°F. (Ref. #1 and #3)

3. The <u>weld nugget</u> (C) is an ellipsoidal volume of metal which has been melted by the welding current, possibly being stirred so as to effect a redistribution of its chemical constituents, and which has then solidified into two distinct zones as a cast structure. (Ref. #4) The dendritic zone (C') shows evidence of very rapid solidification, while the equiaxed zone (C") shows evidence of relatively slower cooling. The nugget is softer than the parent sheet and develops only about 18,000 to 22,000 psi. shear strength. (Ref. #3)

4. The <u>corona region</u> (D) surrounds the weld nugget at the faying plane, and is that area of the Alclad coating which has been subject to pressure and heat during the welding process. The nature of the corona may depend upon the surface preparation of the sheet before welding, and in the corona region there may be no bonding, partial bonding, or complete areal bonding depending upon the sheet condition and the conditions of welding. It is not

safe to assume the bonded area of corona to be proportional to nugget area, for the purposes of nondestructive test development. The complete corona bonding may develop as much as 9500 or 10500 psi. shearing strength. (Ref. #3)

5. The Alclad inclusion (E) into the weld nugget at the faying plane consists of aluminum of the Alclad layer which has not been alloyed into the nugget. The extent of Alclad inclusion is quite variable, and tends to be greater with thick Alclad layers, and in low energy welds with thin nuggets. Excessive Alclad inclusion weakens a weld in shear loading, since it decreases the effective nugget area at the faying plane. It is possible to develop a nugget in both sheets, yet have 100% Alclad inclusion. (Ref. #3) In this case, the weld nugget contributes nothing whatever to the weld strength.

6. The penetration (F) of the weld nugget into the parent sheet measures the portion of the sheet thickness occupied by the weld nugget. Penetrations of 20% to 80% of the sheet thickness are usually considered acceptable. (Ref. #5) Excessive penetration (80% to 100%) usually indicates a brittle, cracked, or porous weld, and it is undesirable both because of

lack of ductility in the weld, and because the cracks may spread to the surface breaking the Alclad layer and permitting corrosion. Inadequate penetration (below 20%) is frequently accompanied by excessive Alclad inclusion and inconsistency in strength. In the normal range (20% to 80%), penetration seems to have little or no effect on weld strength.

7. The <u>heat affected zone</u> (G) is that region of the parent metal surrounding the weld nugget whose properties have been changed as a result of exposure to elevated temperatures. The shear and tensile strengths of the 24ST alloy are reduced in this region. Structural changes, such as incipient melting of the material and intrusion of eutectic along grain boundaries, occur in this zone. (Ref. #6) Very large welds tend to "pull a button" when they fail under shear loading, the failure possibly occurring in part through this heat affected zone. (Ref.#7) Weaker welds, which fail by shearing the nugget through the faying plane are not greatly affected by this zone insofar as the shear load required for failure is concerned.

8. The <u>faying plane</u> (H) is the plane of joining between the welded sheets. Bonding between the

two sheets in this plane gives the weld its strength.

C. Factors Contributing to Weld Shear Strength and Quality

Sportwelds are seldom designed to be loaded in tension. The spotweld is much stronger under shear loading and is normally designed to carry (supposedly) static shear loads. The most commonly used measurement of weld strength is the static shear strength of a single spot lap joint. (Ref.#5) It is this static shear strength which must be predicted reliably by non-destructive tests, to obtain their general acceptance. If static shear strength cannot be predicted reliably, the non-destructive test method must be considered a failure, regardless of how well it measures other weld properties.

Unfortunately, static shear strength alone is not a good measure of spotweld quality. Weak welds without any nugget bonding whatever at the faying surface may pass minimum acceptable static shear strength requirements by virtue of Alclad bonding; yet these welds might fail in service. Very large welds with oversized, cracked, brittle nuggets and insufficient ductility may show very high static shear strengths, yet contribute to early fatigue failure and rapid corrosion. An ideal non-destructive test ought to distinguish between these defects, but to do so without excessive complication in test equipment or interpretation usually results in less reliable prediction of static shear strength. Likewise, welds with nugget penetrations of 50 to 80% of the thickness of the parent sheet are much more reliably detected by certain non-destructive tests than welds with 20 to 50% penetration. However, to increase or further restrict the standards of acceptable spotwelding, merely to make possible the use of a non-destructive test method, is out of the question in practical industrial spotwelding applications.

The single spotweld parameter which by itself correlates most reliably with static shear strength is the weld nugget diameter at the faying plane. More precisely, it is the net area of cast alloy (total nugget area less the area of the Alclad inclusion) at the faying plane which determines weld strength. With excessive Alclad inclusions, measurement of the overall nugget diameter can be misleading to the extent of 100% error in predicting weld strengths. With normal Alclad inclusions, the nugget diameter measures weld static shear strength with an error of plus or minus 10% to plus or minus 20% of actual weld strength (See Fig. 41) For welds without excessive Alclad inclusions or corona bonding, which fail by shearing the nugget through the faying plane, the correlation is quite reliable. For stronger welds which fail by "pulling a button", the correlation is less reliable, but in all such cases the weld strength is less than would be expected for failure by shearing through the nugget at the faying plane.

The second parameter, in addition to the net area of cast alloy at the faying plane, which contributes significantly to spotweld shear strength, is the effective area of Alclad or corona bonding at the faying plane. In cases where the cladding is fully bonded between the sheets near the weld, there occurs a strength contribution per unit area of bonded cladding, equal to approximately half the unit strength of the cast alloy. In weak welds, the area of bonded cladding may easily exceed the cast alloy area in the ratio of 3 or 4 to 1. In these cases the bonded cladding contributes a major portion of the static shear strength of the weld. This added strength would be evident in the static shear pull test, yet could not be relied upon for the life of a welded structure, as the Alclad bond is of questionable nature.

It is difficult to measure the net area of Alclad bonding, not including the area of nugget bonding, in a non-destructive test. However, if reliable independent measurements can be made of the total bonded area and of the net nugget area at the faying plane, their difference measures the area of bonded cladding. Adding the strength contributions of both nugget and Alclad bonding makes possible the prediction of spotweld strength with an error of less than plus or minus 5% to plus or minus 15% of actual weld strength. (See Section IV D)

Other geometric parameters of the spotweld have little influence upon weld strength, under normal conditions. Penetration, in the acceptable range of 20% to 80% of the sheet thickness, has no significant influence, although welds of low penetration seem to show increased unit strength in the nugget because of the strength contributions of proportionately larger areas of Alclad bonding. (Compare with conclusions of Reference 8) Nugget volume and shape are significant only as they affect the cast alloy area at the faying plane.

Cracking and porosity within the weld nugget have negligible effect upon static shear strength, except insofar as they affect the bonded area at the faying plane. Cracks to the sheet surface greatly increase corrosion. Cracks also probably contribute to fatigue failures in spotwelded structures.*

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* The extent of this effect probably depends critically upon the geometry of the crack. Small spherical cavities and similar porous conditions might have negligible effect upon fatigue strength.

The influence of the different types of metallurgical structure on the characteristics of spotwelds is not known at present but it is probably of much less importance than factors such as size, shape, soundness, and freedom from cracking. (Ref.#6) Our measurements have shown no reliable direct correlation between any metallurgical property and weld strength, except insofar as nugget geometry has been measured by structural properties.

D. Weld Types to be Discriminated

The task of developing non-destructive tests for spotwelds is frequently given by production welding groups to research groups or outside organizations whose familiarity with production welding conditions is limited. All t oo frequently, these research workers have a falsely simplified concept of the nature, geometry, and structure of spotwelds, on which to base their non-destructive test developments. It must therefore be recognized that the size, shape, and bonding, particularly of weak welds, are exceedingly variable. Static shear tests alone tell very little about weld geometry, size, and quality. Many anomolous conditions exist, which tend to invalidate non-destructive test methods.

To aid in evaluating developments of non-destructive spotweld tests, a <u>classification chart</u> is now given showing the faying surface and a section through the nugget for several typical spotwelds made under industrial welding conditions. These welds were made on energy storage welders of both the magnetic and condenser types, which tend to produce similar weld structures. No a.c. welds are included, but similar results can be obtained with a.c. welders under certain conditions.

For simplicity, the classification chart begins with very low energy welds, and progresses to larger and stronger welds made with increasing energy. In this manner the significance of the various weld regions in contributing to weld strength can be easily determined.

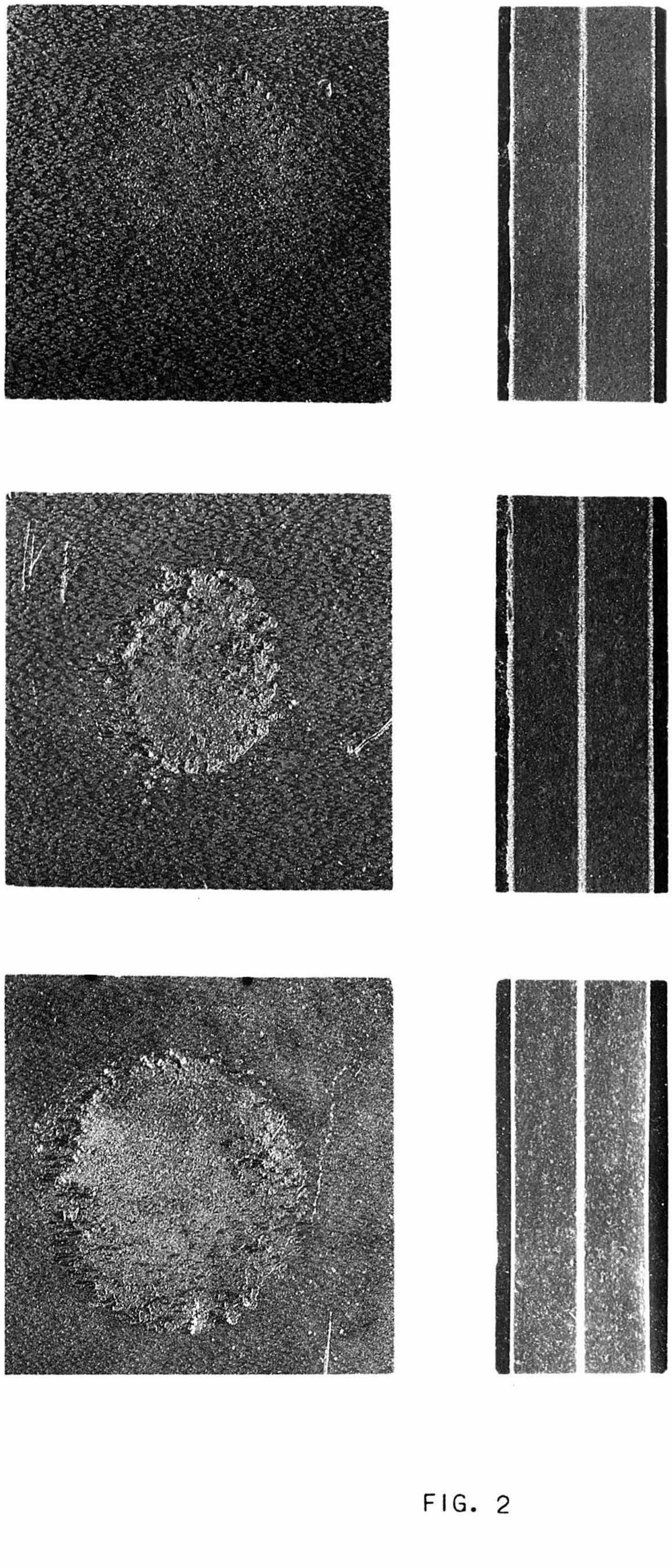
These welds were made on industrial spotwelding machines with all preparation and welding conditions normal, except energy setting or, in a few cases, forge pressure delay time. Thus, the net heat developed in the weld was used as the chief variable in producing these weld types. The bad welds were purposefully made weak for use in developing non-destructive spotweld tests. (See Table I)

<u>Type A Welds - Alclad Bonding Only With No Nugget Formation.</u>

Weld A-1*--represents the lowest energy setting

*--Specimen welds shown are all made in .040" 24ST Alclad sheets. All are shown at 10X magnification.

TYPE A WELDS – – ALCLAD
BONDING WITHOUT NUGGET FORMATION



A – 1

STRENGTH BELOW 50 POUNDS

A – 2

STRENGTH 100 POUNDS

A – 3

STRENGTH 215 POUNDS

FIG. 2

of the welding machine producing observable bonding at the faying surface. A small region of the Alclad layers has been heated and subjected to pressure, producing a weak bond possibly due to plastic deformation and keying at the faying surface. This weld fell apart upon handling. The bonded points are good conductors of heat and electricity across the faying surface between the sheets; the surrounding faying surface is a very poor conductor as a result of the presence of a thin layer of aluminum oxide, which acts as an insulator. No significant changes have occurred in the parent metal, and no nugget formation has occurred.

Weld A-2 -- was made under the conditions of Weld A-1, but more extensive bonding has occurred at the faying plane. The Alclad layer has bonded over a slightly larger area. The static shear strength was 100 pounds. This bond, because of increased area, shows less overall resistance to the flow of heat and electric current across the faying plane than the bond of weld A-1.

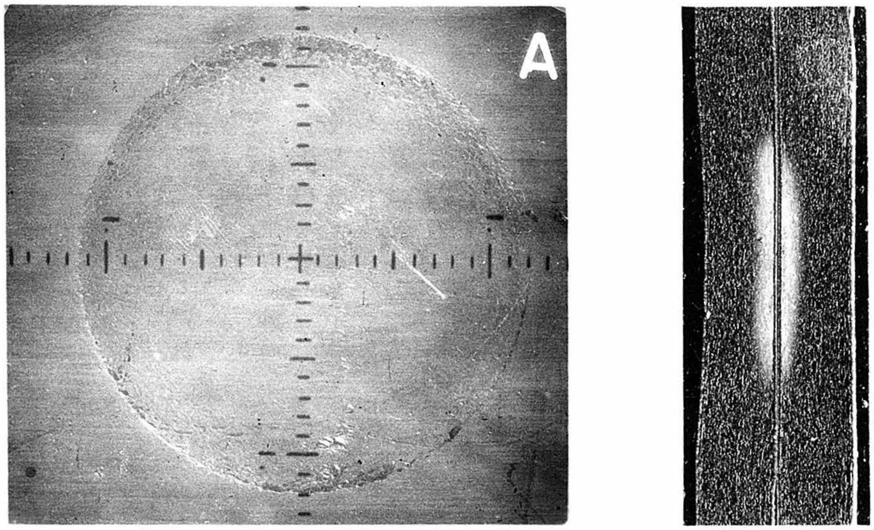
Weld A-3 -- made with increased energy shows a still larger area of Alclad bonding, and developed a static shear strength of 215 pounds. The resistance of this bond to the flow of electric current and heat is still less than that of Weld A-2, because of the increased bonding area.

All the welds of Type A, frequently called "stuck" welds, involve only Alclad or corona bonding without any nugget development whatever, and should be classified as worthless. This type of bonding results only under a locally ideal condition of surface preparation, such as wire brushing or careful etching. A fingerprint or the use of other methods of surface preparation may result in absoluetely no bonding under the same conditions of welding. Welds of this type have been frequently observed with much larger areas of Alclad bonding, which develop more than the Army minimum acceptable static shear strengths. The weld shear strength is directly proportional to the net area of true bonding, and the unit shear strength is near 10,000 psi.

Type B Welds - Elementary Nugget Formation

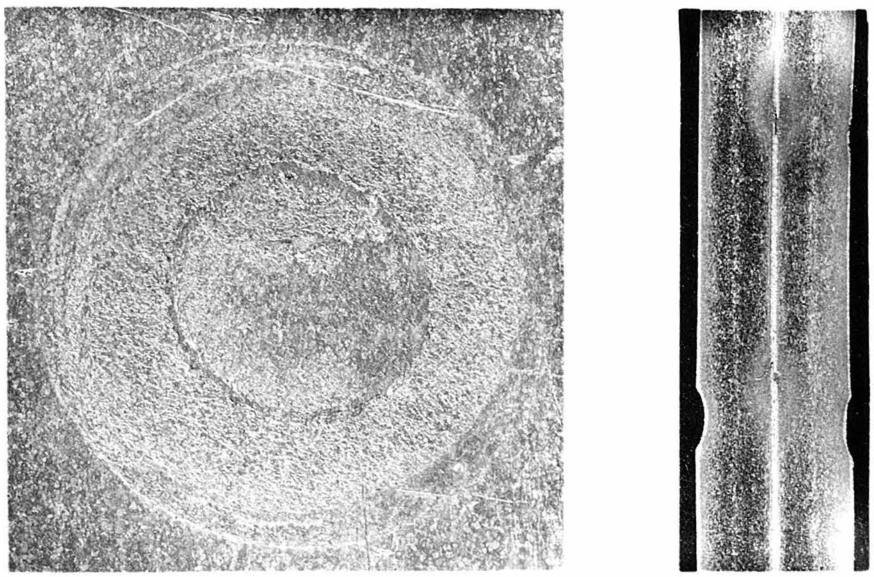
Weld B-1 -- shows the effect of a different method of surface cleaning upon the bond at the faying surface. Sufficient welding energy to provide an elementary nugget in both sheets has been supplied, yet almost no bonding whatever has occurred

TYPE B WELDS - - ELEMENTARY NUGGET FORMATION
WITH OR WITHOUT ALCLAD BONDING



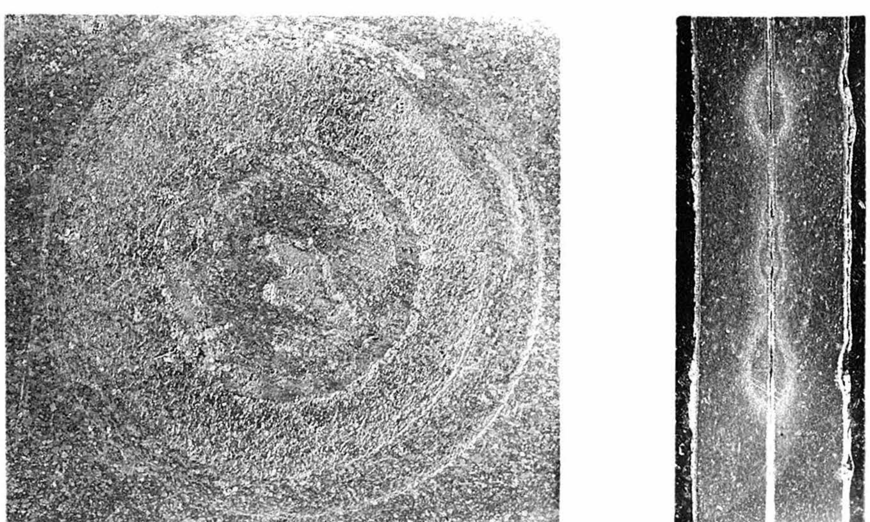
B - 1

STRENGTH BELOW
50
POUNDS



B - 2

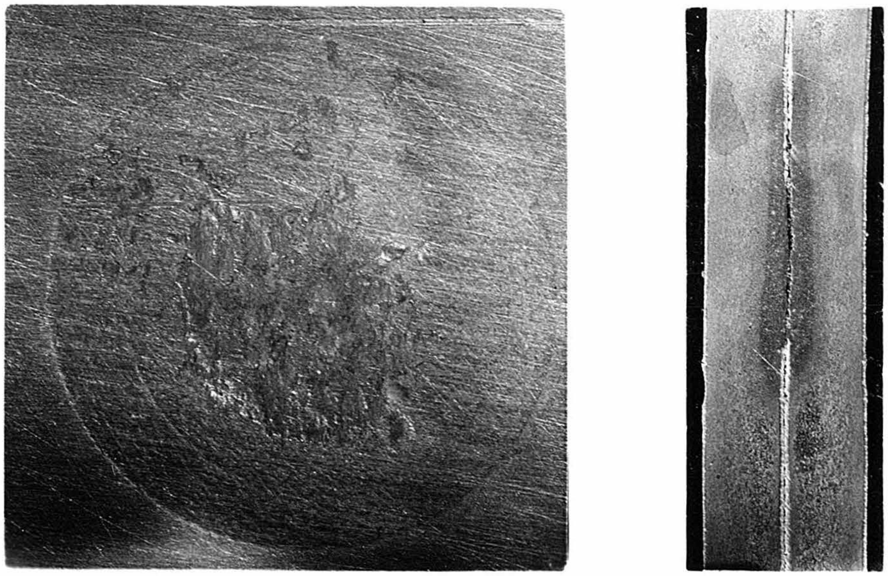
STRENGTH 360
POUNDS



B - 3

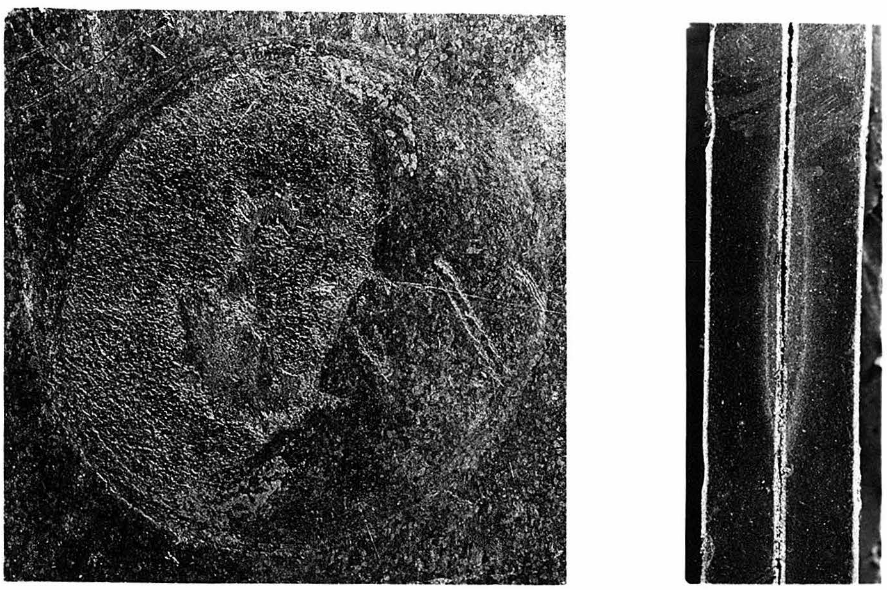
STRENGTH 580
POUNDS

FIG. 3



B - 4

STRENGTH 480 POUNDS



B - 5

STRENGTH 340 POUNDS

FIG. 3

save on the periphery of the heated area. This "weld" fell apart upon handling.

Weld B-2 -- represents a slightly higher weld energy than the welds of Type A, with very elementary tendencies toward nugget formation. Nearly 100% of the bonded area consists of Alclad bonding with an almost negligible area of cast alloy or nugget bonding. This weld failed at a shear load of 360 pounds, the increase in strength over weld A-3 resulting chiefly from the increased area of bonding.

Weld B-3 -- represents a further increase in weld energy, producing a "crescent" or "doughnut" shaped nugget development. Some of the Alclad layer has been melted and alloyed with the nugget material, permitting the cast alloy of the nugget itself to form a direct bond over a small ring shaped area. This weld developed 580 pounds in static shear test, most of the gain in strength over weld B-2 resulting not from a change in the area of bonding, but rather from a change in the type of bonding--from Alclad bonding to cast alloy bonding in the nugget area. The cast alloy bond usually develops about 20,000 psi. unit shear strength, approximately twice that characteristic of the Alclad bond. Thus this weld would not be discriminated from weld

B-2 by non-destructive tests involving only the measurement of the total area of bonding at the faying surface.

Weld B-4 -- made with still greater energy, developed a flat nugget of larger size, but seems to lack Alclad bonding entirely. Its strength of 480 pounds is consequently lower than might be expected. This failure of corona bonding may have resulted from local surface contamination of the faying plane, as by a fingerprint. Thus neither the relative size of nugget nor the relative bonded area of this weld can measure its strength reliably in comparison with preceding welds. Non-destructive tests based only on measurement of the conducting area at the faying plane would classify this weld as near to weld A-2, which has about 50% of its area, yet only 21% of its strength, and so the tests would be 100% in error. Tests based on nugget size alone would classify it as stronger than weld B-3, and would probably be 40 to 50% in error.

Weld B-5 -- developed a flat nugget comparable to that of weld B-4, but the total bonded area covered only half the usual circular area, and contained only a small area of cast alloy bonding. Consequently, this weld is weaker strength (340 pound) than welds B-2 and B-3.

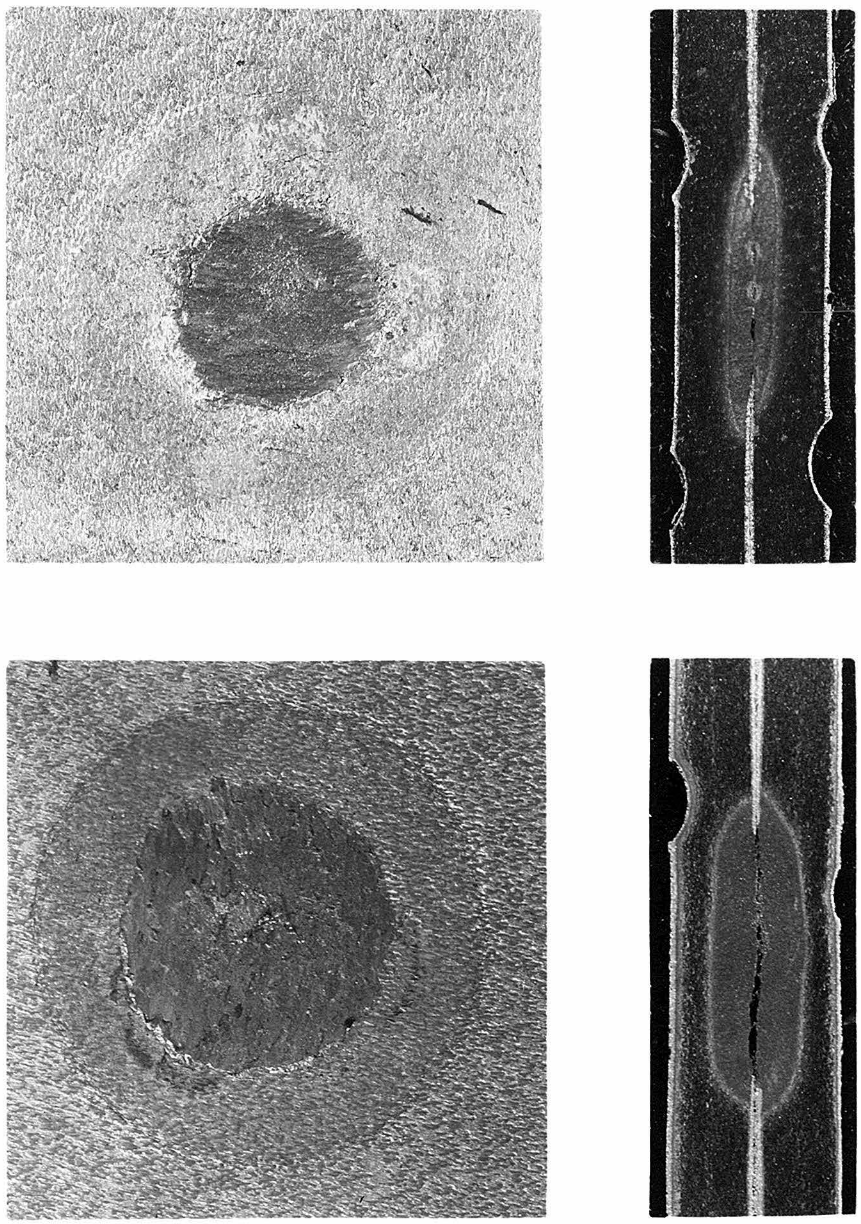
All the welds of Type B, frequently called "doughnut" or "crescent" welds, involve small regions of cast alloy or nugget development with or without extensive Alclad bonding depending upon conditions of surface preparation. The cast alloy bond develops about twice the unit shear strength of the complete Alclad bond. Hence weld strength is not measured reliably by the total area of bonding at the faying surface. Usually the strength varies widely between successive welds made under these welding conditions, so that all these welds are undesirable because of lack of consistency, even though a group of these welds may pass the minimum acceptable shear strength requirement.

Incidentally, the changes in weld energy in this group of welds were obtained with constant energy (current relay) setting of the Sciaky welder by advancing by varying amounts of time the application of forging pressure.

Type C Welds - Small Diameter Nuggets With Normal Alclad Inclusions and Low Penetration.

Weld C-1 -- has a small nugget of normal shape

TYPE C WELDS - - SMALL DIAMETER NUGGETS WITH NORMAL ALCLAD INCLUSIONS AND LOW PENETRATION



C - 1

STRENGTH 200 POUNDS

C - 2

STRENGTH 380 POUNDS

FIG. 4

and a reasonable amount of Alclad inclusion, typical of welds made with higher energy than the type B welds, but with insufficient energy to produce full size nuggets. Little Alclad bonding occurred on this weld. The weld strength is only 200 pounds. The penetration is low, amounting to about 30% of the sheet thickness.

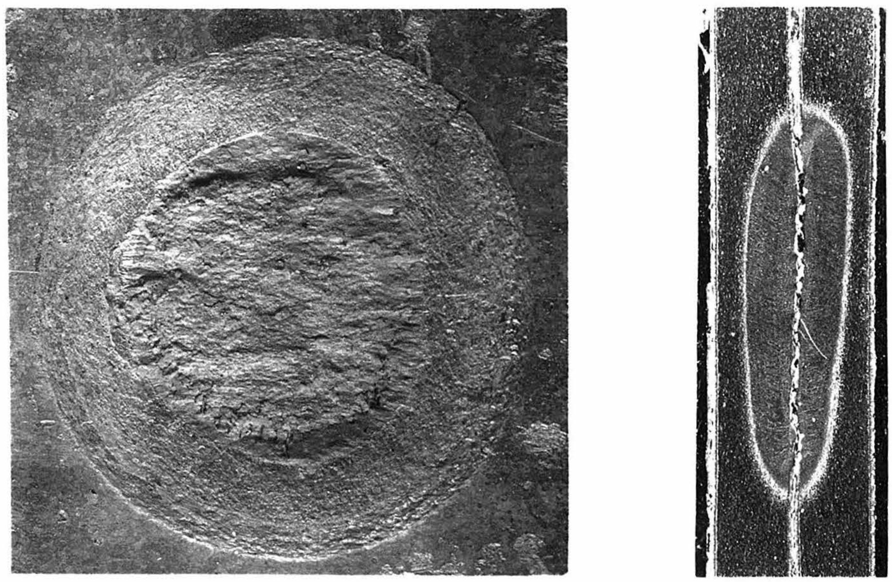
Weld C-2 -- was made with greater energy than weld C-1 and has somewhat larger diameter and about 55% penetration. The strength is 380 pounds. The nature of the corona bond on this weld is questionable.

Type C welds result under otherwise normal welding conditions when weld energy is slightly low for the production of normal size welds. If the corona bond happens to be extensive the welds develop normal static shear strength. However, if corona bonding is absent, the weld strength is low. Inconsistency of strengths results, particularly if surface preparation and cleaning of the sheet were inadequate.

Type D Welds - Normal Diameter Nuggets with Normal Penetration

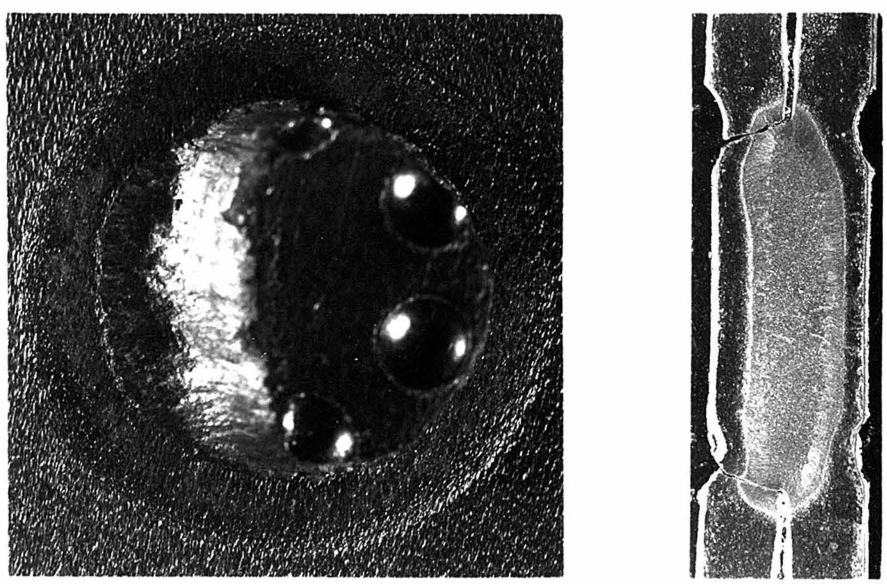
Weld D-1 -- is a weld of normal diameter, penetration, and shape. Its strength was 725 pounds.

TYPE D WELDS - - NORMAL DIAMETER
NUGGETS WITH NORMAL PENETRATION



D - 1

STRENGTH 725
POUNDS



D - 2

STRENGTH 580
POUNDS

FIG. 5

It has an adequate area of cast alloy bonding at the faying surface, to which corona bonding adds further strength. The Alclad inclusion is not excessive. The weld is "sound" i.e. it is free of cracks and porosity. The penetration is not excessive, since the heat affected zone does not extend to the surface of the 24ST alloy. This is the preferred type of weld. Its maximum strength has been realized because it failed by shearing through the nugget at the faying plane.

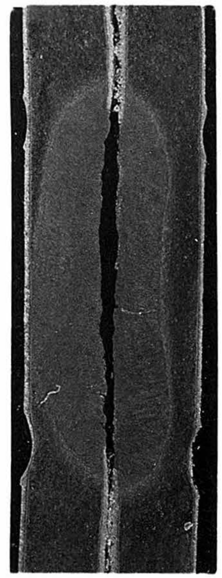
Weld D-2--is a weld of normal penetration and shape, with slightly larger diameter than weld D-1. It failed by "pulling a button", with partial shearing of the nugget, and so developed only 580 pounds shear strength.

The welds of Type D consistemtly develop acceptable static shear strength, and are characterized by normal diameter, well shaped nuggets of reasonable penetration. The welds are usually sound and free from defects (cracks, porosity, and lack of fusion).

Type E Welds - Oversized Nuggets with Excessive Penetration, Cracks, Porosity, or Spitting.

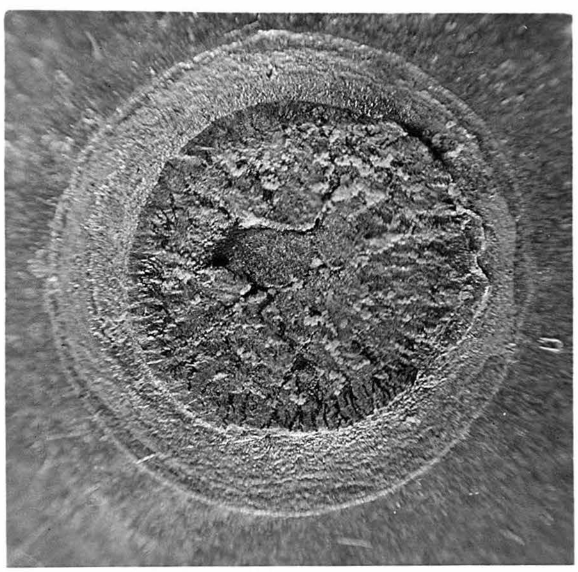
Weld E-1--has a nugget of normal diameter with excessive penetration into one sheet, and a tendency

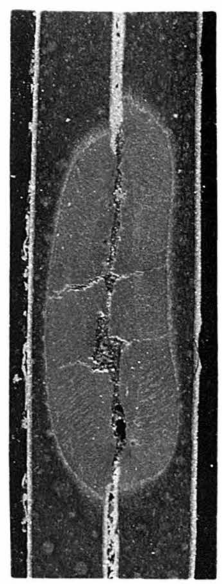
TYPE E WELDS - - OVERSIZE NUGGETS WITH EXCESSIVE PENETRATION, CRACKS, POROSITY OR SPITTING



E - 1

STRENGTH 700 POUNDS

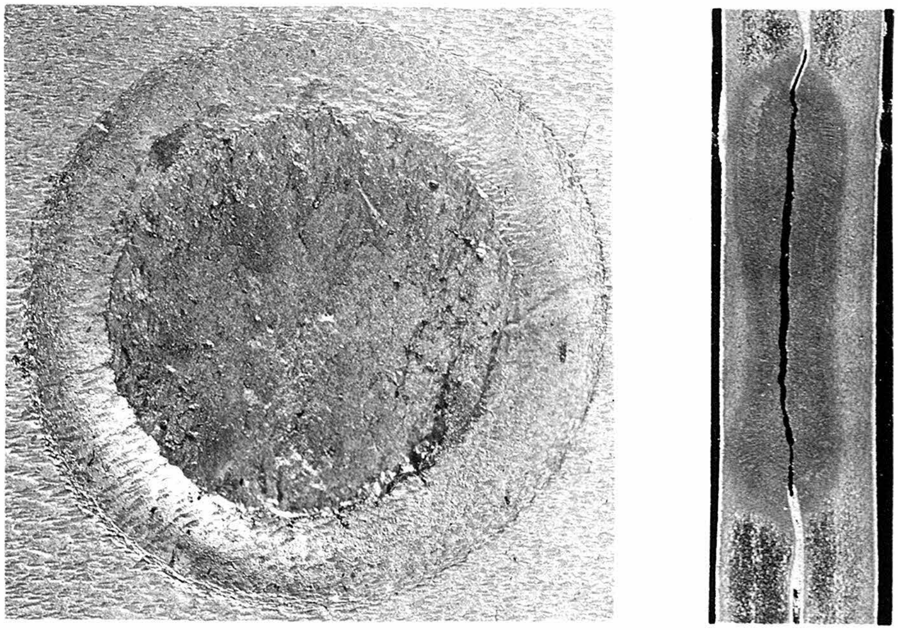




E - 2

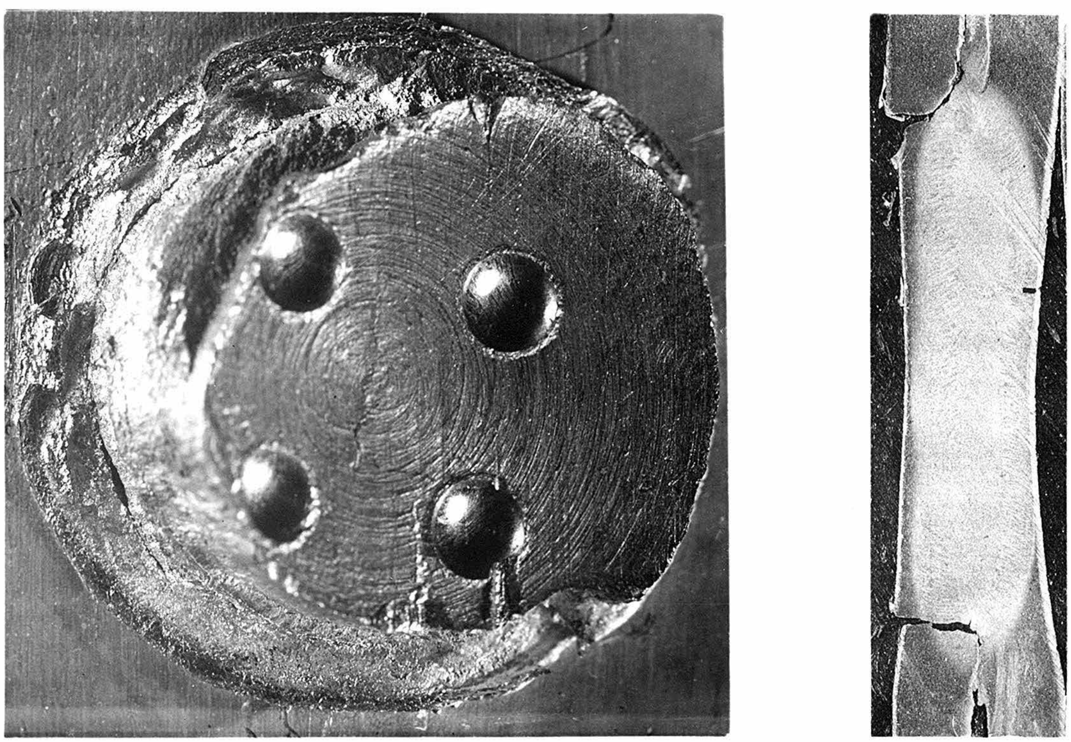
STRENGTH 590 POUNDS

FIG. 6



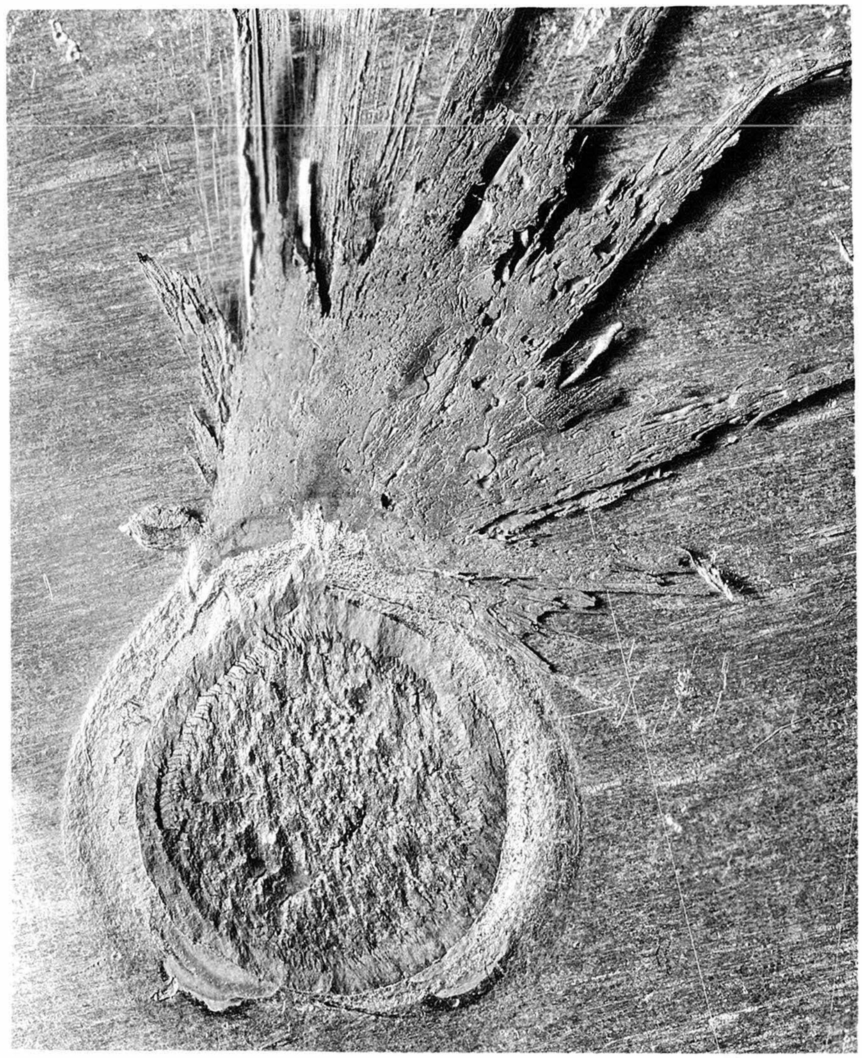
E – 3

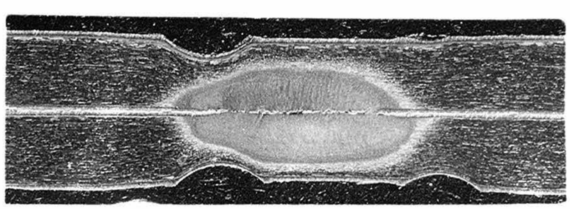
STRENGTH 680 POUNDS



E – 4 STRENGTH 1385 POUNDS

FIG. 6





E – 5 STRENGTH 640 POUNDS

FIG. 6

toward cracking in the nugget. Sheet efficiency may be impaired by the excessive penetration, and fatigue strength might be lowered through further growth of the cracks. Should the cracks extend themselves to the sheet surface, corrosion would further impair the weld quality. Strength was 700 pounds, no greater than that of a normal penetration weld with the same nugget diameter.

Weld E-2--shows excessive cracking in a weld of nearly normal nugget diameter and penetration. This results from inadequate electrode pressure during welding--in this particular case the application of forging pressure was purposefully delayed to obtain this result. The fatigue and corrosion resistant properties of the weld may be impaired. Strength was 590 pounds.

Nugget cracks usually lie in planes normal to the sheet surface, and radiate spoke-like from the center of the nugget. Current and heat flow through the bonded area normal to the faying surface are not appreciably affected by such cracks. X-rays, or eddy current flow parallel to the plane of the sheet will detect this type of cracking.

Weld E-3--has a large diameter nugget with excessive penetration into one sheet. Cracking is frequently present in such oversize welds, particularly where inadequate tip pressure has been used. Further increase in nugget size offers little advantage, for possible increase in static shear strength is offset by reductions in fatigue strength, sheet efficiency, ductility and corrosion resistance, when excessive penetration and cracking result.

Weld E-4--has an abnormally large nugget with excessive penetration and cracks extending to the sheet surface. It developed a static shear strength of 1385 pounds, but the crack would serve as a focal point for corrosion or fatigue failure.

Weld E-5--exhibits "spitting" at the faying surface, a condition which is usually accompanied by porosity and reduced strength (640 pounds).

Welds of Type E may occasionally develop greater static shear strength than normal welds, but this gain is offset by a decrease in strength consistency, and a probability of excessive penetration and cracking.

III - PROPOSED METHODS FOR THE NON-DESTRUCTIVE TESTING OF SPOTWELDS IN ALCLAD ALUMINUM ALLOY SHEETS

At the time this research was begun, several methods for the non-destructive testing of spotwelds in aluminum alloys had been proposed. Each of these methods involved an attempt to measure the total area of bonding at the faying plane, through the flow of direct current, alternating or eddy current, heat, vibration or sound waves across the faying plane at the bond. No reliable test of this type had been developed by previous research.

Also, radiographic methods of inspecting spotwelds had been developed to show great promise. (Ref. #4, 6, 8, 9 & 10) The radiographing of spotwelds, however, seemed unattractive to aircraft manufacturers because of the cost, time delay and skill required in testing, as well as the possibility of misinterpretation of the radiographs or misuse of the method. The practicability of the method had not been proven for industrial production inspection. It had not been shown that weld strength could be determined from radiographs.

Test methods investigated in this research are now listed and described. Methods proposed and developed independently at California Institute of Technology are indicated with a (ø) sign. Methods proposed elsewhere are indicated by a superscript letter. General information on the method is included where it may prove useful. These methods include:

(a) Visual Inspection of Spotwelds

(b) Electric Current (Conduction) Tests

(c) Eddy Current (Induction) Tests

(d) Thermal (Heat Flow) Tests

(e) Sonic and Vibration Tests

(f) Sheet Surface Condition Tests

(g) Impressor or Penetrator Tests

(h) Mechanical Proof Tests

(i) Radiographic Tests

A. <u>Visual Inspection of Spotwelds</u>

Quality control of spotwelds in the aircraft industry is obtained at present by: (Ref. #5)

1. Careful process control
2. Qualification testing of machines
3. Percentage destructive testing
4. Strength consistency tests
5. Weld metal structure tests, and
6. Visual inspection of welded parts and structures

Visual inspection is the only non-destructive test which has received general acceptance in the industry.

A skilled inspector, familiar with the conditions of preparation and welding, and the characteristics of particular machines in a given plant, can obtain a great amount of information concerning weld quality by visual inspection of the finished parts. Parts showing excessive indentations of the sheets by the welder electrodes are, of course, rejected for surfaces exposed to the air stream.

The presence of spits or flashes, or evidence of excessive tip pick-up, often indicates bad welding conditions. Welds with cracks extending to the sheet surface are easily observed, and cannot be accepted because these cracks serve as focal points for corrosion. Evidences of excessive sheet separation indicate bad welding conditions, with possible expulsion of metal from the weld zone and resultant cracks or porosity. Certain surface conditions can be correlated with ductility or, conversely, with brittleness in the weld. Under controlled conditions of welding, nugget size, weld energy, and timing of forge pressure can be correlated with surface indentation of the sheet. Good judgment on the part of the inspector is required as surface conditions do not provide complete information as to weld quality.

3. Electric Current Conduction Tests

Indications obtained in electric current conduction tests depend upon the measurement of resistance in the weld region. They depend in particular upon the geometry of the conducting path, and upon the specific resistivity of volumes and surface regions in that path. Due to the very low resistance of aluminum alloys, even with a current path limited to the weld region (to obtain sensitivity to weld conditions), large currents (10 to 100 amperes) are usually required. Sensitive pickup units with low internal resistance, designed to respond to 5 to 100 micro-volts, are needed. Only a small portion of the total energy input to the weld region is available to actuate the indicating instrument in the pickup system. The relatively large effects of contact resistances and thermal electromotive forces must be reduced in the measuring circuits.

It is difficult to detect variations in the specific resistivity in the various metallurgical regions of the spotweld, from the outer surface of the sheet. Despite the fact that 24ST has approximately twice the resistivity of 2SO, and about 167% of the resistivity of 24SO, the usual weld nugget has little resistivity effect upon electrical measurements from the outer surface of the sheet. There are no boundary regions of very high resistance between the nugget and the parent metal. For welds of normal or low penetration, the overlying layer of parent metal tends to mask small changes in resistivity within the nugget.

As an example of this condition, a rectangular prism containing half a weld nugget was cut from an .064" 24ST Alclad sheet containing typical spotwelds. The sides of the prism were machined smooth and parallel, resulting in a block .064" x .020" x 1" containing half the weld nugget, as shown in Fig. 7. Direct current was passed through the strip from end to end. The potential distribution was measured by means of a potentiometer easily adjusted to 1/2% of the total voltage drop in the piece, through the use of a sharpened aluminum alloy probe and a dividing engine. The potential distribution was found to be that shown in Fig. 7 for measurements on the side of the block which had been the faying plane. No significant discontinuities exist. Measurements on the opposite side of the block showed a linear potential distribution. Similar profiles in which the difference in voltage between two probes .04" apart was measured as the probe assembly was moved

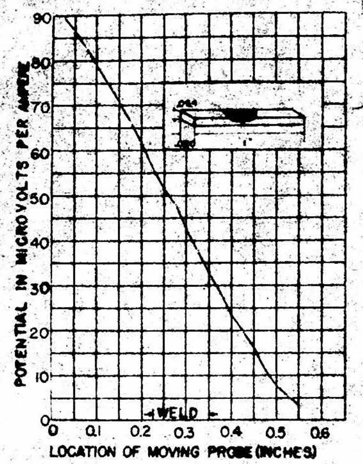


Fig. 7. Potential Distribution Along The Surface Of A Prism Cut Out Of An Alclad Sheet Containing A Spotweld Nugget, With Direct Current Flowing Along Strip.

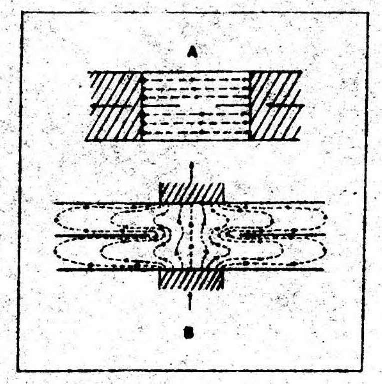


Fig. 8. Measurement Of Bonded Area Of A Spotweld By The Flow Of Electric Current.
A. Current Flow Parallel To The Faying Plane Does Not Measure The Area Of Bonding.
B. Current Flow Normal To The Faying Plane Does Measure The Area Of Bonding.

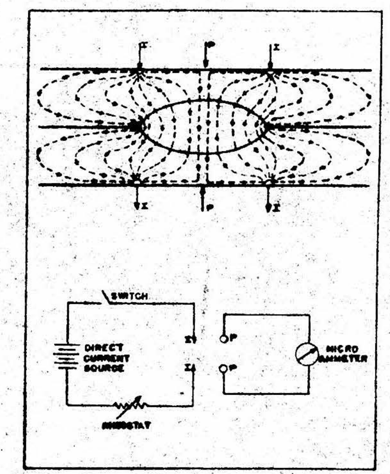


Fig. 9. The Two-Side Direct Current Test Of The Bonded Area At The Faying Plane Of The Spotweld. Current Flows Between Cylindrical Electrodes In Contact With Top And Bottom Sheet Surfaces At I. Potential Is Measured Between Probes (P).

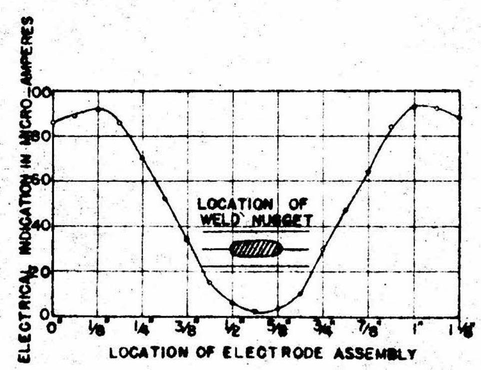


Fig. 10. Results Of A Two-Side Direct Current Profile Test Of A Small Spotweld In .064" 24ST Alclad.

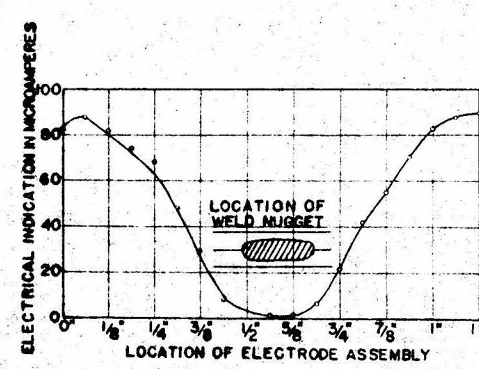


Fig. 11. Results Of A Two-Side Direct Current Profile Test Of A Large Spotweld In .064" 24ST Alclad.

along the piece also showed no resistance discontinuities. In the absence of pores and cracks, therefore, it is obviously very difficult to use specific volume resistivity measurements from the outer surface of the welded sheets to measure weld size or quality.

It is feasible to detect variation in the total conducting area of the bond between the sheets at the faying plane of a spotweld. This may be done by using direct current flowing across the faying plane (normal to the sheet surface) at the bond. Several direct current tests of this type have been proposed. Direct current flowing in the plane of the sheet does not measure the area of bonding, unless a sizeable normal component of flow through the bond can be established. (See Fig. 8)

Advantages of direct current methods lie in their simplicity and their immediate response.

Disadvantages of direct current test methods lie in the difficulties of establishing satisfactory probe systems without excessive contact resistance or thermal electromotive forces, as well as in the small energy available in the pickup system.

1. Two Side Direct Current Test[a] ∅

In this test, a large direct current is passed from a current electrode (I) in contact with the sheet surface above the spotweld through the weld normal to the faying plane to a similar current electrode in contact with the sheet surface below the spotweld. (See Fig. 9) Potential probes (P) in contact with the outer sheet surfaces and connected to a low resistance galvanometer, measure the potential drop through the weld. This test measures the total bonded area at the faying plane of the weld. For welds with small areas of bonding, the lines of current flow are crowded together at the faying plane and produce a relatively higher potential drop than for welds with a large area of bonding. (Figs. 10 & 11) Higher potential readings thus tend to indicate smaller, and presumably weaker, welds.

Precautions to be observed in making this test are:

1. The current electrodes must be fixed relative to one another and be very carefully centered above the actual weld. (Incidentally, the weld may not be centered under the impression of the tip of the welder electrode.) A displacement of the current electrode 1/16" from the optimum point with respect to the weld may introduce a 100% change in potential indication. (See Fig. 10) Each area of the current electrode must make the same degree of contact, and carry the same proportion of the total current, on successive measurements, in spite of variations in the geometry of the indentation of the sheet surface by the welding tips.

2. The potential probes must be very carefully and permanently located with respect to the current electrodes. A displacement of 1/64" produces a large error in potential indication. Centering the potential probe symmetrically with respect to the current electrodes, so as to measure only the voltage drop due to current flow normal to the sheet surface,

has been shown to give optimum sensitivity.

3. The potential probe should have a sharp tip of a hardened alloy, capable of puncturing the oxide film on the surface of the aluminum sheet without requiring the application of excessive pressure or penetrating a variable distance into the sheet. Low, constant contact resistance must be obtained. Furthermore, the potential probes must be made of an alloy which develops only a very small thermal emf. when in contact with aluminum. This is necessary because the potential drop across the weld amounts to only a few microvolts (0 to 50) in ordinary welds, for total currents large enough to heat the weld region appreciably.

4. The applied pressure and total test current should not be large enough to cause further fusing of Alclad at the faying surface, as this naturally introduces erroneous test indications.

5. Cleaning the sheet surfaces above the weld with steel wool and acetone tends to improve test consistency.

Inherent errors in this test method, present even when test equipment is correctly designed, accurately built, and properly used, are:

1. An error in predicting weld strength amounting to as much as 100% of actual weld strength, resulting

from the inability of this test to discriminate the relative areas of Alclad and nugget bonding at the faying plane. Both types of bonding have low resistance in comparison with the unbonded oxide coated areas of the faying plane, and both types of bonding serve equally well as electrically conducting areas in this test.

2. An error of as much as 100% in potential indication, resulting from displacements of the electrode assembly by 1/32" or more from concentricity with the bonded area at the faying plane. Since there is no indication on the outer sheet surface of the exact location of the bond at the faying plane, save the indentation caused by the welder tips, this error cannot be remedied except by profiling the weld region to obtain a minimum indication. Results of typical profile electrical tests on welds are given in Figs. 10 & 11.

3. An error of variable magnitude resulting from variations in the shape of the conducting area at the faying plane. A long narrow bonded area might develop the same shear strength as a circular bonded area of equal magnitude, but test indications would vary.

4. An error of variable magnitude resulting from the presence of adjacent welds or rivets near the weld under test. A portion of the testing current is shunted through these adjacent bonded areas, lowering the test

indication. Similar large errors in indication may result when "spits" or expulsion of metal occur and bond the faying surface near the weld under test.

Improvements in this test method were obtained by following the listed precautions, and, in addition:

1. By modifying the originally proposed 3 point current electrode assemblies to use 4 to 6 points (ø) or areas of contact arranged in a circle, or a cylindrical surface. This eliminated errors occuring on welds of type B-3 or B-4, when chance alone determined whether only one, or two of the current electrodes in the 3 electrode assembly lay over the bonded half of the weld.

2. By selecting the diameter of the circular current electrode slightly larger than the bonded area of the normal weld, optimum sensitivity to weld area was obtained, with minimum shunting of current through adjacent welds.

3. By applying a measured pressure (ø) to the current electrodes which were accurately aligned in the form of a circle of spherical contacts or a cylindrical contact, variation in depth of penetration of the current electrodes into the sheet, and errors in alignment, were greatly reduced.

Advantages of the two side direct current test include:

(a) its simplicity, (b) its great sensitivity to weld presence (indications increase by a factor of 80:1 as the electrode assembly is moved off a weld to a point half way between two welds one inch apart), (c) its effectiveness in measuring the area of contact regardless of type of bonding present (the extent of Alclad bonding is very difficult to measure by other methods):

Disadvantages of the two-side direct current test include: (a) its inability to measure strength due to the weld nugget separately from the effect of Alclad corona bonding. (b) its inherent errors, (c) the fact that it requires access to both sides of the weld, (d) the large testing currents required, (e) the small energy available in the potential circuit.

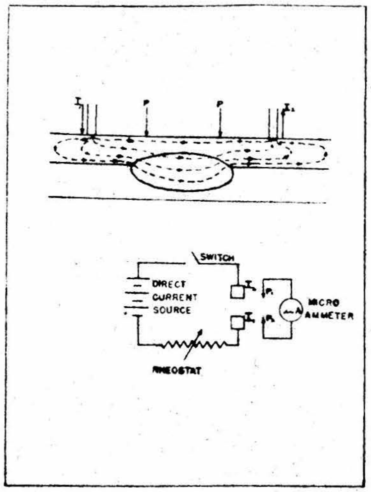
Description of test equipment and detailed results of two-side direct current tests on a large number of industrially made spotwelds are given in Sections V and VII, respectively.

2. One-Side Direct Current Test[b]

In this test, a direct current is passed between two current electrodes (I) both of which are in contact with the same outer sheet surface above the spotweld. The potential drop between two probes (b) placed on the center line of the current electrodes, also in contact with the same outer surface of the sheet is measured by a potentiometer or low resistance glavanometer (See Fig. 12). In the weld region, some of the current tends to flow down below the faying plane through the bonded area, reducing the current density in the upper sheet above the weld. Thus the potential gradient is lowered above a spotweld with a large area of bonding, and lower potential indications result.

Precautions identical with those listed for the two-side test must be observed with this method.

Inherent errors identical with those listed for the two-side test exist with this test method. In addition, the one-side test is very much less sensitive to the presence of a weld (let alone its size) than the two-side test. Whereas the two-side test indication changes by a factor of 80:1 as the test assembly is moved from a location 1/2" from the weld to a point over the weld, the one-side test changes its indication less than 20% with a similar movement of the assembly. Since only a small fraction of the total current flows below the faying plane at the weld, the percentage change in indication between small welds and large welds is less than 10%, under optimum test conditions involving only one weld in a 1" wide shear test strip. See Fig. 13 for typical results of of tests made on 29 spotwelds in one inch one spot lap joint



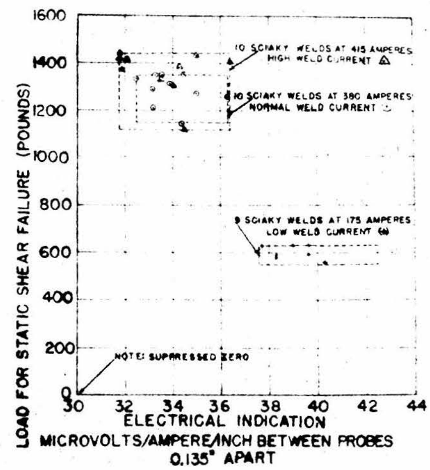
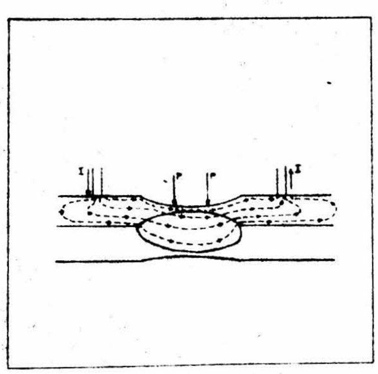


FIG. 12. THE ONE-SIDE DIRECT CURRENT TEST OF THE BONDED AREA AT THE FAYING PLANE OF THE SPOTWELD. DIRECT CURRENT FLOWS BETWEEN I_1 AND I_2 THROUGH SHEET POTENTIAL IS MEASURED BETWEEN P_1 AND P_2.

FIG. 13. RESULTS OF ONE-SIDE DIRECT CURRENT TESTS ON SINGLE SPOTWELD SPECIMENS IN ONE INCH SHEAR TEST STRIPS. NO DIFFERENCES IN INDICATION ARE OBTAINED BETWEEN LARGE AND SMALL WELDS IN EXTENDED SHEETS BY THIS TEST.



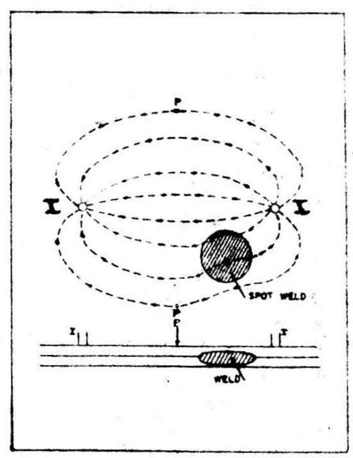


FIG. 14. EFFECT OF SHEET INDENTATION IN MASKING INDICATIONS OF BONDED AREA AT THE FAYING PLANE BY THE ONE-SIDE DIRECT CURRENT TEST.

FIG. 15. WHEATSTONE BRIDGE FORM OF THE ONE-SIDE DIRECT CURRENT TEST OF THE BONDED AREA AT THE FAYING PLANE OF THE SPOTWELD. CURRENT FLOWS BETWEEN CONTACT POINTS (I). POTENTIAL IS MEASURED ACROSS EQUIDISTANT POTENTIAL PROBES (P). THE ELECTRODES FORM A WHEATSTONE BRIDGE CIRCUIT, WHICH IS UNBALANCED BY THE PRESENCE OF A WELD.

test strips of .064" 24ST Alclad sheet. In large sheets containing many welds, the change in indication becomes exceedingly small and very difficult to detect--experiments on industrially made welds showed this change to be entirely masked by the inverse effect of the indentation of the sheet by the welder electrode. (See Fig. 14). The limits of sensitivity of this method, determined by calculations, and checked by potential measurements in a large scale salt-water model of the conductor in the weld region, are very low. In practice, it is difficult to realize even a fraction of the theoretical limit of sensitivity.

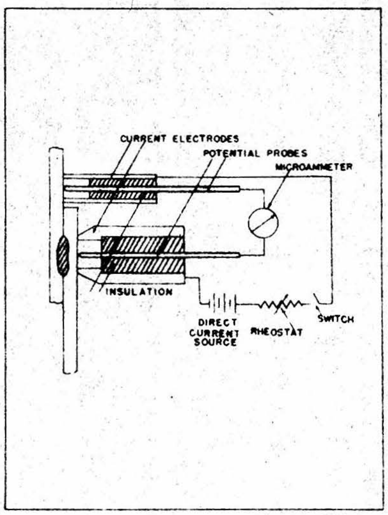
Improvements in this test method were obtained by following the listed precautions, and in addition by modifying the electrode assembly to form a Wheatstone bridge circuit with the weld under one leg of the bridge. (See Fig. 15). The direct current passes through the sheet from electrode I_1 to electrode I_2. The weld, if adequately bonded, lowers the resistance of one leg of the bridge. A potential appears between P_1 and P_2 due only to the effect of the weld in unbalancing the current distribution. A far greater percentage change in indication with change in weld size is obtained than with the unmodified one-side test. This test also discriminated welds with large bonded area from welds with small bonded area in single spotweld 1" test strips, but suffered great loss of sensitivity when applied to large sheets with many welds.

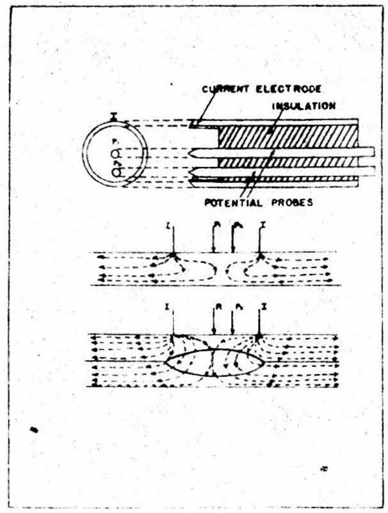
The advantage of the one-side test lies in the fact that access is required to only one side of the welded structure. Although 90% to 95% of all spotwelds in aircraft structures are accessible from both sides at some point in the fabrication process, this test would make possible the testing of welds even on closed structures.

The disadvantages of the one-side test lie in its inherent errors and in its very low sensitivity. Only small deflections can be obtained, even with long period, high sensitivity galvanometers in the potential circuit. Test indications are affected as much by sheet indentation as by the presence of weld bonding. No practical reliable form of this test has been developed as yet.

3. Lap Joint Direct Current Test (ø)

In this test a direct current is passed through the weld between two current electrodes, one of which is in contact with the top surface of the upper sheet directly above the weld, while the other is in contact with the top surface of the lower sheet adjacent to the weld. (See Fig. 16). The major part of the current thus passes normally through the faying surface of the weld under investigation. The potential probes are located at the centers of the cylindrical current electrodes, in one form of the test assembly. Variations in the area of bonding at the weld introduce variations in the potential drop near the faying





5. THE LAP JOINT DIRECT CURRENT TEST OF THE BONDED AREA AT THE FAYING PLANE OF THE SPOTWELD.

FIG. 18. ONE ELECTRODE DIRECT CURRENT TEST OF THE BONDED AREA AT THE FAYING PLANE OF THE SPOTWELD.

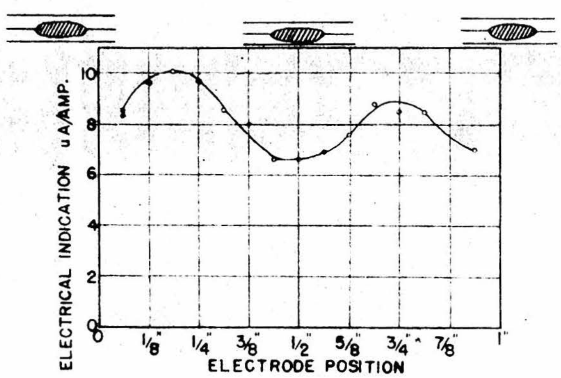


FIG. 17. SENSITIVITY OF THE LAP JOINT DIRECT CURRENT TEST TO THE PRESENCE OF SPOTWELDS, AS SHOWN BY PROFILE TESTS.

surface which tend to introduce variations in the total drop between the potential probes. Higher potential drops should occur with weak welds of small bonded area.

Precautions to be observed in making this test include those listed for the two side d.c. test, except that the current electrode in contact with the lower sheet must be in a fixed position with respect to the weld, as close as possible to the weld. This electrode should contact only the lower sheet.

Inherent errors, similar to those listed for the two side d.c. test, exist for this method. In addition, much larger errors, due to extended path of current flow along the lower sheet, result from variations in geometry of structure, edge effects, adjacent welds, and amount of overlap in the lap joint.

The disadvantage of this test, which makes it worthless, is its very low sensitivity. The maximum possible variations in the total potential which could result from varying the geometry of bonding at the faying surface of the weld are only 5 to 10% of the total potential drop. This is not nearly a sufficient degree of sensitivity. Uncontrollable variations due to other factors are of the same order of magnitude. In general, the variations at the faying surface are completely masked, and the test is of no value.

Fig. 17 shows the sensitivity of the assembly to the presence of a weld. The assembly was moved lengthwise over the surface of the weld, and readings taken every 1/16". Comparison of this curve with Figs. 10 & 11 for the two side test shows clearly how much less sensitive this assembly is to the presence of a weld. In the two-sided test, the ratio of potential measurement halfway between welds to potential measurement directly over the weld is about 80 to 1; whereas in this case the ratio is only about 1.5 to 1.

4. One Electrode Direct Current Test (ø)

In this test, current passes into the weld region from one electrode (frequently a ring contact), and is collected from the spotwelded structure at remote points. Two potential probes (P) are radially displaced within the current electrode (I). (See Fig. 18). Over the center of a uniform sheet, very little potential difference appears across the potential probes when current flows away from the current electrode symmetrically through the sheet. If current flows into the lower sheet of a joint through a weld under the electrode assembly, a larger difference of potential appears between the radially displaced potential probes. The potential distribution in the weld region is similar to that obtained with heat flow from a source in contact with the sheet surface. The variability of the return current path makes this test less reliable than even the lap joint direct current test.

5. Alternating Current Conduction Tests (ø)

Each of the types of test described for direct current might conceivably be used with alternating current, provided inductive pickup could be eliminated from the potential probes and leads, and provided a suitable detector for 5 to 50 microvolts a.c. can be supplied. A.C. galvanometers are too insensitive for use as potential indicators, so vacuum tube amplifiers with stable calibrations are usually indicated. A d.c. galvanometer used with a suitable copper oxide rectifier of very low resistance can also be applied, for larger potential drops.

In addition to the precautions listed for direct current tests, especial care must be used to avoid inductive pickup in the potential probes and leads. The resistance drop of potential across the weld is so small that the inductive pickup in unshielded potential leads would be several hundred times larger. Even though this induced voltage be 99% cancelled by a reverse inductive voltage purposely introduced in the potential circuit, a large error in indication would remain. This difficulty nullifies other apparent advantages in the use of alternating current.

Inherent errors, identical with those listed for corresponding d.c. tests, exist with alternating current conduction tests.

Advantages of alternating current over direct current in conduction tests lie in the simplicity of high current power supply transformers and the possibility of instantaneous indications.

Disadvantages due to inductive pickup and lack of sensitive a.c. potential indicators have been cited.

C. Eddy Current - (Induction) Tests

Several types of eddy current tests have been proposed. In these tests, alternating magnetic fields are established in the region of the weld, resulting in a flow of alternating electric current through closed paths within the welded sheets. Since the resistivity differences of the various regions of sound welds are too small to serve effectively for discrimination of weld quality, eddy current tests, like conduction tests, must measure the area of bonding at the faying plane to predict weld strength. This can be achieved only by a flow of current normal to the faying surface at the bond.

But in thin conducting sheets it is very difficult to establish a significant component of current flow normal to the sheet surface. A variety of induction assemblies have been tried, some even using massive blocks of good conductor to force the magnetic field down into the sheet, with no success whatever in establishing a significant amount of current flow normal to the faying surface at the bond. Detection devices producing eddy currents flowing predominately in planes parallel to the sheet surfaces have not been able to differentiate between good and bad spotwelds. (See Fig. 19).

Eddy current test devices respond sensitively to sheet surface geometry, weld cracking, and porosity. (Ref. #11). They are applicable in detecting these conditions which may correlate with the fatigue strength of the weld, but which do not measure static shear strength. No eddy current device proposed and known to the author measures static shear strength effectively.

Advantages of eddy current test methods are: (1) access is required to only one side of the welded sheet, (2) no electrical contact with the sheet surfaces is required, (3) instantaneous indications are possible, (4) depth sensitivity may be adjusted by choice of frequency.

Disadvantages of eddy current test methods are: (1) difficulty is encountered in establishing current flow normal to the bonded area at the faying surface, (2) probe assemblies pick up very little energy, (3) cracks, porosity and sheet indentation tend to affect indications [illegible]

FIG. 20 TRANSFORMER LOADING EDDY CURRENT INDUCTION TEST OF SHEET THICKNESS, WELD CRACKS, POROSITY, AND SHEET INDENTATION.

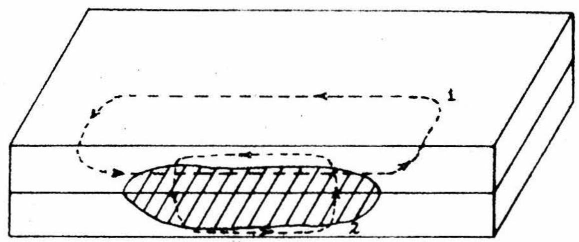


FIG. 19. EFFECT OF PLANE OF FLOW OF EDDY CURRENT UPON MEASUREMENT OF BONDED AREA AT THE FAYING PLANE OF THE SPOTWELD.
A. EDDY CURRENTS FLOWING IN PATH 1 PARALLEL TO THE FAYING SURFACE DO NOT MEASURE AREA OF BONDING.
B. EDDY CURRENTS FLOWING IN PATH 2 NORMAL TO THE FAYING SURFACE DO MEASURE AREA OF BONDING.

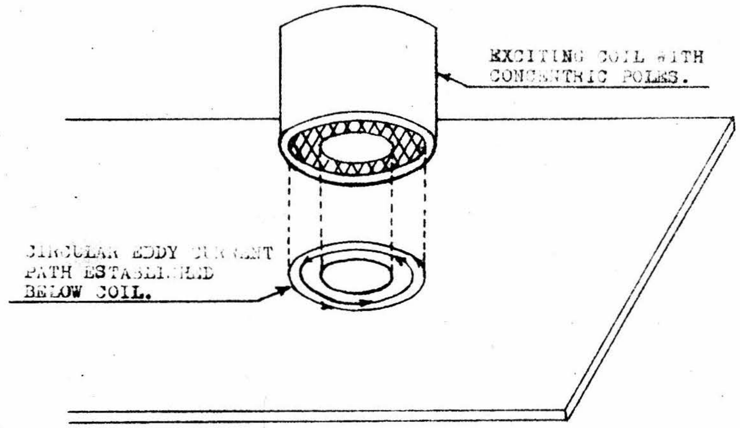


FIG. 20 A. EXCITING COIL AND CIRCULAR EDDY CURRENT PATH ESTABLISHED.

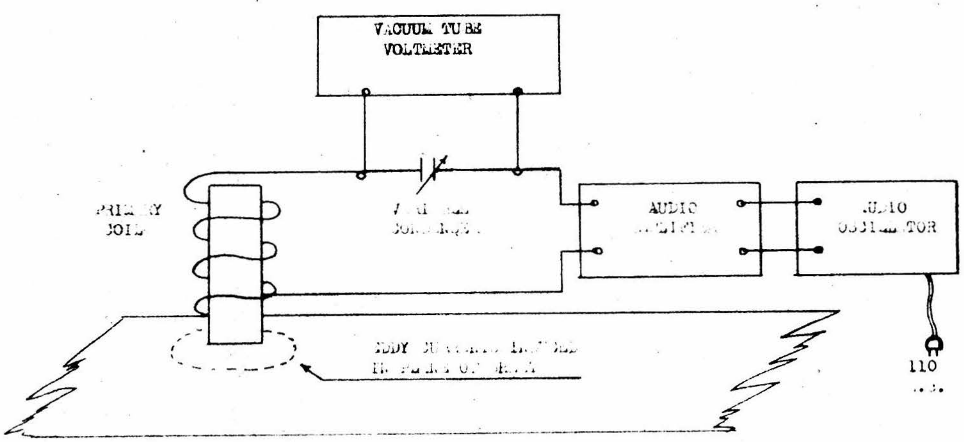


FIG. 20 B. SERIES RESONANT CIRCUIT USED WITH TRANSFORMER INDUCTION TEST.

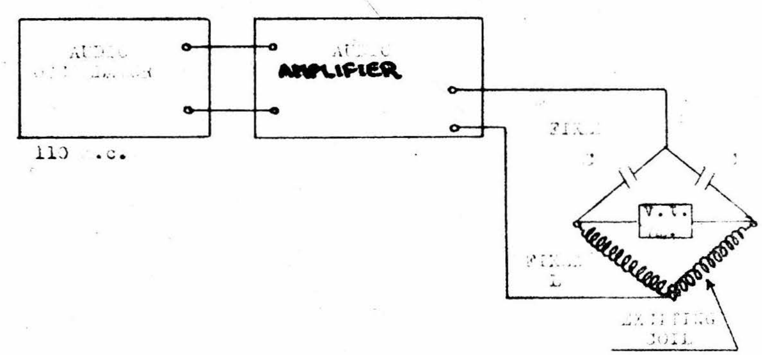


FIG. 20 C. RESONANT BRIDGE CIRCUIT USED WITH TRANSFORMER INDUCTION TEST.

far more than does the area of bonding at the faying plane, (4) edge effects and adjacent welds affect indications, and (5) even if eddy current flow could be established normal to the faying plane at the weld bond, no discrimination between cast alloy bonding and Alclad bonding (with only half the strength of the former) could be obtained.

1. Transformer Loading Induction Test (ø)

The simplest eddy current induction test unit consists of a coil carrying alternating current placed above the conducting sheet so as to produce eddy currents which act as a secondary transformer load on the coil. Using cores of powdered iron in wax moulded about small coils, a highly sensitive system of measuring sheet thickness, surface indentation, and resistance to the flow of eddy currents flowing in planes parallel to the sheet surface has been obtained. No pickup coils or amplifiers are used; instead the coil and a suitable condenser are made parts of a series resonant arm of an a.c. bridge, the flow of eddy currents in the sheet being reflected in the coil by increased primary coil current. (See Fig. 20). The change in inductance due to the secondary currents detunes the resonant circuit, and for a coil Q* as low as 20, a 300%

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* -- Q is the ratio of stored energy to dissipated energy in the coil, and is given by $Q = W^{L}/R$, where $W = 2\pi$ times the frequency, L is the inductance, and R is the effective resistance of the coil.

change in voltage across the condenser occurs when the unit is lifted from the surface of the conducting sheet. A 2% change in the thickness of an .080" sheet can be readily detected, without the bridge circuit, by measuring changes in voltage across the condenser with a vacuum tube voltmeter (1% changes are observable with the bridge circuit assembly).

The location of the eddy current path in the conducting sheet can be controlled by the use of a concentric pole assembly which can be easily formed to any desired shape (using the powdered iron in wax). A few of the more useful configurations are shown in Fig. 21. The depth of penetration of the eddy currents may be decreased by increasing the applied frequency. A quick check on eddy current penetration may be obtained by bringing a massive block of conductor into contact with the sheet surface opposite the coil, and observing the highest frequency at which it affects the indication.

No arrangement of pole pieces has yet been devised to force sizeable components of the eddy currents to flow normal to the sheet surface at the weld. The flow of eddy currents in small circular paths in the plane of the sheets has proven very effective in detecting weld cracking and porosity. Such weld cracks are usually radial cracks, normal to the sheet surface, extending outward from the center of the weld nugget, and so lie

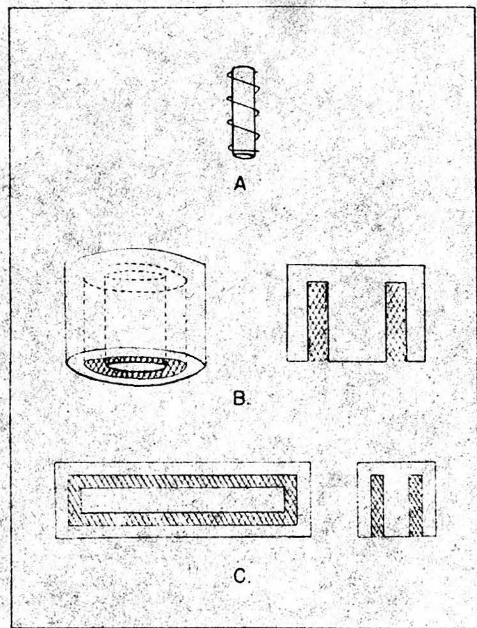

FIG. 21. USEFUL CONFIGURATIONS OF EDDY CURRENT INDUCTION POLE ASSEMBLIES.
A. SINGLE CORE ASSEMBLY USED TO MEASURE SHEET THICKNESS.
B. CONCENTRIC CIRCULAR POLE ASSEMBLY USED TO RESTRICT EDDY CURRENTS TO A CIRCULAR PATH.
C. RECTANGULAR POLE ASSEMBLY USED TO RESTRICT EDDY CURRENTS TO A RECTANGULAR PATH.

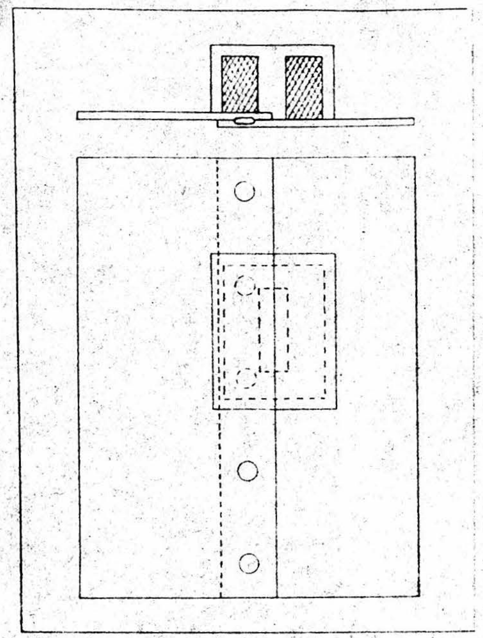

FIG. 23. THE LAP JOINT TRANSFORMER INDUCTION TEST OF THE BONDED AREA AT THE FAYING PLANE OF THE SPOTWELD.

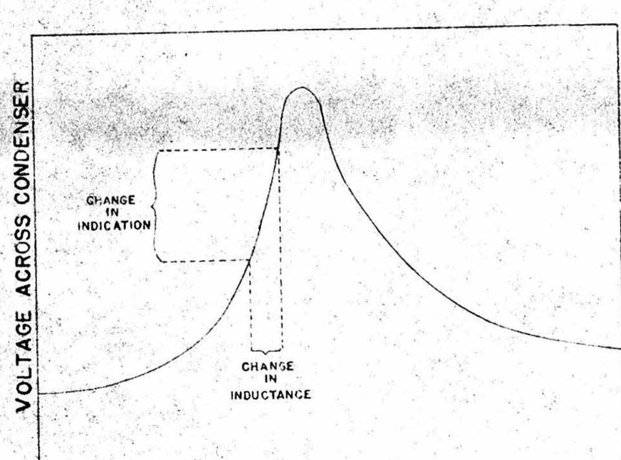

FIG. 22. RESONANT CIRCUIT RESPONSE OF TRANSFORMER EDDY CURRENT INDUCTION UNIT. SMALL CHANGES IN INDUCTANCE PRODUCE LARGE CHANGES IN INDICATION.

directly across the path of the circular currents. (See Figs. 6 & 20) The indication measures the overall extent of cracking and porosity, without measuring the geometry of individual cracks.

This device is also sensitive to the air gap between the pole pieces and the sheet surface. Thus it responds to indentation of the sheet by the electrodes of the welder, and actually has appeared to discriminate between good and bad welds through the measurement of the increased indentation which tends to accompany larger weld nuggets.

Precautions to be observed in using the transformer eddy current assembly are: (1) frequency must be selected to obtain eddy current penetration adequate for sensitivity to weld properties, (2) the air gap between pole pieces and sheet surface must be maintained constant, (3) corrections must be made for changes in sheet thickness, material, and temper, and (4) it must be recognized that current flow is predominately in the plane of the sheet and that the test does not measure static shear strength of spotwelds, since its indications are independent of the bond between the sheets.

Inherent errors in this test method are (1) its inability to discriminate among porosity or small cracks, certain larger crack defects, and local changes in the resistivity of the material.

Improvements in this test method were obtained by using low loss powdered iron in a highly insulating wax, and operating at the highest frequency consistent with adequate penetration of eddy currents into the sheet under test.* A high coil "Q" was thus obtained, resulting in a sharp, high resonant peak in the low resistance circuit. By operating on the steep slope of the resonance curve (see Fig. 22) maximum sensitivity to sheet resistivity conditions is obtained. By including the coil or capacity in one leg of an a.c. bridge, the indicator may be set to zero when the coil is in position above normal sound sheet material, and vary its indication only when the coil is over cracks and unsound sheet material. By using concentric poles, the eddy current path may be confined to a narrow ring, eliminating effects of adjacent edges, holes, and welds not under test.

Advantages of this test method are: (1) Access is required to only one side of the sheet, (2) no sheet preparation or cleaning is required, and no electrical contacts are made with the sheet, (3) measurements may be made through paint or insulating coatings without

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* - Frequencies of 3,000 to 30,000 cycles were found useful with sheet thicknesses varying from .181" to .016". Example: for .064" sheet, L= 34 millihenries, C=.0025 μf, f=17,000 gave a change from 24 to 100 volts across condenser when coil assembly was lifted off sheet.

damage or puncture, (4) no probes or low energy indicating circuits are used -- hence no difficulties due to contact resistance, thermal emfs., inductive pickup, high gain amplifiers or sensitive meters are encountered, (5) wide flexibility, due to choice of frequency, geometry of pole assembly, and sharpness of tuning, can be obtained in applications, (6) the eddy current pattern is ideal for the detection of radial cracks in spotwelds, and (7) the device serves effectively as a thickness or alloy detector for conducting sheets.

Disadvantages of this test method are: (1) only eddy currents flowing in planes parallel to the sheet surface can be established readily, so bonding at the faying surface is not measured, (thus spotweld static shear strength cannot be measured); (2) variations in the air gap between pole pieces and sheet surface have a large effect upon indications; (3) indentations and variations in sheet thickness affect indications; (4) the exact geometry of cracks and porous defects cannot be determined.

2. Transformer Loading Induction Test Modified for Lap Joints.[c]

A modification of the simple transformer loading test makes possible the induction of eddy currents which flow normally through the weld bond at the faying surface, if a return path can be provided. An exciting coil with concentric cores is designed to fit over the lap joint, as shown in Fig. 23. Frequency is adjusted so that eddy currents are not induced in significant amounts at a depth greater than one sheet thickness. If the exciting coil is placed on the lap joint between two spotwelds, the eddy currents flowing beneath the turns of the exciting coil (between the inner and outer magnetic poles) tend to follow a path through the upper sheet, down through one weld to the lower sheet, and return through the second weld. Small bonded areas at the welds tend to introduce resistance into the eddy current path, while with no conducting bond at the welds, a very high resistance is introduced. These conditions are reflected in the resonant primary circuit and indicated by a vacuum tube voltmeter.

Inherent errors in this test method make it practically worthless for spotweld inspections. These errors include (1) all the inherent erros listed for the two side direct current test; (2) large errors due to edge effects, holes, rivets, and the irregular spacing between adjacent spotwelds; (3) an error due to variations in overlap and in the distance of the weld from the lap edge of the sheet; (4) errors resulting from effects of welds in the return path (at least two welds affect each indication). The location of the spotwelds with respect to the lap joint has a greater effect upon indications than does weld size or quality.

3. Pickup Coil Eddy Current Tests[d]

In these tests, eddy currents are induced in the sheets under test by currents in exciting coils, and variations in the eddy current pattern are detected by sensitive pickup coils connected through high gain amplifiers to suitable indicators. (Ref. #12) In many designs, the pickup coils measure only the departure of the eddy current pattern from the pattern in a uniform sheet. Several typical pickup units are shown in Fig. 24.

Pickup Unit A[d] has an exciting coil and concentric poles similar to those described for the transformer induction test. In addition, however, a sensitive magnetic pickup system is symmetrically located within the center leg of the core. The two poles of the pickup are slightly displaced from each other. The pickup coil is shielded from the magnetic field of the exciting coil. With the normal circular flow of eddy currents established in sound continuous conducting sheet by the exciting coil, no magnetic flux variations occur in the core of the pick up coil. When the coil is placed over a crack or discontinuity, however, the modified eddy current pattern produces an alternating magnetic field through the pickup coil. (See Fig. 25)

Pickup Unit B[e] was specifically designed in the Naval Research Laboratory for use in testing spotwelds, with the hope that a sizeable component of eddy current flow might be

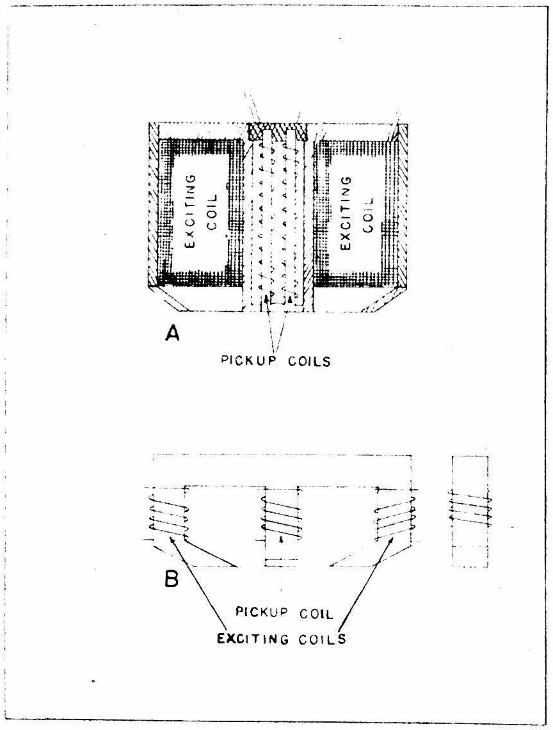

FIG. 24. TYPICAL PICK-UP COIL EDDY CURRENT TEST UNITS.
A. UNIT FOR FLAW DETECTION IN HOMOGENEOUS PLATES DEVELOPED BY ROSS GUNN, N. R. L. (REF. # 12.)
B. UNIT FOR DETECTION OF CRACKS AND POROSITY IN SPOTWELDS DEVELOPED BY N. R. L. (REF. " 11.)

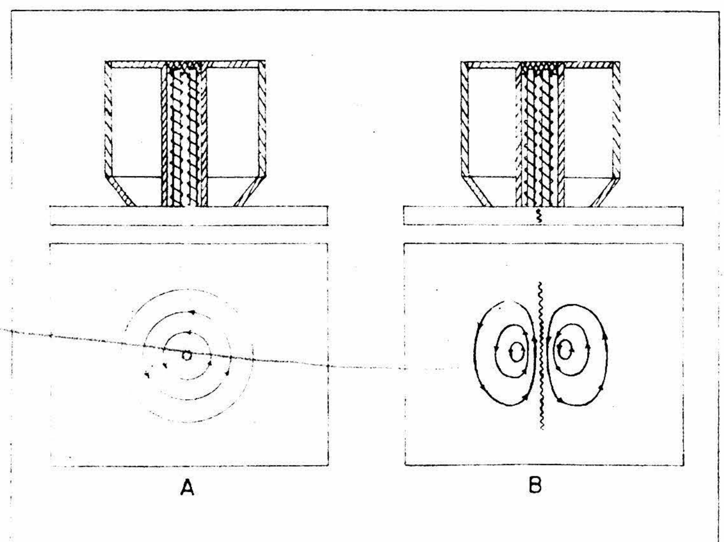

FIG. 25. EDDY CURRENT FIELD INDUCED BY PICKUP UNIT A.
A. FIELD IN HOMOGENEOUS PLATE.
B. FIELD IN PLATE WITH FLAW.

established across the faying surface into the lower sheet at the weld, producing an unbalance current in the pickup. The frame on which the coils are wound is made of transformer laminations. The magnetic field of the exciting coils is additive so that the outer pole faces are of opposite magnetic polarity. An exciting frequency of 1000 cycles was used. Analysis of eddy current patterns shows that if the weld is cracked or porous, or if eddy currents do flow below the faying plane through the weld bond a pickup due to unbalance should result if the weld is unsymmetrically located with respect to the center pole on which the pickup coil is located. Scanning is required to obtain maximum information concerning a weld.

Naval Research Laboratory tests of this unit indicated:

(1) This eddy current method is not satisfactory for the detection of the quality of fusion between the two welded sheets.

(2) The effect of porosity or cracks on the detector was such as to overshadow all other effects. This makes possible the detection of cracks or porosity with little difficulty.

Tests at the California Institute of Technology on similar units confirm these results.

A pickup unit[f] designed at the Lockheed Aircraft Corporation for use in testing spotwelds employed large blocks of copper conductor to force the magnetic field of the exciting coils into the welded sheet. Despite several modifications, the difficulty in establishing a sufficient eddy current flow normal to the faying plane at the weld prevented successful measurement of the area of fusion at the weld.

In general, research has shown the pickup coil eddy current tests to be subject to the limitations and inherent errors previously listed for eddy current tests. No successful method has been devised for measuring the bonded area at the faying plane through the use of eddy currents.

D. Thermal Test Methods

Thermal test methods involve the flow of heat through the weld region and the measurement of resultant temperatures or temperature gradients. The presence of the weld modifies the heat flow pattern in an unwelded sheet:

1. geometrically, since heat tends to flow normally across the faying plane through the weld to the opposite sheet and so possibly measures weld nugget diameter; and

2. through its variable heat conductivity (if differences in conductivity do exist in various regions of the weld) and the presence of cracks and porosity. Heat capacity of the region under test affects the transient temperature response only.

Advantages--Heat flow methods are readily adaptable to one-side testing, as well as to two-side testing. No return paths are necessary. Heat flow may measure total weld diameter at faying surface.

Disadvantages--Due to heat capacity effects, het flow methods cannot be instantaneous and usually are slow tests. Ambient temperature, surface thermal contact resistance, size of parts welded, original temperature of work, presence of cracks, nature of heating and method of temperature measurements--all change resultant temperatures and tend to invalidate readings. Thermocouples to measure temperature have small energy output, give slow readings and require sensitive indicators. Although heat flow indications respond to weld cracking and porosity, they do not differentiate sufficiently between the cast alloy nugget and the parent metal to measure nugget geometry. Also, heat flow tests fail to differentiate between cast alloy bonding and Alclad bonding at the faying surface, so the static shear strength of welds is not accurately measured.

1. Heat Reservoir Thermal Test:[g]

A copper heat reservoir (similar to a massive soldering iron) with two contact lugs carrying imbedded thermocouples (See Fig. 26) is heated to a temperature considerably above that of the weld to be tested. One lug is placed in contact with the sheet surface above

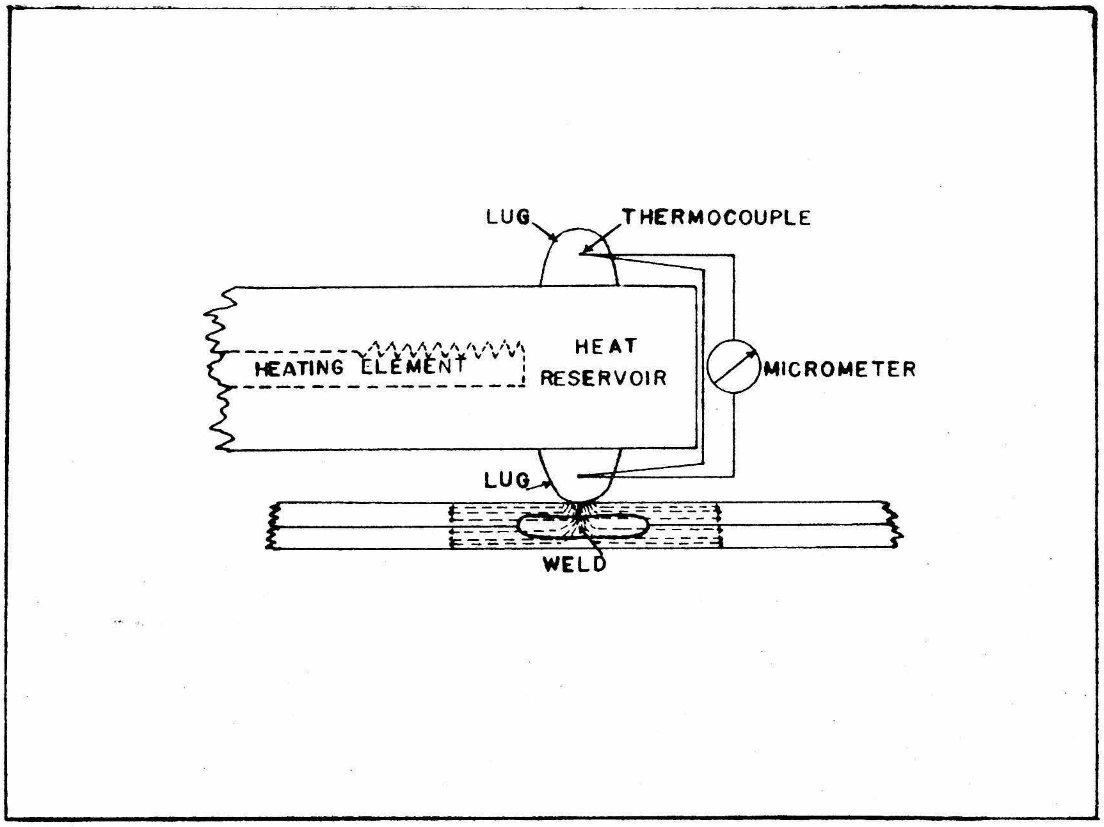

FIG. 26. HEAT RESERVOIR THERMAL TEST OF THE BONDED AREA AT THE FAYING PLANE OF THE SPOTWELD.

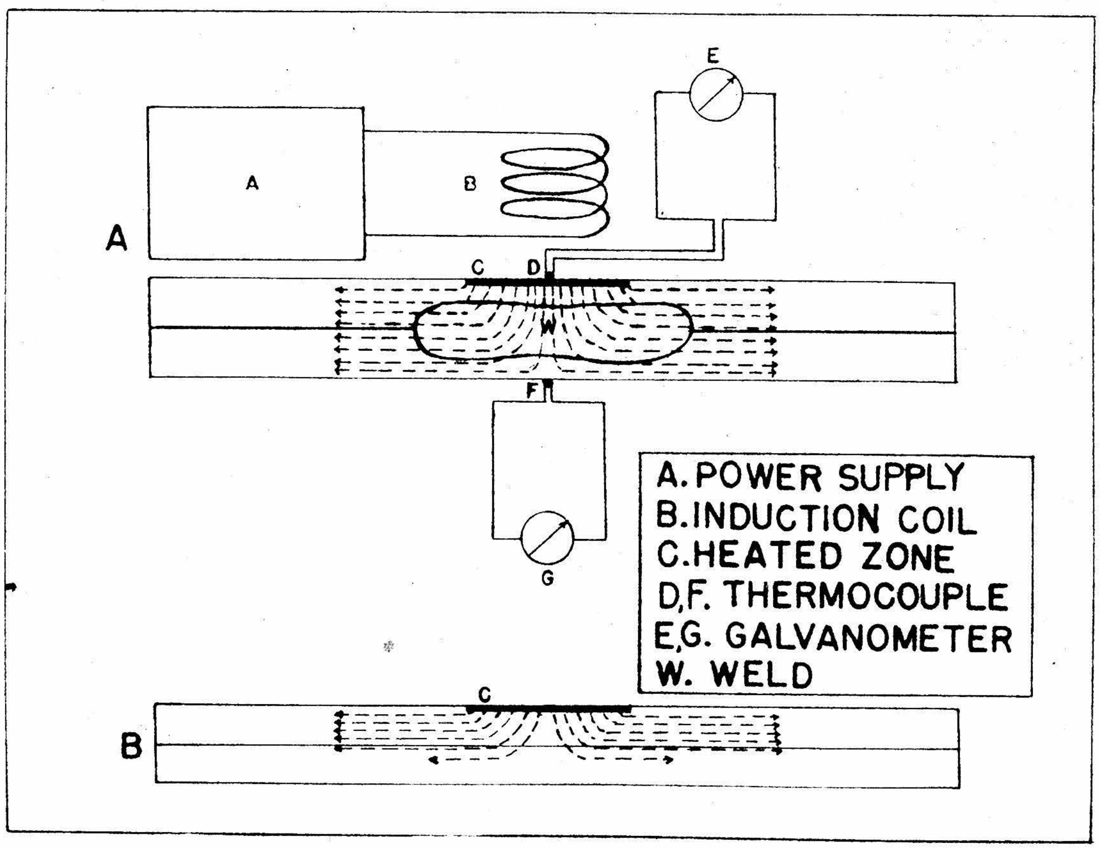

FIG. 27. INDUCTION HEATING THERMAL TEST OF THE BONDED AREA AT THE FAYING PLANE OF THE SPOTWELD.

A. HEAT FLOWS ACROSS FAYING PLANE AT WELD.

B. LITTLE HEAT FLOWS ACROSS FAYING PLANE WHERE NO BOND EXIXTS.

the weld, and heat flows into the weld region by conduction. If a weld is present, heat flows through the bonded area of the faying plane to the lower sheet, and the total rate of heat flow from the reservoir is greater than when the weld is absent, for in the latter case only the upper sheet conducts heat away from the reservoir. The drop in temperature recorded by the thermocouple imbedded in the lug in contact with the sheet is a measure of the rate of heat flow from the reservoir to the sheet. The thermocouple imbedded in the second lug through which no heat flows measures the temperature of the reservoir. A sensitive galvanometer is employed to measure the differential output of the thermocouples.

Precautions to be observed in making this test are:

1. The heat source lug must be accurately located above the weld, and must make contact with the same sheet area on each weld tested. (Variation in the shape of the electrode indentation makes this very difficult in practice).

2. The sheets to be tested should not vary widely in temperature, and should preferably be at ambient temperature.

3. The ambient air must be still--a slight draft

changes indications far more than the presence of a weld.

Inherent Errors in this test method, identical with those listed for the two side direct current test, exist.

1. In addition, a very large error results from variations in the thermal contact resistance at the sheet surface where heat is being introduced, due both to changes in contact area and to surface films of variable nature.

2. Changes in ambient temperature or air velocity, and in material temperature, affect indications greatly.

3. Progressive heating of the work as successive welds are tested changes indications, even on identical welds.

4. The presence of adjacent welds, rivets, edges, masses of metal, holes in the sheet, "spit" or expulsion of metal from the weld region--all result in erroneous indications.

Improvements on this test method were obtained by following the listed precautions, by insulating the heat reservoir and lugs from the ambient air, by cleaning the sheets and lugs and removing oxide before each test, by holding the unit on the sheet surface under controlled pressure a fixed period of time, and by working in a small closed room with work at room temperature. This latter item required a delay between weld measurements, the time being used for cooling and cleaning the sheet over the next weld with acetone.

Advantages of the heat reservoir thermal test are: (a) access is required to only one side of the work (b) the heater and temperature indicator may be in a single unit requiring only one application (c) no marking of or damage to welds results.

Disadvantages of this test include: (a) its inherent errors (b) its sensitivity to ambient air conditions (c) the difficulty of obtaining uniform thermal contact with the sheet surface and (d) its inability to measure weld static shear strength.

2. Induction Heating Tests: (∅)

In these tests heat is supplied rapidly to a small area of the Alclad sheet directly above the weld, at a measured rate or in fixed amount, by modified industrial induction surface hardening equipment. The frequency is chosen sufficiently high to limit the penetration of the heat-producing eddy currents to a thin layer at the sheet surface. Thus thermal contact resistance between heat source and sheet are eliminated as variables, and the rate and amount of heat production are controlled. When a large area of weld bonding is present a large fraction of the generated heat flows normally across the faying plane into the lower sheet. With no weld bonding, all the heat must flow away in the upper sheet. (See Fig. 27). Thus the heat flow is sensitive to the area of bonding.

For one side testing, the temperature indicator must lie under the induction heater on the same surface of the work--hence must not be affected by the high frequency field. Only a carefully shielded thermocouple would be suitable. However, by closing the thermocouple circuit to its indicating galvanometer only after the high frequency field is turned off, the cooling transient of the sheet surface may be recorded, provided the galvanometer responds with sufficient rapidity. Some success has been attained by the use of a thin layer of wax* or thermoplastic in the sheet surface, by observing the diameter of the softened melted area which results when the controlled quantity of heat is generated above the weld.

For two side testing, the indicator is placed on the side of the work opposite the weld, where it is not affected by the high frequency field. In this case, the heat which reaches the temperature indicator must flow through the weld at the faying plane. The entire heating and cooling transient for the controlled heat generation cycle can be observed, with great sensitivity to the size of the bonded area. Both thermocouple and wax film indicators have proven to be effective.

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*--Suitable calibrated wax temperature indicators are commercially available from the Tëmpil Corporation in the form of Tempilstiks, Tempil Pellets and Tempilaq.

The most convenient form of thermocouple indicator developed for this purpose consists of a low thermal capacity thermocouple supported against the sheet surface by a small rubber suction cup. The inner surface of the cup is coated with a heat reflecting surface thermally insulated from the rubber, and the suction cup excludes the ambient air--hence, despite sheet surface condition, the thermocouple follows the sheet temperature closely. The second junction is similarly attached to the sheet at a remote point, so that only temperature differences due to the heating of the weld region are measured. Both junctions are quickly and easily attached to any point of the sheet surface by means of the suction cups, and may be pulled off and moved at will.

The laboratory wax film indicator consists of a thin layer of parawax or thermoplastic material placed on the sheet surface. When cool and hard, a dry, colored powder or dye is sprinkled over the wax. When heat generated in the opposite sheet at the weld flows through the weld in sufficient quantity, the wax above the bonded area melts, and in this region the powder becomes imbedded. A complete joint may be tested at one time, and a permanent record obtained by subsequently placing a strip of Scotch tape over the line of welds. The tape picks up the powder over all areas except where the wax has melted and imbedded the powder. For practical use "Tempilaq" may be used as a temperature indicator. Large welds, small welds, and no bond whatever are readily discriminated from one another by the extent of melting of the wax.

Precautions to be observed in using the induction test are:

1. The induction heating unit must be accurately located above the weld. The temperature indicator must be equally accurately located, as the temperature gradient in the plane of the sheet is quite large.

2. The rate and amount of heat generation must be precisely controlled by synchronous or electronic timing units, if bonded area is to be determined accurately from temperature indications.

3. Ambient air should be quiescent. No condensed moisture should be present on the structure. All parts of the joint should be approximately at room temperature.

Inherent errors in this test method are similar to those listed for the heat reservoir test, save that errors due to contact resistance are eliminated.

Advantages of the induction heating method are: (a) the test may be made with access to either one or both surfaces of the work (b) the method measures total bonded area reliably, and permanent records can be easily produced (c) contact thermal resistances are eliminated as variables.

Disadvantages are (a) Finite heating times (a few seconds) are required (b) Careful positioning and control of ambient conditions is necessary (c) Spotweld shear strength is not measured reliably. (d) Adjacent welds, edges, holes, and masses of metal introduce large errors.

3. Radiant Heating Tests: (∅)

In these thermal tests, heat is supplied to the surface of the welded sheet by radiation, as from a concentrated heat lamp and focussing system. The sheet surface must be cleaned or painted to obtain uniform heat absorbtion over the test area. Thermocouples may be used on the one side test if shielded from direct radiation, without internal heating effects present with induction heating methods. The method is slow, and is subject to the previously listed errors of thermal tests. Temperature indications are obtained as in the induction heating test, when the indicator is on the opposite side of the weld from the radiant heat source.

4. Contact Drop Heating Test (∅)

One condition has been found in which electric current flowing from pointed electrodes into Alclad sheet produces a contact drop of potential approximately constant at about 0.2 volts for currents from 20 to 90 amperes d.c., releasing considerable heat at the point of contact. This is equivalent to a point source of heat, and the rate of temperature rise per watt of energy input would be affected by weld presence. This method is especially suitable for use with wax temperature indicators, either in one or two side test, although thermocouples may be used.

5. Differential Heating Tests(ø)

In methods 2, 3 and 4, effects of weld presence could be increased, and the effects of variable ambient conditions reduced by the heating of two areas, one over the weld and one not over the weld, under identical conditions, and measuring the differential temperature of the two regions by a thermocouple system. Because of the duplication of heating equipment required, this modification has not been investigated in this research.

[illegible]. Sonic and Vibration Tests:

Sonic and vibration tests are usually of three basic orms: measurements of vibration damping; measurements of ave reflections; measurements of the natural frequencies of scillations. Each type has been proposed for the non-destructive esting of spotwelds in aluminum alloy sheets.

Sonic and vibration tests, by their very nature, are more asily applied to pieces of fixed size and shape, to detect aterial properties and defects, than to structures of irregular ıd variable shape. Spotwelded structures offer a less promising field of application because of their complex shapes, which affect test indications considerably. Hence, care must be taken to avoid the development of test procedures which cannot be reduced to practical forms applicable to spotwelds.

1. Vibration Damping Tests:

One form of vibration or damping test proposed for spotweld testing employs a driver to establish oscillations of adjustable frequency in the weld region and a detector to measure the resultant amplitude. For sonic and lower frequencies, a coupled electromagnetic-mechanical transducer (similar to the driving units of loud speakers) is employed as driver, while for supersonic frequencies, magneto-struction or quartzhcrystal generators are used.* Power is supplied from variable frequency oscillators to these driving units. Detectors for measuring the resultant vibration amplitude usually consist of a piezo-electric pickup or other microphonic device, connected through suitable vacuum tube amplifiers to indicating instruments (See Fig. 28).

The damping can be determined for a system of any shape, provided it can vibrate. In one method of measurement, constant energy is supplied the driver at varying frequency, to obtain in the detector a resonance curve (See Fig. 29) showing the amplitude of vibration as frequency

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* -- Magnetostriction generators are useful from about 8,000 to 50,000 cycles, and quartz crystal generators are useful at higher frequencies.

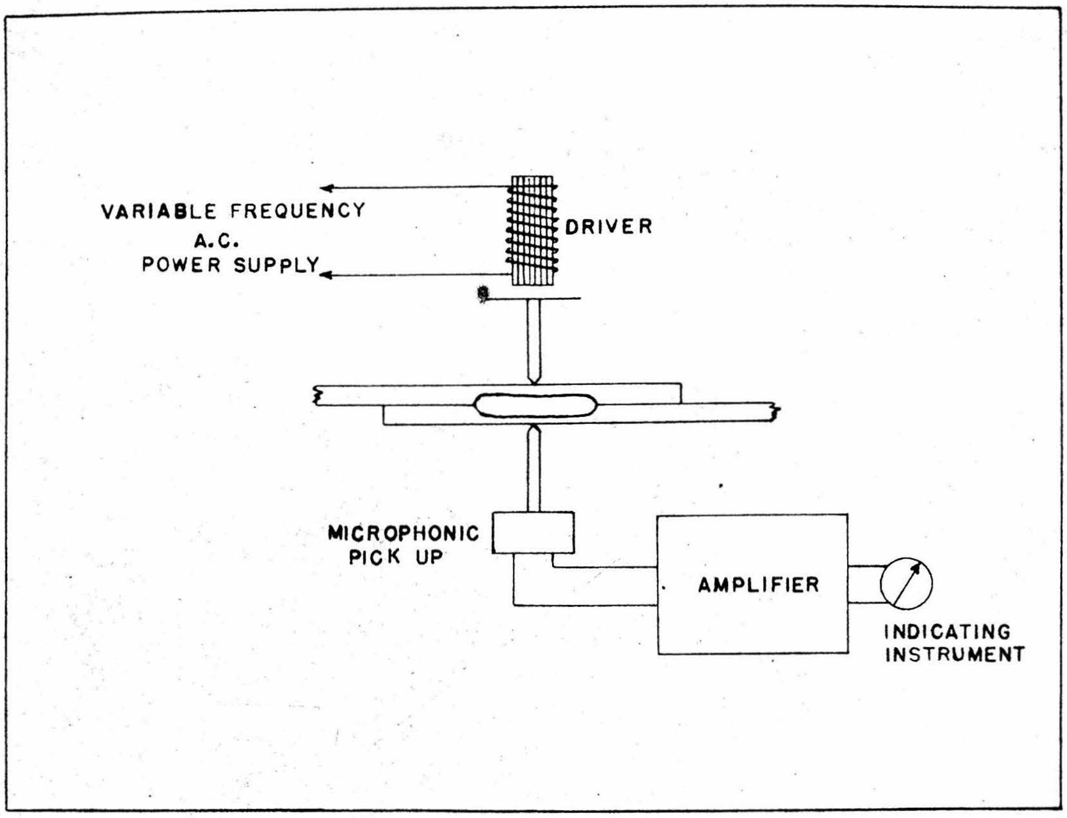


FIG. 28. VIBRATION DAMPING TEST ARRANGEMENT.

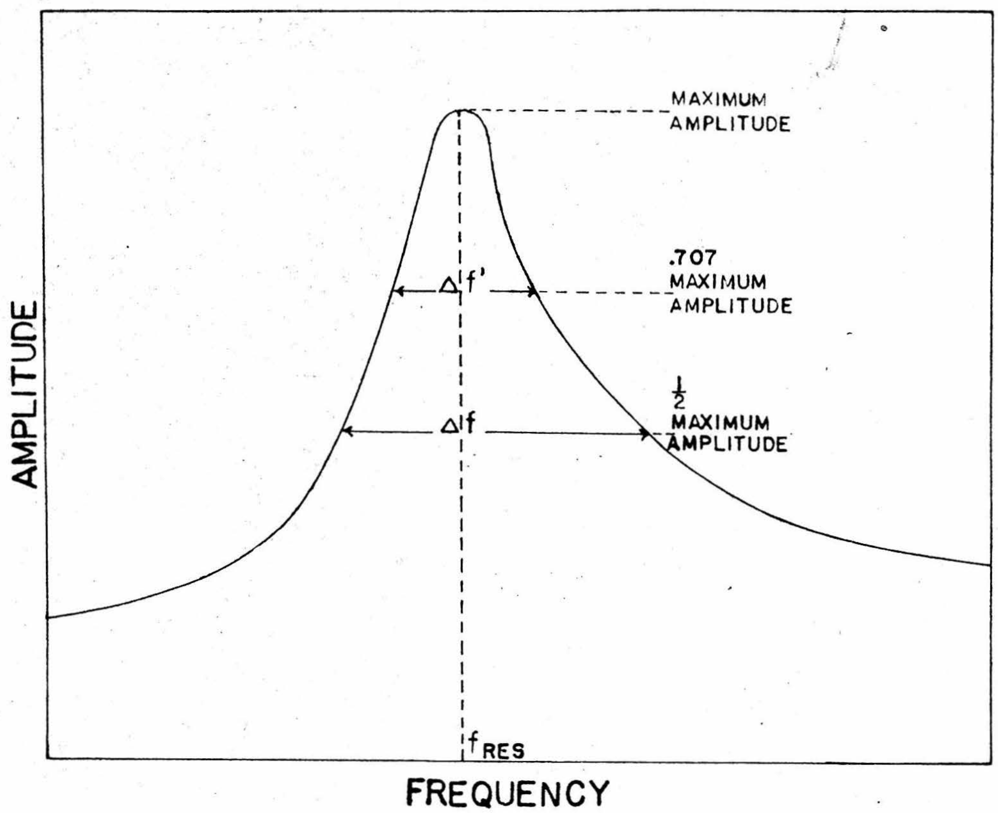


FIG. 29. VIBRATION RESONANCE AND DAMPING CURVES. THE DECREMENT FACTOR δ IS GIVEN BY

$$\delta = 1.814 \frac{\Delta f}{f_{RES}} = \pi \frac{\Delta f'}{f_{RES}}$$

is varied through one of the natural frequencies of the system. Theory indicates that the mechanical damping of resonance curves can be readily determined from their breadth. If f represents the breadth of the resonance curve at half the maximum amplitude, then the damping δ is given by

$$\delta = 1.814 \frac{\Delta f_{\frac{1}{2}}}{f_{res}}$$

where the resonant frequency f_{res} and the frequency difference of the half amplitude points, $f_{\frac{1}{2}}$, are measured in cycles or vibrations per second.

A second method of measuring damping requires that oscillations be established, then be allowed to die out by disconnecting the driver. If the amplitude of successive vibrations are observed by the use of a cathode ray oscillograph or equivalent, the damping may be determined as

$$\delta = \ln_e \frac{A_n}{A_{n+1}}$$

where A_n and A_{n+1} are two consecutive amplitudes of the free vibration. Where the frequency is too high or too small to make possible this measurement, the damping may be determined from the time required for the amplitude of the resonant oscillation to fall to one half its original value, by the relation

$$\delta = \frac{0.693}{t_{\frac{1}{2}} f_{res}}$$

this time $t_{\frac{1}{2}}$, or even the product $t_{\frac{1}{2}} f_{res}$, may be determined directly by the use of electron tube indicators, even with very high frequency oscillations. (Ref. #13).

In bars of fixed geometry, faults of any kind in the material combine to raise the damping, so that cavities, cracks and porosity are easily determined. In spotwelds, large differences of geometry may exist, in addition to possible cracks or porosity, and cast and wrought alloy, as well as pure aluminum cladding, are present simultaneously. The soft nugget material tends to increase damping, and a change in nugget volume could not be differentiated in tests from the introductionoof cracking. Preliminary tests showed damping indications to depend upon too many weld properties to serve as a reliable indicator of spotweld properties. Further development of the method was postponed while simpler test methods were exploited.

2. Wave Reflection Tests(i)

It has been proposed that the area of bonding of spotwelds might be measured by supersonic waves, which would reflect from the faying surface of unbonded regions, but would pass through the faying surface at the weld bond. For one side test methods, the presence of bonding might be detected through (a) the frequency at which standing waves (half wave resonance) could be established between the oscillator and reflecting surface, or (b) the <u>time</u> required for a wave train to pass from the sender to the reflecting surface and return. (See Fig. 30).

A fine development of supersonic testing equipment has been carried out by Professor F. A. Firestone of the University of Michigan. His equipment produces three wave types--longitudinal, shear, and surface--and provides suitable detection and recording equipment. Using his Supersonic Reflectoscope, Professor Firestone has distinguished a spot which is welded from one which is not bonded as follows (quoted from a letter from Professor Firestone):

> "A wave train of longitudinal waves is sent in at the upper face of the weld. The weld assembly is so thin that the first reflection from the other side of it cannot be distinguished but the waves reverberate back and forth through the thickness of the weld assembly while the total distance of their travel back and forth may be several inches. Their successive impingement on the crystal generates a voltage which can be observed on the reflectoscope screen several inches after the sending out of the wave train.

"If, now, one holds his oily finger against the bottom face of the weld, these successive reflections will be damped out, thereby proving that the waves are rally passing through to the bottom face and that there is, therefore, a weld.

If there is no weld, a similar series of successive reflections is observed, but upon touching the oily finger to the bottom face of the weld there is no change in the appearance of the reflectogram, thereby proving that the waves are not entering the lower plate. Thus far, the method is not quantitative, but merely all or none.

One can imagine improvements in the method as the result of research which would improve its usefulness. The above-mentioned tests were made with 5-megacycle longitudinal waves, but we have produced as high as 20 megacycles and we have also produced shear waves which travel half as fast as longitudinal waves so that this represents a factor of 8 reduction in wave length. With these shorter wave lengths, it might be possible to actually explore over the surface of the weld and thereby determine the actual welded areas. This would be particularly feasible on the heavier gages where the weld is comparatively large.

One can imagine sending comparatively powerful continuous waves throughthe weld and have the back side coated with something like paraffin which would be melted in those areas where the wave energy was being received and would thereby outline the welded area.

We have used longitudinal or shear waves for the accurate measurement of the thickness of a sheet when one side is inaccessible using the general method of establishing a half-wave resonance through the thickness of the plate and then determining the frequency. This method might be applied to weld testing since, if there is no weld under the area being tested, the thickness thus indicated would be approximately that of one sheet, while if the weld exists the thickness is approximately that of two sheets.

We can also produce surface waves which run over the surface of a metal part in much the same way that water waves travel. Surface waves could be sent along the lower face of the upper plate and reflection obtained from the closest point in the weld, even though that might be in the cladding."

Present indications are that detection of the area of bonding of a spotweld at the faying surface might thus be feasible by supersonic testing, but the ability of supersonic tests to discriminate between cast alloy bonding and Alclad bonding has not yet been demonstrated. Likewise, there would probably be some difficulty in detecting weld nugget geometry by wave reflection methods. Hence, for the inspection of spotwelds, supersonic reflection test indications seem to be limited to measurements of the total bonded area at the faying surface. The two-side electrical test makes this measurement with simple testing equipment, and since this measurement alon is not a reliable indication of spotweld strength, no elaborate development of supersonic test equipment has been included in this research program.

3. Nugget Oscillation Tests:

Assuming an ideal homogeneous weld nugget of flattened spheroidal shape, enclosed within a homogenous mass of harder, tempered parent metal with physical properties different from those of the weld nugget, the frequency of natural oscillations of the weld nugget may be calculated. It has been proposed to excite such nugget oscillations by means of quartz crystal coupled to the sheet surface, as by an oil drop, and after a fixed excitation period, to use the same crystal as a detector to observe the damping of the free oscillation. Correlations between natural frequency and nugget size, and between damping and ductility, cracking and porosity have been predicted.

This test has not seemed sufficiently feasible to justify development. Weld nuggets are of very irregular shape and have internal inhomogeneities and defects. Weld nugget volume does not measure weld strength precisely. The difference between nugget and parent metal properties is not sufficient to provide an effective discontinuity to the flow of vibration energy. The natural frequency of nugget oscillations would be extremely high. Effects of adjacent material and sheet geometry might affect test indications excessively. Simpler test methods offer more promise.

4. <u>Ultra Sonic Wave Pattern Test:</u> (ø)

This test differs from those previously outlined in the method of application of the energy source and in the method of pickup. A moderately high ultrasonic frequency has been used (about 1,000,000 vibrations per second) to obtain high resolving power by the sound waves. The sound is transmitted from an ultrasonic generator to the sheet surface below a spotweld by an anvil and the vibrations travel through the weld to the upper sheet surface. If oil or other liquids are placed thereon, radial circles centered over the weld will be observed. These are standing wave patterns the configurations of which may indicate the bonded area of the weld. By the substitution of a material such as collodion for the indicating oil, a permanent record of the weld has been obtained. The results so far obtained on this test are not conclusive but the method shows promise and should receive further consideration and investigation.

Advantages - The weld geometry can probably be determined from this test, through the analysis of the wave-patterns produced. Obviously if little or no mechanical coupling exists between the upper and the lower sheets at the weld, bonding at the faying plane is lacking and resulting patterns differ from those denoting satisfactory bonding conditions.

Disadvantages of this test method are: (1) The equipment necessary for the test is rather elaborate, and includes an oscillator capable of supplying about 1 K.W. of radio-frequency power to the ultrasonic generator, which in turn has auxillary equipment necessary for continuous operation. This auxillary equipment is somewhat compensated for by the stable and reliable operation secured. (2) Training is required for one unskilled in this method of testing to reliably interpret patterns in terms of weld quality. (3) Errors may result from possible dispersion effects and variation in treatment and/or composition of material to be examined. (4) The coupling anvil should be properly centered on the bottom indentation to secure uniform mechanical coupling, and anvil contours should fit those of the weld indentation.

F. Sheet Surface and Material Property Tests

It has been suggested that spotweld properties might be correlated with conditions measured at or near the sheet surface above the weld. Properties included are: sheet surface indentation by welder electrodes, measurement of surface marks or condition, thickness of Alclad layer, toughness, ductility, elasticity, impact resistance, scratch or wear resistance, and metallurgical structure at various depths from the sheet surface at the weld.

1. Welder Electrode Indentation Tests[ø]

Indentation of the surface of the Alclad sheet by the welder electrode is a function of electrode size and shape, weld current and temperature transients, pressure program, and sheet properties. With reasonable control of current wave shape and electrode tip contour, and precise control of timing and amplitude of the tip pressure, the sheet indentation will correlate well with weld nugget size. The larger the volume of melted alloy, the greater the indentation caused by the tips, provided the pressure program is precisely controlled and sufficient hold down pressure is exerted to prevent expulsion of metal at the faying plane.

The sheet indentation may most easily be measured through the use of a sensitive dial gauge graduated in .0001" units, provided with a suitable collar to rest on the sheet surface just outside the indentation. Eddy current or electrical capacitance gauges may be employed, and provided with permanent record devices if desired.

Inherent errors in this test method result from normal production conditions, to an extent sufficient to invalidate the test. Large changes in electrode shape and contour produce correspondingly large changes in indentation, although the effect of repeated tip cleaning in a few hours run on the set of tips is not extensive. Changes in tip pressure, or in forge pressure time delay, change indentation greatly. The ease with which tip pressure and contour may be changed in production welding would prevent this test from attaining reliability.

As control of welding conditions improves, tip shape and pressure program will be more precisely controlled, in

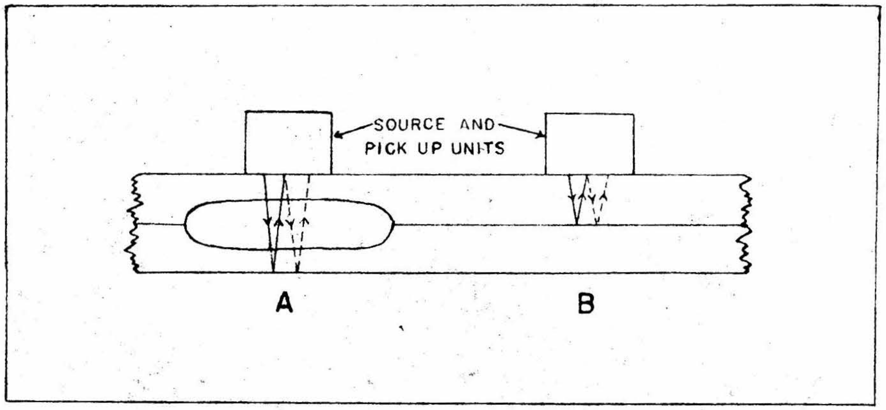


FIG. 30. WAVE REFLECTION TEST OF BOUNDED AREA OF SPOTSELDS.
(A) WAVES PASS THROUGH WELDS AT FAYING PLANE.
(B) WAVES REFLECT FROM FAYING PLANE WHERE NO BOND EXISTS.

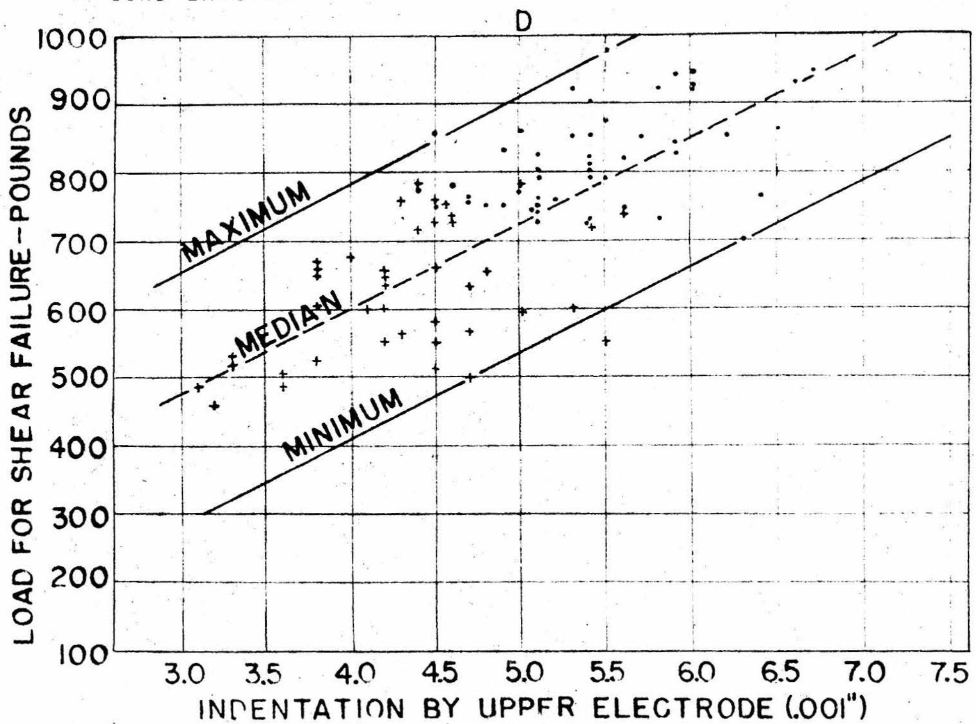
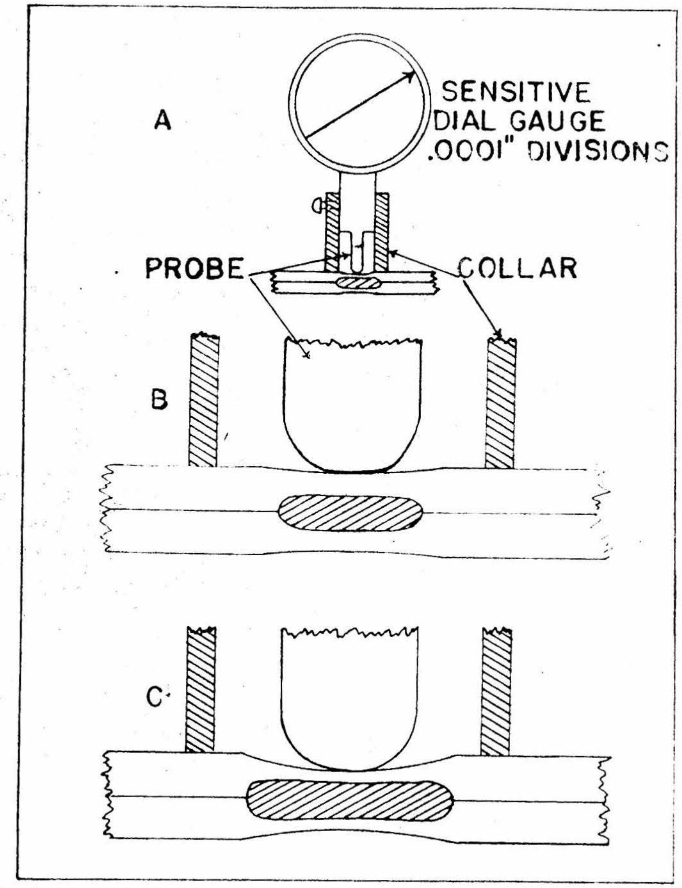


FIG. 31. ELECTRODE INDENTATION OF WELDED SHEET TEST OF SPOTWELD SIZE AND STRENGTH.



A. DIAL GUAGE WITH COLLAR
B. SMALL LUDENTATION OVER SMALL WELD
C. LARGE INDENTATION OVER LARGE WELD
D. RESULTS OF INDENTATION TESTS ON 141 SCIAKY WELDS IN .040" 24ST ALCLAD.

which case the validity of the tip indentation test will improve. (See Figure 31 for results of indentation measurements on industrially made welds).

2. Sheet Surface Property Tests:

No measurements of physical properties of the sheet surface layers have shown any correlation with weld size or quality. Marking or thickness of the Alclad layer have no significance whatever. The structure and metallurgical properties of the 24ST alloy are very little affected except in the weld nugget and narrow adjacent regions where incipient melting along grain boundaries and intrusion of eutectic occur. Only measurements of properties in and adjacent to the weld nugget correlate with weld strength and quality. Superficial surface tests measure nothing significant except when the weld nuggets penetrate to the sheet surface (excessive penetration).

G. Impressor or Penetrator Tests:

In these tests a loaded penetrator or group of penetrators is forced into the welded sheet above and/or below the spotweld to such a distance that properties and extent of the softened cast alloy of the weld nugget, rather than of the tempered parent metal, determine the depth of penetration. Any other type of penetrator or hardness test has little significance. It has been found that the tempered parent metal is reasonably homogeneous except in a narrow zone adjacent the weld nugget where incipient melting and intrusion of eutectic occur along grain boundaries, while on the other hand the entire volume of the weld nugget has been very appreciably softened. Hence penetrator tests measure weld nugget geometry. By profiling the weld region with suitable penetrators, the shape of the weld nugget can be mapped quite accurately. [illegible]

Although properly applied penetrator tests can measure weld nugget geometry reliably, it must be noted that measurements from the outer surface of the welded sheet measure <u>only</u> the geometry of the outer boundary of the nugget in the sheet under test. The nature of the bond at the faying surface, particularly where excessive Alclad inclusions exist, is not measured in this test. The geometry of the nugget in the opposite sheet is not determined by penetrator tests on only one side of the weld.

<u>Inherent errors</u> in penetrator tests result from (1) inhomogenieties in the composition and heat treatment of the arent sheet (2) variations in the thickness of the cladding layer of pure aluminum (3) insensitiveness with weld nuggets of low penetration because of the thick layer of parent metal through which the penetration test must measure nugget geometry.

<u>Advantages</u> of properly conducted penetrator tests are:

(1) The method is feasible for either one or two side testing, (2) the test actually measures nugget geometry (nugget diameter is the single weld parameter which correlates reliably with the static shear strength of spot welds), (3) indications are nearly instantaneous.

Disadvantages of penetrator tests are: (1) The test becomes insensitive with thin nuggets (2) conditions at the faying plane are not measured.

1. One-Side, One Point Penetrator Test.

In this test, a single penetrator is forced into the sheet surface above the center of a spotweld, in a manner similar to ordinary hardness testing, but applied in this case to a non-homogeneous structure. The change in penetration between the application of a preload (sufficient to force the penetrator through local surface regions) and application of full load (sufficient to force the penetrator into a region where the weld nugget affects penetration) is measured by a sensitive dial gauge. The one point measurement tends to measure nugget penetration at the center of the weld. (See Fig. 32). Nugget penetration is indirectly correlated with nugget volume and diameter, for welds made with similar electrodes under similar welding conditions. Hence the one point penetrator test predicts weld strength only through a chain of

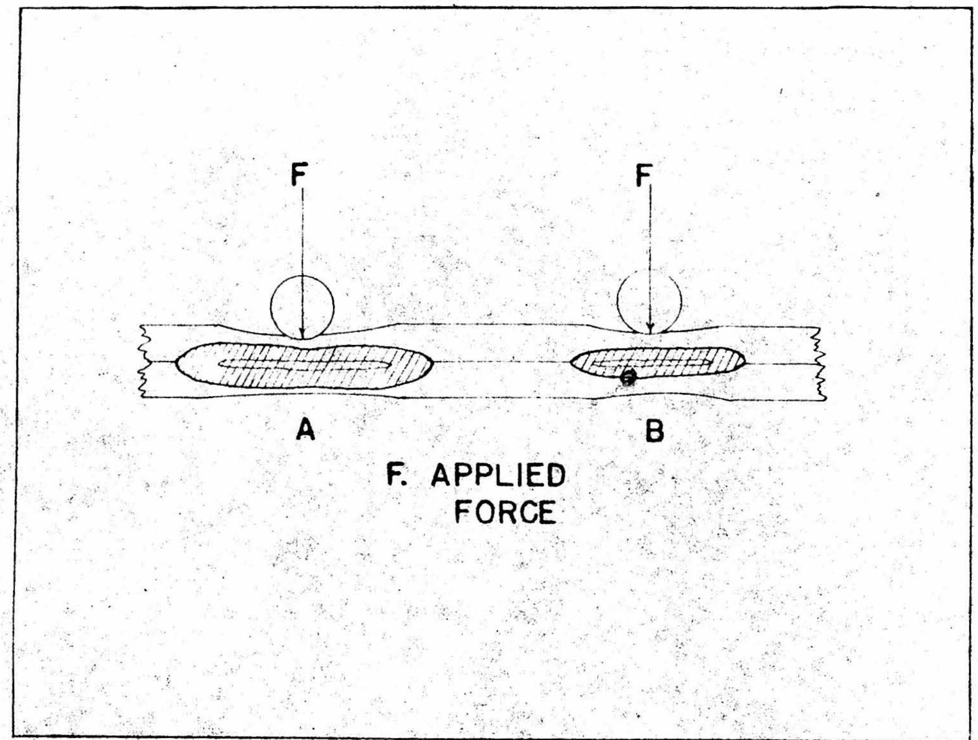


FIG. 32. ONE POINT ONE SIDE PENETRATOR TEST OF SPOT WELD NUGGET PENETRATION. GREATER INDENTATIONS RESULT OVER LARGE NUGGETS (A) THEN OVER SMALL NUGGETS (B).

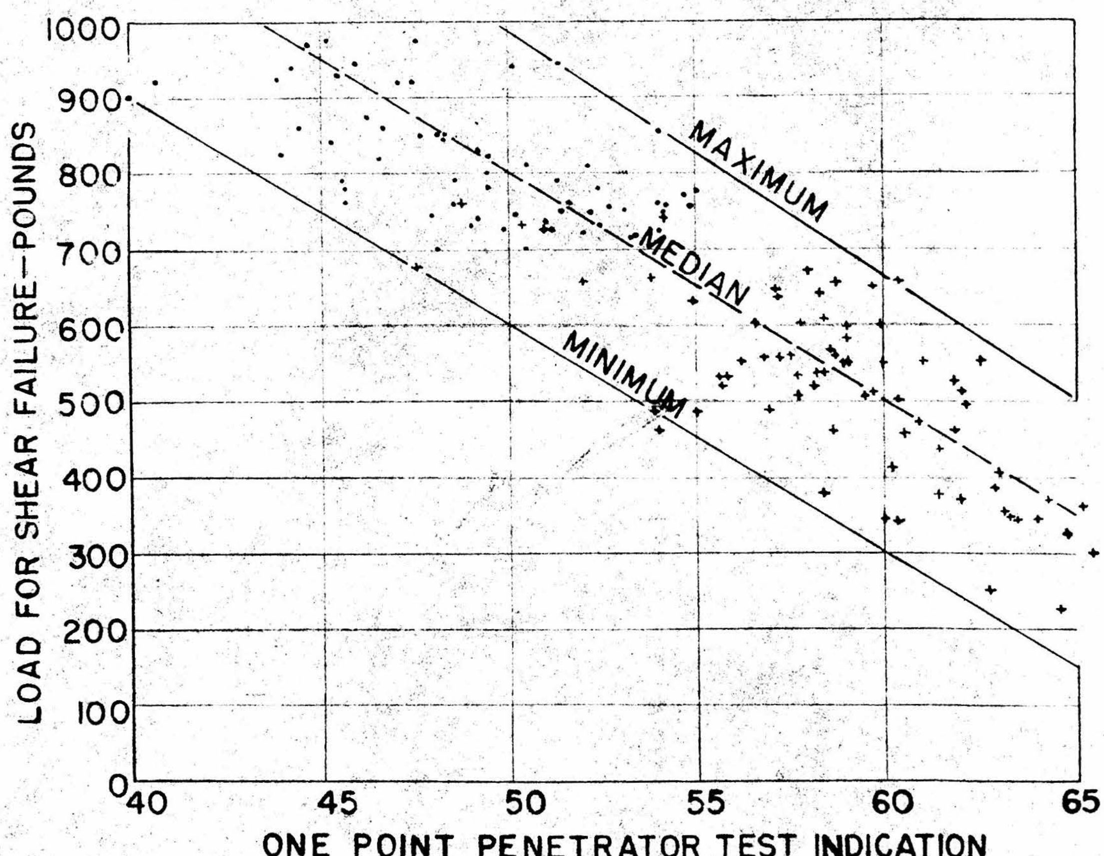


FIG. 33. RESULTS OF ONE POINT ONE SIDE PENETRATOR TEST OF 141 SCIAKY WELDS IN .040" 24ST ALCLAD.

correlations with weld nugget diameter.

<u>Precautions</u> to be observed in applying the one point penetrator test are: (1) The penetrator must be very carefully located over the center of the weld nugget (2) The shape and size of the penetrator must be fixed and constant (3) The conditions of loading must be controlled accurately (4) Tests must be made on welds all of which have been made with identical welder tip size and contour, and on the side of the sheet which was in contact with a particular electrode tip.

<u>Inherent Errors</u> of this method include: (1) Errors due to the lack of a reliable correlation between nugget diameter and nugget thickness (2) Errors due to unsymmetrically shaped nuggets or nuggets whose centers are displaced from the faying plane (3) Errors due to inaccurate positioning.

<u>Advantages</u> of this method have been listed under penetrator tests. Standard hardness testing machines may be used if desired. This test requires access to only one side of the work.

<u>Disadvantages</u> of this test are (1) its relative unreliability, due to its indirect correlation with weld nugget diameter, and (2) its inherent errors.

<u>Typical results</u> of one-side, one point penetrator tests made on industrially made spotwelds with a Rockwell Standard Hardness Testing machine as penetrator are shown in Fig. 33.

2. Simultaneous Two-Side, One Point Penetrator Tests.

This test method differs from the one-side, one point test only in that simultaneous penetration tests from both sheet surfaces are made on the weld. This test has the slight advantage of checking symmetry with respect to the faying plane and of detecting welds with nearly all the weld nugget on one side only of the faying plane. However, it requires access to both sides of the work.

3. Penetrator Profile Tests.

The penetrator profile test is the most reliable method of determining weld nugget diameter shape and penetration. In this test a suitably loaded penetrator carries out a succession of measurements over the sheet surface above and/or below the spotweld. The shape of the nugget along any section can be determined by penetrator profile measurements along a line over that section. (See Fig. 34 for characteristic penetrator profiles of spotwelds in .064" 24ST Alclad Sheet). Increased sensitivity to weld nugget geometry is obtained with penetrator profile tests as sheet thickness is decreased. From penetrator profile measurements, nugget size, shape, and thickness can be determined. Instead of a succession of point penetration measurements, a continuous profile by a rolling sphere or wheel following a linear or spiral path may be used. Simultaneous two-side penetration profile testing is feasible under some conditions

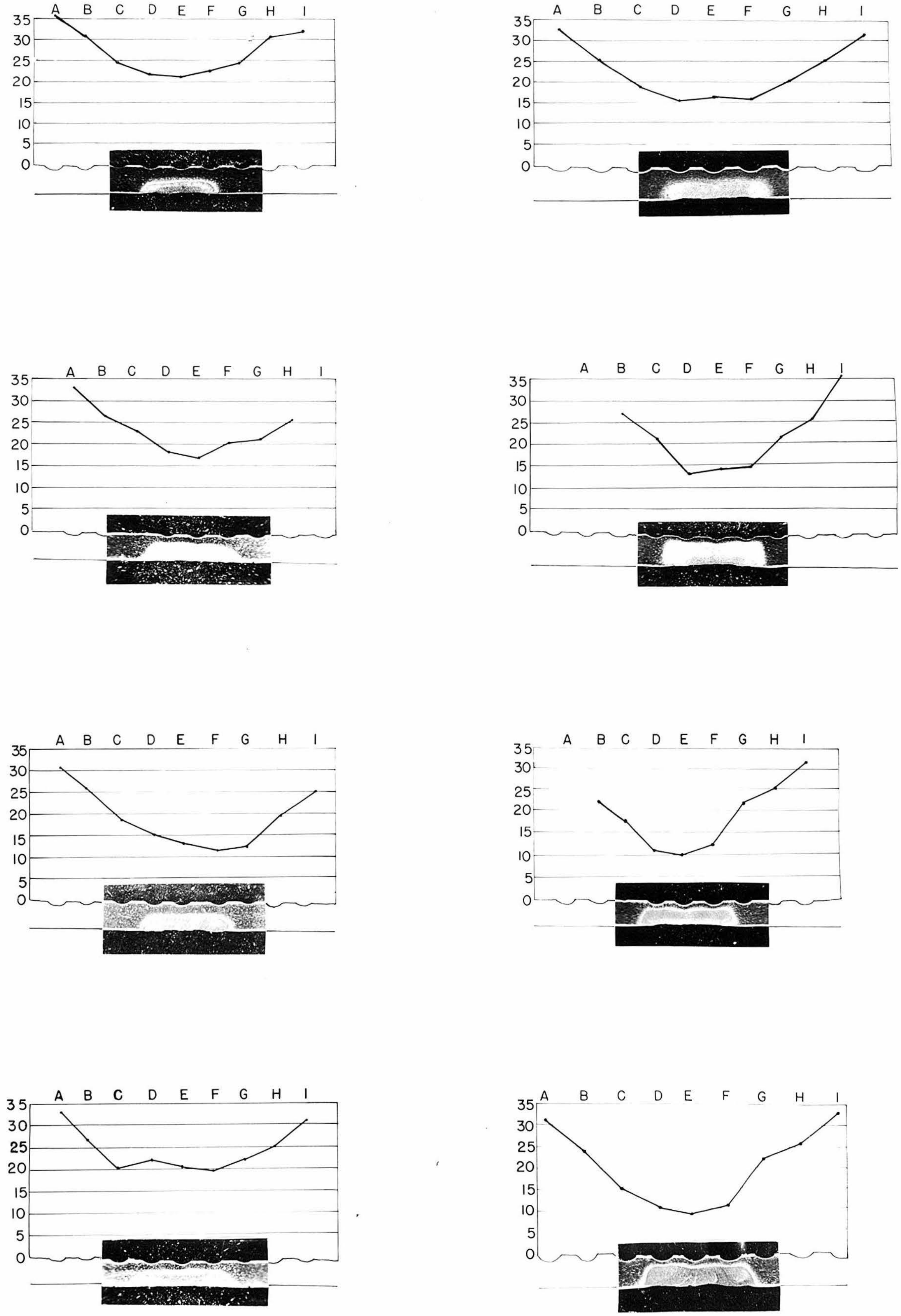


FIG. 34 CHARACTERISTIC PENETRATOR PROFILES OF SPOTWELDS

Precautions. (1) The single point penetrations must be spaced sufficiently far apart to be independent of effects of precedeing penetrations (2) Rolling profile units must be very rigidly mounted to avoid deflection due to the large forces required to move them over the work. (3) Resultant grooves must not cause a "notch effect" to weaken the welded joint (4) Sensitive measurements with respect to the sheet surface, accurate to nearly 1/10,000 inch, are required.

Advantages of penetrator profile measurements lie in their complete mapping of weld nugget geometry.

Disadvantages of penetrator profile measurements lie in (1) the complexity and accuracy required in suitable testing apparatus, (2) the time required for testing, (3) possible weakening of the joint by grooves.

4. Multipoint or Ring Penetrator Tests.

These tests are designed to obtain the significant information of the profile tests, with simpler equipment. A direct measurement of nugget diameter is made by a suitable ring impressor or circle of point penetrators capable of determining whether or not the nugget lies under the circle of penetrators. (See Figs. 52-60 incl., also Section V). If the nugget is smaller than the penetrator circle, or has excessively low penetration (0-20%), the penetrators indicate only parent metal to be present. If the nugget diameter approaches and passes that of the ring, penetrator indications detect this change sensitively. All nuggets of diameter much greater than the ring diameter, are recorded as large nuggets. For any sheet thickness, the range of very high test sensitivity can be matched to any chosed weld nugget diameter by selection of the appropriate penetrator ring diameter. One-side or simultaneous two-side testing is feasible. The accuracy of measurement of weld nugget diameter and of weld strength is nearly identical with the accuracy with which weld strength and diameter can be correlated to the diameter observed by destructively sectioning the weld nugget. (See Fig. 41 and Fig. 59).

Precautions to be observed in applying ring penetrator tests include: (1) The penetrator assembly must be accurately centered over the weld nugget. (The fact that the nugget does not always lie directly under the indentation "dimple" on the sheet surface introduces the largest error in this measurement). (2) The size, shape, and arrangement of penetrators must remain constant (3) Effects of variations in sheet temper must be compensated.

Inherent errors are (1) an error of increasing magnitude with decreasing nugget penetration, due to decreasing test sensitivity. With less than 20% nugget penetration, test indicates no nugget. However, Alclad inclusions are usually excessive, and weld quality is very unreliable with such

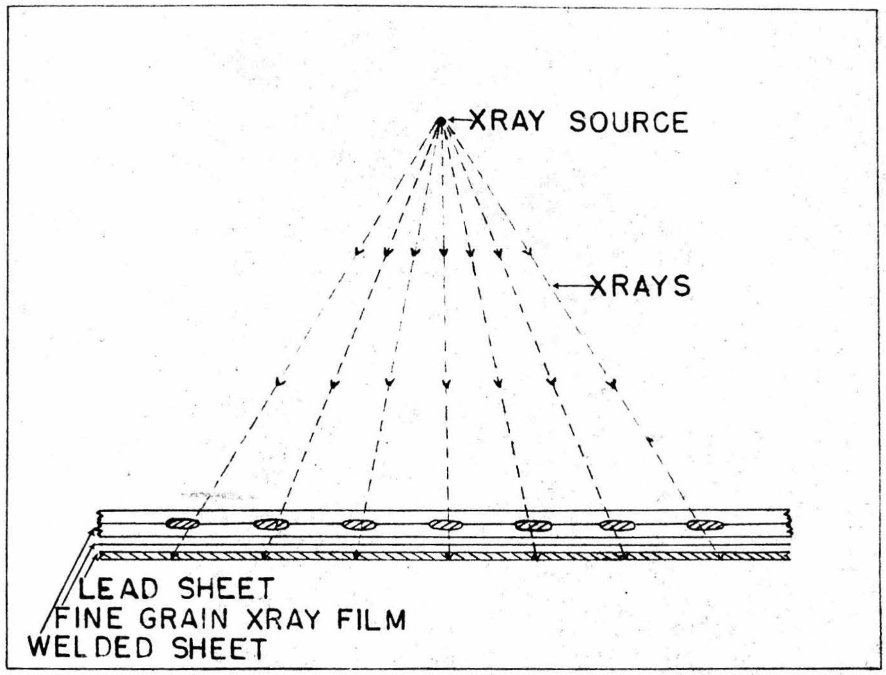


FIG. 35. RADIOGRAPHY OF SPOT WELDS.

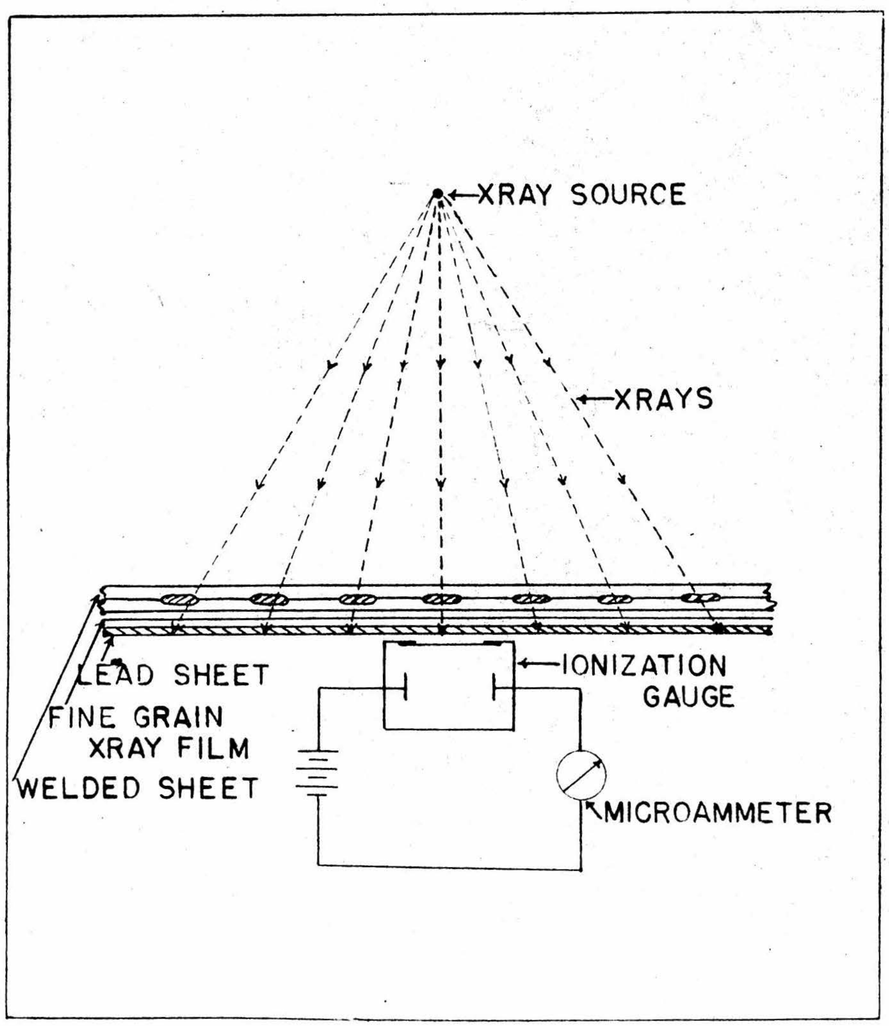


FIG. 36. ARRANGEMENT OF EQUIPMENT FOR IONIZATION GAUGE TESTS OF SPOTWELDS.

Tests of equipment built by the General Electric X-Ray Corporation and tried at the Glenn L. Martin Company in Baltimore, Md. as well as research at the Taylor Winfield Company (Ref. #4) of Warren, Ohio and the Aluminum Company of America (Ref. #6) at New Kensington, Penn. indicated that the radiographic inspection of spotwelds on fine grain film was probably feasible. Most radiographers do not believe fluoroscopic inspection of spotwelds to be feasible because fluoroscopic screens in use today have a grain size some 10,000 times larger than fine grain X-ray film and because image intensity differences are small. Ionization gauge inspection is likewise considered very difficult because of the complexity of spotweld images.

1. Weld Outline Test (Ref. #14)

In this test, a fluid containing radiographically opaque materials is caused to penetrate between the welded sheets at the faying plane. The penetrating qualities of the fluid cause it to cover the faying plane up to the very boundaries of the bonded zone at each weld. If the joint is now exposed to X-rays, while the image is recorded on X-ray film or viewed on a fluoroscopic screen, the welds appear as regions relatively transparent to X-rays surrounded by more opaque areas. The outline of the actual total bonded area of each weld is thus detected readily.

Precautions to be observed in applying this test are (1) The fluid carrying the radiographically opaque materials must not damage or corrode the aluminum sheet, nor should the joint be spread in order to introduce the fluid, (2) Reasonably constant radiographic density should be obtained outside the weld region, (3) The fluid must penetrate to the boundary of the bonded area of the weld, and into any interstices between bonded areas.

Inherent errors may result if the fluid fails to penetrate to the boundary of the bonded area at all points. The contribution of the corona bonding to weld strength is not necessarily measured.

Advantages of the method are:(1) the total area of bonding can be measured reliably (2) exposure conditions need not be precisely controlled (3) special fine grain films are not necessary (4) X-rays from standard industrial equipment (30 Kvp to 150 Kvp) may be applied.

Disadvantages of the method are: The inherent error listed (2) the additional operations of flowing in the fluid before exposure and of cleaning the sheet after exposure (3) the added cost of film and delay of developing film, requiring identification of welds (4) a possible hazard to inspectors if fluoroscopic visual inspection is employed, without adequate precautions (5) relatively elaborate equipment and skilled operators are required.

Careful tests of this method during this research have shown that the extent of penetration of the solvent through the corona region of spotwelds is very variable. Trials of all available solvents, with suitable dye indicators, with many methods of flowing the fluids into the faying plane (vacuum and pressure techniques, supersonic pumping, heating, etc.) have shown that some welds permit the fluid to flow through the corona region (even when appreciable corona bonding is present) while other welds of identical strength stop the fluid at the corona boundary. Tests on several hundreds of welds indicated the fluid outline to be a poor measure of weld bonding and a misleading indication of weld strength. In some cases, the fluid and dye penetrated to the inner extremity of the Alclad inclusion into the weld nugget. Had this been universally the case, the method would have been exceedingly useful, as it was the only non-destructive test which ever showed promise of indicating the extent of the Alclad inclusion into the weld nugget.

2. Radiographic Tests: (Ref. #4, #6, #8, #9, #10)

In these tests, the welds are subjected to irradiation by carefully controlled low voltage X-rays and the weld image is recorded on fine grain photographic film placed behind the welded joint. The X-ray voltage should be stabilized to plus or minus $\frac{1}{4}$ KV., and should be selected to obtain maximum radiographic contrast. (Twelve KV.X-rays produce appreciably greater contrast than 40 KV. X-rays (Ref. #9).) The effective focal area of the tube should be small in comparison with the target film distance. An effective focal area one millimeter square with a 36 inch target to film distance has given acceptable definition with standard industrial X-ray equipment (Ref. #6). The film should have fine grain (Eastman Type M and Agfa Superay B have been used successfully), be wrapped only in photographic paper with 1/16 inch lead backing behind the film, and be placed reasonably close to the weld. Two or three layers of X-ray film can be used without appreciable loss in definition.

Exposure conditons must be precisely controlled to obtain optimum contrast and definition. (See Section VI). This research has shown that under optimum exposure conditions, images of the quality shown in Figs. 66 to 67 may be obtained consistently on production X-ray equipment rated as high as 150 KVP.

Precautions to be observed include: (1) The film must be wrapped only in thin paper opaque to light but transparent to X-rays of low voltage, (2) Exposure conditions and film processing should be precisely controlled, (3) Personnel should be protected from X-rays.

Inherent errors include (1) errors resulting from inability of method to discriminate extent of Alclad inclusion into the weld mugget. Such inclusion occurs frequently with thin, small weld nuggets, and lowers weld strength appreciably, (2) Errors resulting from lack of definition in radiographic images of spotwelds with thin weld nuggets, (3) Errors in interpretation of spotweld radiographic images.

Advantages of the test include (1) very complete information as to weld structure, geometry, size and strength is obtained (See Section VI). (2) the weld is not damaged by the test, (3) the weld need not be located precisely, (4) permanent records are obtained.

Disadvantages include (1) the test requires access to both sides of the weld, (2) long exposures (4 to 30 minutes) are required with standard radiographic equipment* (3) film must be used, involving added cost, (4) delay of developing takes time, requires identification of welds, (5) relatively elaborate equipment and skilled operators are required, (6) careful interpretation of radiographs is required.

Results of an extensive investigation of spotweld radiography are given in Section VI and VII.

3. Fluoroscopic Inspection Methods.

In these tests, the welds are subjected to carefully controlled X-rays and the resultant images are viewed by means of a fine grain fluoroscopic screen placed close to the welded sheet. Under optimum conditions, images similar to those obtained with fine grain film might be expected.

However, available fluoroscopic screens are far too coarse-grained to obtain definition adequate for spotweld inspection. Also the contrast between regions of the spotweld is too low for easy fluoroscopic inspection.

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*During this research, techniques have been developed so that adequate spotweld radiographs are obtained with exposure times as low as five seconds (See Section XII).

Precautions are: (1) the inspector must be protected from excessive X-ray exposure, (2) to obtain reliable results careful "dark adaptation" of the eyes (30 minutes in a completely darkened room) is required before inspection begins, (3) lack of sensitivity or failure to indicate fualts should not be taken as proof of weld quality.

Advantages of the method include: (1) no film is required, so inspection cost is low, (2) results of inspection are available immediately, so no marking or identification of welds is needed, (3) welds need not be located accurately for testing.

Disadvantages include: (1) a darkened room is needed for viewing the fluoroscopic screen (2) inspectors have time delays because of fatigue and time needed for "dark adaptation", (3) access is required to both sides of the weld, (4) special equipment may be required for the protection of personnel.

4. Ionization Gauge Method:*

In this test, X-rays pass from the source through the welded sheets into a suitable ionization gauge, which measures the quantity of X-rays passing through the sheets at the weld. (See Fig. 36). The gauge may make

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* This method is now under investigation by other research investigators.

either an overall measurement, or profile the weld region to obtain fine detail of the X-ray image of the weld. To avoid lengthy exposures exceedingly sensitive ionization gauges are required, particularly for profiling the weld.

Inherent errors include (1) errors due to failure to observe fine detail of weld in the overall test, (2) possible effects of cracks and porosity, (3) errors due to misalignment of the actual weld nugget and the ionization gauge, (4) errors due to excessive sheet indentation and other geometric factors.

Advantages include (1) response is immediate, making marking or identification of welds unnecessary, (2) indications are independent of operator and could be automatic in operation.

Disadvantages include (1) access is required to both sides of the weld, (2) careful locating of the weld is required, (3) cracking or excessive sheet indentation may introduce erroneous indication.

No development of ionization gauge testing equipment has been included in this research, since the penetrator and electrical tests provide equivalent information with simpler equipment.

I. Mechanical Proof Tests:

In mechanical proof tests, the spotweld is loaded to a predetermined fraction of acceptable strength in shear or tension by a suitable mechanical testing tool. With welds in extended sheets, it is very difficult to load individual spots in shear without excessive sheet distortion. As a result, most mechanical proof tests are designed to load the spotweld in tension. However, it must be recognized that tension strength is not necessarily proportional to the shear strength of the weld. Hence these tests are indicative of, but do not measure shear strength. They do discriminate between "stuck" welds and welds of acceptable strength.

The greatest disadvantage of mechanical proof tests is the possibility that the proof load might damage the weld. This need not necessarily occur--in fact it is probable that spotwelds which were damaged by proof loading to a fraction of minimum acceptable strength would not be suitable for use in aircraft anyhow. Experience with static shear pull tests on thousands of spotwelds fails to show any damage resulting from partial loading, in welds of acceptable strength and quality.

The advantage of proof tests lies in their complete reliability, when the load can be properly applied to an individual spot.

1. Pry Test Methods:

Following the method of the inspector who pries the sheets apart near the spotwelds to detect weak welds, calibrated prying tools designed to exert known loads have been developed. Regardless of the force exerted by the operator, clutch or spring devices prevent the force applied to the weld from exceeding a certain maximum. Hence known proof loads may be applied without damage to good welds. The method has a direct appeal to to the inspector because it follows proven inspection procedure with additional accuracy. (See Section XI [illegible]).

A precaution to be observed in applying pry tools is that the tool must be properly applied, and applied only to joints and sheet thicknesses for which it has been designed and adjusted, to avoid damage to the welds or structure.

Inherent errors include (1) errors resulting from the presence of other welds very close to the weld under test, if the load is distributed to these other welds, (2) errors due to variable sheet stiffness.

Advantages of pry testing tools are: (1) measurements are simple and direct, (2) the load is applied to weld at faying plane, rather than throggh sheet.

Disadvantages of pry testing tools are: (1) the sheets are separated and may be distorted by the test,

(2) welds are difficult to reach through large overlap, (3) sheet surface is scratched at faying surface, (4) damage to the weld may result from careless use.

No very practical forms of pry testing tools have been developed in this research, although preliminary designs for such tools have been proposed.

2. Adhesive Bond Test:

In this test, suitable small plates are bonded to the outer sheet surface above the weld, and/or to the opposite sheet surface, using recently developed metal to metal adhesives applied under heat and pressure. A typical adhesive * applied in these tests consistently developed more than 2500 p.s.i. shear strength and 2000 p.s.i. tensile strength in bonds between Alclad sheets. It is applied with a brush and allowed to dry in air for an hour. Then heat and pressure are applied 5 to 10 minutes to cure the bond. (See Fig. 37 A). Suitable loading tools then lift the bonded plates from the sheet, loading the individual spot in tension. (See Fig. 37 B). Weak welds fail under the chosen proof load. Acceptable welds are not damaged and the sheet is not distorted by this test.

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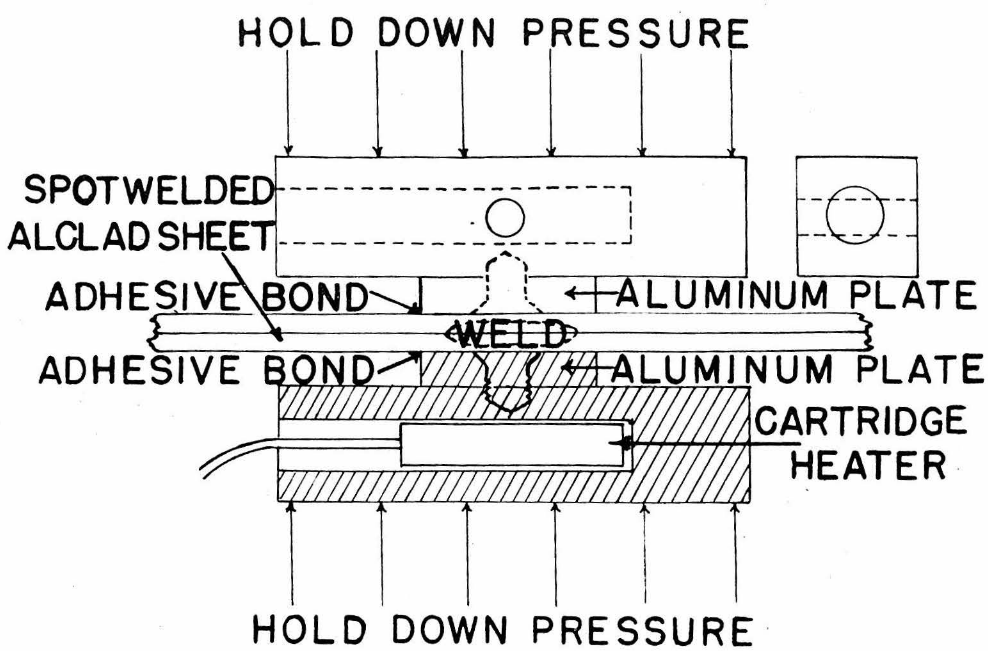
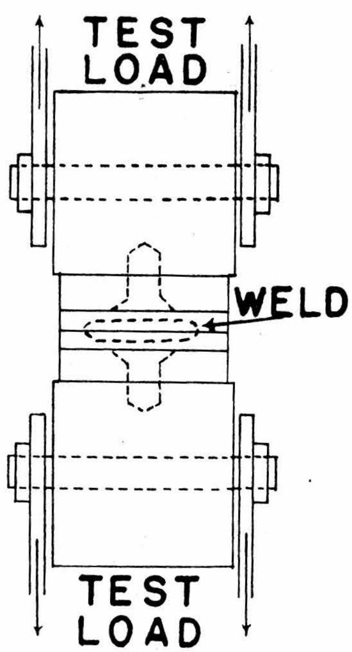
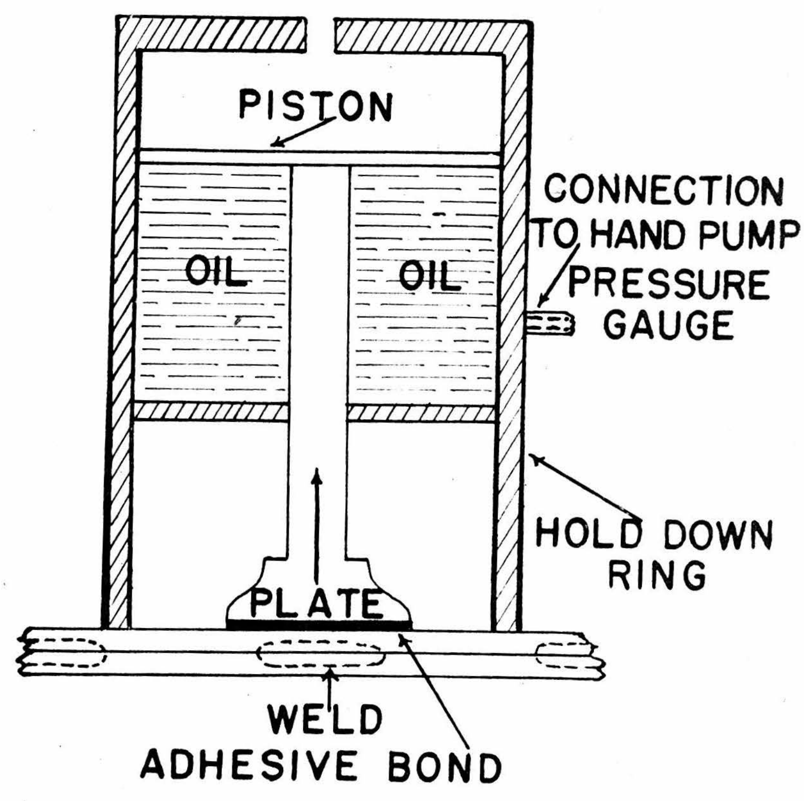
* Furnished by B-B Chemical Company, Cambridge, Massachusetts.



A. Bonding loading disc to sheet



B. Tension testing of weld



C. Hydraulic loading device

Fig. 37. Adhesive bond proof test of spot weld

Precautions to be observed in applying these tests include: (1) the sheet surface must be properly cleaned and the adhesive bond must be made carefully, (2) the load must be applied normal to the sheet surface so as to avoid progressive failure of the adhesive bond, (3) the applied load should not exceed the chosen proof load.

Limitations in the application of the method are: (1) it is not applicable to welds between two rigid sections, as the load would be distributed to several welds, (2) it may be applied to thin sheets welded to stiffeners, by loading from only one side, or to sheet to sheet welds with loading from above and below the weld.

Advantages of the method are: (1) the sheet is not distorted and good welds are not damaged by the test, (2) direct, reliable measurements are obtained.

Disadvantages of the method are: (1) tests on individual welds involve excessive time delay, although large numbers of welds may be tested relatively quickly, (2) heating and pressure equipment must be used to make the bond, and heat is needed to weaken the adhesive bond after testing, to remove the test plate.

Fig. 37-C shows a design for a loading tool for use with the adhesive bond proof test.

3. Proof Testing at Welder[ø]

It has been proposed that proof testing be carried out at the welder directly after each weld is made, so that defective welds can be detected immediately and replaced. Such testing might be made an integral part of the welding operation, automatically applied as the head of the welder rises so as to entail negligible loss of time. Special clamp tools, possibly operated by the welder air supply, would be necessary to hold the sheet and load the weld. On long continuous joints, these clamps might also serve to move and position the sheet for welding. The device would load the weld only to a fixed proof load, and release the sheet when this load was attained, to avoid excessive sheet distortion. Hold down devices might be needed to avoid loading adjacent welds. Care would be exercised to avoid excessive sheet separation because of the clamps inserted at the faying plane. Cold rolling subsequent to welding might be necessary to reduce sheet separation to a minimum.

Precautions include (1) care to avoid damage to the weld through excessive proof loading.

Advantages are: (1) proof testing can be carried out on all welds, (2) defective welds can be detected and rewelded with negligible lost time, (3) the test would be reliable and conclusive.

Disadvantages are: (1) proof loads might damage the welds, (2) sheet separation and distortion might result, (3) the time required for welding might be increased, (4) the flexibility of the welder might be reduced. (5) new fixtures might be required for special shapes of structure to be welded.

No development of this type of equipment has been included in this research. A sketch of a possible method of applying load by means of straps appears in Fig. 6S.

IV. SELECTION OF SUITABLE TEST METHODS:

To select from the proposed test methods those showing the greatest promise, it was necessary to determine:

A. The correlation of weld properties with static shear strength.

B. Effect of sheet preparation and conditions of welding upon weld properties.

C. The destructive tests of spotwelds equivalent to loading conditions in aircraft structures in use.

D. The measurements required of non-destructive tests.

E. Suitable components of non-destructive spotweld testers.

The results of measurements on more than a thousand industrially made spotwelds from several sources were used to establish the following facts, on which the selection of suitable test methods was based.

A. Correlation of Weld Properties with Static Shear Strength

1. Types of Failure

The failure of spotwelds under static shear loading is usually of one of three basic types:

(a) Shear through the nugget at the faying plane (See Fig. 38). In this type of failure the maximum strength of the weld is developed. Any contributions to weld strength by corona bonding will be realized in addition to the strength of the cast alloy nugget area.

(b) "Pulling a button" in which case failure usually

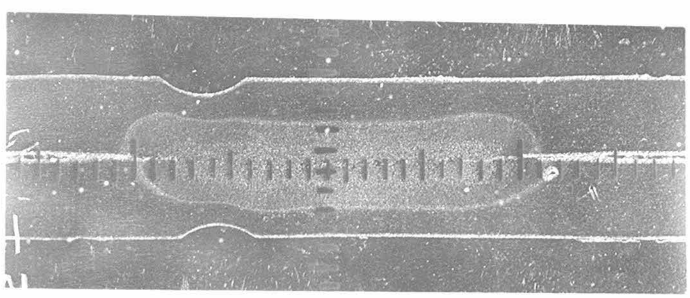


FIG. 38. SPOT WELD FAILURE BY SHEAR THROUGH THE NUGGET AT THE FAYING PLANE.

occurs at the periphery of the nugget along the walls of a circular cylinder through one of the sheets as shown in Figure 39. In this case the full strength of the spotweld will not be developed and the strength depends only upon the effective diameter of the nugget and the qualities of the heat-affected zone at the nugget boundary. The presence of corona bonding and the shear strength of the cast alloy at the faying plane do not contribute to the ultimate strength of the weld. They do represent, however, a measure of the maximum strength which could possibly be developed even when failure is by "pulling a button". Failure by pulling a button whose size corresponds to the inner extremity of the Alclad inclusion (such as occurred in weld F-90, Fig. 74) results in reduced strength proportional to the diameter of the actual button pulled.

(c) Pulling a partial button with shear through nugget. (See Fig. 40). In this case, failure starts most frequently at the inner extremity of the Alclad inclusion into the weld nugget and progresses through the cast alloy of the nugget to the sheet surfaces, usually pulling about one-half of the normal button. The strength developed in this type of failure is quite variable and depends almost entirely upon the geometry of the surfaces of cleavage.

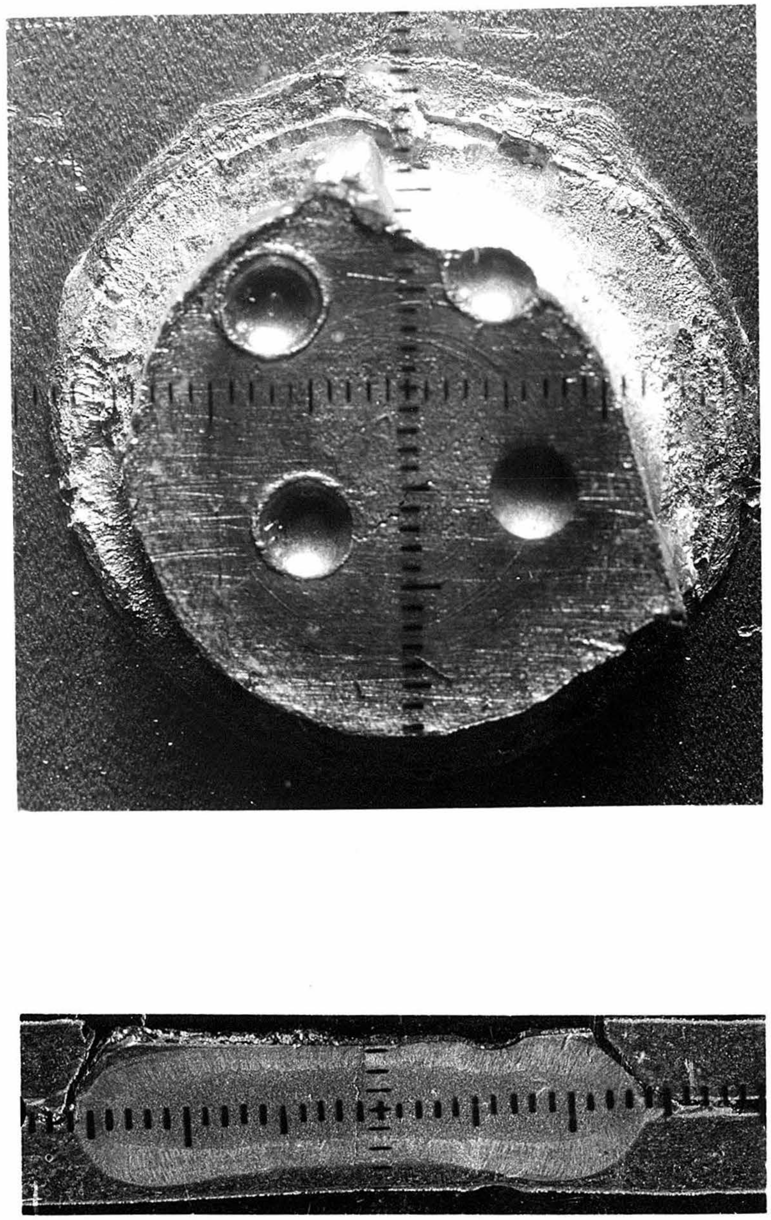


FIG. 39. SPOTWELD FAILURE BY "PULLING A BUTTON".

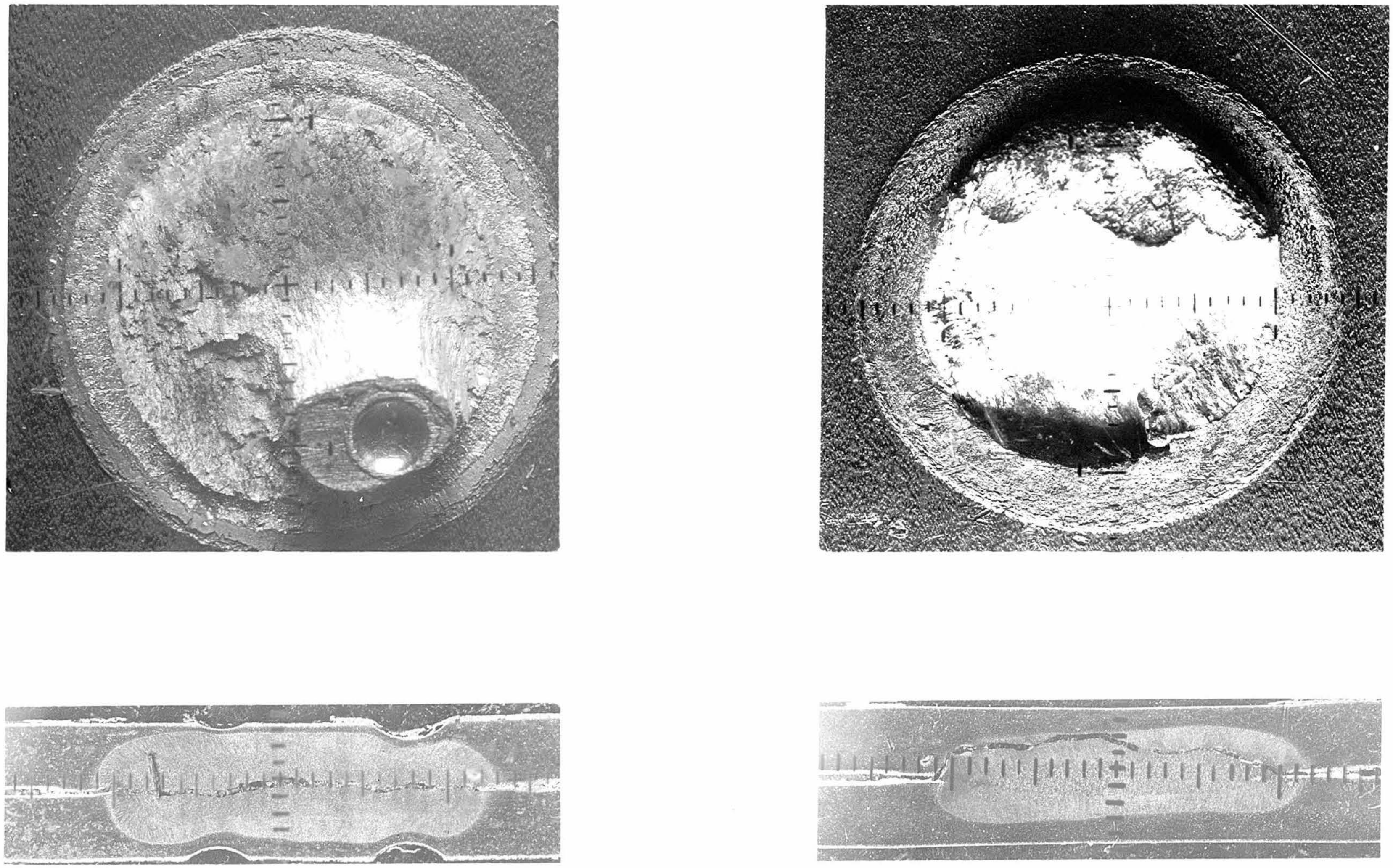


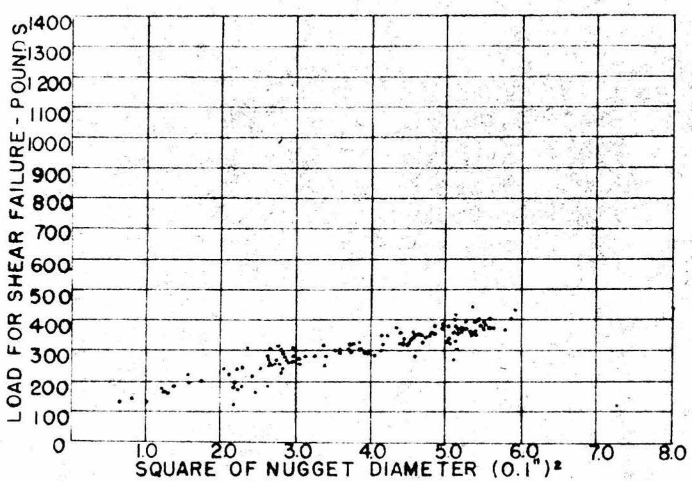
FIG. 40. SPOTWELD FAILURE BY PULLING A PARTIAL BUTTON WITH SHEAR THROUGH NUGGET.

2. <u>Nugget Diameter and Shape</u>

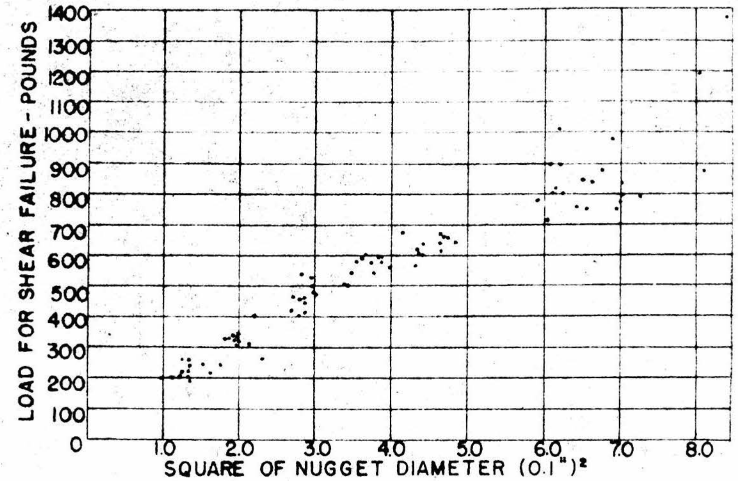
The single weld parameter which correlates most reliably with static shear strength is the area of cast alloy bonding at the faying plane, which is measured approximately by the diameter of the nugget at the faying plane if Alclad inclusions are not excessive.

In normal welds the cast alloy of the nugget at the faying plane develops from 18,000 to 22,000 p.s.i. static shear strength with the average value for typical welds close to 20,000 p.s.i. Hence, most of the weld strength is developed in the nugget in normal welds and, in case the failure is by shear at the faying plane, the area of cast alloy determines the weld strength reliably. However, in many cases, an additional bonded area of Alclad material exists outside the weld nugget and contributes to weld strength. Figure 41 shows typical correlations between static shear strength and cast alloy area at the faying plane for several hundred welds. In general, most of the welds with a given cast alloy area will have strengths within plus or minus 10% of the median strength in that area. These results have been confirmed by research in other laboratories (Ref. #3 & #8).

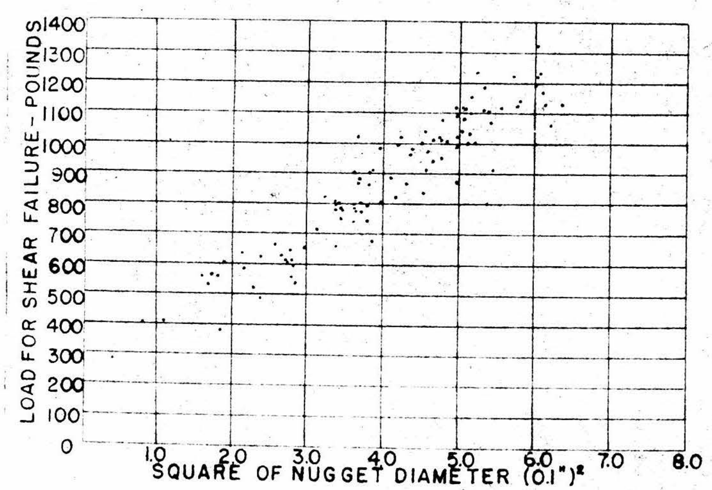
The shape of the nugget, provided it be reasonably symmetrical, is not critical to the weld strength. Misshapen nuggets, however, are often an indication of poor surface preparation or bad welding conditions and usually go along with welds



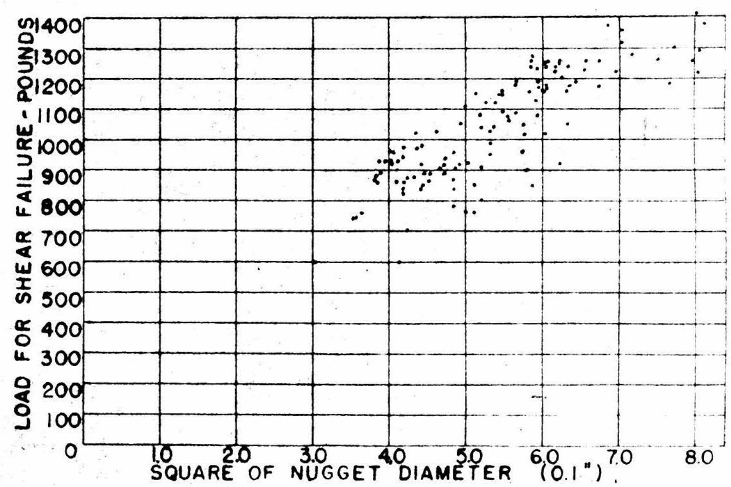
A. 138 WELDS IN .020" 24 S-T ALCLAD MADE ON SCIAKY WELDER AT LOCKHEED AIRCRAFT CORPORATION.



B. 138 WELDS IN .040" 24 S-T ALCLAD MADE ON TAYLOR-WINFIELD WELDER AT CONSOLIDATED-VULTEE. AIRCRAFT CORPORATION, SAN DIEGO, CALIFORNIA.



C. 108 WELDS IN .064" 24 S-T ALCLAD MADE ON SCIAKY WELDER AT LOCKHEED AIRCRAFT COPORATION.



D. 138 WELDS IN .081" 24 S-T ALCLAD MADE ON TAYLOR-WINFIELD WELDER AT THE UNIVERSITY OF SOUTHERN CALIFORNIA.

NOTE: THESE WELDS WERE PURPOSELY MADE VARIABLE IN STRENGTH FOR USE IN DEVELOPING NON-DESTRUCTIVE TESTS.

of inconsistent or low strengths.

3. <u>Nugget Penetration and Volume</u>

The thickness of the weld nugget measured by its penetration into the parent sheet is not critical in determining static shear strength, provided that the penetration lies between 20% and 80% of the sheet thickness. (Ref. #5). With penetration below 20% nugget formation is very irregular and extensive Alclad inclusions may result in great weakening of the bond at the faying surface. These low penetration welds should be classified as not acceptable because they could not pass strength consistency requirements. Welds whose nuggets penetrate to more than 80% of the sheet thickness are indicative of welding conditions under which cracked welds frequently occur and are undesirable because the excessive nugget thickness weakens the parent sheet at the bond and usually results in a large heat-affected region surrounding the nugget in which the strength of the 24 ST alloy may be considerably reduced. Such welds may fail by pulling buttons where the surface of failure may lie in this weakened zone. They do not develop as much shear strength as could have been developed had the nugget sheared through the faying plane.

Our experience does not show that within the acceptable range of 20% to 80% penetration the unit shear strength of the weld depends significantly upon penetration. Instead we find that with welds of lower penetration there is frequently present a relatively larger area of Alclad bonding, whose strength contribution is responsible for the apparent fictitious increase in the unit shear strength of the nugget (Ref. #3).

4. Total Bonded Area at the Faying Plane

The total bonded area at the faying plane consists of (a) the cast alloy region of the nugget and (b) the region of corona bonding. In the usual case the cast alloy area is uniform and completely bonded. However, the corona bonding is variable from no bonding whatever to a complete areal bonding. With complete bonding the corona region develops about 9500 p.s.i. unit shear strength. With incomplete bonding (small points bonded with surrounding interstices) the apparent unit shear strength of the corona for a group of welds may be as low as 6500# or even 4500#. The quality of the corona bond depends critically upon the method of sheet preparation and cleaning, in addition to the conditions of welding. Under some conditions no corona bonding whatever will develop.

The weld strength correlates more closely with

$$(A_n \times S_n) + (A_c \times S_c)$$

where

A_n = Net Cast Alloy (Nugget) Area at Faying Plane

S_n = Unit Shear Strength of Cast Alloy (Nugget)

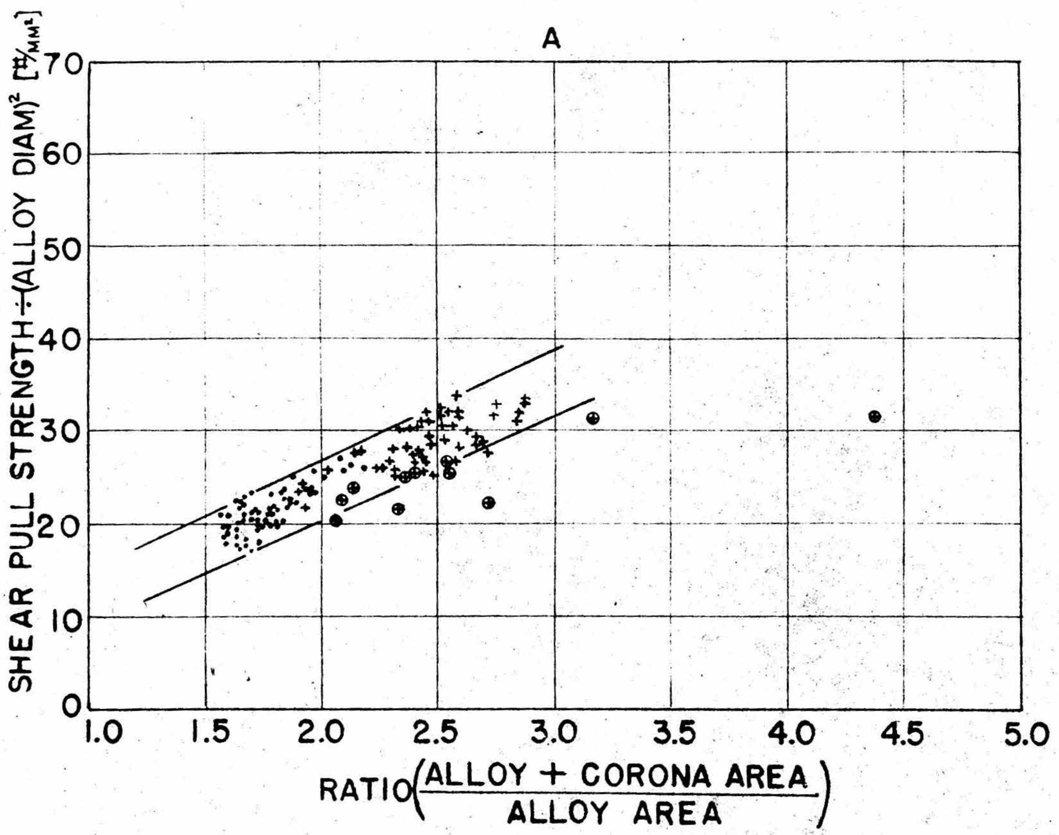
A_c = Effectively Bonded Area of Alclad Corona

S_c = Unit Shear Strength of Corona Bonding

than with any other combination of measureable spotweld parameters, despite the fact that in some cases failure occurs by mechanisms other than failure by shear at the faying plane.

5. Corona and Nugget Unit Shear Strengths

The actual unit shear strengths of the cast alloy bonding and the corona bonding can be determined for a group of welds by plotting (a) the ratio of the shear strength to the square of the corona diameter against (b) the ratio of the square of the nugget diameter to the square of the corona diameter. Such curves are shown in Figure 42 for welds in .040" 24 ST Alclad sheet. The intercept of the median line of the curve with the vertical axis gives the unit shear strength of the corona bonding. The slope of the median line gives the unit shear strength of the cast alloy. For the group of welds shown the measurement shows the unit shear strength of the corona bonding to be about 9,600 p.s.i. while that of the nugget is 20,500 p.s.i. Similar results have been obtained in other gauges with all sizes of welds. Using these unit shear strengths in the relation given in Section IV(D), the actual strength of any normal weld can be predicted within plus or minus 10% in the usual case from



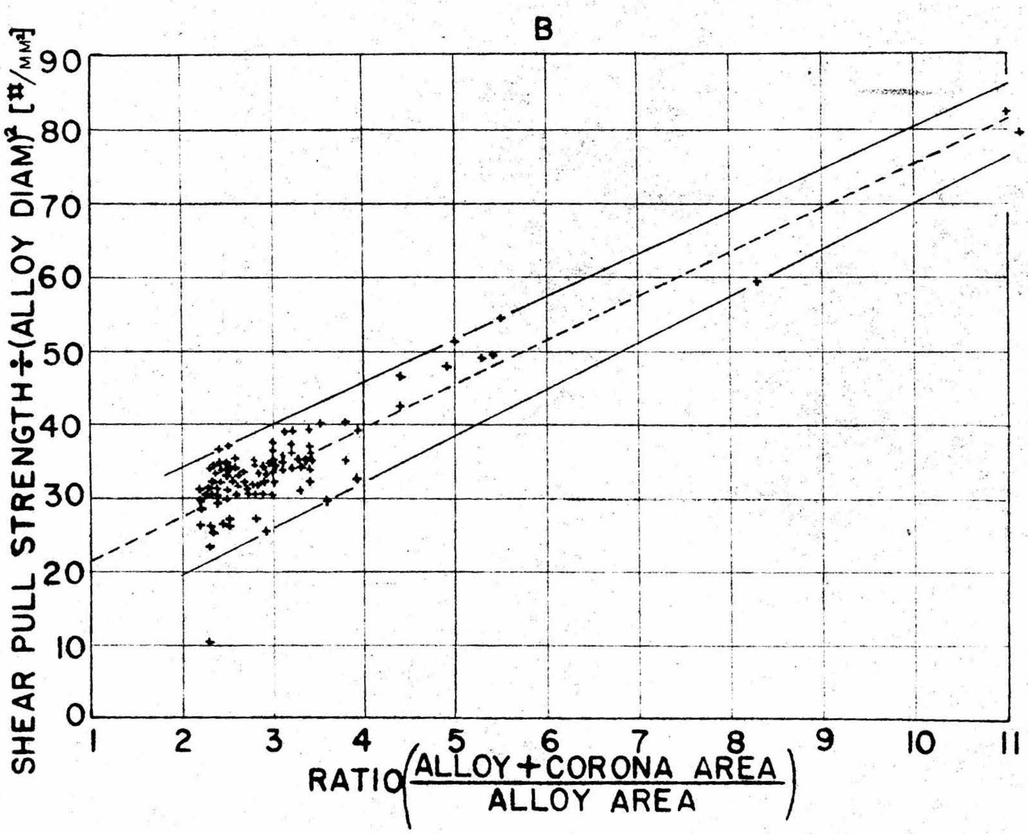


FIG. 42. GRAPH USED FOR CALCULATION OF UNIT SHEAR STRENGTHS OF CAST ALLOY AND CORONA BOUNDED REGIONS AT FAYING PLANE OF SPOTWELDS.

A. 141 SCIAKY WELDS IN .040" 24ST ALCLAD.

B. 108 SCIAKY WELDS IN .064" 24ST ALCLAD.

its nugget and corona diameters.

6. Electrical Resistivity

As previously indicated in Section III B, the differences in resistivity of specific volumes of metal in the weld region are too small to serve effectively as a measure of weld size and geometry, when measurements must be made from the sheet surface through a thick layer of parent metal. The presence of cracks and porosity and of extensive sheet indentation further reduce the reliability of such measurements.

7. Penetrator Measurements

Penetrations resulting when a loaded probe is pressed into this outer surface of the sheet above the spotweld nugget at a single point tend to measure the thickness of tempered parent metal lying above the weld nugget at that point. A succession of such measurements is capable of determining the geometry of the nugget boundary in the sheet under test. Figure 34 shows typical penetrator indentation profiles obtained by using a Rockwell Hardness Testing Machine on welds in .064" 24 ST Alclad sheet. These show the method to be especially sensitive when the weld nugget lies close to the sheet surface and to lose sensitivity rapidly when the weld nugget penetrates only 20% to 30% into the sheet (See Fig. 34). Similar measurements can be made with small hand testing devices. (The Barcol Impressor serves suitably for thin gauges of aluminum sheet, .032" and thinner). (See Fig. 64).

8. <u>Metallurgical Structure</u>

Metallurgical structure is of less importance than nugget size, shape, soundness, freedom from cracking, and extent of corona bond in determining weld strength and quality. No metallurgical characteristic has yet been reliable correlated with weld strength.

The ductility of the weld metal is, however, of great importance, as one of the chief defects met in spotwelds is lack of sufficient ductility to permit even distribution of applied loads across the bonded area. Brittleness seems to reduce weld strength especially under impact and fatigue loading, yet its effects upon static shear strength are very small. Hence, ductility alone cannot be used to measure static shear strength. However, spotwelds to be acceptable must show appreciable ductility.

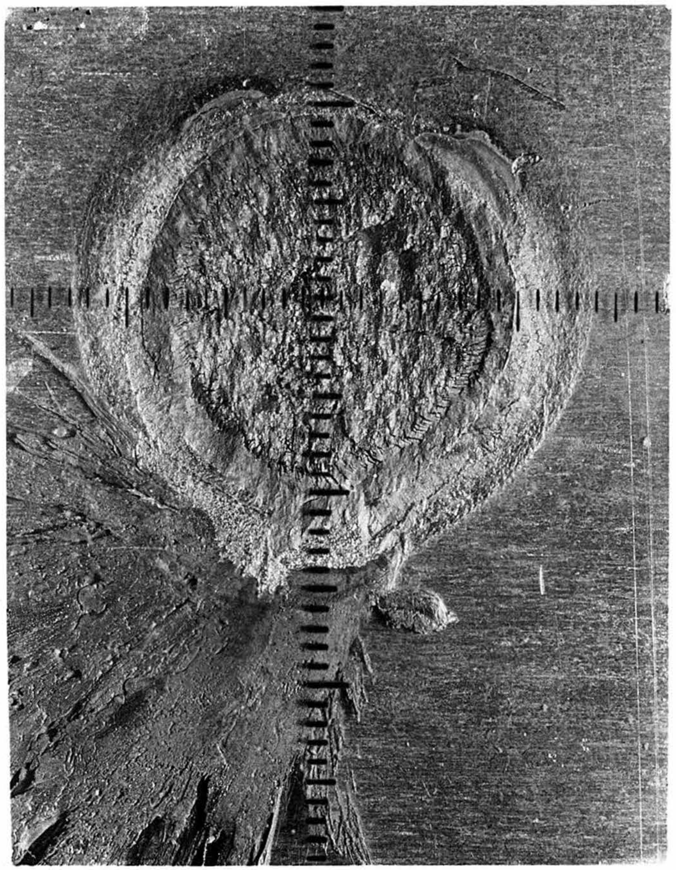
B. Effect of Sheet Preparation and Condition of Welding Upon Weld Properties

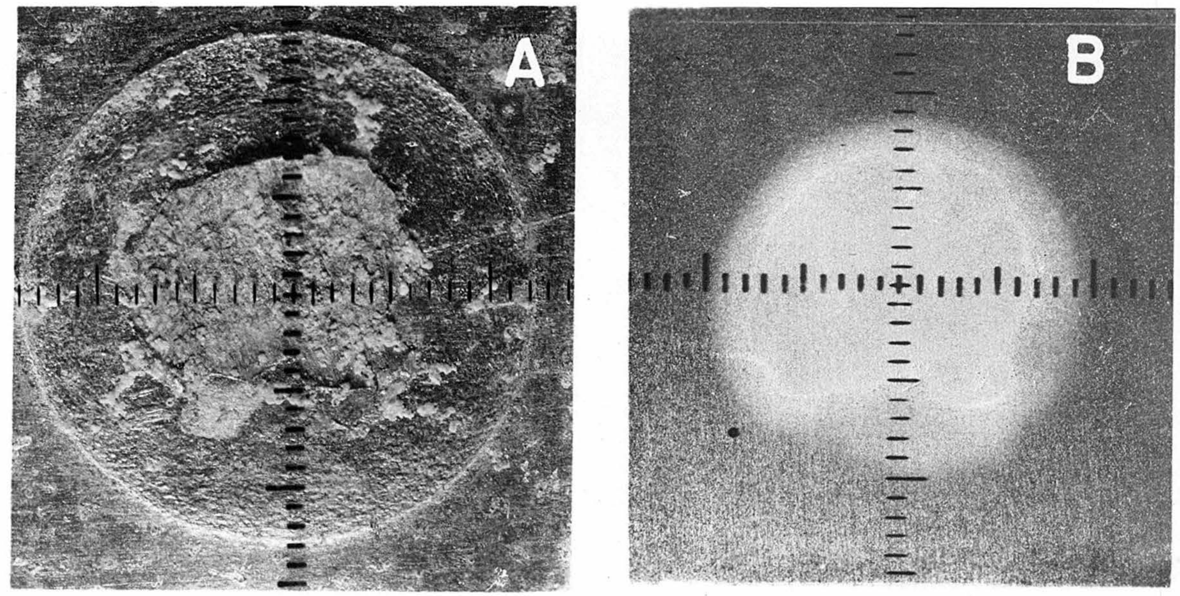
The size, shape and structure of the spotweld nugget and the extent and nature of Alclad bonding at the faying plane are critically dependent upon the methods of cleaning and preparing sheet for welding and upon the conditions of welding.

1. Sheet Preparation

One of the most variable parameters controlling spotweld quality is the method of sheet preparation and cleaning. There is little agreement as yet on the precise procedure of etching and cleaning among the various manufacturers of aircraft. As a result, the surface condition of the sheets, although usually consistent in any one factory, varies widely from one company to another. Uniform surface conditions are required for consistent weld strength. The surface conditions, if irregular, result in misshapen weld nuggets, spitting, and other weld defects, as well as in variable strength (See Fig. 43). The size of the nugget developed is a function of the resistance at the faying plane during the period of welding, so that a change in cleaning conditions may result in a change in weld size although all controllable conditions of welding are kept constant.

The nature of the corona bond varies greatly with sheet surface condition. Sheets cleaned adequately for good welding





FAYING PLANES.

SECTION BELOW ALCLAD.

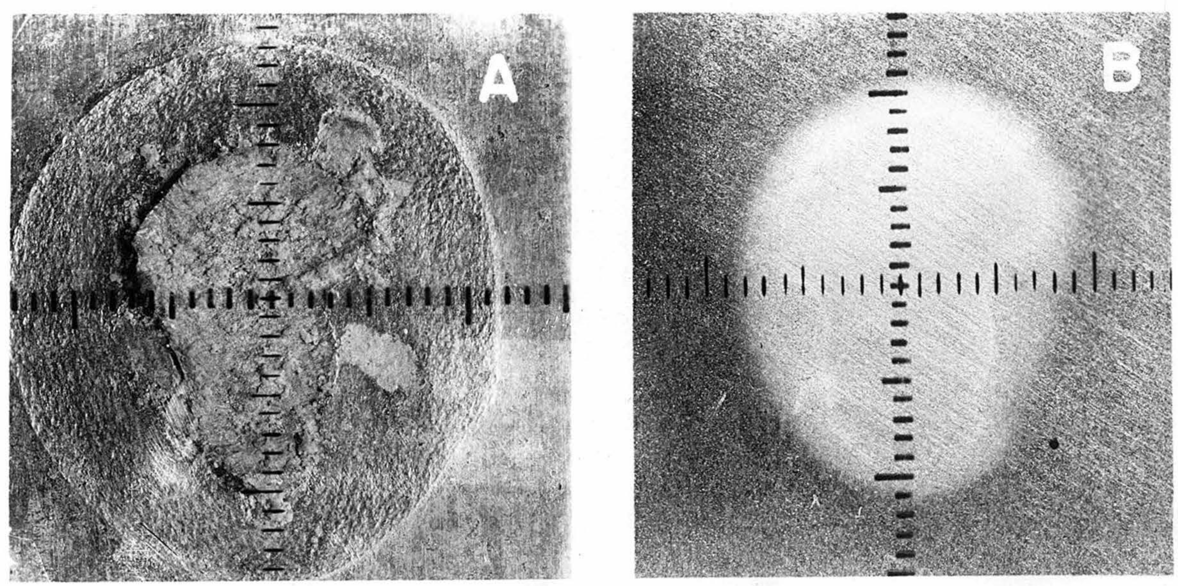


FIG. 43

MISSHAPEN AND DEFECTIVE WELDS TYPICALLY RESULTING FROM NON UNIFORM SHEET SURFACE CONDITIONS.

may, if finger-printed, cause the corona bond to fail to develop. Where Alclad inclusions into the nugget are extensive the failure to develop corona bonding introduces a discontinuity into the stressed region of the weld nugget and contributes to early failure under certain types of loading. Thus cleaning condititons may be responsible for a change of 100% in weld strength for welds with identical nugget sizes, simply as a result of the failure to obtain corona bonding. See Figure 44 for typical variations in corona bonding which may result from non-uniform sheet surface conditions.

2. Electrode Shape

The geometry and surface condition of the welding electrodes has a critical effect upon the shape and extent of nugget development in the spotweld and upon the nature and extent of the heat-affected zone of the parent metal adjacent to the nugget. Sharp, small electrode tips tend to cause nugget development nearer to the outer sheet surface in contact with the small tips. Furthermore, as the tips grow dirty the nuggets tend to develop greater penetration and approach the outer sheet surface because of the increased heat developed at the tip contact. On the other hand, flat electrode tips frequently cause the nugget to develop less penetration. When a rounded tip and a flat tip are used together to make the weld the nugget will frequently be

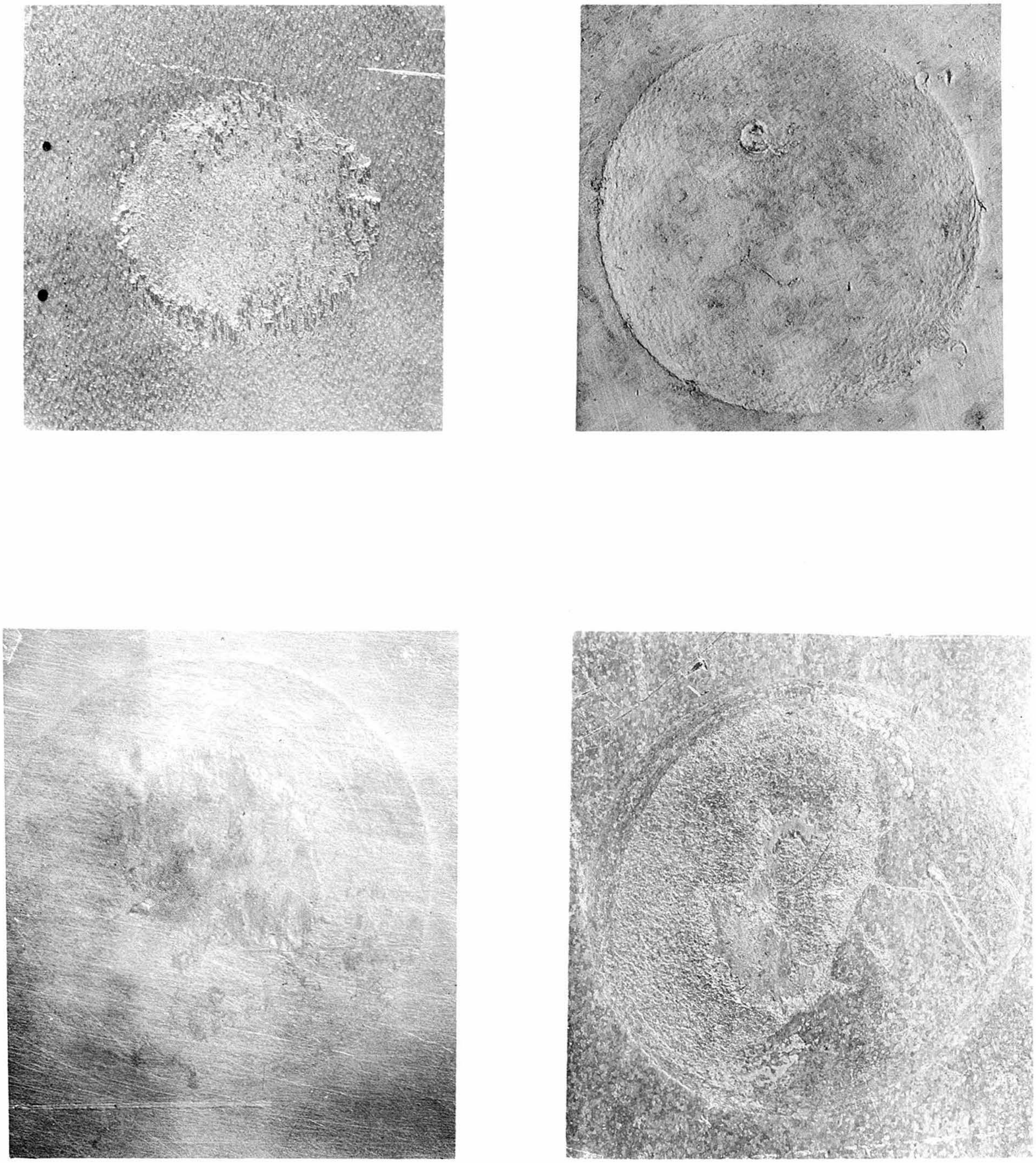


FIG. 44. VARIATIONS IN CORONA BONDING WHICH MAY RESULT FROM NON-UNIFORM SHEET SURFACE CONDITIONS.

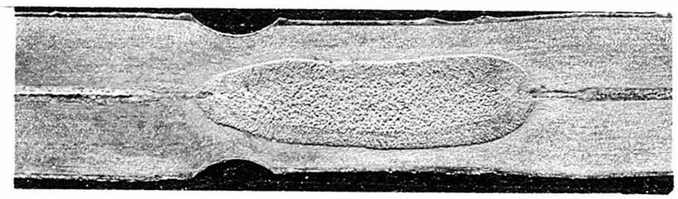
displaced from the faying plane toward the rounded tip. As the tips grow dirtier or are heated up during the process of welding, extensive pickup from the sheet surface occurs. To avoid this pickup, tips are periodically cleaned during welding. Figure 45 shows typical variations in nugget position resulting from changes in electrode shape and size. Non-destructive test methods must not give erroneous indications as a result of variations in tip conditions which have not changed weld quality.

3. Welding Current, Power and Energy

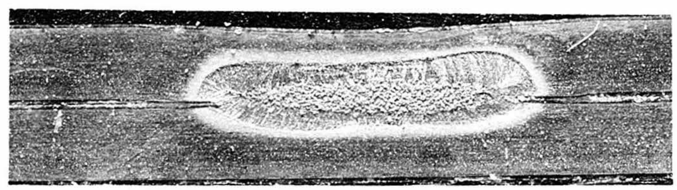
The energy delivered to the weld determines the size of the weld nugget and the bonded area. The net energy developed in the sheets during welding will be given by the integral.

This energy obviously depends upon the welding current, the resistance at the faying plane of the weld, and the time during which the current flows. Because of the very high heat conductivity of aluminum, the rate at which energy is supplied to the weld region is critical. In general, the heat must be developed very rapidly in order that the temperature may be raised above the melting point of the cast alloy at the weld. Hence, the wave shape of the current is very important. Steep-fronted, short-duration current surges tend to produce more extensive melting per watt second of energy delivered to the weld region than do long-duration waves with slowly changing

A. 3" RADIUS DOME 5/8" DIAMETER UPPER ELECTRODE FLAT 5/8" DIAMETER LOWER ELECTRODE.



B. 5" RADIUS DOME 5/8" DIAMETER UPPER ELECTRODE FLAT 5/8" DIAMETER LOWER ELECTRODE.



C. 3°5 CONE UPPER ELECTRODE FLAT 5/8" DIAMETER LOWER ELECTRODE.

D. 7°0 CONE UPPER ELECTRODE FLAT 5/8" DIAMETER LOWER ELECTRODE.

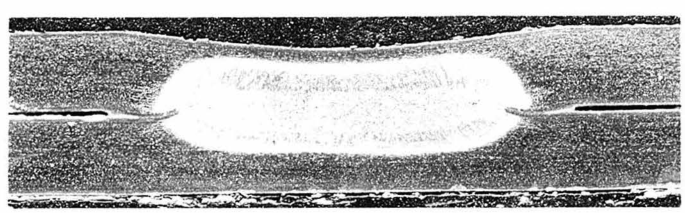


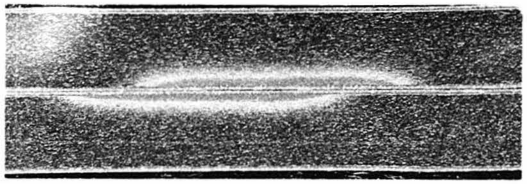
FIG. 45. VARIATIONS IN SPOT WELD NUGGET SHAPE AND POSITION RESULTING FROM CHANGES IN ELECTRODE SHAPE AND SIZE.

currents. Furthermore, the wave shape of the current will have an important effect upon the actual timing between the melting of the alloy and the application of forging pressure. Typical variations in weld nugget size as welding energy increases are shown in Fig. 46. Non-destructive test methods should measure weld quality and strength independently of the current conditions during welding.

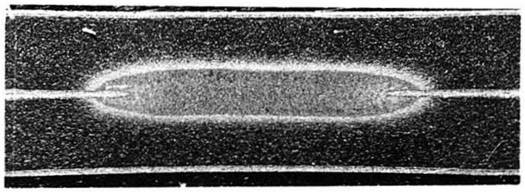
4. Pre-Compression, Welding Pressure and Forge Pressure

Tip pressure conditions during welding have a large effect upon the electrical resistance at the faying plane and upon the energy developed in the weld. High pressure at the beginning of the welding cycle lowers the effective resistance and decreases the weld energy. Insufficient pressure during the period that the alloy is melting results in expulsion of metal at the faying plane and excessive expansion in the heated region. During the period of subsequent cooling from the periphery of the nugget toward its center, cracking and porosity develop. Excessive forging pressure after the nugget has been formed results in excessive sheet indentation. Inadequate forging pressure produces inadequate bonding at the faying surface. Excessively advanced forging pressure has the same effect as excessive pressure during the welding period, namely,

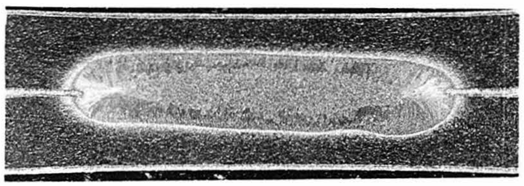
Fig. 46. Effect of increased welding energy on weld nugget size.
Taylor Winfield welder.



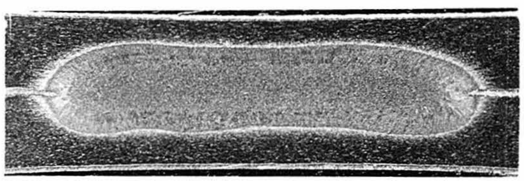
960 MFD.
1800 VOLTS.



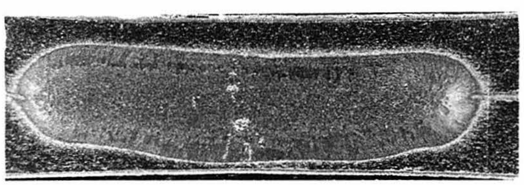
960 MFD.
2000 VOLTS.



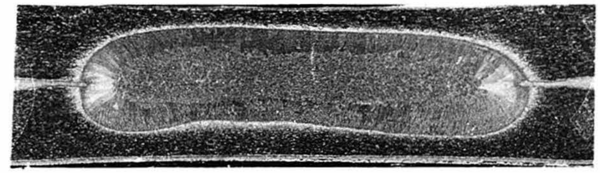
960 MFD.
2200 VOLTS.



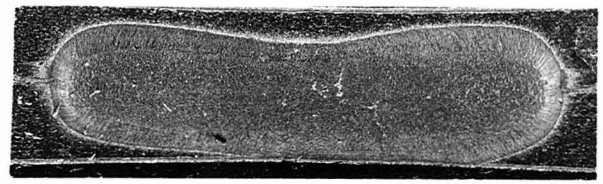
960 MFD.
2400 VOLTS.



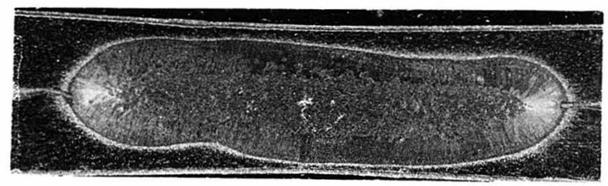
960 MFD.
2600 VOLTS.



960 MFD.
2800 VOLTS.



1200 MFD.
2200 VOLTS.



1200 MFD.
2400 VOLTS.

1200 MFD.
2600 VOLTS.

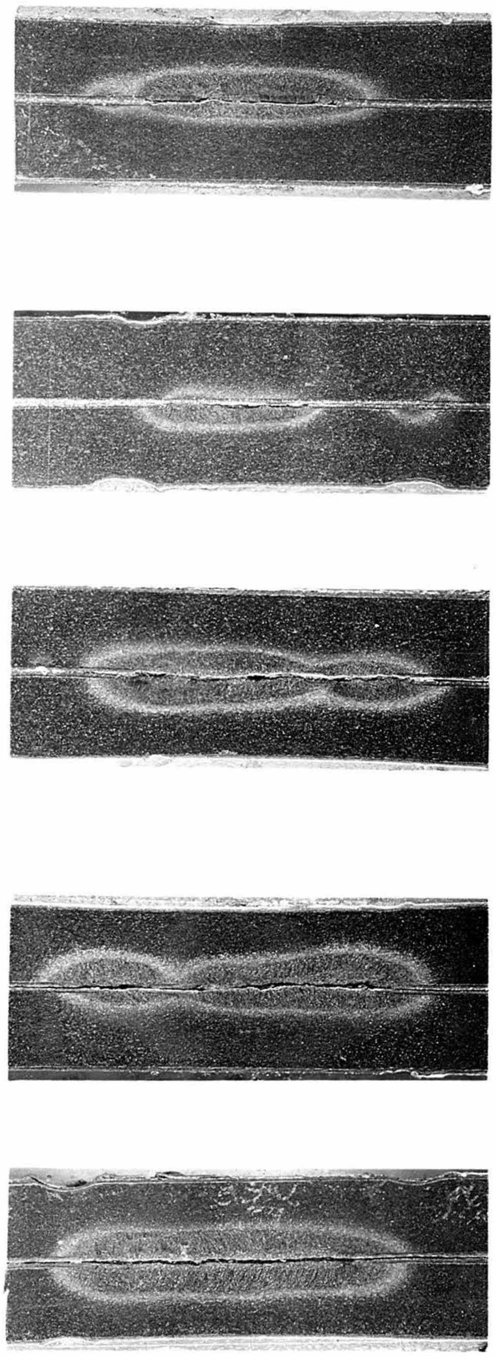
1200 MFD.
2800 VOLTS.

it reduces the resistance at the faying plane and hence reduces the weld energy. Excessively delayed forging time is undesirable because the weld nugget will have solidified before forging pressure is applied, nullifying its effects. The effect of advancing and delaying the application of forge pressure upon welds made at constant energy setting of the welder is shown in Figure 47.

5. Process Control and Non-destructive Testing

To meet Army and Navy specifications for minimum weld strength and strength consistency, aircraft manufacturers now use extensive process control in the spotwelding departments. As a result, in any one plant, variables in cleaning and conditions of welding are held reasonably constant. For this reason, it is not necessary for non-destructive test methods to be sensitive to exceedingly abnormal conditions, but rather to be able to detect weld quality and strength reliably under normal variations of industrial welding conditions.

FIG. 47. EFFECT OF CHANGING THE TIME OF APPLICATION OF FORGING PRESSURE UPON WELDS MADE AT CONSTANT CURRENT RELAY SETTINGS OF SCIAKY WELDER.



A. FORGE TIME SETTING 165 -- VERY ADVANCED FORGE --

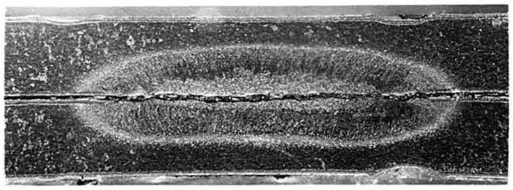
B. FORGE TIME SETTING 175 -- LESS ADVANCED FORGE --

C. FORGE TIME SETTING 200 -- LESS ADVANCED FORGE --

D. FORGE TIME SETTING 210 -- LESS ADVANCED FORGE --

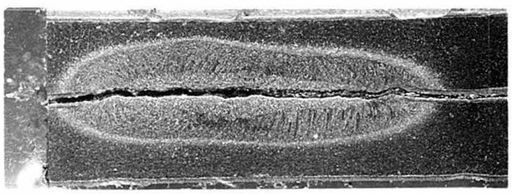
E. FORGE TIME SETTING 215 -- LESS ADVANCED FORGE --

FIG. 47, CONT'D.

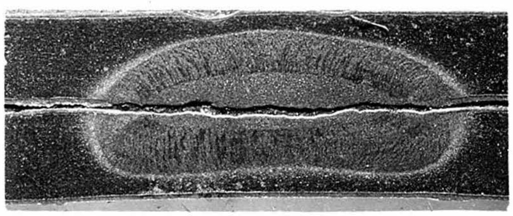


F. FORGE TIME SETTING 220 — — NORMAL FORGE.

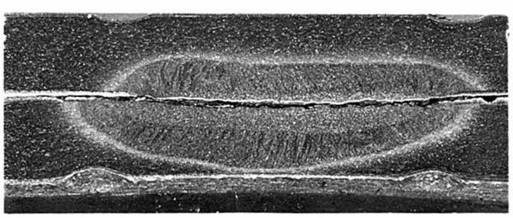
G. FORGE TIME SETTING 225 — — NORMAL FORGE.



H. FORGE TIME SETTING 230 — — DELAYED FORGE.



I. FORGE TIME SETTING 235 — — DELAYED FORGE.



J. FORGE TIME SETTING 240 — — MORE DELAYED FORGE.

K. FORGE TIME SETTING 245— — EXCESSIVELY DELAYED FORGE.

C. DESTRUCTIVE TESTS OF SPOTWELDS

Non-destructive tests must predict the strength of spotwelds as shown by destructive pull tests of spotweld specimens. The strength of the spotweld depends critically upon the nature of the load applied to cause its failure. Hence, non-destructive tests must be specifically designed to predict the strength of the weld under the type of loading met in aircraft structures in use.

1. Nature of Loads on Welds in Aircraft

Spotwelds used in aircraft structures are usually constituents of multiple spot lap joints, in which several welds share the applied load. As a result of this type of use most of the welds are loaded in shear, despite the nature of the total applied load. Furthermore, spotwelds are weak in tension and normal design calls for loading of spotwelds only in shear. The presence of adjacent welds holding the sheets together tends to prevent the application of tension loads under normal conditions. The loads applied include static, impact, and fatigue—but calculations are usually based on design static shear strength, which is less than the minimum acceptable test strength by a suitable factor of safety.

2. Static Shear Loads

Normal design calls for specified static shear strengths in spotwelded joints. Specimen welds and coupons welded during runs on aircraft structures are tested in the shop by simple static tension loads on single lap single spot joints arranged to load the weld itself in shear. A typical shear specimen is shown in Figure 48. The strength developed on this test will depend upon not only the weld qualities but also the method of testing and the method of applying the load. Components of torsion load or of tension on the spot should be eliminated if reproduceable shear strengths are to be obtained. A simple machine developed for the shear testing of spotwelds in this research is shown in Figure 49. The method of loading, by means of pins through holes drilled in line with the spotweld, prevents the application of twist or tension loading. Welds may be tested as rapidly as two a minute with plus or minus 3% accuracy on this machine. Clamp grips are frequently found to be objectionable because if tightened while slightly out of line appreciable moments are developed at the weld. The static shear test is by far the simplest test to be applied for routine checks on spotweld strength.

3 Fatigue and Impact Shear Loads

In flight, and particularly under battle conditions and when landing, aircraft structures are subjected to fatigue and impact loading. Spotwelds have been found to be very weak under certain types of impact loading. Likewise, fatigue load-

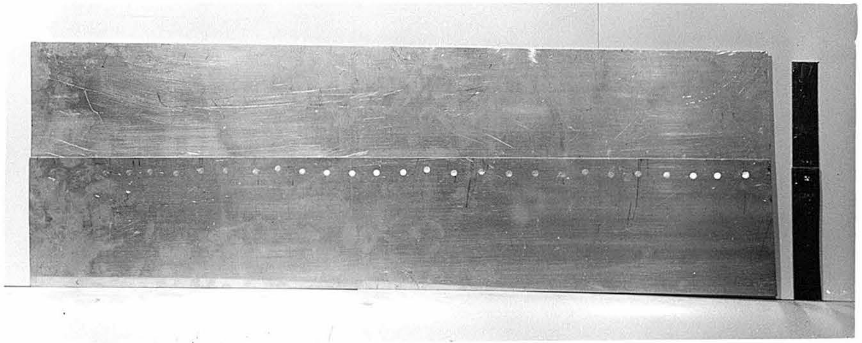


FIG. 48. TEST PANEL AND SHEARED ONE INCH SINGLE SPOT STATIC SHEAR TEST STRIP.

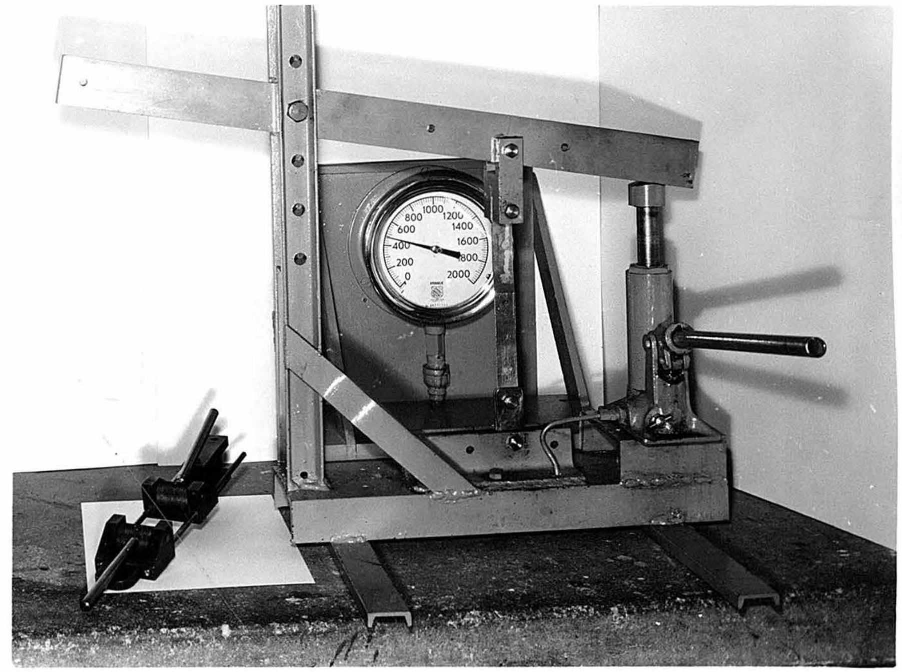


FIG. 49. SPOTWELD STATIC SHEAR STRENGTH TESTING MACHINE. (IN USE, CROSS ARM IS MAINTAINED HORIZONTAL)

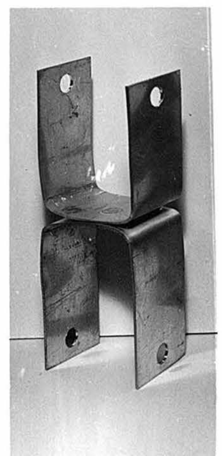


FIG. 50. SINGLE SPOT TENSION TEST SPECIMEN.

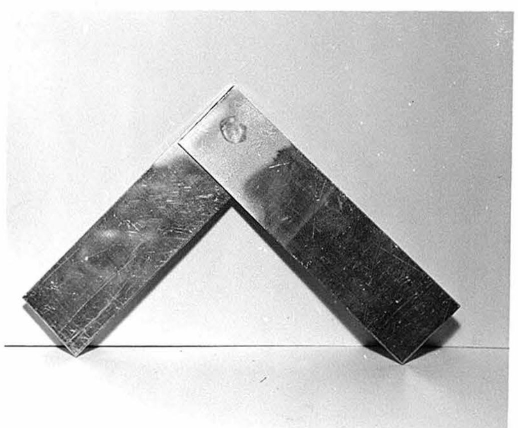


FIG. 51. SINGLE SPOT TORSION TEST SPECIMEN.

ing which is known to be present in joints in aircraft structures may lead to early failure of spotwelded joints, particularly if cracking is present, or if the weld is not sufficiently ductile. At present extensive research on the fatigue properties of spotwelded joints is under way (Ref. #15). The complete results of this research have not yet been presented. Thus it is not known whether fatigue strength is a better measure of spotweld quality than the static shear strenght. Hence, the simpler of the two tests, namely, static shear loading is most widely used at present to determine weld quality.

4. Tension Loads

It has been felt by several research organizations that the true quality of spotwelds is more adequately measured by loading the spotweld in tension as indicated in Figure 50. In this case the properties of the weld nugget and of the heat-affected zones surrounding the nugget have a significant effect upon the measured strength of the weld. Also, there has been a tendency to correlate the ductility of the weld with the ratio of the tension to the shear strength. However, for development of significant non-destructive tests it is more important to predict accurately the s tatic shear strength which is the assumed actual loading of the welds in use.

5. Torsion Shear Loads

Spotwelds are exceedingly weak in torsion because of the small moment of area of the bonded zone about its center, so that applied moments of force result in very high shear stress in the weld nugget. The ductility of the weld is frequently measured by applying a twisting moment to a single spot specimen prepared as shown in Figure 51. As yet the significance of the torsion tests has not yet been proven and therefore it is not necessary that non-destructive tests predict this weld quality.

As a result of the conditions listed, static shear loading has been used for the destructive testing of spotwelds in this research. Non-destructive tests have been designed to predict the static shear strength of spotwelds, with only coincidental correlation with these other strengths.

D. MEASUREMENTS REQUIRED OF NON-DESTRUCTIVE TESTS

To measure weld quality and static shear strength reliably the non-destructive test must measure certain spotweld parameters and conditions precisely. The simplest measurements of each of these parameters is the preferred one. The minimum requirement is that the non-destructive test measure nugget diameter reliably. For more accurate measurement of weld strength it is necessary to measure the total bonded area at the faying surface and to determine which portion of this area is cast alloy bonding and which portion is corona or Alclad bonding. Supplementary measurements which would be desirable are: a measurement of the penetration of the nugget into the parent sheet, a measurement of the extent of the heat-affected zone, a measurement of the spotweld's ductility, and a measurement of the extent of cracking and porosity. None of these last named measurements is necessary, however, to predict the static shear strength of the welds.

It is recognized that a visual inspection will be necessary to check sheet surface conditions at the weld and so non-destructive tests are not intended to measure any weld condition which can be observed reliably from the sheet surface.

E. SUITABLE COMPONENTS OF NON-DESTRUCTIVE SPOTWELD TESTERS.

Selection of the most promising test methods in accordance with the requirements of an acceptable test listed in Section II and the facts presented in this section has resulted in the choice of (a) the radiographic test method, and (b) the penetrator and ring electrode tests, for further development.

The radiographic test provides an indication of weld nugget shape, diameter, and penetration, as well as evidence of defects. It is definitely non-destructive, and by development could be made to satisfy the requirements of an acceptable test.

The simplest non-radiographic test would consist of: (a) a penetrator measurement of nugget diameter, (b) an electrical measurement of the total bonded area, and (c) if desired, an eddy current measurement of the extent of cracking and porosity in the weld nugget.

The remaining sections of this thesis present details of the development of equipment, technique, and procedures for interpreting the measurements obtained, for the radiographic, penetrator, and electrical non-destructive tests. Results of test measurements on several hundred industrially prepared spotwelds are included.

V. DEVELOPMENT OF PENETRATOR AND RING ELECTRODE TESTS.

For laboratory trials with the penetrator and ring electrode tests, careful alignment of penetrators, electrodes, and probes, and measurement of loads, deflections, currents, and potentials were required. Since it was found impractical to hold the component parts by hand, vise, or wooden frame, a machined steel press was designed and built. This machine has served for all penetrator and electrical spot weld tests to date.

A. DESIGN AND CONSTRUCTION OF SPOTWELD TESTING MACHINE #1

Spotweld Testing Machine #1 is a laboratory device designed to test the principles of the penetrator and electrical non-destructive tests. It has not been designed to take extensive structures, but will handle standard shear test panels with spotwelded lap joints. Compact construction was used to avoid excessive deflections of the frame of the machine under loading. The machine combines two test operations in one sequence, namely: two side ring penetrator tests of the nugget diameter, and two side electrical tests of the total area of bonding. Figure 52 shows the entire machine.

For the ring penetrator test, a hydraulic jack (a) applies loads measured by weighing block (b) and indicated on dial gauge (c) to the moving pressure cylinder (d) which slides

FIG. 52. SPOTWELD NON-DESTRUCTIVE TESTING MACHINE NO. 1.

A. HYDRAULIC JACK.
B. WEIGHING BLOCK.
C. LOAD DIAL GUAGE.
D. MOVING CYLINDER.
E. CYLINDRICAL GUIDE.
F. FRAME.
G. BALLPENETRATORS-LOWER.
H. ANVIL INSERT.
I. ANVIL-LOWER.
J. BALL PENETRATORS-UPPER.
K. ANVIL INSERT.
L. ANVIL-UPPER.
M. TOP PLATE.
N. PROBES.
O. CONTACT TIPS.
P. Q. DIAL GUAGES.
R. PISTON CAP.
T,U. TERMINALS.
V. MICROSWITCH.

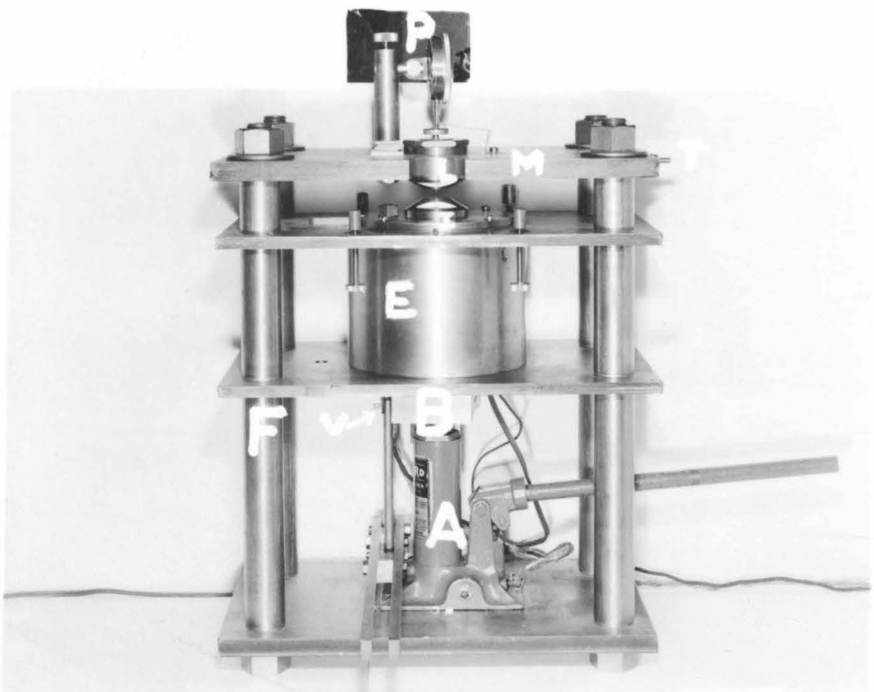


FIG. 52A. SIDE VIEW OF ASSEMBLED MACHINE.

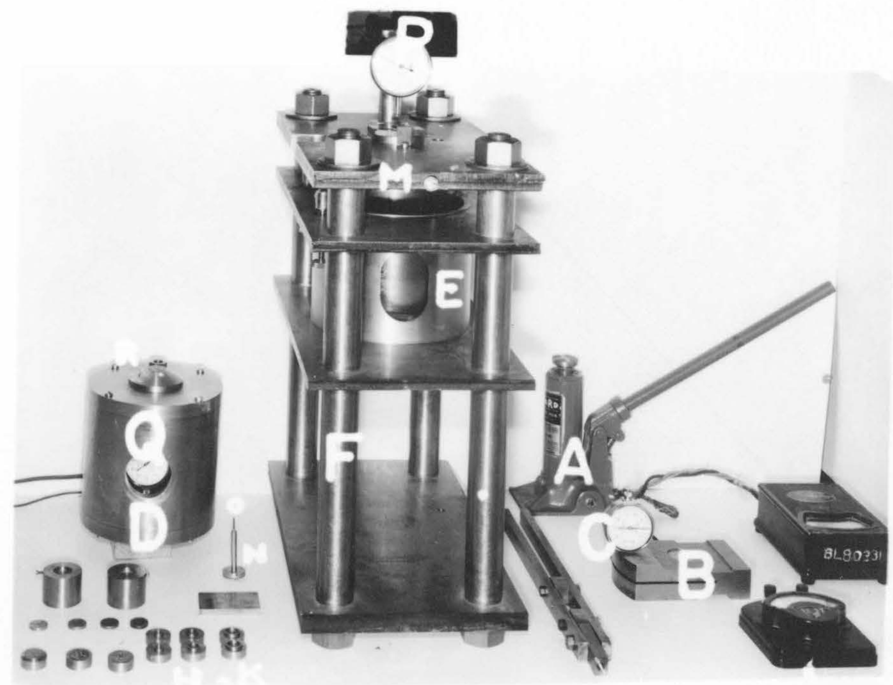


FIG. 52B. DETAIL OF MACHINE, DISASSEMBLED.

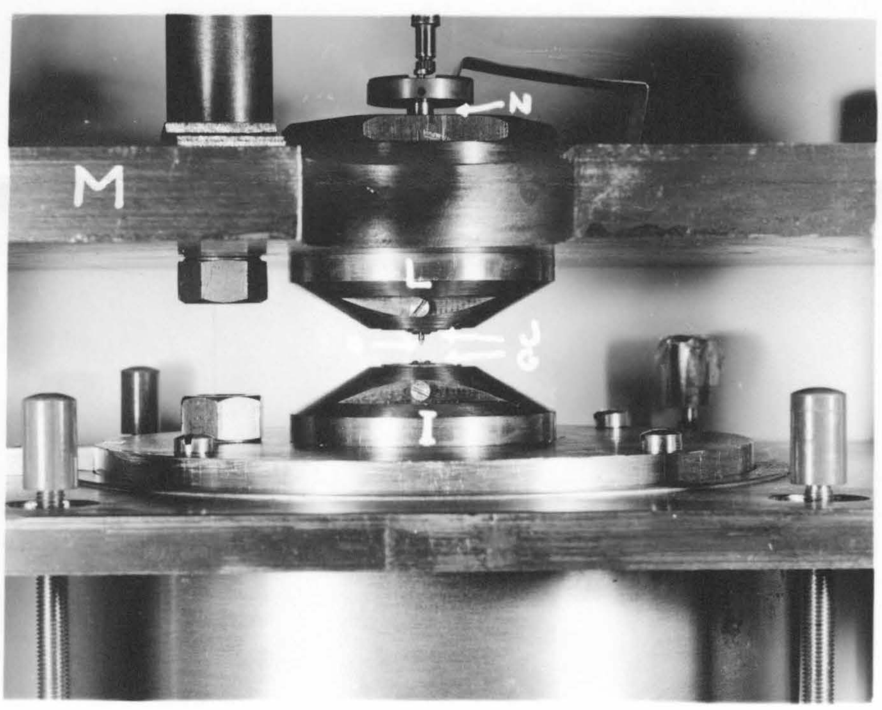


FIG. 52C. DETAIL OF ANVIL AND PENETRATOR ASSEMBLY

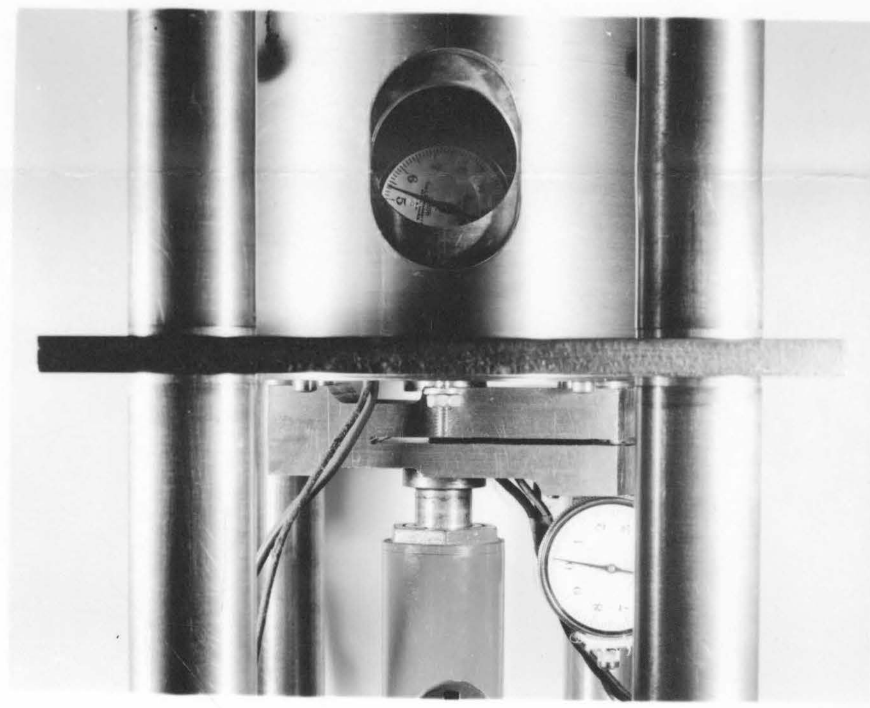


FIG. 52D. DETAIL OF WEIGHING BLOCK.

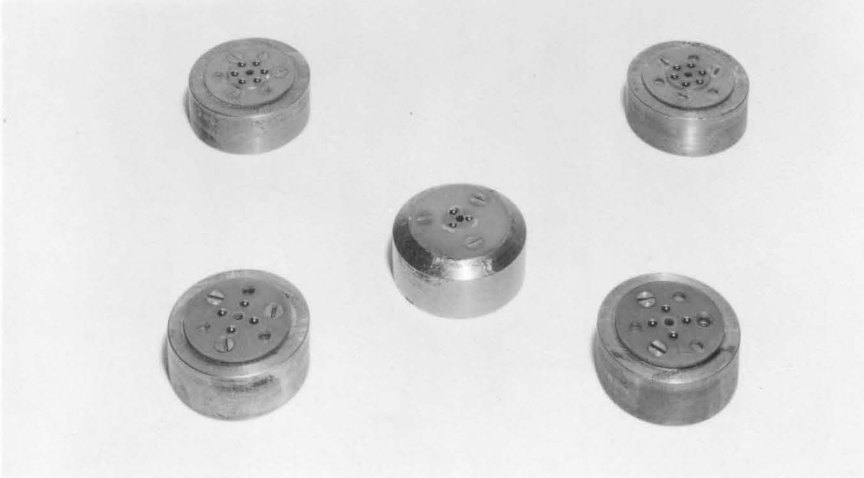


FIG. 53. RING PENETRATOR ASSEMBLIES USED ON TESTING MACHINE NO. 1.

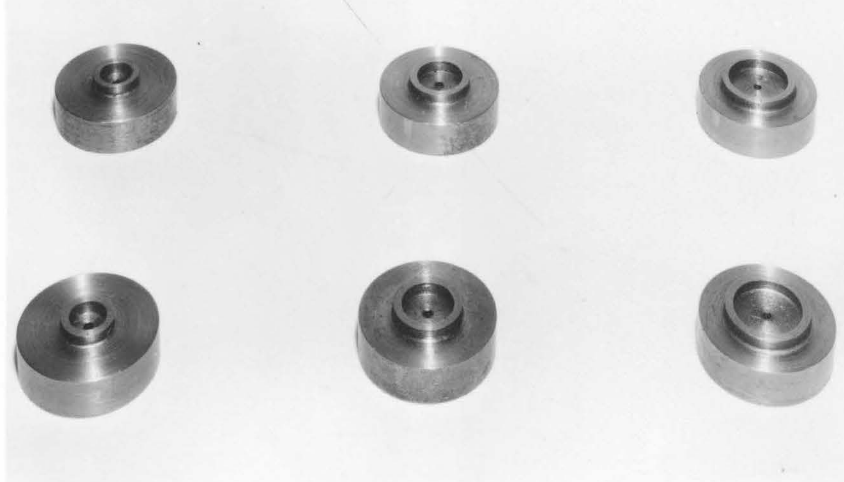


FIG. 54. RING ELECTRODE ASSEMBLIES USED ON TESTING MACHINE NO. 1.

in an accurately machined cylindrical guide (e) supported by the frame of the machine (f). The ball penetrators (g) are carried on removable anvil inserts (h) held by a set screw in a socket in the anvil (i), and are carefully aligned on the axis of the moving cylinder. Similar penetrators (j) are carried on the anvil insert (k) in the upper anvil (l). This anvil is set into the top plate (m)which is securely fastened to, but electrically insulated from, the frame (f). These upper penetrators are carefully aligned with the lower penetrator balls on the moving cylinder. Probes (n) slide freely in the anvils, and have replaceable contact tips (o) which pass through small holes in the anvil inserts (k). The heads of these probes are in contact with sensitive dial gauges (p) and (q) fastened firmly by posts to the top plate (m) and the piston cap (r), respectively. These gauges measure the penetration of the penetrator balls under loading. In operation, the spotwelded panel is inserted between the head and the moving cylinder and the spotweld is carefully centered under the penetrator assembly. Loads are applied as desired.

For the two side electricat test, either the anvil inserts carrying the ball penetrators, or similar inserts with circular ring penetrators (s) may be used as electrodes. Electric current from an external direct current current generator is introduced into the top plate (m) (which is insulated from the frame) at contact (t). This current flows from the upper penetrator or electrode (j) through the weld to the lower electrode (g), and leaves the machine through the terminal (u) on the moving cylinder. The current then returns to the generator through an external ammeter and control resistance. The potential drop across the probes (n) is measured by a low resistance microammeter. These probes are carefully insulated from the anvil inserts. Microswitch (v) on the weighing block (b) is inter-locked with the current switch to prevent the switching on of current with inadequate electrode pressure.

The ring penetrator assemblies used on Testing Machine #1 are shown in Figure 53. For laboratory tests, 1/16" diameter hardened steel balls (commercially available for Rockwell Hardness Testing Machines) were used as penetrators. Calibrated sharpened steel points (commercially available for use in the Barcol Impressor) can be used to obtain equivalent penetrator tests with much lighter applied loads. The penetrators are mounted on circles of diameter chosen to correspond to acceptable spotweld nugget diameters in various gauges of aluminum alloy sheet, and are supported on hard steel anvil inserts. These inserts may be quickly exchanged when it is desired to test spotwelds in different gauges of alloy sheet.

The ring electrode assemblies used on Testing Machine #1 are shown in Figure 54. The electrodes are circular contact areas of diameter slightly larger than the total bonded areas of acceptable spotwelds ineach sheet thickness. These electrode units are of the same dimensions as the penetrator anvil inserts and may be used interchangeably in Testing Machine #1.

B. Principle of Operation of Machine

The ring penetrator tests of spotweld testing machine #1 are based upon results of the penetrator profile tests shown in Figure 34. From these tests it was found that the typical penetration profile had the characteristic shape shown in Figure 55. The ring penetrator units of spotweld testing machine #1 are designed with the diameter such that the penetrators fall on the points A-A of the penetrator profile curve for normal good welds in each gauge of aluminum alloy sheet. If the weld nuggets are smaller than the normal acceptable weld nugget the penetrators fall outside the weld nugget over the tempered parent metal, at points on the penetrator profile curve identified by B-B. If, however, the nugget is larger than the normal size, the penetrators fall over the center of the nugget and the indications correspond to the points C-C of the penetrator profile. Sections through typical weld nuggets of various sizes in .040" 24St Alclad sheet are shown in Figure 56

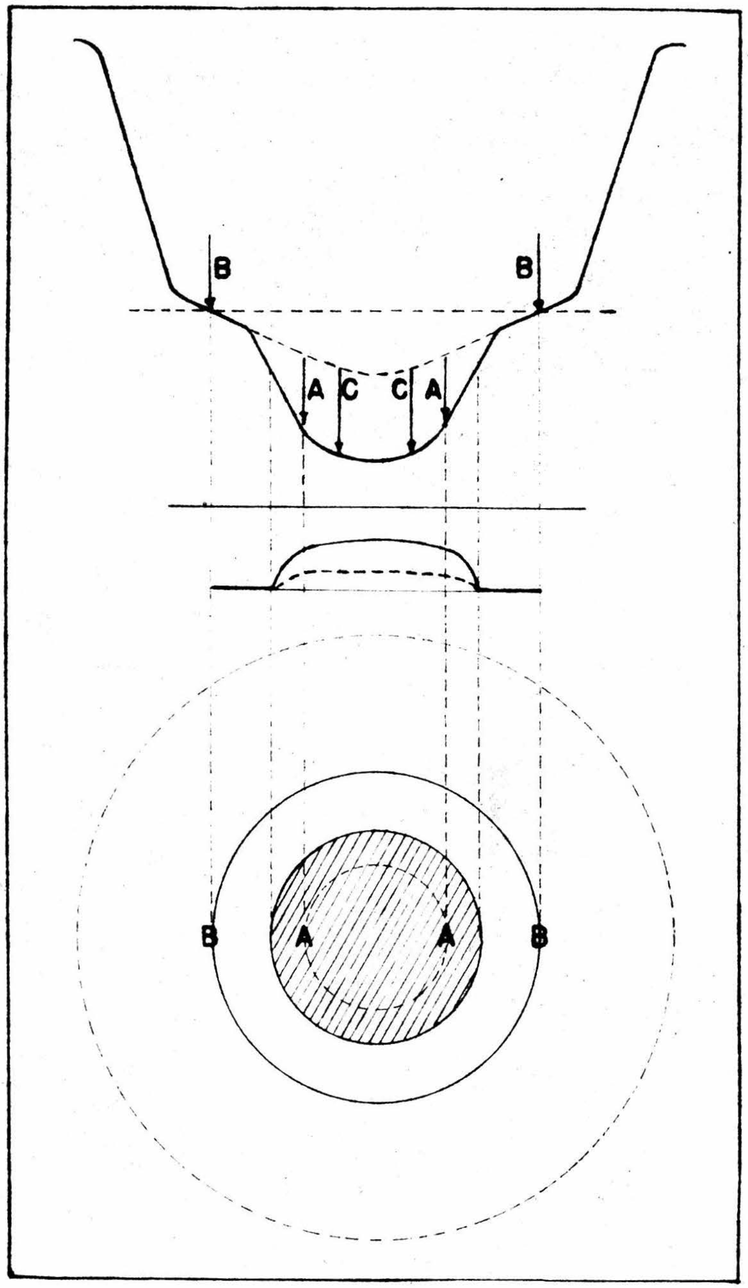


FIG. 55. CHARACTERISTIC SHAPE OF PENETRATOR PROFILE.
TOP. PENETRATOR INDICATION PROFILE.
CENTER. SECTION THROUGH NUGGET.
BOTTOM. FAYING SURFACE OF WELD.
DOTTED CURVE CORRESPONDS TO THIN NUGGET.

Taylor Winfield Welds in .040" 24ST Alclad.

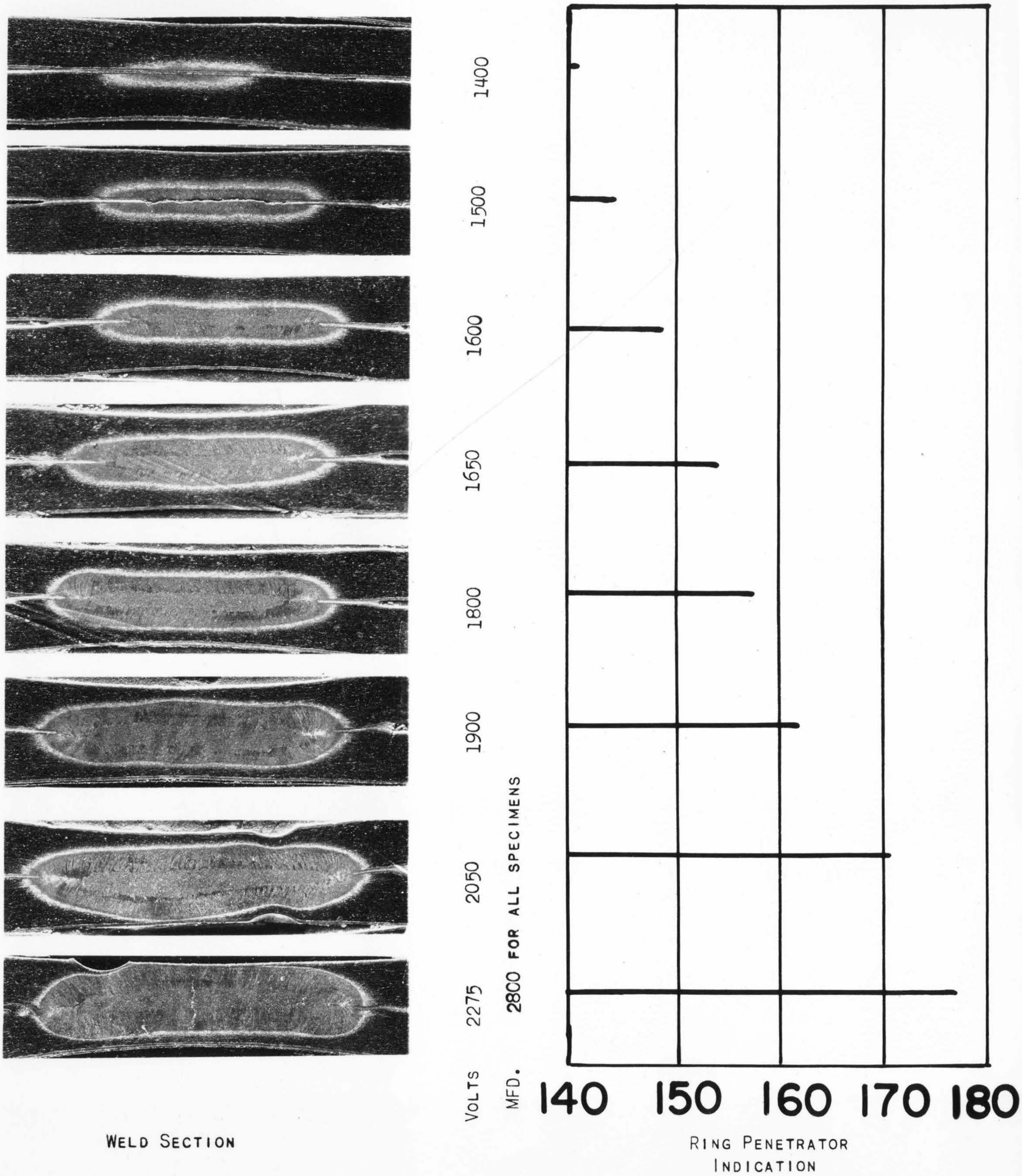


Fig. 56. Macrographs of sections of unpulled weld specimens, and indications of the ring penetrator test for these specimens.

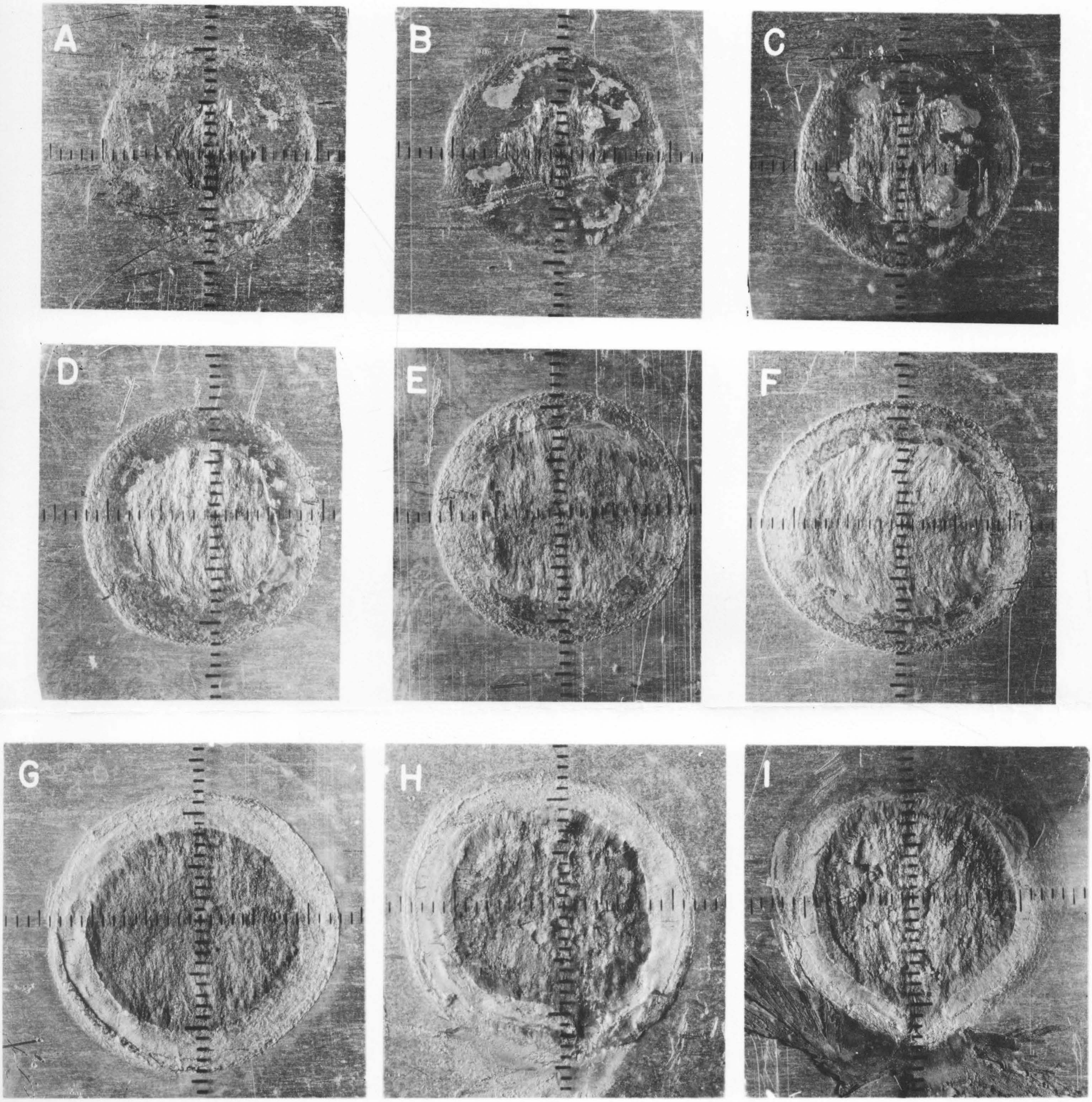
with the indentation of the ring penetrator test visible on the macrographs. The penetrator test indication is shown for each of the welds. It may be seen that the penetration of the ring penetrator measures weld diameter sensitively and reliably, and that small weld nuggets are differentiated from large weld nuggets by significant changes in indication.

The ring electrode two side direct current test of spotweld testing machine #1 are based upon preliminary tests of the two-side direct current method of determining the total bonded area at the faying plane. (See Section IIIB-1 and Figures 9, 10 and 11). Macrographs of the faying plane of typical spotwelds of various sizes in .040" 24 ST Alclad sheet are shown in Figure 57, with the indication of the two-side electrical test shown for each weld. It may be seen that the electrical test indications correlates with the total bonded area of the spotweld.

C. Procedure in Operation of Machine

To conduct non-destructive tests of spotwelds the machine is first calibrated for penetrator tests by using a block of homogeneous material of known hardness,* and applying a fixed load by means of a hydraulic jack. The penetration is measured on top and bottom dial gauges and compared with previous results on the same test block. Any change of shape in the penetrators can be observed and the penetrator balls (1/16" diameter steel balls, identical with those used in Rockwell

* -- Rockwell Hardness Testing Machine calibration blocks



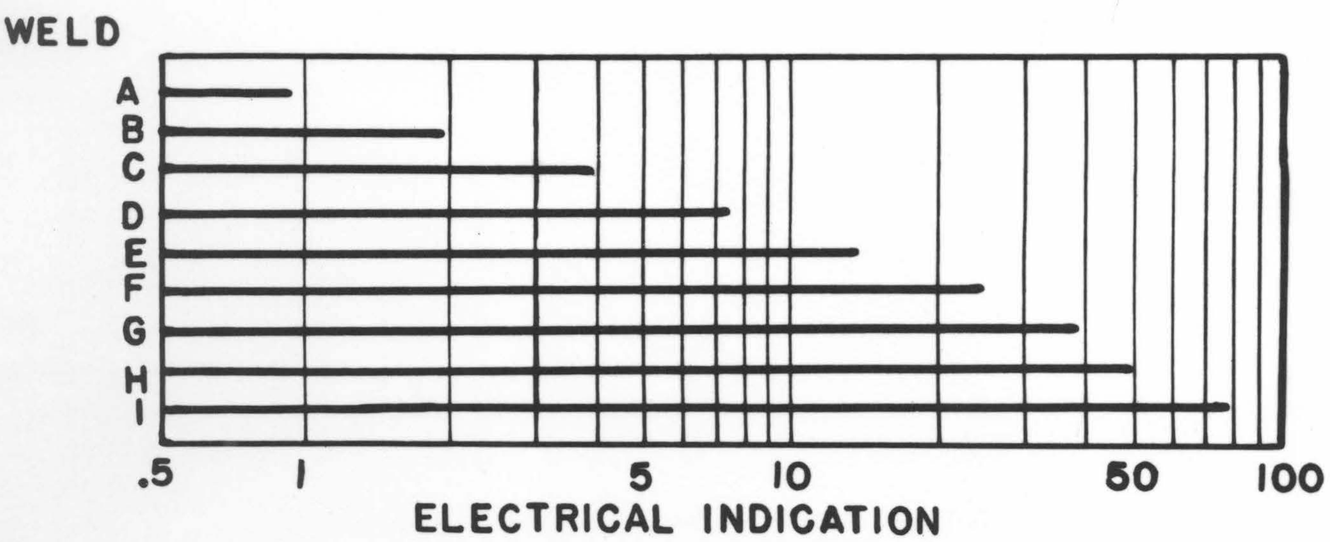


FIG. 57. INDICATIONS OF THE RING ELECTRODE TWO SIDE DIRECT CURRENT TEST FOR TYPICAL SPOT WELDS (FAYING SURFACES SHOWN AFTER SHEAR PULL TEST.)

Hardness Testing Machines) may be replaced, if necessary.

Before conducting electrical tests, the electrical system is checked by applying a fixed current to a similar calibration block of known thickness and resistivity and comparing the potential indication with that obtained previously. Corrections are made if indications are abnormal. These checks should be made before beginning a new set of tests and after every two hundred welds tested.

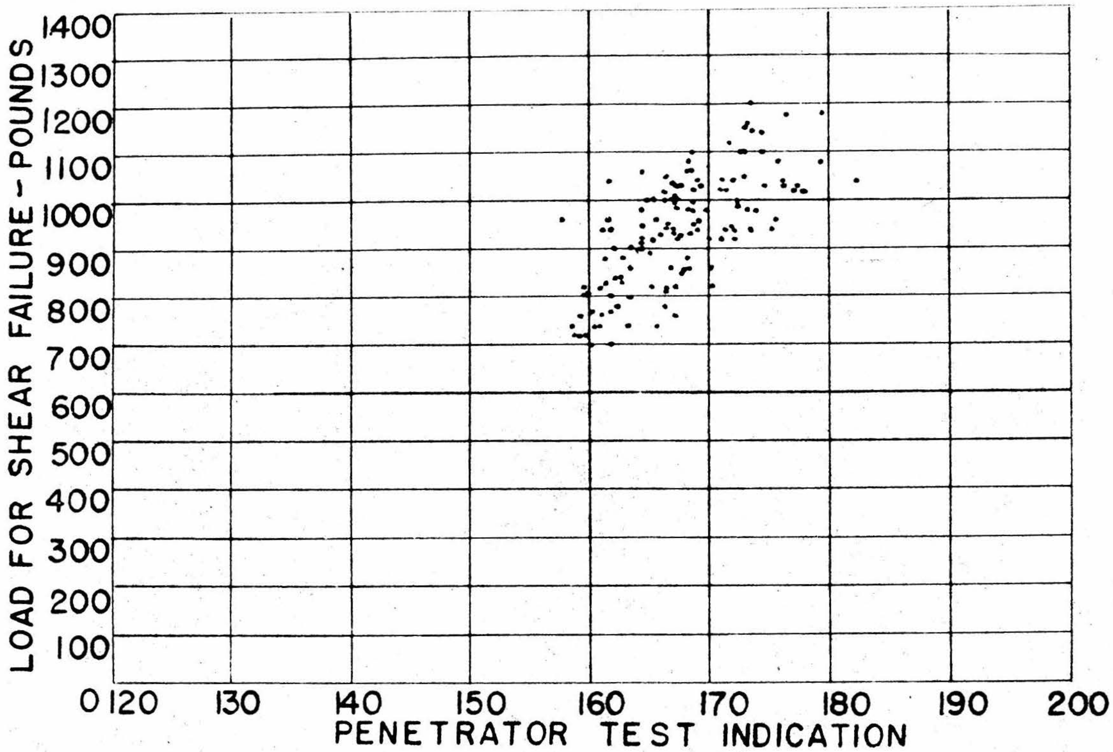
After the calibration of the machine, a spotwelded panel is inserted in the gap between the electrodes and the first spotweld is carefully centered under the potential probe of the head of the tester. A pre-load of fixed amount (200 pounds with 4-ball impressors) is applied by means of the hydraulic jack, the load being indicated by the dial gauge on the weighing block. The indication of each penetrator dial gauge is recorded. The load is then increased to the full load setting (1000 lbs. on the 4-ball assembly), and the indication of each dial gauge is again recorded. If electrical tests are being conducted with the same set of electrodes the direct current is applied and the potential indication recorded. The current is then interrupted and the load released so that the welded panel may be moved and the next weld tested. The sum of the changes in indication of the upper and lower dial gauges between pre-load and full load is then taken as the indication of penetration. The ratio of the total testing current to the potential indication is taken as the indication of bonded area at the faying plane. For greater sensitivity, current electrodes of diameter larger than that of the penetrator ring may be used to indicate the total bonded area, in a separate direct current test following the penetrator test.

Even on the laboratory testing machine, a weld may be tested in less than a minute, reading all dials and meters by eye. For production measurements, a machine capable of taking any shape of structure which can be spotwelded could be used for the same measurements. The pre-load and full load could be applied automatically by connecting the loading pistons to sources of low and high hydraulic or air pressures, and by recording the deflection of the weighing block and of the penetrator indicators by means of magnetic or electric strain gauges. All this might be controlled automatically by simply pressing a button to initiate the sequence of operation and observing resultant indications on a recording instrument or indicator device. The only portion of the test which is inherently slow is the centering of the spotweld under the testing assembly. By far the greatest portion of the time required in the testing operation would be required for this item alone. With such a machine, it should be possible to test 10 to 30 spots a minute without difficulty.

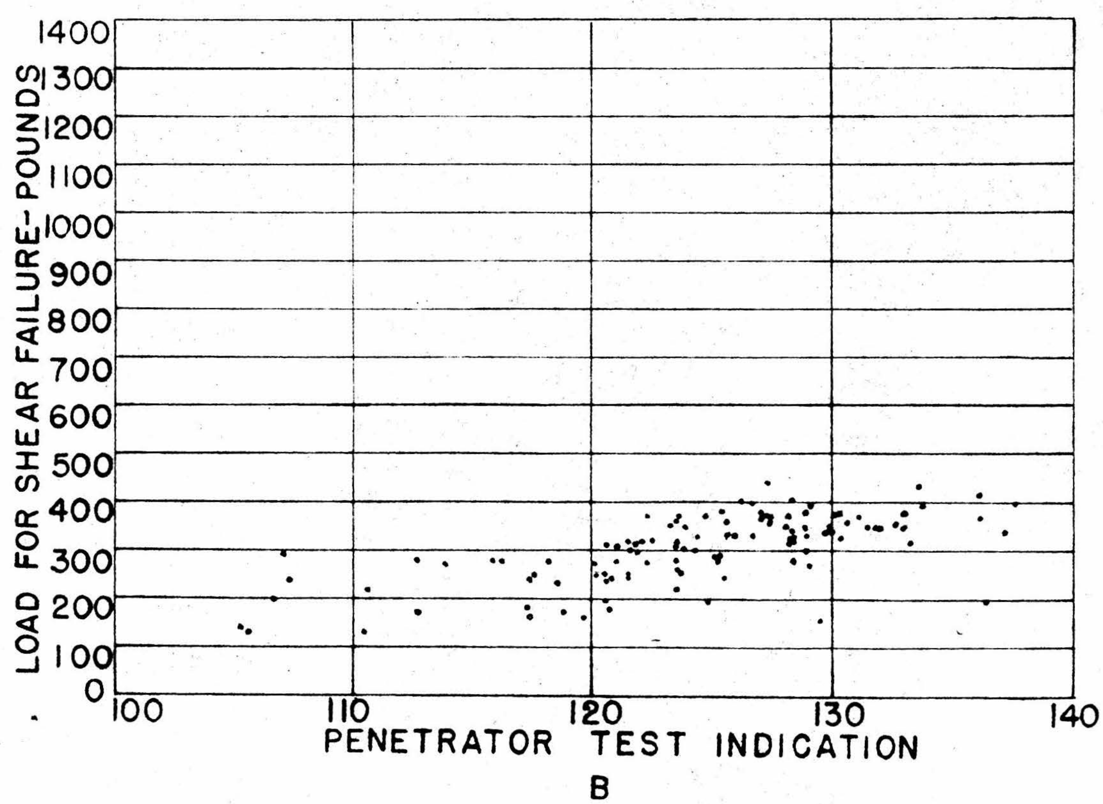
D. Results of Tests

Testing Machine #1 has been used under several conditions in the testing of spotwelds in aluminum alloy sheets. Various penetrator arrangements have been employed and several gauges of sheet tested. The first arrangement consisted of three special hardened steel balls placed equidistant on the periphery of a circle (See Fig. 53A). Tests showed this device to be capable of discriminating weld strength reliably on welds of normal shape (See Figures 5 and 58) but on welds of type B-4, (See Fig. 3), erroneous indications resulted because of the irregular shape of the area of bonding. Improved assemblies with four and six balls placed on the circumference of the critical circle showed improved performance (See Fig. 53B and 53C). Likewise, the use of circular electrodes of diameter larger than the penetrator circle as electrodes for the electrical test resulted in an improvement in the measurement of the area of bonding (See Fig. 54A to 54C).

<u>The diameter of the weld nuggets</u> is measured to within plus or minus 10 to 15% by the penetrator test alone as shown in Figure 59, typical of results on several hundred spotwelds made in different West Coast aircraft factories under normal industrial conditions of welding. These tests prove the machine to be capable of measuring weld nugget diameter reliably. It is because of the reliability of this measurement that the machine is capable of measuring the strength of the weld.



A



B

FIG. 58. RESULTS OF PENETRATOR TESTS USING 3 BALL PENETRATOR ADJUSTED FOR .040" 24ST SHEET ON:

A. 175 TAYLOR - WINFIELD SPOTWELDS IN .064" 24ST SHEET.

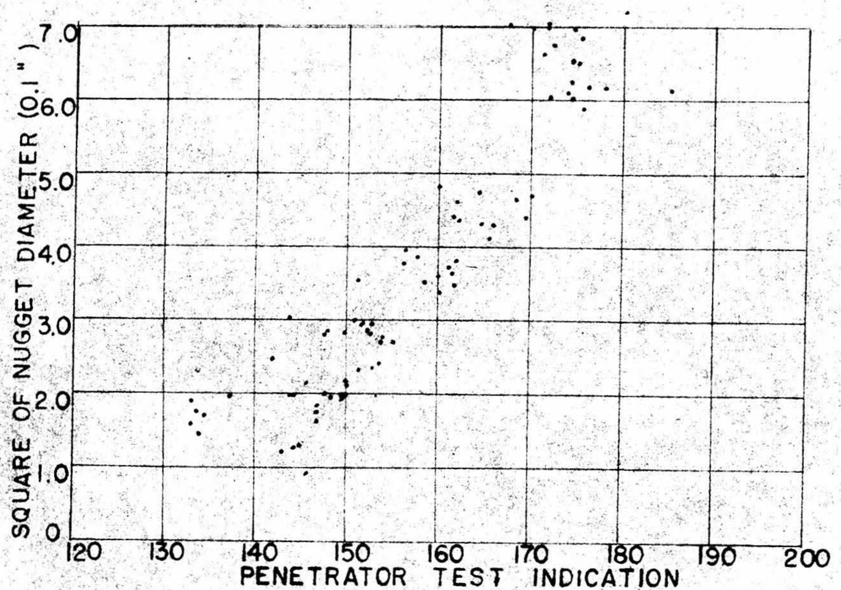
B. 138 SCIAKY SPOTWELDS IN .020" 24ST SHEET (SEE FIG. 41A).

<u>The static shear strength</u> of the spotwelds is measured to plus or minus 10% by the penetrator test alone in the range for which penetrator is adjusted as shown in Figure 60 on the same sets of industrially made spotwelds. This measurement compares favorably with the correlation between the strength and spotweld nugget diameter shown in Figure 41 for the same sets of spotwelds. It is seen that the penetration test measures weld strength with an error equal to only twice the median error in the correlation between weld nugget diameter and strength. This quality of measurement in itself is adequate for the non-destructive testing of spotwelds in industry.

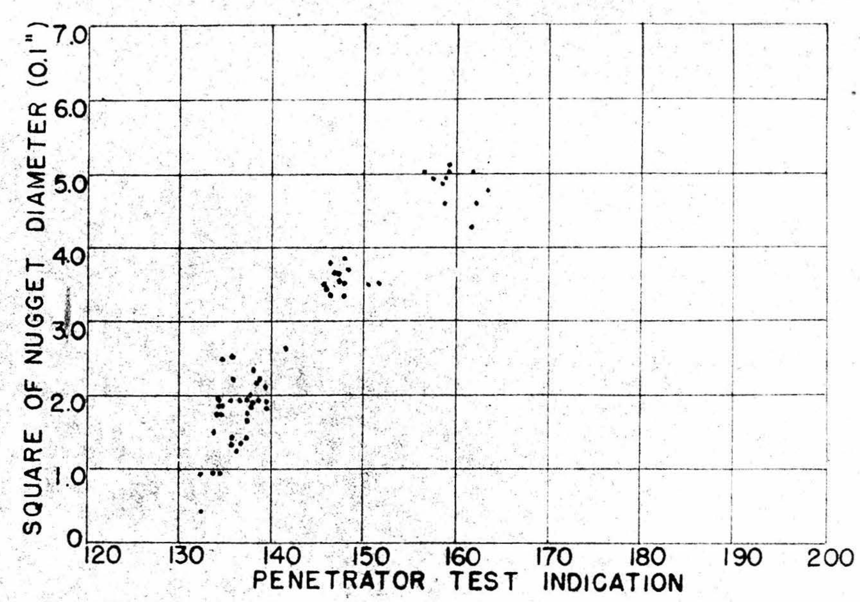
<u>The total area of bonding</u> at the faying plane is measured to plus or minus 10% by the electrical test (See Fig. 61). Because of the variation in the nature of the corona bonding and the difficulty of visually measuring the corona area on the pulled welds this correlation is appreciably less accurate than that between penetrator tests and nugget size. The direct correlation between electrical test indications and spotweld static shear strength is poor because the test does not discriminate the type of bonding at the faying surface (See Fig. 62).

<u>The static shear strength</u> of the spotwelds is measured to plus or minus 10% by the combined penetrator and electrical test indications (See Fig. 63). The total strength is determined in accordance with the relation given in Section IV-D.

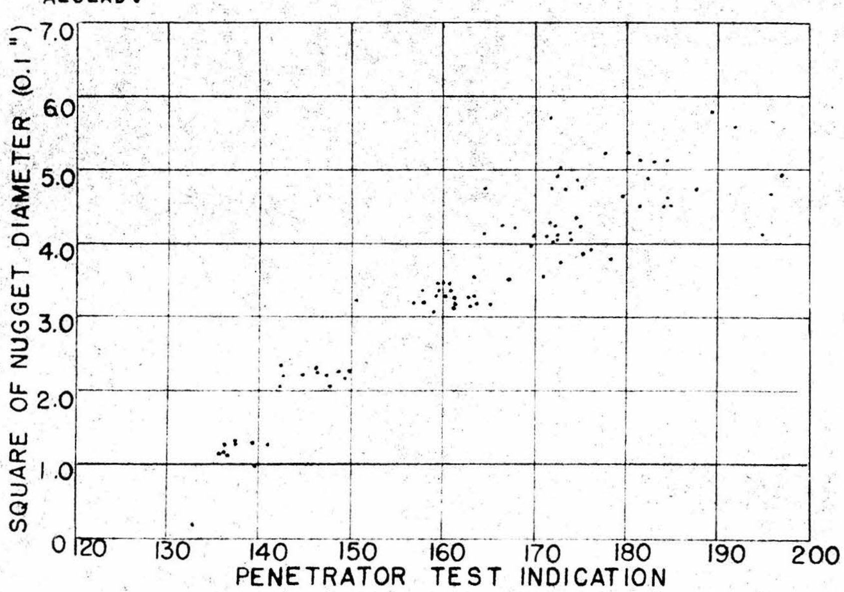
Fig. 59. Measurement of Spotweld Nugget Diameter By Penetrator Test Using 4 Ball Penetrator Assembly.



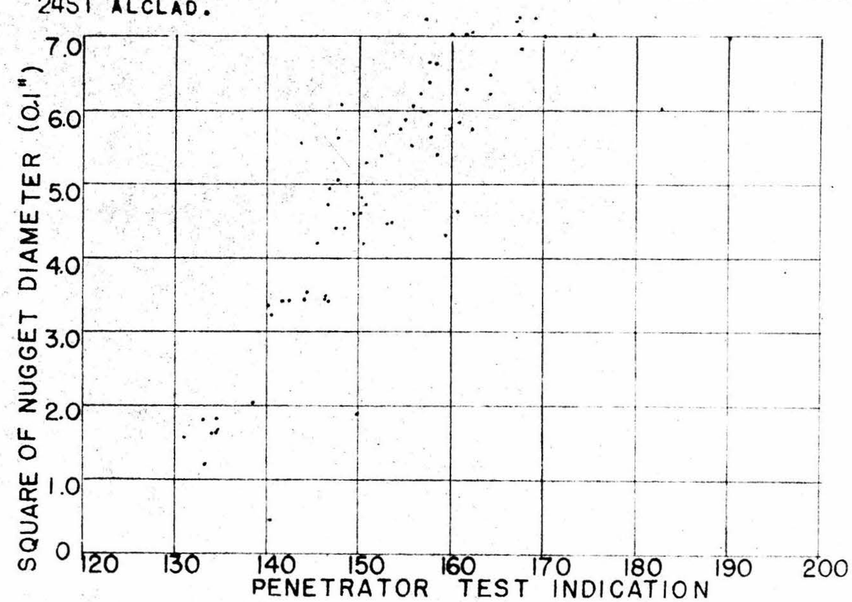
A. 138 Taylor Winfield Spotwelds Made By Consolidated Vultee Aircraft Corporation (San Diego) in .040" 24ST Alclad.



B. 85 Taylor Winfield Spotwelds Made on the Laboratory Welder at the University of Southern California in .040" 24ST Alclad.



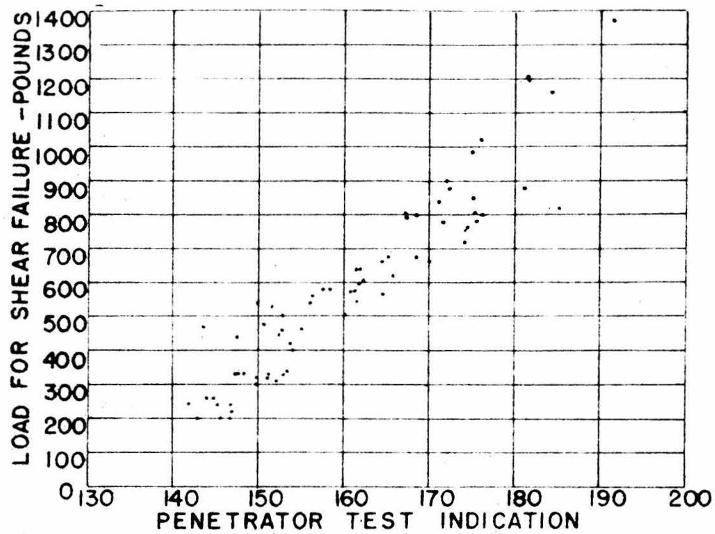
C. 105 Taylor Winfield Spotwelds Made On The Laboratory Welder At The University of Southern California in .040" 24ST Alclad.



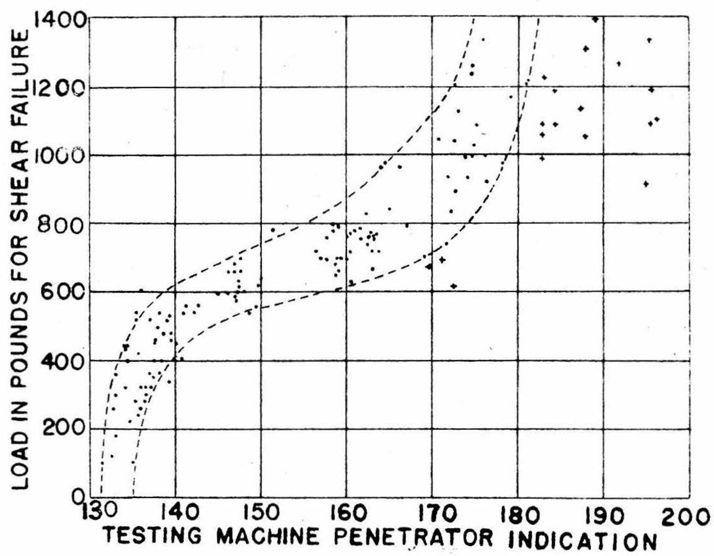
D. 105 Taylor Winfield Spotwelds Made On The Laboratory Welder At The University of Southern California In .040" 24ST Alclad.

Note: These groups of spotwelds were purposely made under widely different conditions for use in developing non-destructive tests.

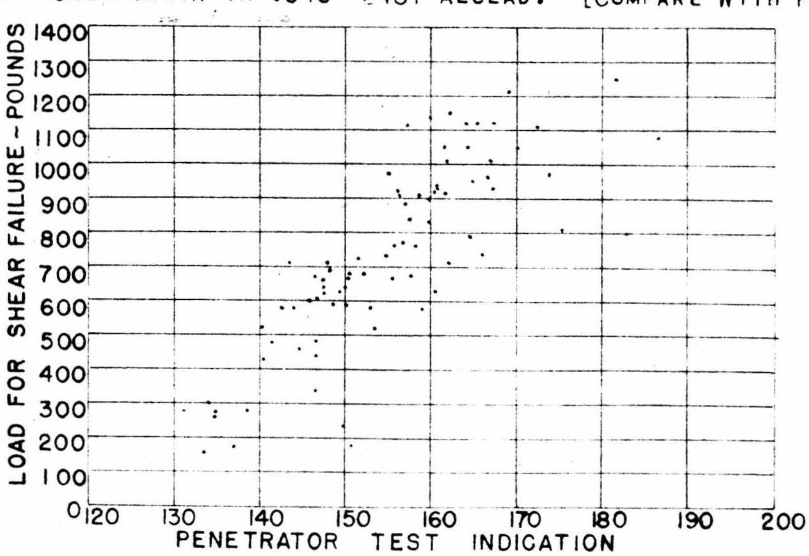
FIG. 60. MEASUREMENT OF STATIC SHEAR STRENGTH OF SPOTWELDS BY PENETRATOR TEST, USING 4 BALL PENETRATOR ASSEMBLY.



A. 138 TAYLOR WINFIELD SPOTWELDS MADE BY CONSOLIDATED VULTEE AIRCRAFT CORPORATION (SAN DIEGO) IN .040" 24ST ALCLAD. [COMPARE WITH FIG. 41 B]

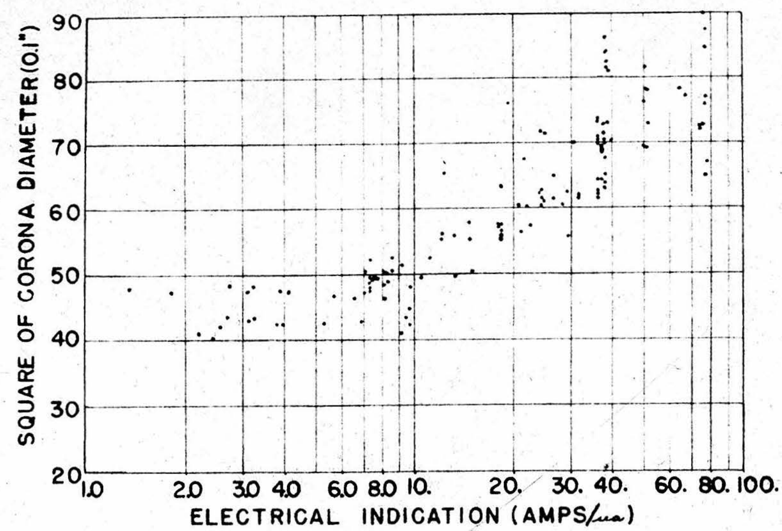


B. 135 TAYLOR WINFIELD SPOTWELDS MADE ON LABORATORY WELDER AT UNIVERSITY OF SOUTHERN CALIFORNIA IN .040" 24ST ALCLAD. [COMPARE WITH FIG. 41 H.]

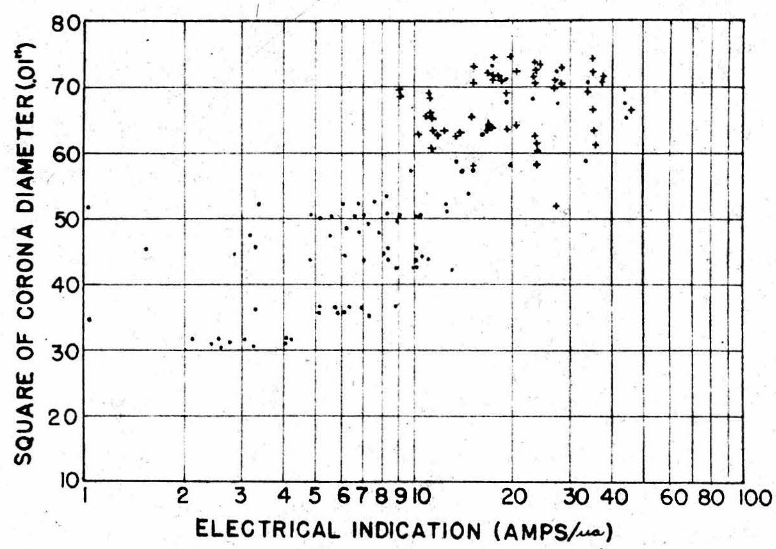


C. 105 TAYLOR WINFIELD SPOTWELDS MADE ON LABORATORY WELDER AT UNIVERSITY OF SOUTHERN CALIFORNIA IN .040" 24ST ALCLAD. [COMPARE WITH FIG. 41 H.]

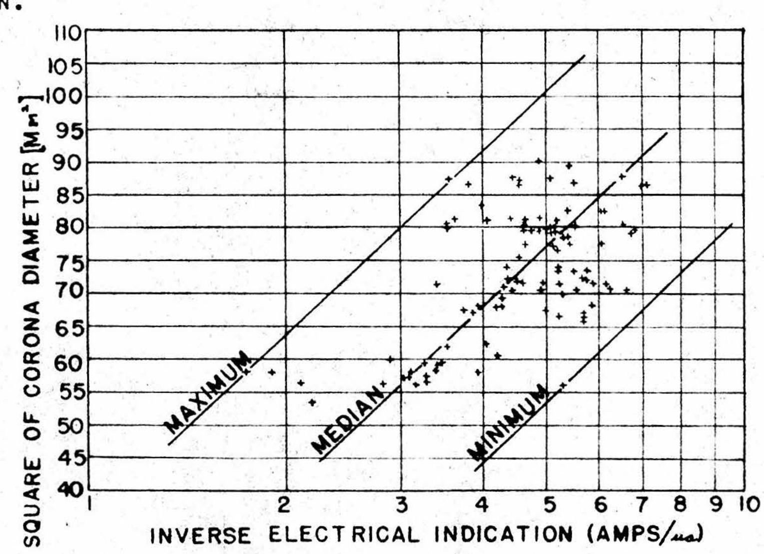
Fig. 61. Correlation Between Electrical Test Indications and the Total Area of Bonding at the Faying Plane of the Spotweld. Tests Made With Ring Electrodes On Industrially-Made Spotwelds.



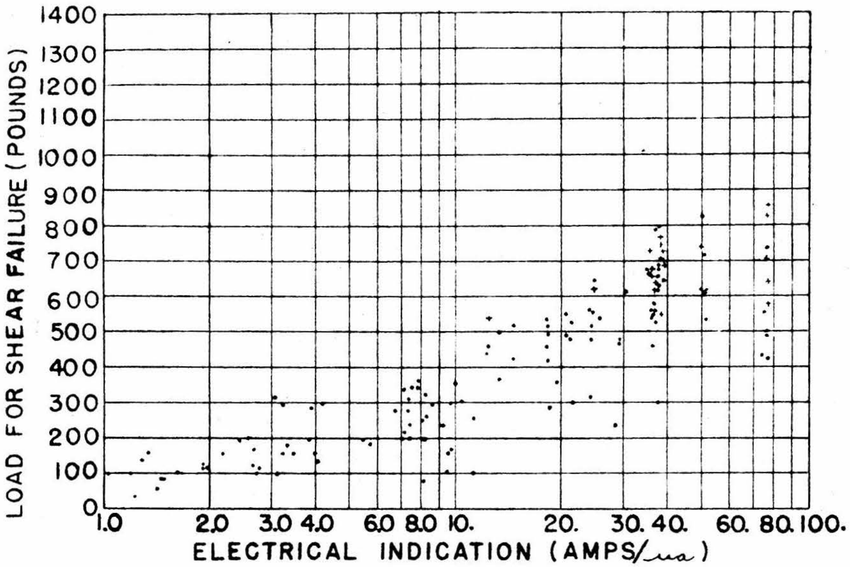
A. 181 Welds in .040" 24ST Alclad Made on Federal Welder At Ryan Aeronautical Corporation, San Diego, California.



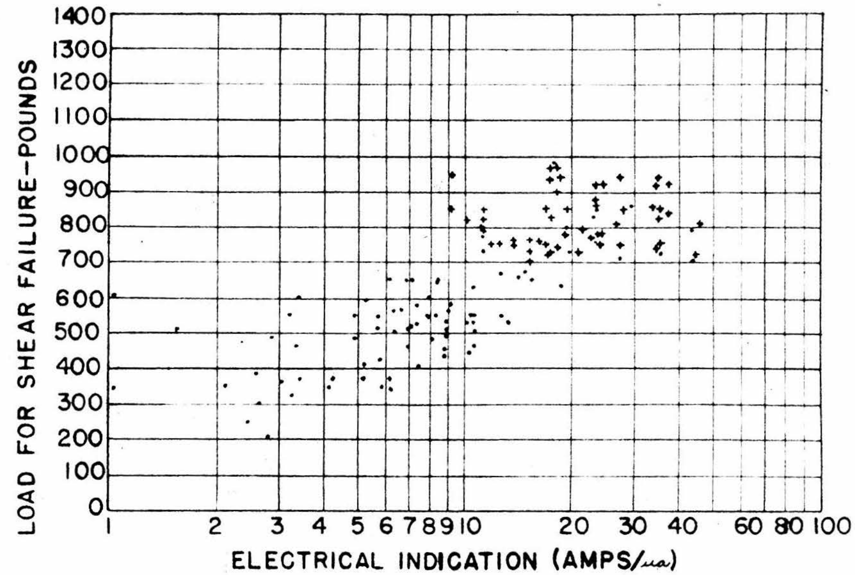
B. 141 Welds in .040" 24ST Alclad Made on Sciaky Welder at Lockheed Aircraft Corporation.



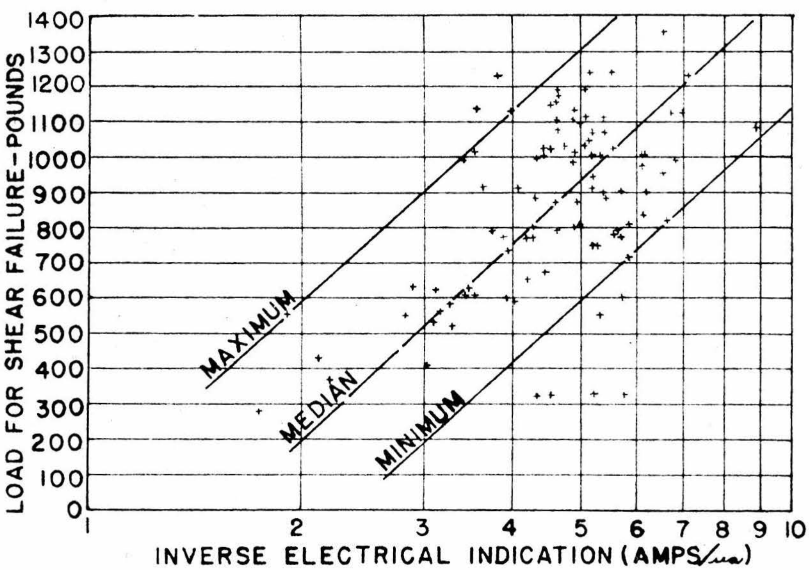
C. 108 Welds in .064" 24ST Alclad Made on Sciaky Welder at Lockheed Aircraft Corporation.



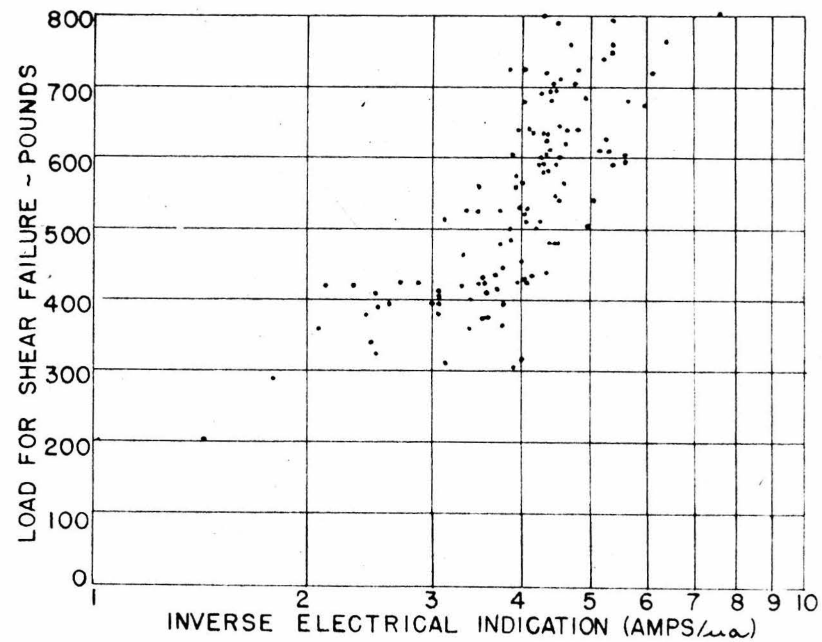
A. 181 Welds in .040" 24ST Alclad Made on Federal Welder at Ryan Aeronautical Corporation, San Diego, California.



B. 141 Welds in .040" 24ST Alclad Made on Sciaky Welder at Lockheed Aircraft Corporation.



C. 108 Welds in .064" 24ST Alclad Made on Sciaky Welder at Lockheed Aircraft Corporation.



D. 140 Welds in .040" 24ST Alclad Made on Sciaky Welder at Lockheed Aircraft Corporation.

Fig. 62. Correlation Between Electrical Test Indications and Spotweld Static Shear Strength on Industrially-Made Spotwelds. (Since the electrical test does not discriminate the type of bonding at the faying surface, it cannot be used alone for reliable prediction of weld strength.)

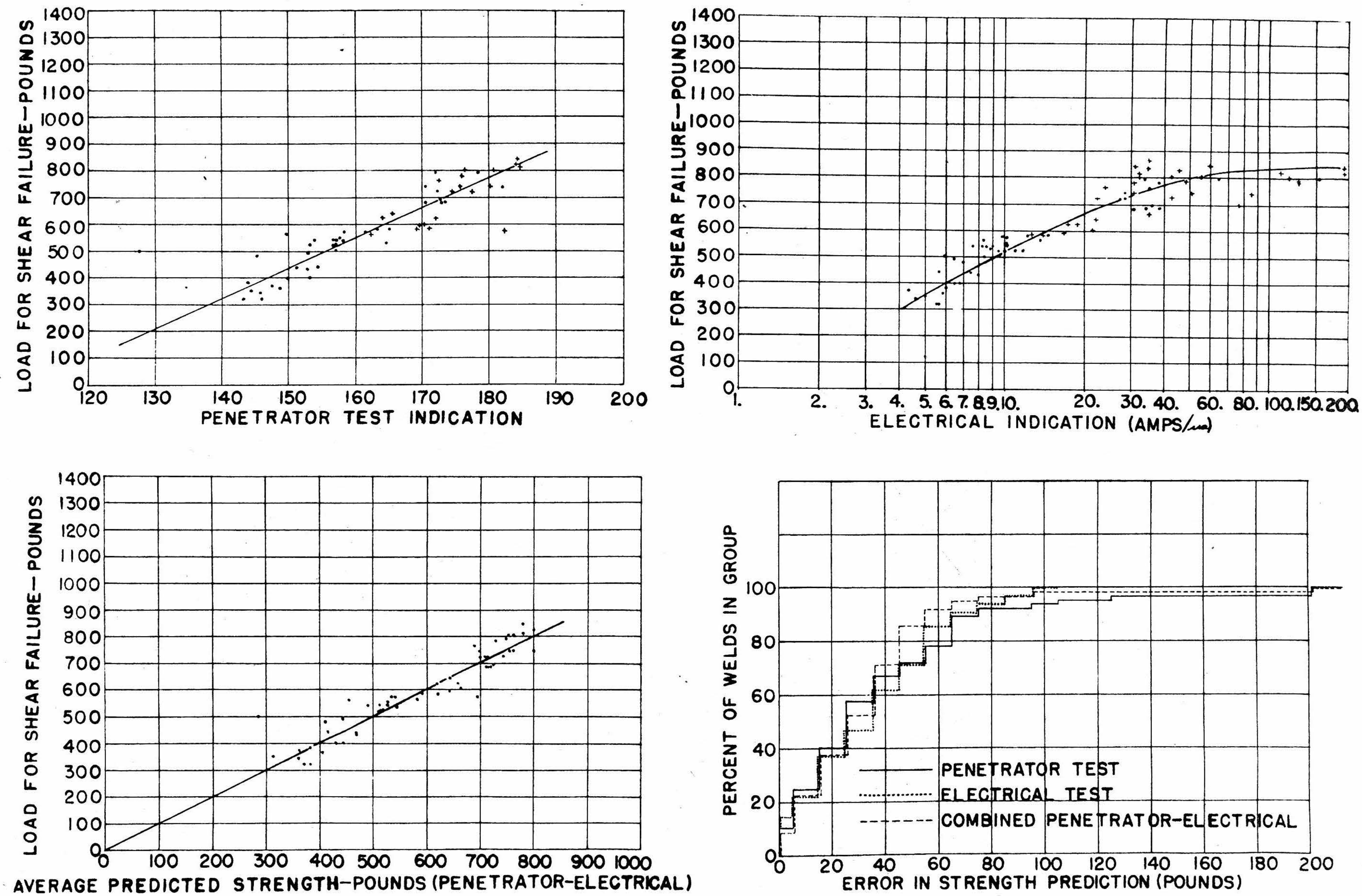


FIG. 63. MEASUREMENT OF SPOTWELD STATIC SHEAR STRENGTH BY COMBINED PENETRATOR AND ELECTRICAL INDICATIONS. 100 WELDS IN .040" 24ST ALCLAD MADE ON TAYLOR-WINFIELD WELDER AT NORTHRUP AIRCRAFT CORPORATION.

The welds used in the tests on which Figures 59 through 63 are based included a large number of laboratory welds, later found to be excessively porous and defective. Results of tests on more than 2000 welds made under production conditions in aircraft factories are indicated in Section VII, and indicate these tests to be more accurate and reliable than was indicated by the initial tests.

E. <u>Conclusions Based on Results of Tests of Testing Machine #1</u>

1. The <u>ring penetrator test</u> alone can be a reliable measure of weld nugget diameter. It measures the component of weld shear strength due to the nugget with nearly as much accuracy as does the diameter of the nugget observed by destructive sectioning. It does not measure the component of weld strength supplied by Alclad bonding (an unreliable contribution) and so, properly calibrated, gives conservative predictions of weld strength.

2. The <u>electrical test</u> alone measures the bonded area to a moderate degree of sensitivity. By itself it is not a reliable measurement of weld shear strength, for shear strength is not measured reliably by the total area of bonding. It does detect welds whose faying surface has bonded poorly or whose bond has been broken after welding, with absolute

reliability. It makes possible an estimate of the contribution of corona bonding to the weld shear strength, and so is a valuable supplement to the ring penetrator test.

3. The chief limitation on the accuracy of all forms of mechanical and electrical tests sensitive to weld size results from the difficulty of locating the center of the weld by observation of the outer surface of the welded sheet. The weld may not be centered under the welder electrode indentation. Thus the major portion of the testing time is required to locate the tester above the weld, while the test itself may be nearly instantaneous. Automatic profiling to locate the weld accurately requires elaborate apparatus and increased testing time.

4. Other limitations result from the fact that penetrator indications depend upon alloy, heat treatment, and sheet thickness. Calibration must be made on that alloy and heat treatment being inspected, with a penetrator ring of diameter suited to spotwelds in the given gauge of sheet.

F. Proposals for Practical Forms of Spotweld Tester

Experience with Spotweld Testing Machine #1 has indicated principles and practical design forms for non-destructive spotweld testers.

1. Proposed Hand Tester A is a small portable penetrator tester, similar to devices now on the market for hand hardness testing of homogeneous materials.* A ring of sharpened calibrated penetrators is spring loaded by hand pressure to make a one-side ring penetrator test equivalent to that of Testing Machine #1. (See Fig. 64). (By using small diameter, sharpened probes, a great reduction in load is obtained for penetrations sensitive to weld nugget presence.) This is a direct measurement of nugget diameter.

The device must be calibrated on the alloy and temper of sheet to be tested. A change to ring penetrators of different diameter is required when spotwelded sheet of greatly different thickness is to be tested. Properly located above each weld, the hand tester should be nearly as reliable as the penetrator test of Testing Machine #1.

2. Proposed Production Tester B is intended for production line use--possibly directly after the spotwelding operation--with welded parts being

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* - The Barcol Impressor, available from Barber Colman Company, Rockford, Illinois.

FIG. 64. HAND HARDNESS TESTER SUITABLE FOR PENETRATOR TESTS OF SPOTWELDS IN THIN ALUMINUM ALLOY SHEETS. (BARCOL IMPRESSOR - - BARBER COLMAN CO.)

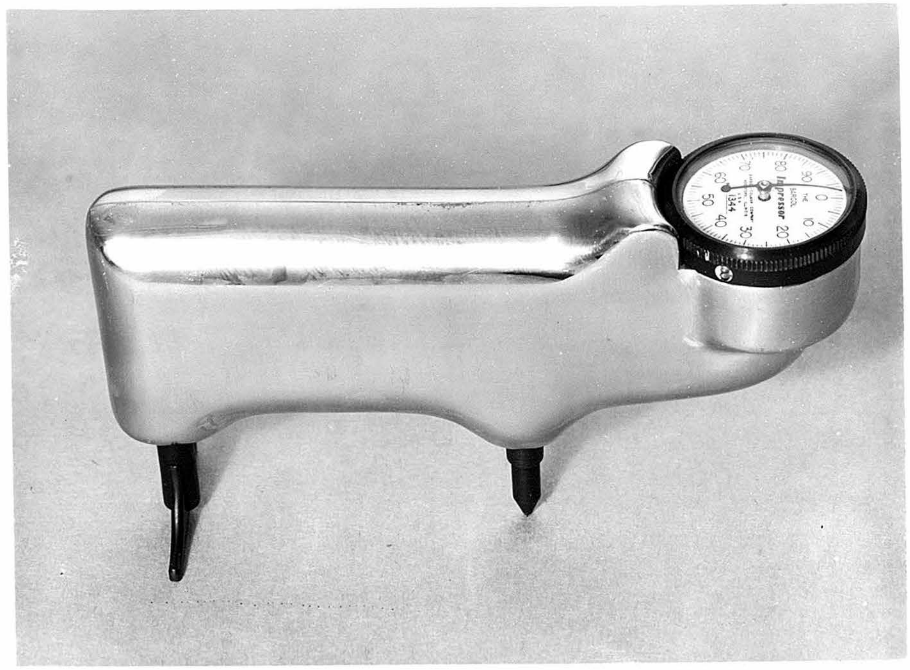
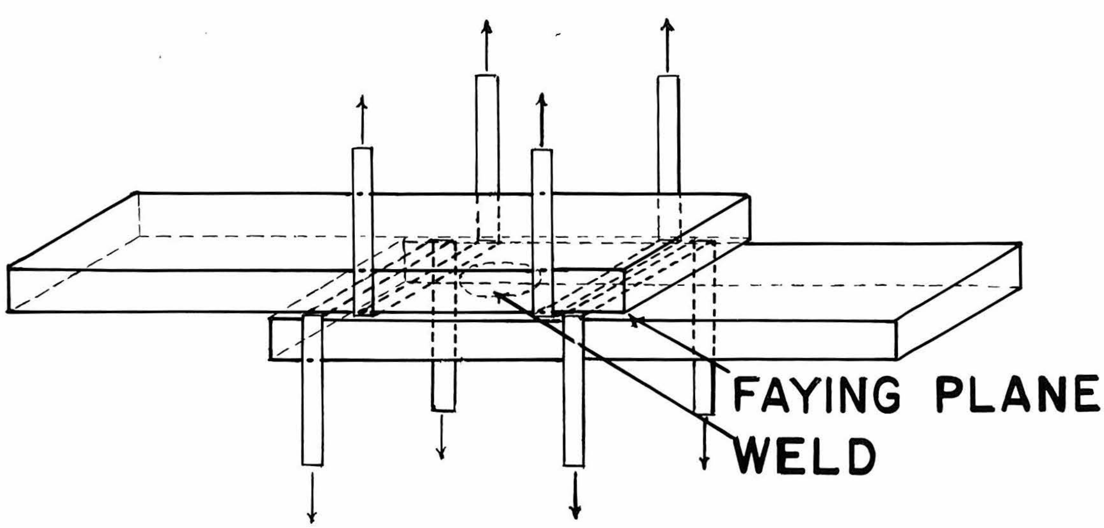


FIG. 65. SKETCH OF MECHANICAL PROOF TESTING TOOL.



brought to the tester. It is equipped with a throat and press or rocker arm of dimensions equivalent to the welders it serves, so that any weld made on the welders can be tested on it. Two-side ring penetrator and electrical tests are automatically carried out and recorded each time the operator presses the foot switch. Air loading and strain gauge recording make possible tests as rapid as the spotwelding operation itself. Strain gauge load measurements, with pre-load and full load applied by air pressure and strain gauge penetration measurements, could be recorded automatically, or actuate indicator devices.

VI Development of Radiographic Inspection Methods.

At the time this research was begun, radiography of spotwelds had been proposed as a non-destructive method of inspection, and spotweld radiographs of high quality had been obtained in research investigations. Long exposures at low voltages with fine grain X-ray film were found necessary to obtain adequate contrast and definition in spotweld radiographs made with standard X-ray equipment. Although such radiographs showed cracking and porosity (when present) in spotweld nuggets, and in most cases showed rings which might possibly be correlated with weld nugget diameter, the nature and extent of the bonding at the spotweld faying surface were not revealed. Not all investigators agreed as to whether or not spotweld strength and quality could be determined reliably from spotweld radiographs. The limitations and the feasibility of the method for practical industrial inspection of spotwelds had not been established, as evidenced by the fact that radiographic inspection of spotwelds in aluminum alloys had not been widely adopted in the aircraft industry, despite the great need for a non-destructive test for spotwelds.

The development of practical radiographic spotweld inspection required:

1. The development of radiographic technique so that spotweld radiographs of acceptable contrast and definition could be obtained using available commercial X-ray equipment and films, with exposure times as short as a few seconds per weld,

2. The development of reliable procedures for interpreting spotweld structure, size, shape, quality, strength, and defects from radiographs, and

3. The application of radiographic inspection to thousands of spotwelds from many industrial sources, to determine the validity, reliability, and accuracy of the radiographic method of spotweld inspection.

A. Technique of Spotweld Radiography

1. X-Ray Equipment:

No radiographic equipment suitable for spotweld inspection was available at California Institute of Technology. Arrangements were made for the use of equipment of Triplett and Barton, Incorporated, of Burbank, California, and for the cooperative services of an x-ray engineer and physicist.

Calibrated production X-ray unit No. 6 (150 Kvp. Triplett and Barton, Incorporated, equipment with rectifier) (see Fig.66) was

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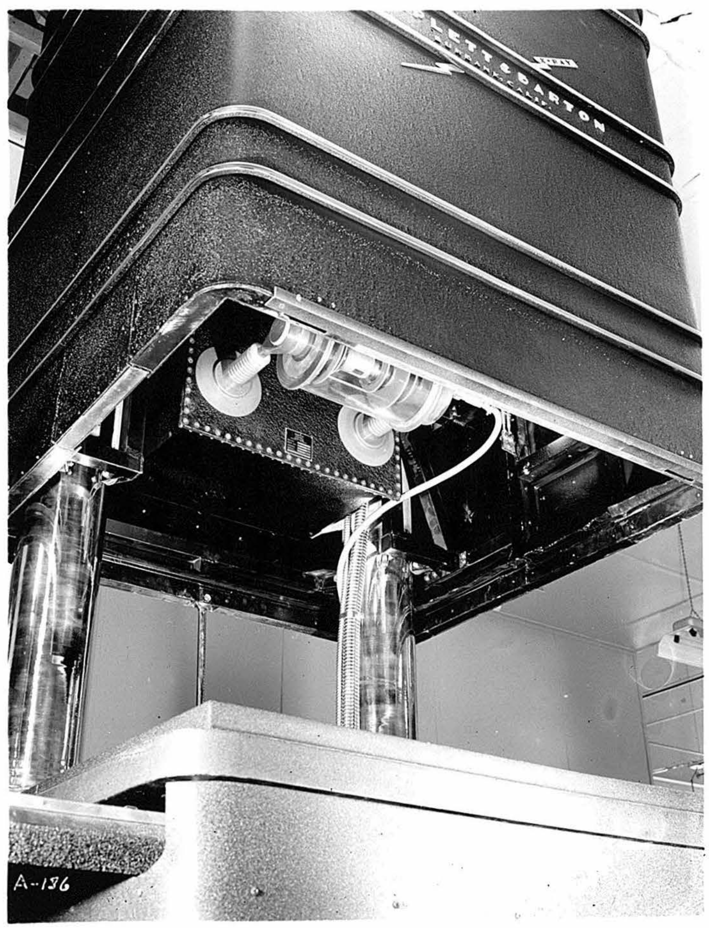
A



B

FIG. 86

PRODUCTION X-RAY EQUIPMENT USED IN THIS RESEARCH.

A. PRODUCTION UNIT

B. TUBE AND TRANSFORMER

used for this research. Standard operating conditions of 10 ma. beam current and 36 inch source-film-distance, with voltage selected from calibration charts to give optimum contrast with the alloy, material thickness, and film used, were employed for all regular tests.

2. Selection and Calibration of X-Ray Film.

Preliminary tests of 80 experimental and commercial X-ray films resulted in the selection of Triplett and Barton Incorporated, Type 60 (commercially available as Eastman Type M) film for all succeeding tests. This film is a high contrast, fine grain type for use without screens. For all spotweld radiographs, this film was wrapped only in black photographic paper lead-backed to prevent back-scatter and placed in intimate contact with the welded sheet.

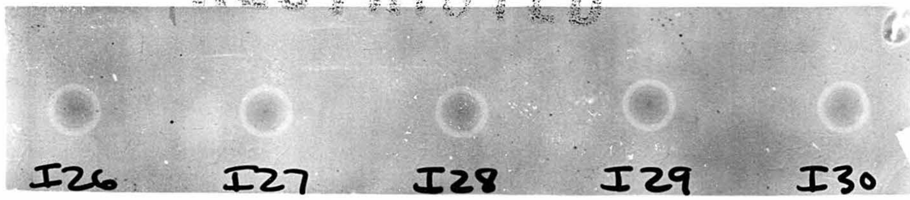
A complete calibration of this film on machine No.6, with 24St alloy in thicknesses from 0.01" to 0.25", was completed with the results shown in Appendix I. Due to the inherent filtration in this X-ray source, optimum contrast was obtained in the range of 30 to 45 primary volts (approximately 30 to 45 KVP.). With spotwelds in .040" sheet, the radiographic contrast was approximately 0.6%, and the film density about 2.7, for 835 second exposures at 10 ma, 36" source-film-distance, 35 primary volts. These exposure conditions were used for all welds in .040" 24ST alloy, with an effective field 14" square at 36" source-film-distance.

3. Radiography of Specimens:

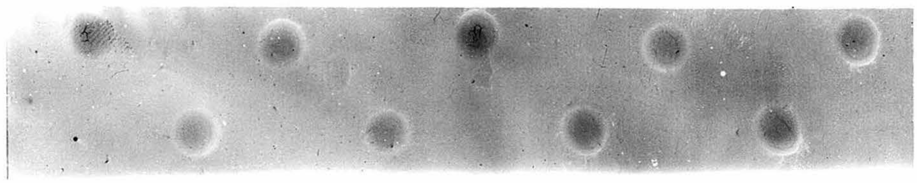
Trials made throughout the range of sheet thicknesses from .016" to .091" in Alclad 24ST alloy indicated that with thicker sheets, optimum radiographs could be obtained with shorter exposures, with higher contrast than could be obtained with thin sheets. All gauges were radiographed adequately for reliable spotweld inspection on this equipment.

Exposures of normal welds in .040" 24ST, 24SO, 3SO, and 61SW alloys indicated that the standard exposure conditions were near the optimum contrast for each of these alloys. (See Fig. 67) 24S alloy, with its 4% copper content, provided the sharpest spotweld radiographs.

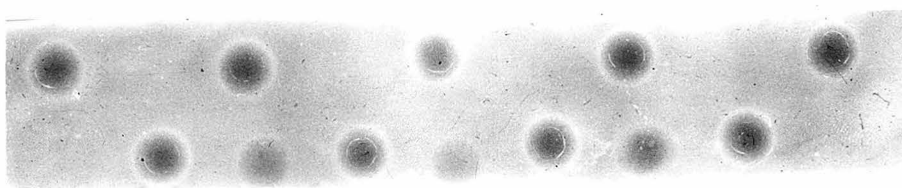
The effect of placing the film varying distances behind the welded specimen was investigated, with the results shown in Fig. 68. With a 36 inch source-film-distance, the film could be placed as much as 2 inches behind the welds



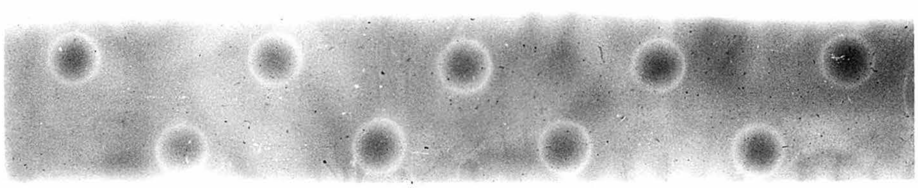
A. 24ST ALLOY



B. 24SO ALLOY



C. 3SO ALLOY



D. 61SW ALLOY

FIG.67. RADIOGRAPHS OF NORMAL SPOTWELDS IN .040" SHEETS OF 24ST, 24SO, 3SO, 61SW ALUMINUM ALLOYS.

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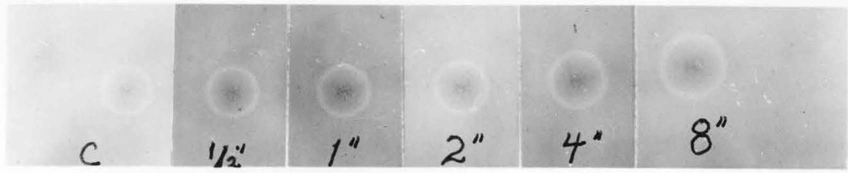


FIG. 68. EFFECT OF PLACING RADIOGRAPHIC FILM VARYING DISTANCES BEHIND THE SPOTWELDED SHEET.

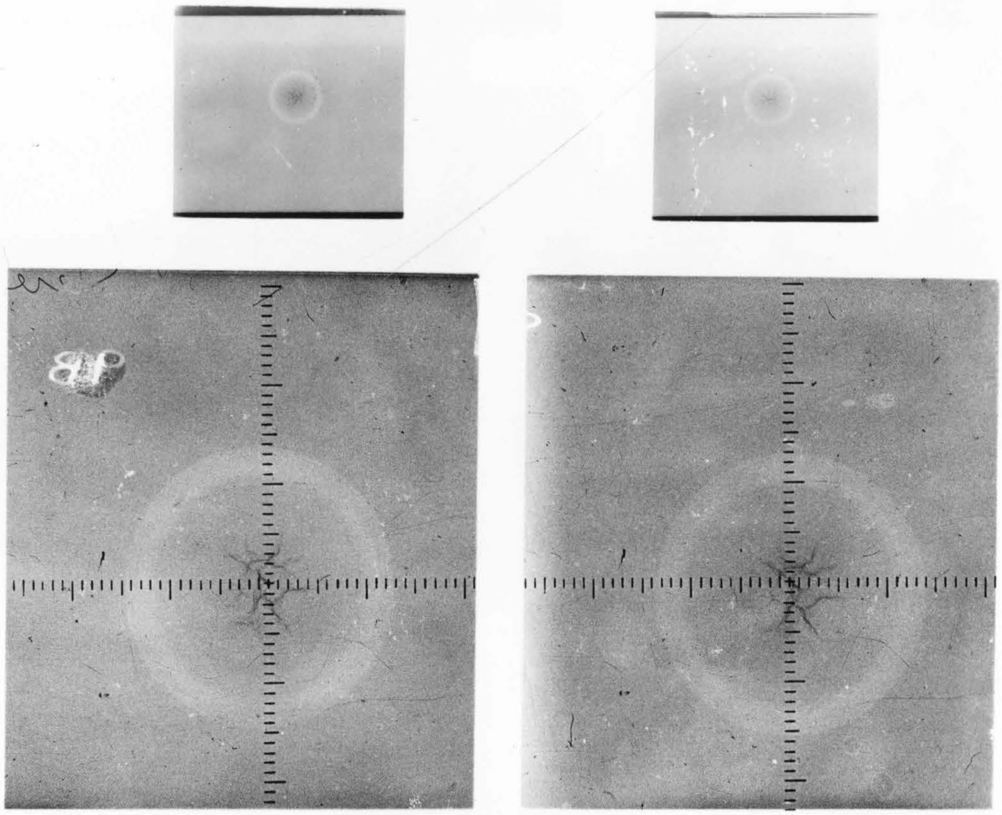
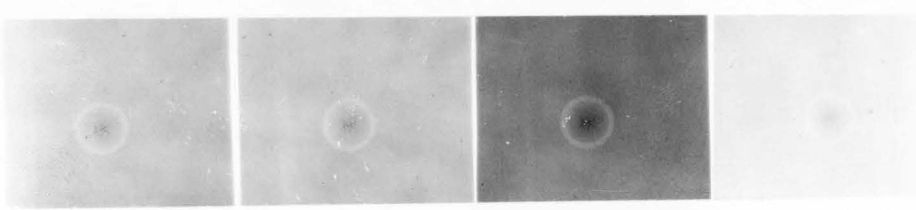


FIG. 69. STEREOSCOPIC X-RAY VIEWS OF A SPOTWELD NUGGET CONTAINING CRACKS.



6.8" LEFT	4.3" LEFT	ON AXIS	6.8" RIGHT

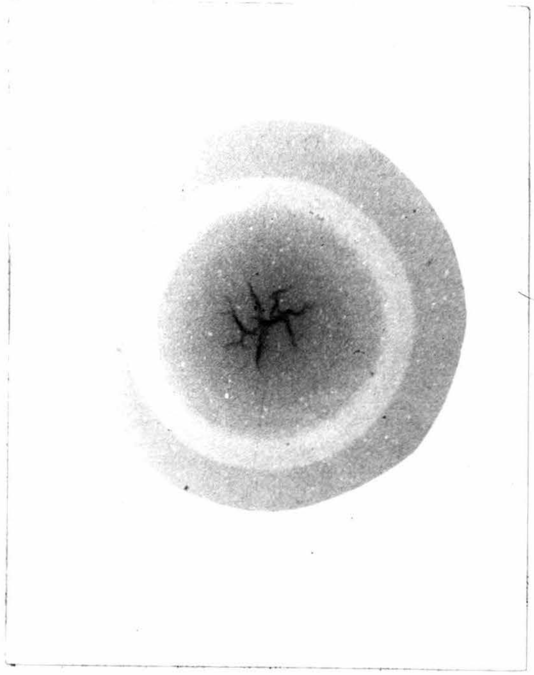
FIG. 70. EFFECTS OF PLACING SPOTWELD OFF THE AXIS OF THE X-RAY TUBE.

without noticable loss of definition or enlargement. With the film 8" behind the sheet, noticable enlargement, accompanied by loss of definition, occurred. Thus it is not necessary, for the film to be in intimate contact with the weld, despite published statements to the contrary.

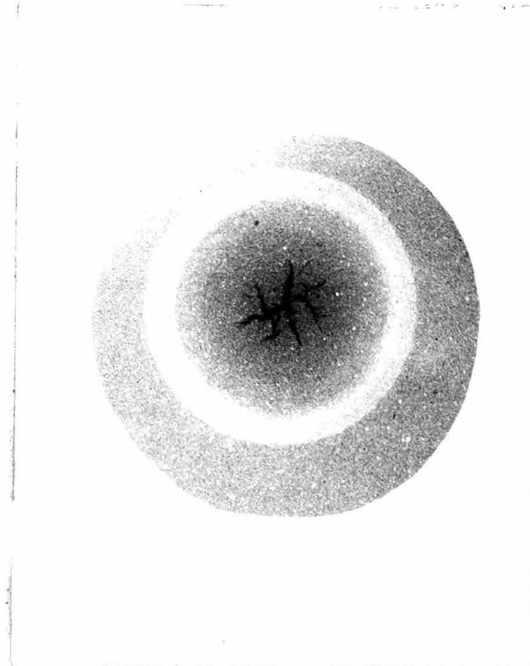
Stereoscopic X-ray views of a spot weld were obtained (see Fig. 69) by two exposures, the specimen having been moved between exposures to obtain this effect. Viewing these radiographs with a stereo-lens viewer, the observer sees a three dimensional image, in which the cracks above and below the faying plane can be discriminated. It is not probable that stereo spotweld inspection would be useful in industry, as very little new information is obtained from second exposure.

The useful field at the standard source-film-distance was investigated, as shown in Fig.70. Further than 7 inches off the axis of the beam, the effective irradiation was reduced sufficiently to lower film density and reduce radiographic contrast noticeably. Some loss of definition also occurred outside the useful field (14 in. square.)

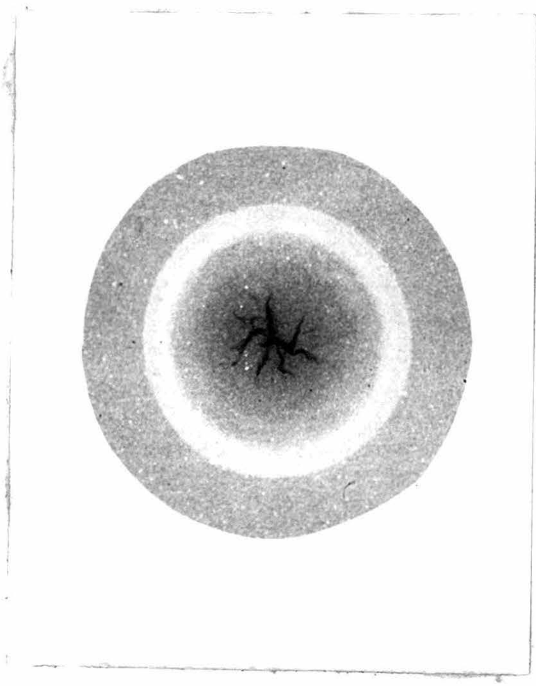
A special tube with fine focal spot (less than 0.7 m.m. square), and thin inverted bubble glass window, target shield, and short filament-target distance was employed in a series of exposures to determine the minimum source-film-distance permitting acceptable definition, and the minimum exposure providing adequate contrast and density (2.5). Excellent radiographs were obtained (see Fig. 71) at source-film distances of 16", 8", 4", and 2", with 30 KVP, 10 ma., and exposure times of 310, 78, 19, and 4.7 seconds, respectively. In the latter case, the field covered was of 5/8" diameter, and the enlargement was 4.5%. Negligible loss in definition occurred. These results demonstrate that it is practical to radiograph individual spotwelds adequately with exposure times as low as 5 seconds, using short source-film distances, portable light weight equipment, and complete protection for personnel against X-rays. With type M film in dental cassettes, a practical, low cost spotweld radiographic inspection of aircraft on the production line becomes possible, with this technique.



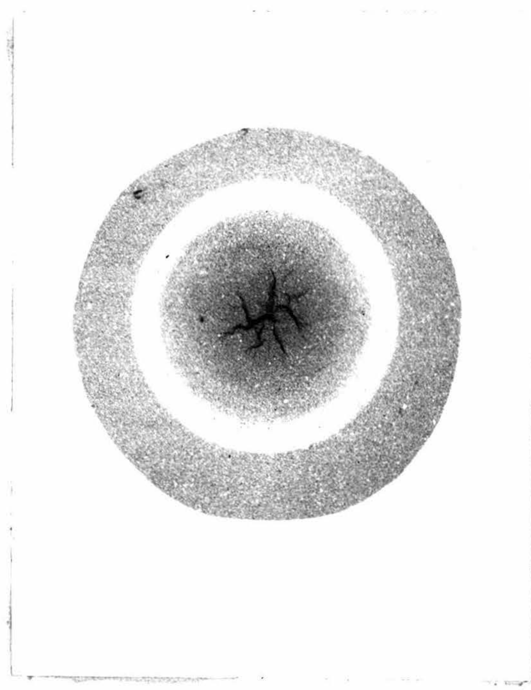
2 Inches S. F. D.



4 Inches S. F. D.



8 Inches S. F. D.



16 Inches S. F. D.

Fig. 71. Effect of Varying Source Film Distance In Spotweld Radiography.

In addition to the short source-film-distance technique for inspection of individual spotwelds, many production assemblies can be radiographed on production equipment at large source-film-distance with resultant large field coverage. Fig. 72 shows a part of a single exposure including several hundred spotwelds in an experimentally spotwelded tail boom of a pursuit ship. Two prints were needed to reproduce the full range of the X-ray film, for the two layer and three layer welds respectively. This is an example of a primary aircraft structure which could be readily radiographed.

B. Interpretation Of Spotweld Radiographs:

The following spotweld properties and defects (when present) can be interpreted from properly made spotweld radiographs:

(1) Structure, including the granular and dendritie zones of the weld nugget, the boundary between cast alloy and parent metal, segregation of copper rich material within the nugget and of eutectic in the parent metal.

(2) Geometry, including the diameter and shape of the weld nugget in the parent sheet near the faying plane, thickness or penetration of

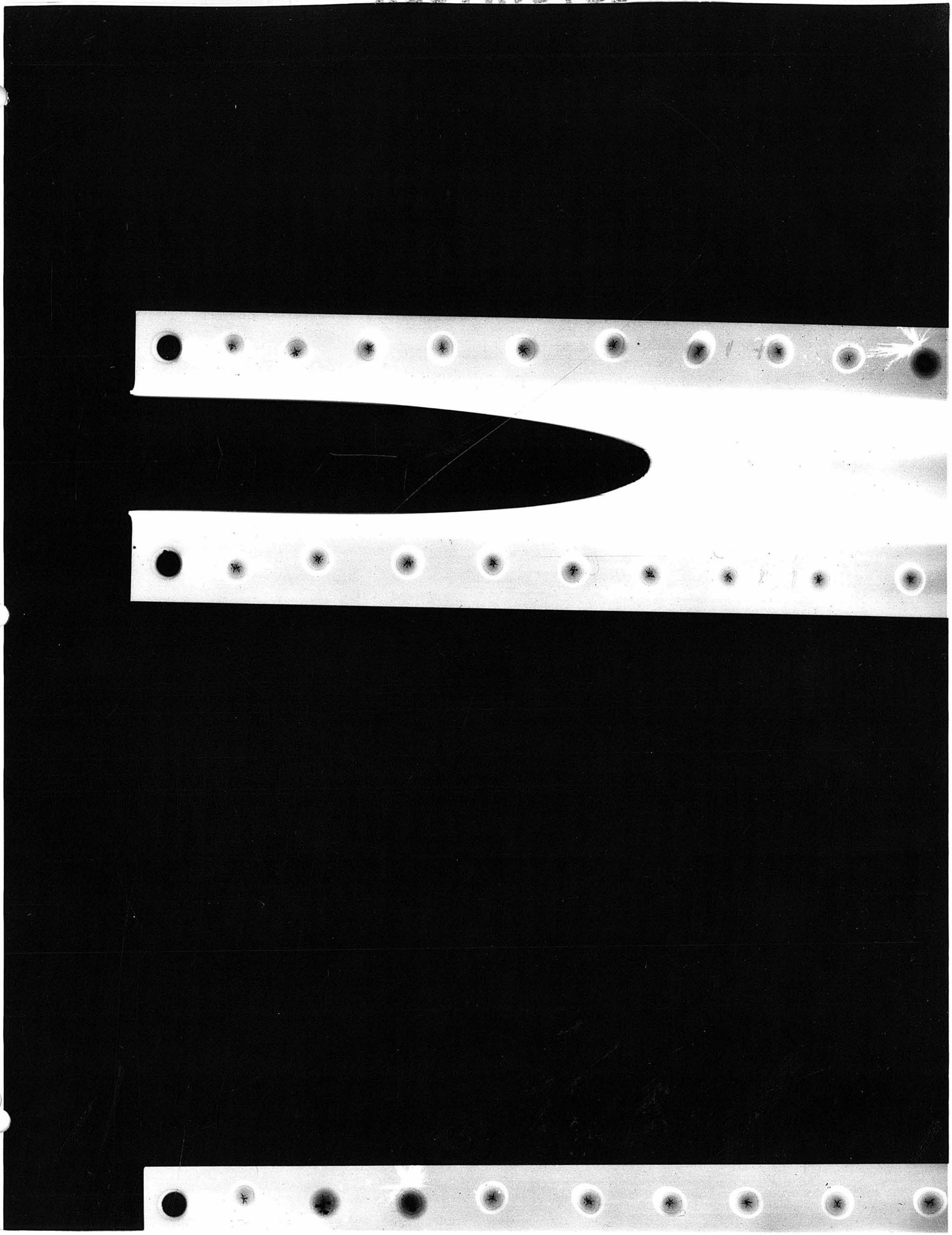


FIG. 72. RADIOGRAPHS OF SPOT WELDS IN TAIL BOOM OF A PURSUIT PLANE.

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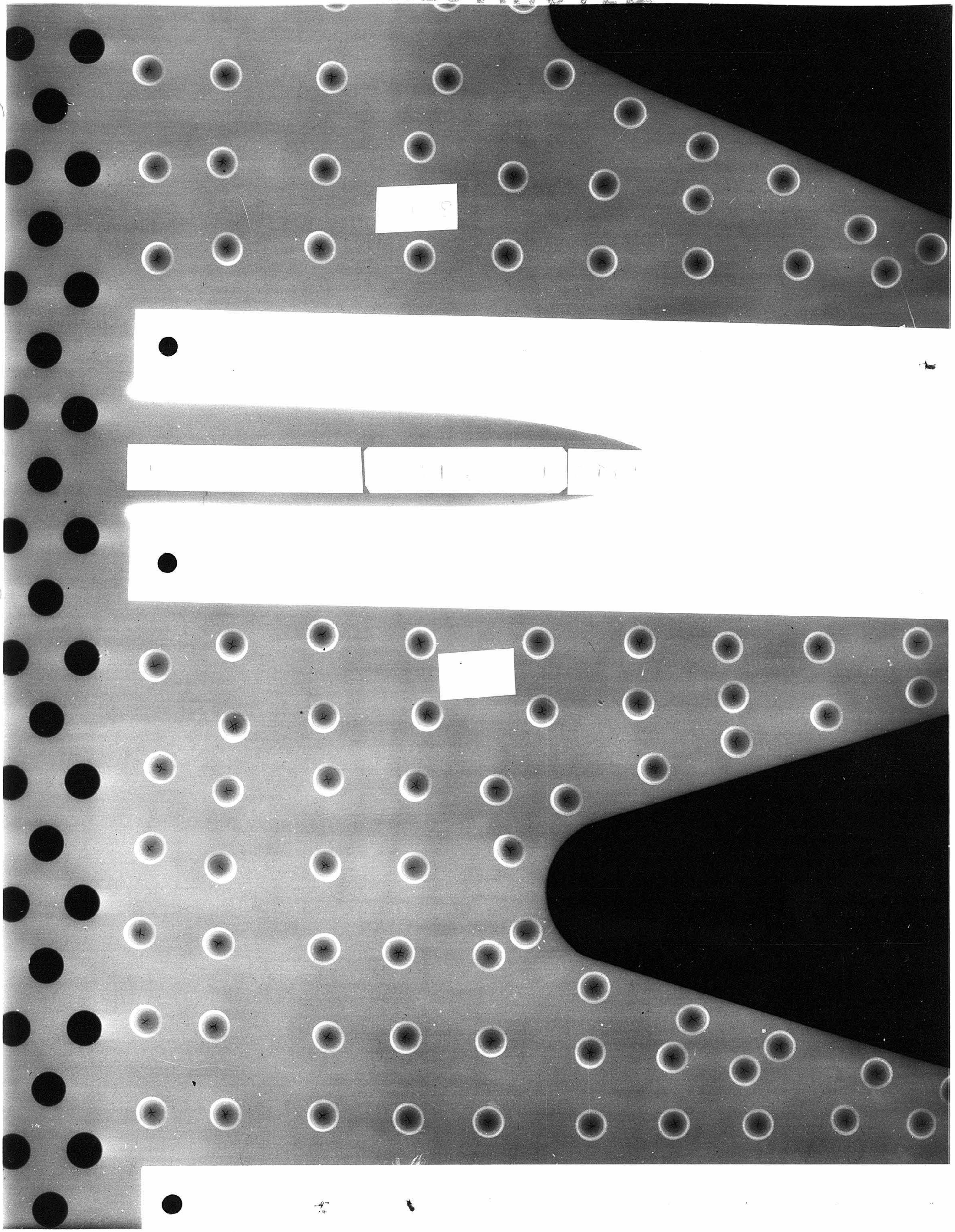


FIG. 72. RADIOGRAPHS OF SPOT WELDS IN TAIL BOOM OF A PURSUIT PLANE.

the nugget into the parent sheet, contour of nugget wall, diameter and shape of corona ring, location of segregations within the nugget, and in the parent metal outside the nugget, and the geometry of cracks, porosity, inclusions, and expulsion of metal.

(3) Defects, including absence of weld nugget, inadequate penetration (or doughnut welds), undersize weld nuggets, excessive penetration in oversize weld nuggets, cracking, porosity, inclusions, expulsion at the faying plane, segregation of eutectic corresponding to excessively large heat affected zones, mis-shapen welds, and excessive tip skid.

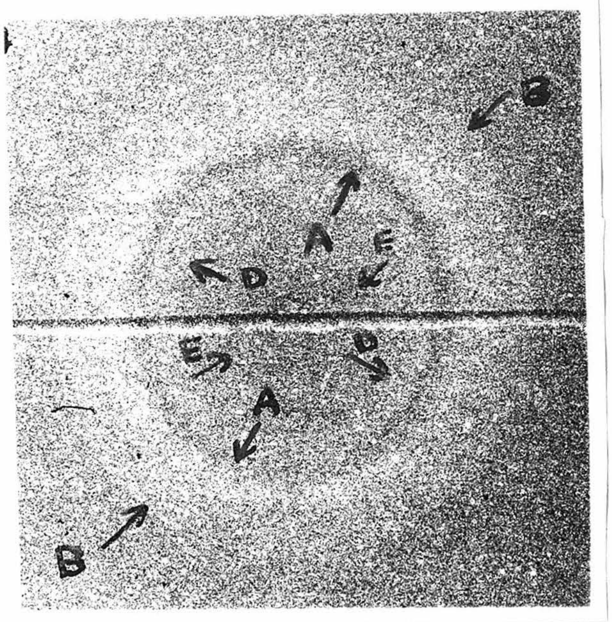
(4) Strength, in normal welds free of undesirable defects and excessive Alclad inclusions, which can be reliably predicted from weld nugget area.

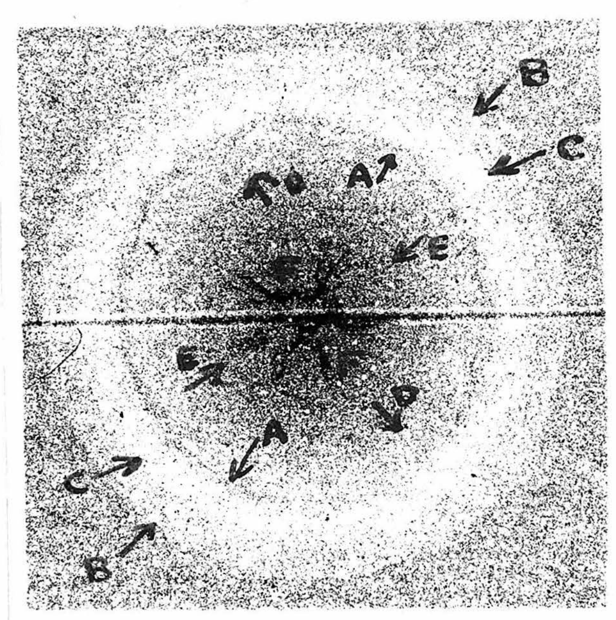
1. Interpretation of Features of Spotweld Radiographs.

a. Prominent Dark Ring A-A, shown in Fig. 73 and succeeding radiographs, indicates spotweld nugget diameter and shape. It occurs because the boundary zone between the cast weld nugget and the parent metal is radiographically less dense than either the body of the nugget of the parent nugget or the parent alloy. Thus a larger portion of the incident X-rays pass through the metal in this region

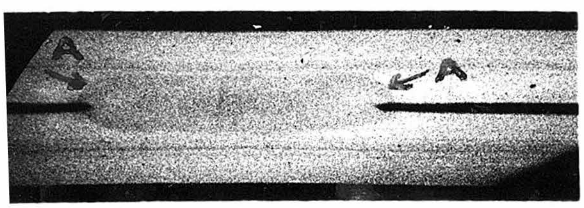
Weld 25

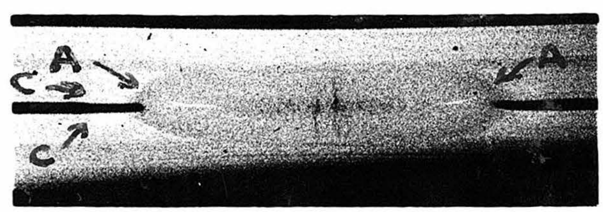
Weld 37



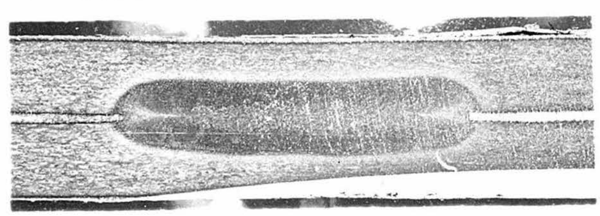


Radiographs





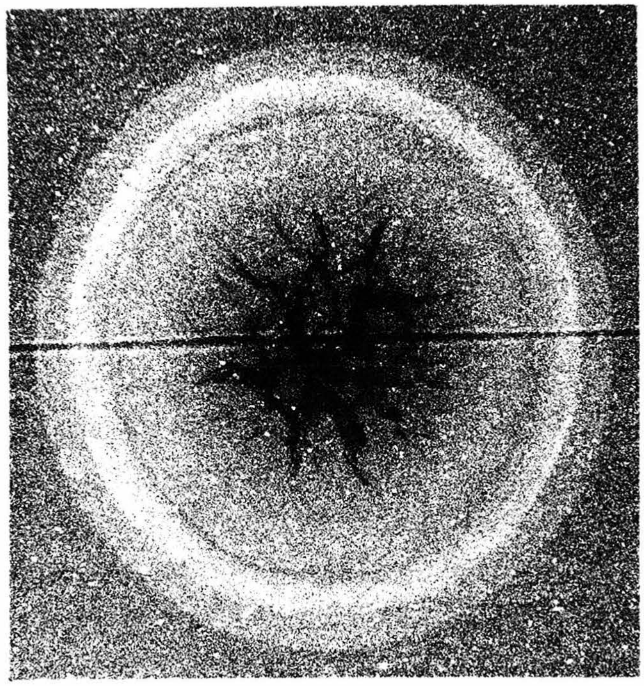
Section Radiographs



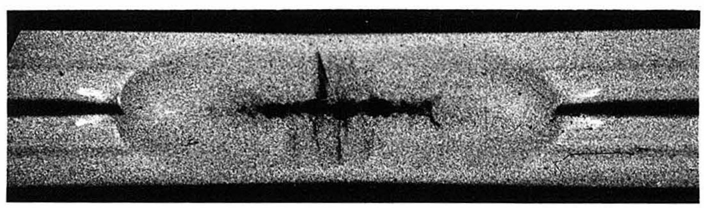
Section Macrographs

Fig. 73. Typical Spotweld Radiographs, With Radiographs and Macrographs of Weld Sections.

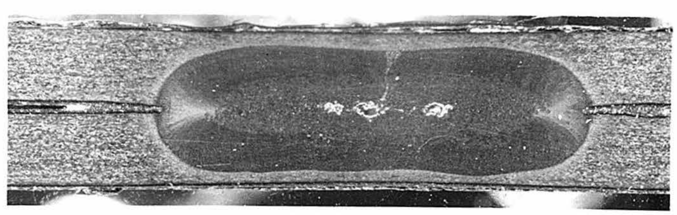
WELD Q #73



Radiograph



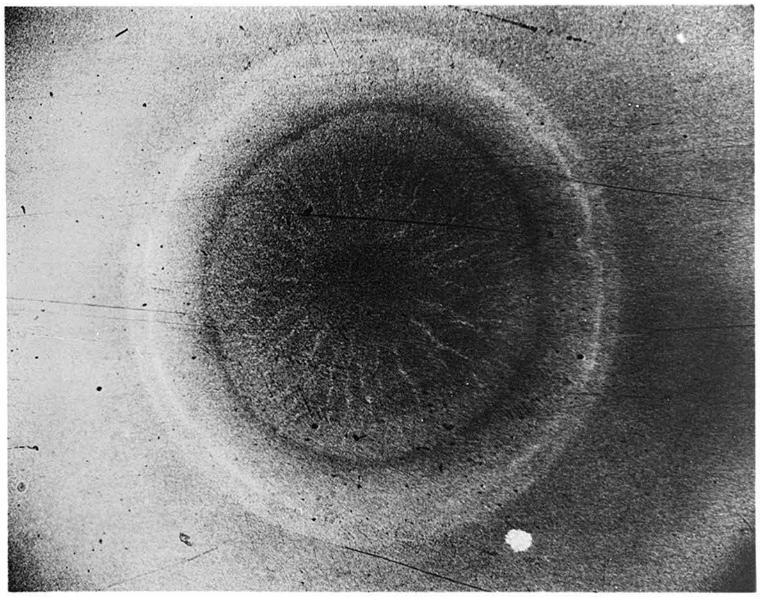
Cross Section Radiograph



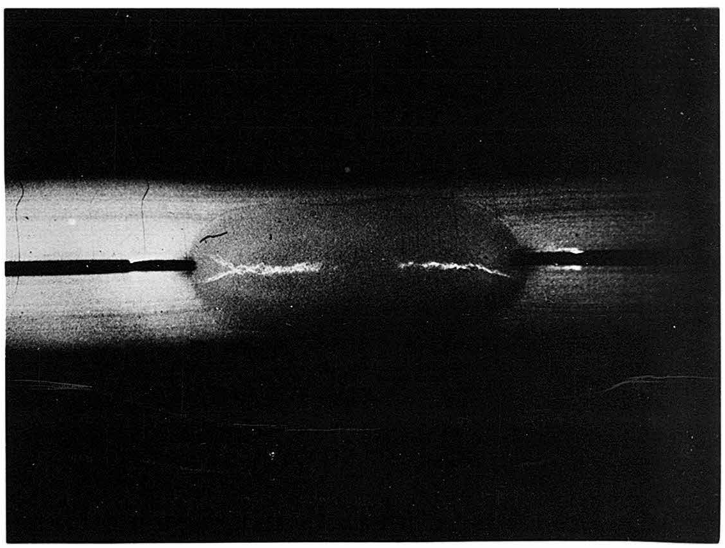
Cross Section Macrograph

Fig. 73, Cont'd.

WELD 100



Radiograph



Cross Section Radiograph

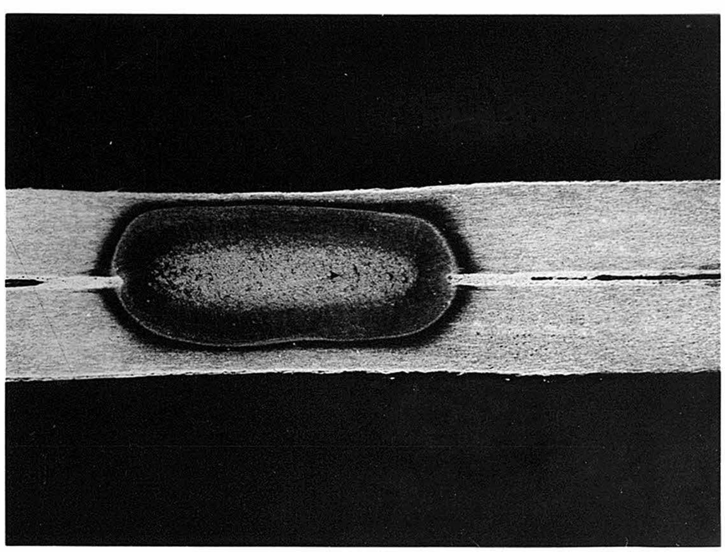


Figure 73, Cont'd.

than elsewhere, with consequent additional darkening of the film.

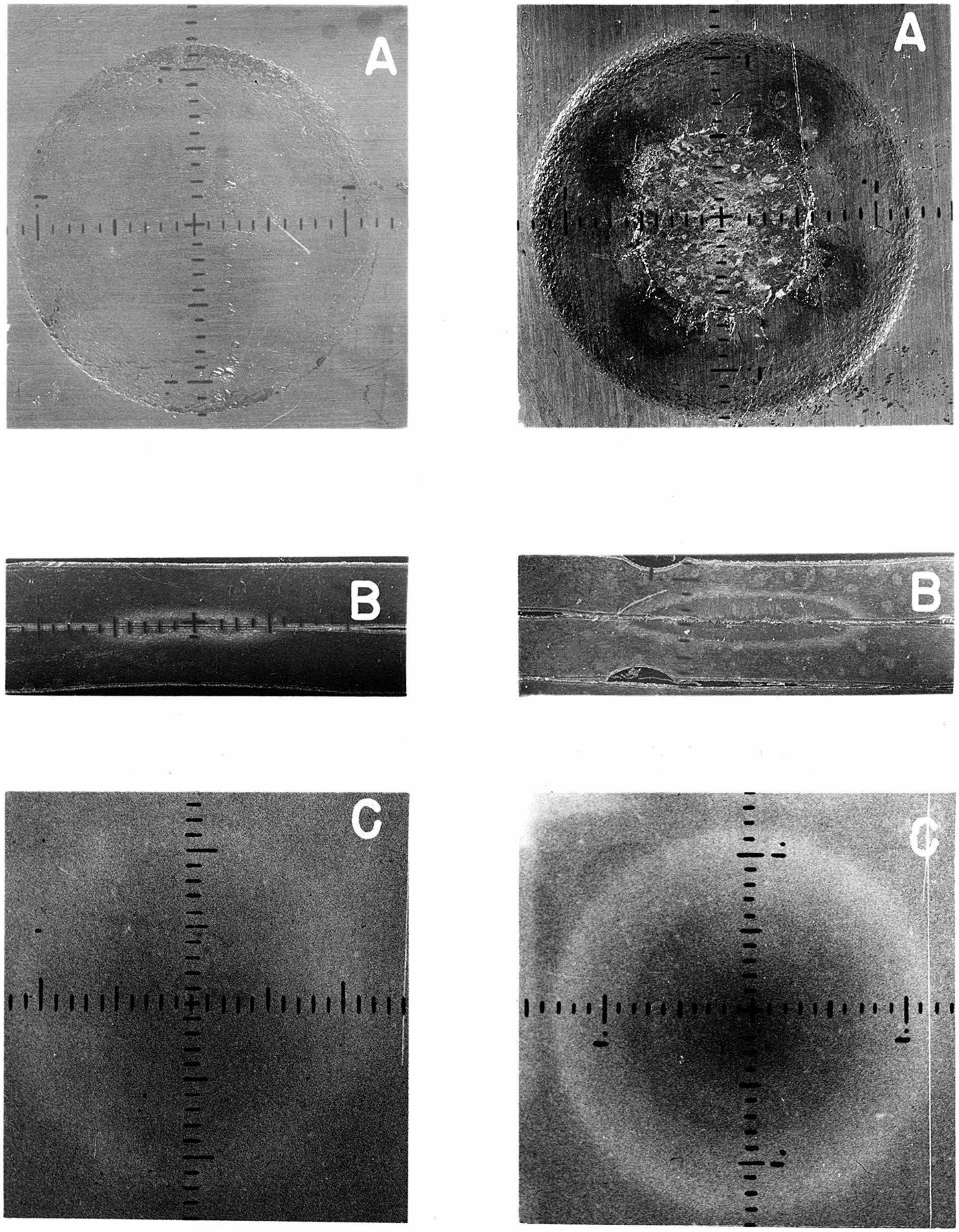
This dark ring is invisible if the weld nugget is absent (see weld F-12, Fig. 74 and Weld F-167, Fig.75) or if the radiograph is improperly made. The dark ring may fade or disappear if weld nugget penetration is very low (below 10% to 20%) (See Weld F-19, Fig. 74).

The dark ring becomes more dense as the vertical projection of the nugget wall increases, i.e. as nugget penetration into the parent sheet increases, or as the wall becomes steeper. (see welds 37 and 73, Fig. 73)

The width of the dark ring increases as the nugget wall becomes less vertical. (Compare Welds 25, Fig. 73, and F-19, Fig. 74 with welds 37, Fig. 73 and F-72, Fig.74)

The diameter and shape of the dark ring correspond faithfully to the outline of the vertical wall of the nugget, which reaches a maximum diameter in the parent sheet near the faying plane. The actual diameter of the weld nugget at the faying plane may be considerably reduced from the outline indicated by the dark ring by excessive Alclad inclusion. (However, in production welds, excessive Alclad inclusions usually occur only in welds of low penetration, which would be rejected). (See entire sequences of Figs. 73 and 74 for change of dark ring diameter in correspondence with changes in nugget diameter). See especially Welds F-42 and F-44,

FIG. 14 - PART I RESTRICTED



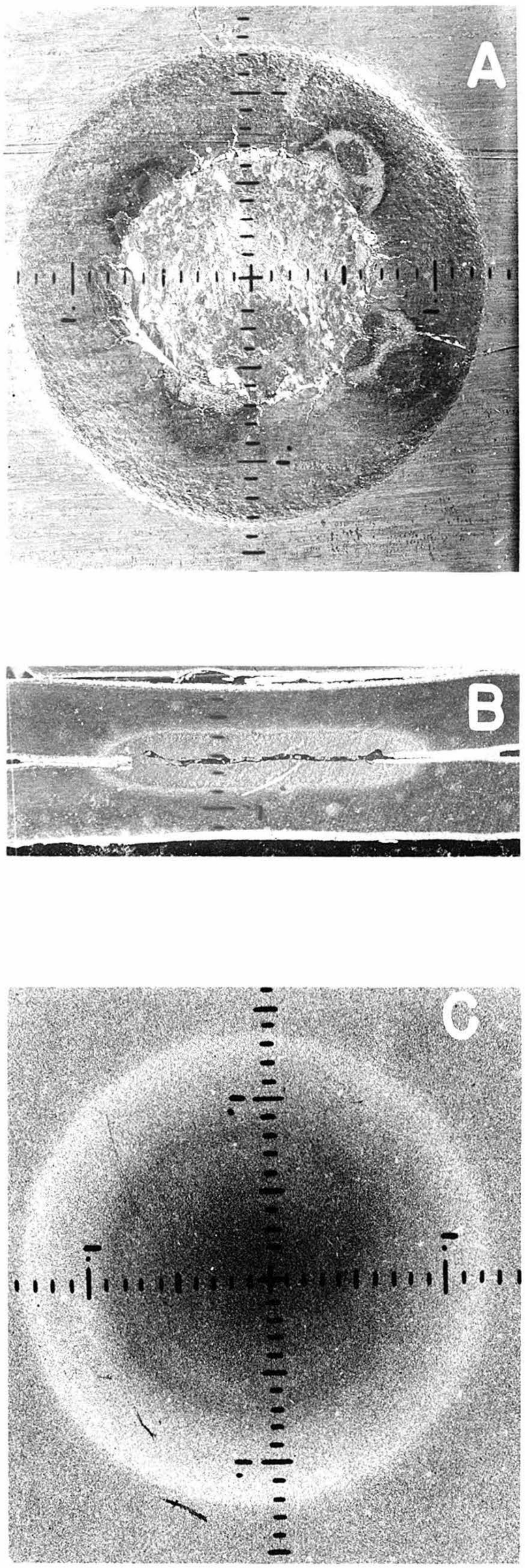
WELD F12 - STRENGTH 0

WELD F-19 STRENGTH
260 POUNDS

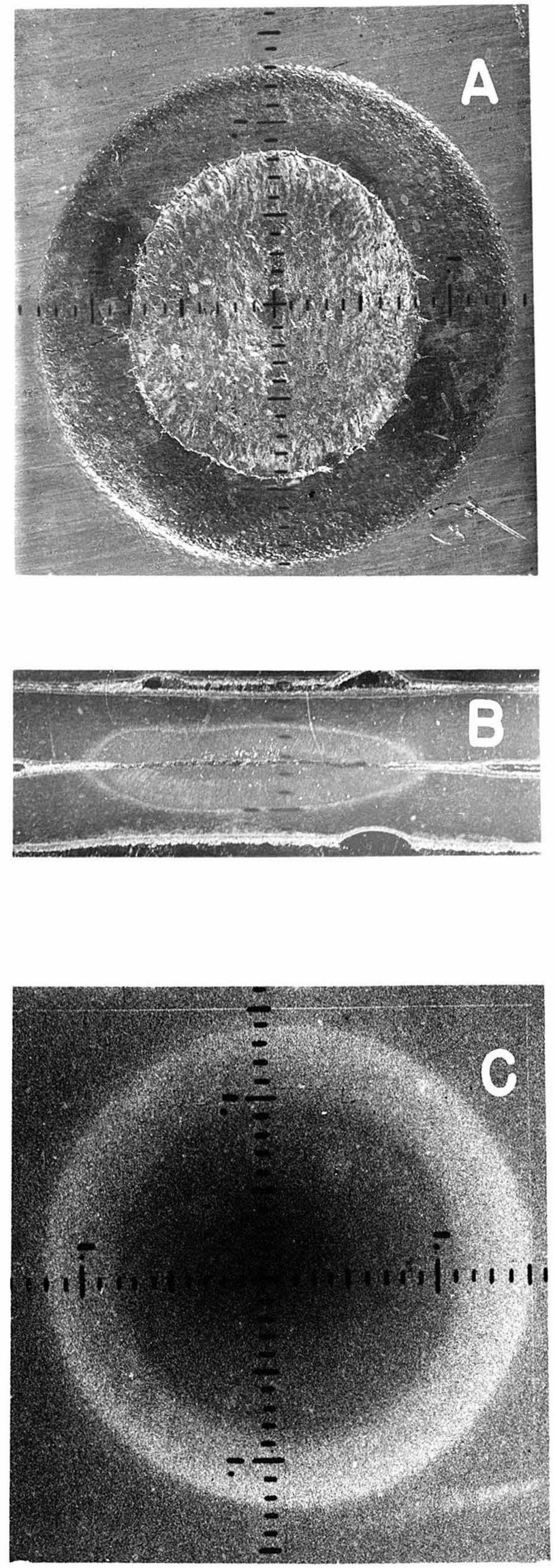
FIG. 12. MACROGRAPHS OF FAYING SURFACE (A), SECTION (B), AND ENLARGED RADIOGRAPHS (C) OF TYPICAL SPOTWELD SPECIMENS (10 DIAMETERS, EACH SCALE DIVISION =0.01")

FIG. 74 - PART II

RESTRICTED



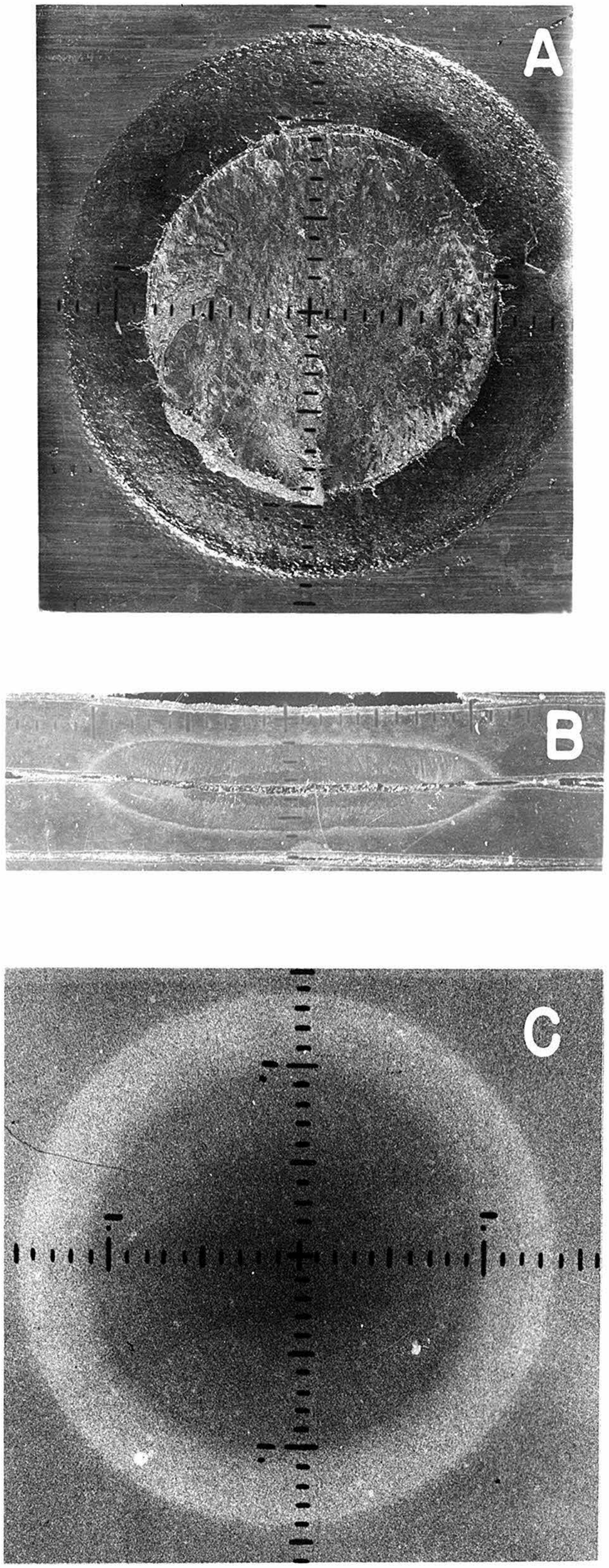
WELD F-39 STRENGTH
330 POUNDS



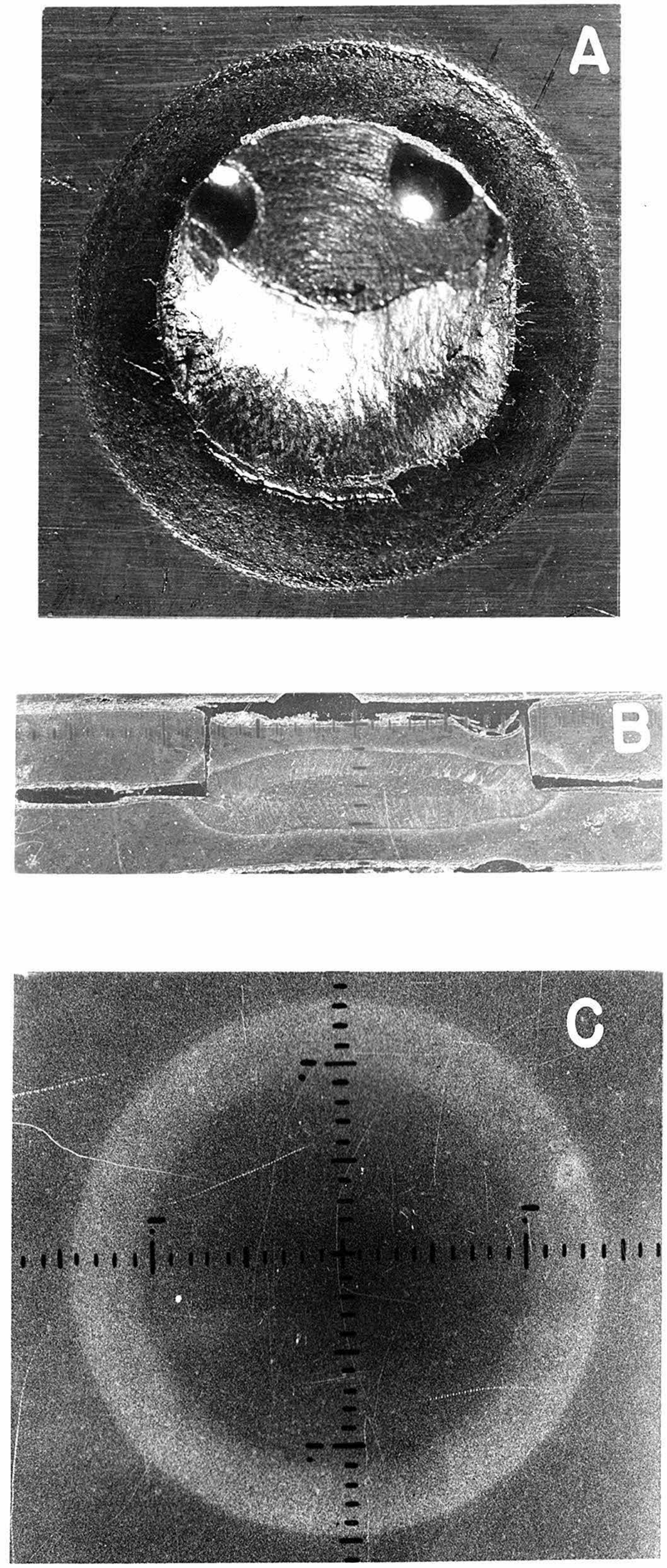
WELD F-56 STRENGTH
500 POUNDS

FIG. 74 - PART III

RESTRICTED



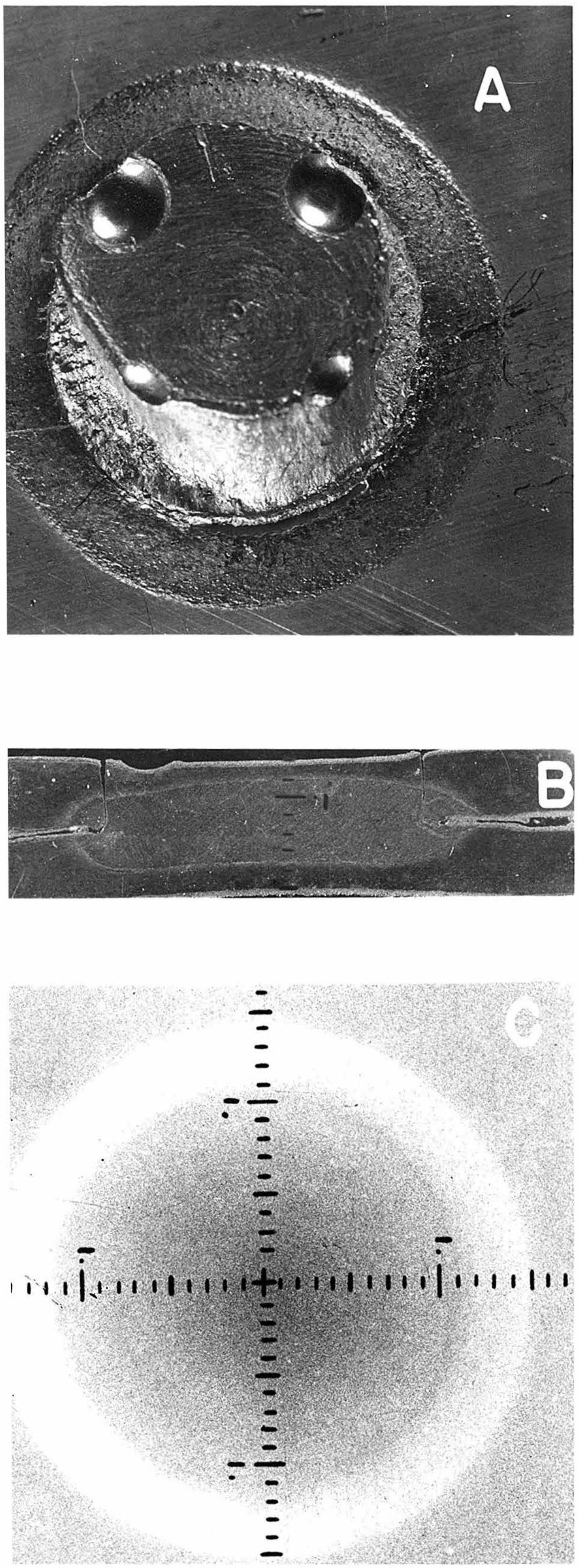
WELD F-72 STRENGTH
580 POUNDS



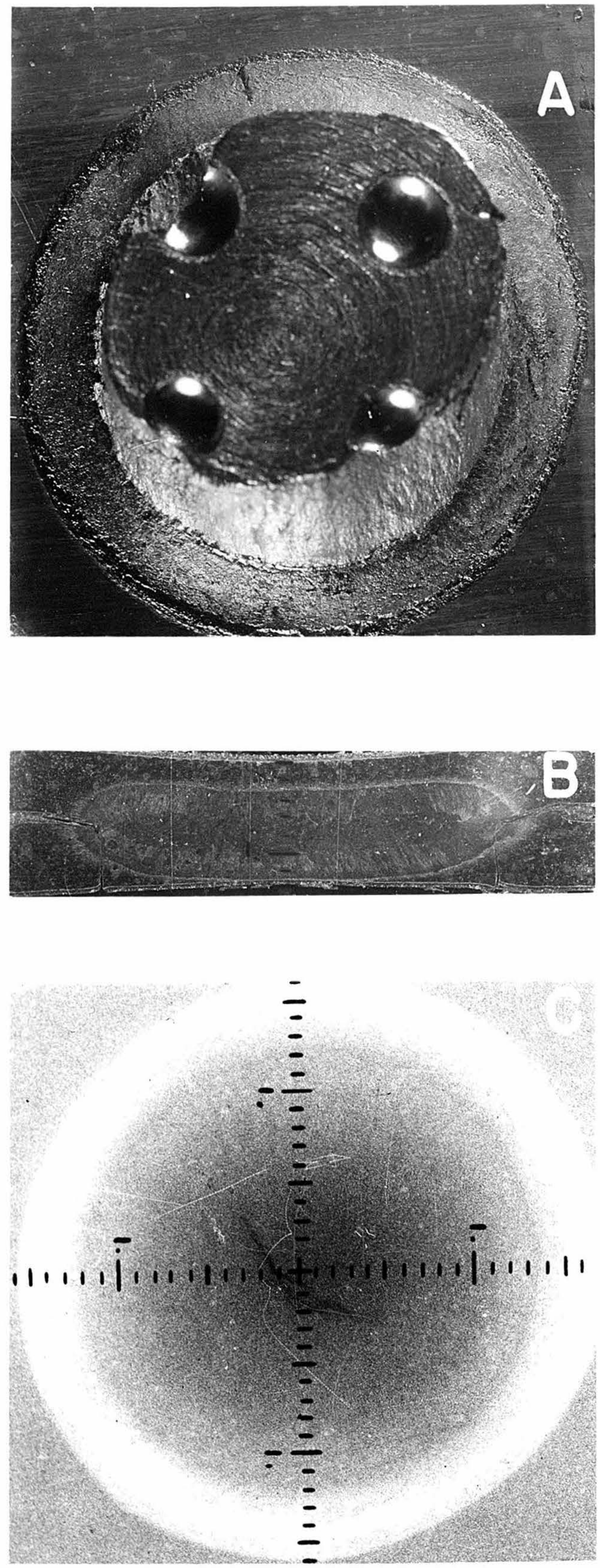
WELD F-76 STRENGTH
560 POUNDS

FIG. 14 - PART IV

RESTRICTED

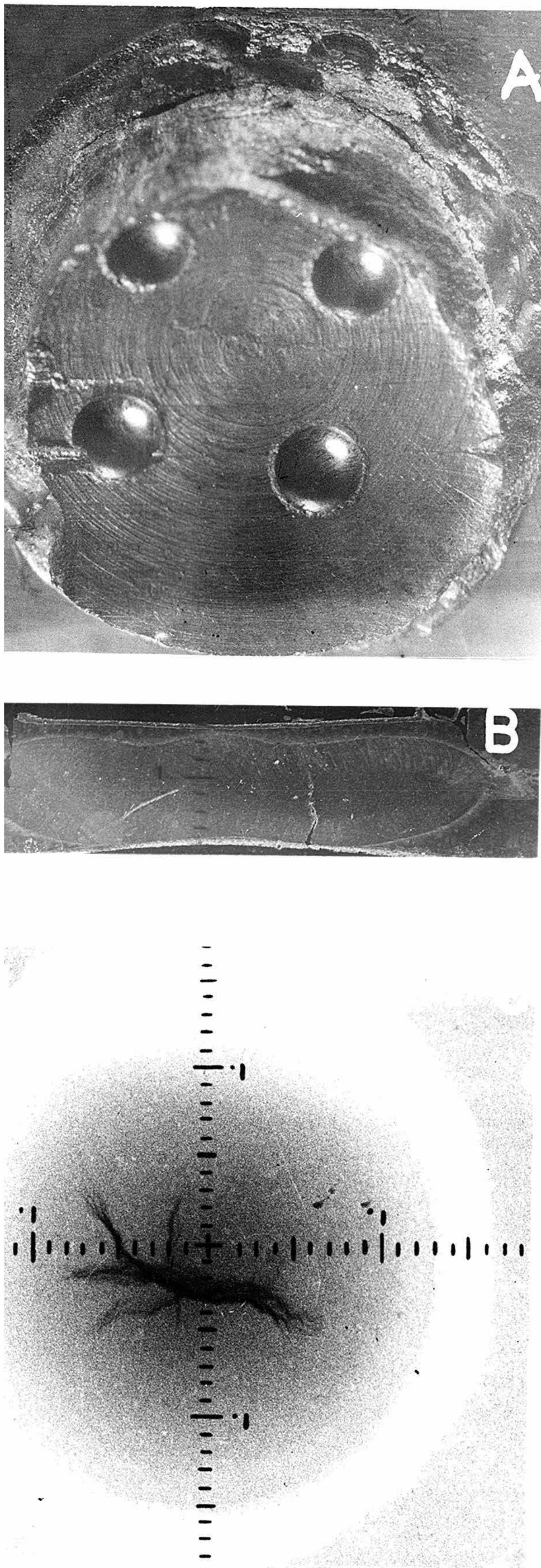


Weld F-90 Strength

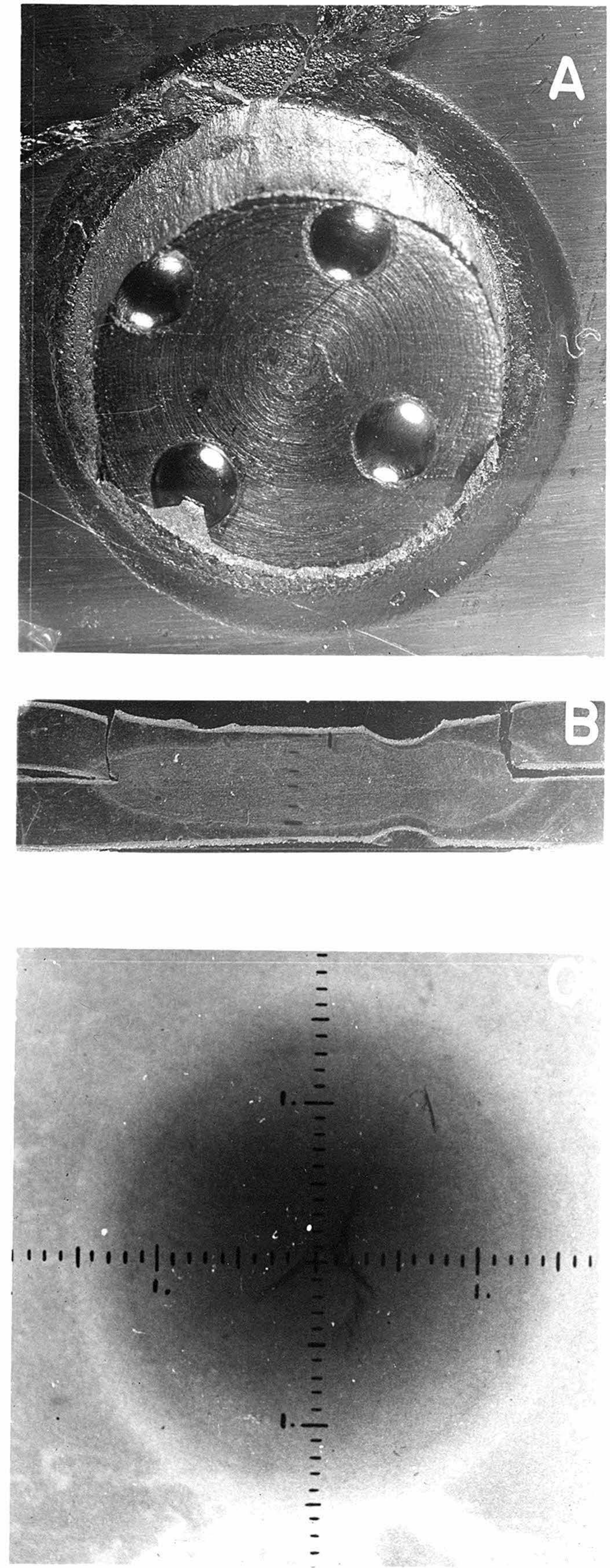


Weld F-112 Strength

FIG. 74 - PART V



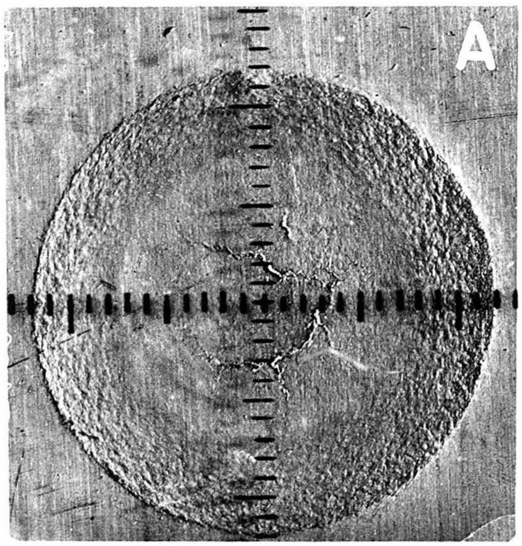
WELD F-122 STRENGTH
1385 POUNDS

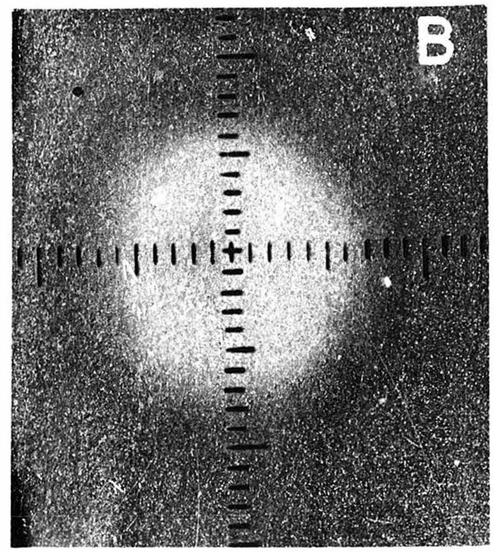


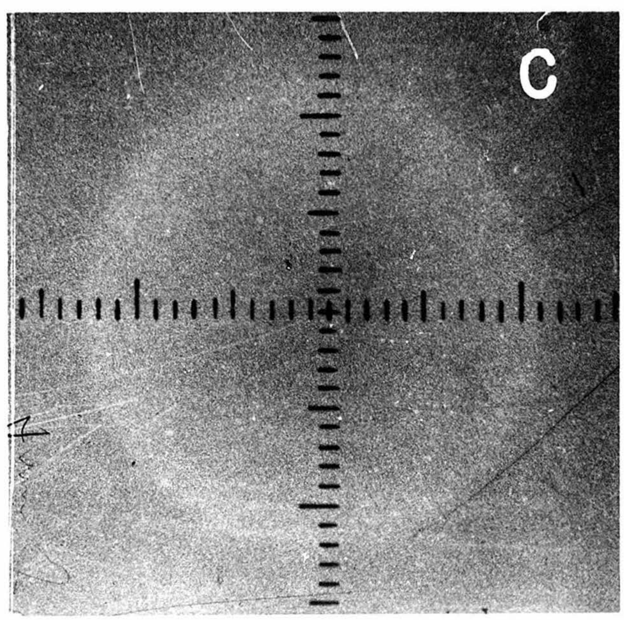
WELD F-126 STRENGTH
840 POUNDS

RESTRICTED

FIG. 15 - PART I







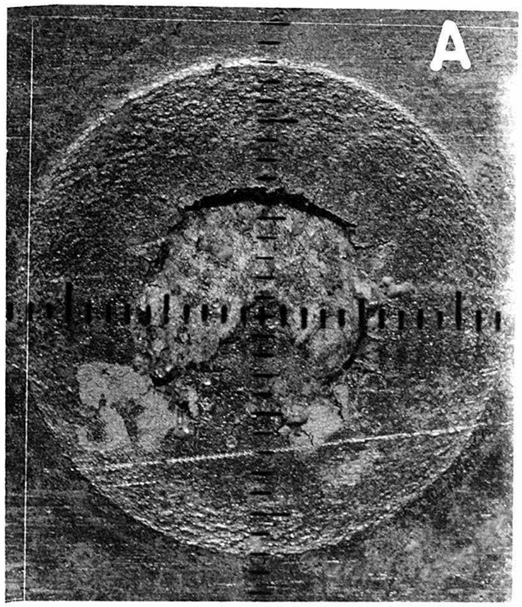
WELD F-16

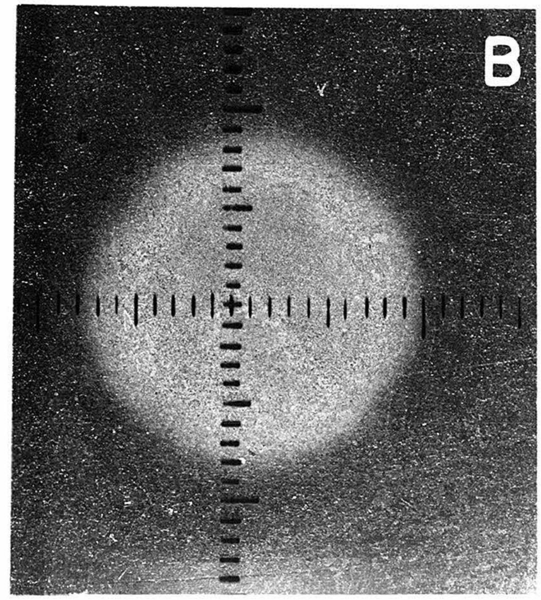
FELL APART

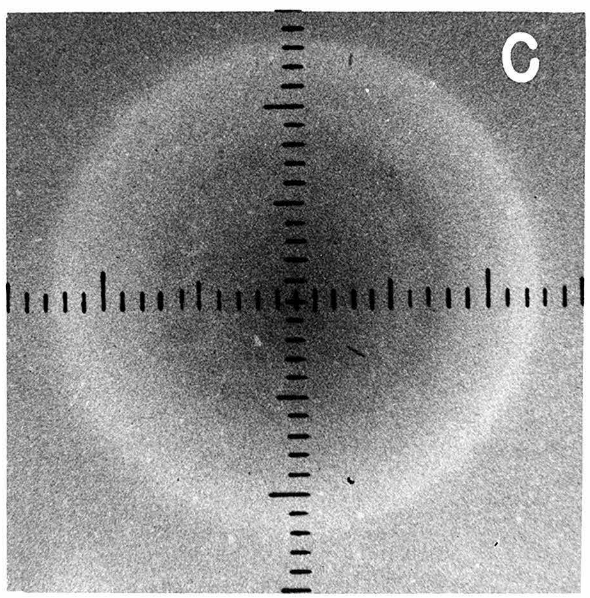
FIG. 13. MACROGRAPHS OF FAYING SURFACE (A), SECTION THROUGH NUGGET BELOW FAYING SURFACE (B) AND ENLARGED RADIOGRAPHS (C) OF TYPICAL SPOTWELD SPECIMENS (10 DIAMETERS. EACH SCALE DIVISION =0.01")

RESTRICTED

FIG. 25 - PART II

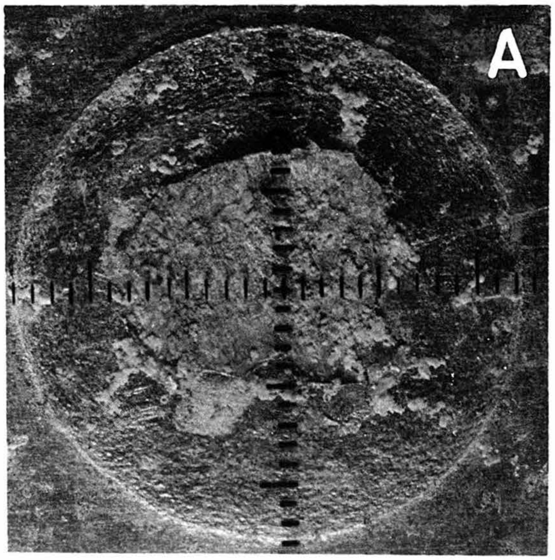


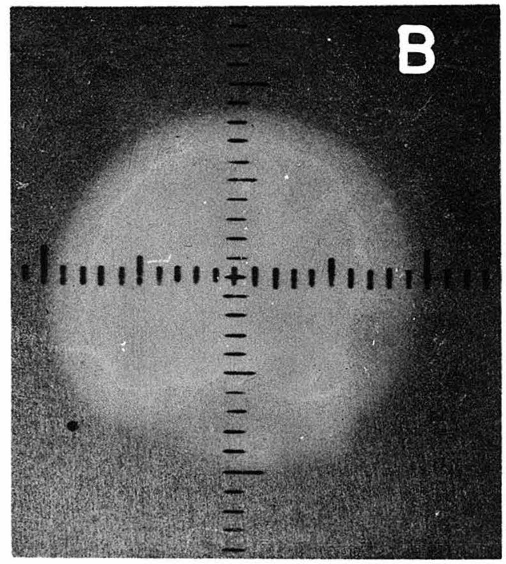


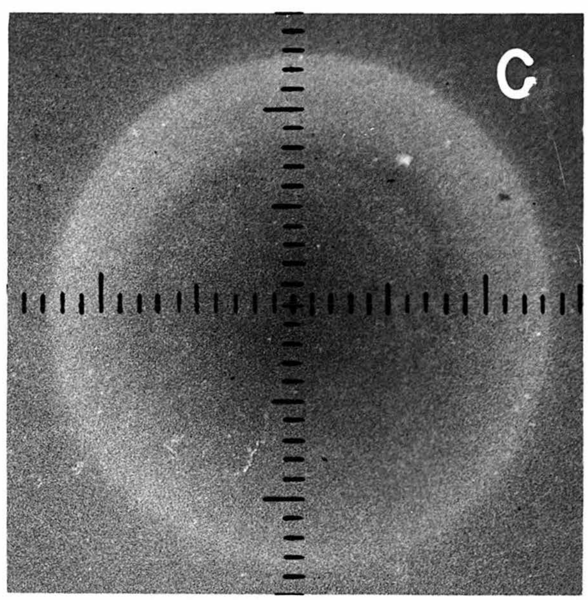


WELD F-30 STRENGTH 200 POUNDS

FIG. 75 - PART III



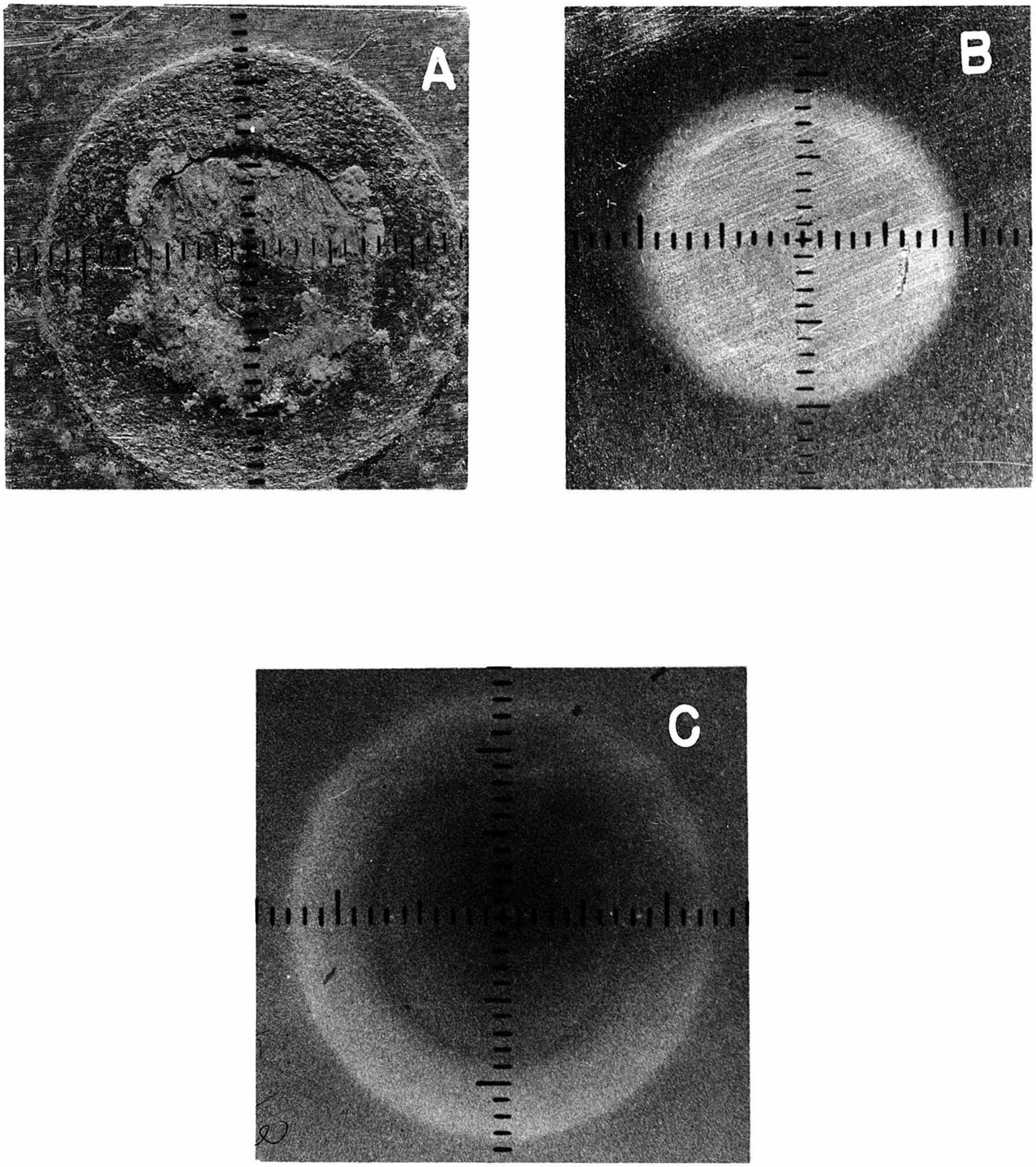




WELD F-42 STRENGTH 330 POUNDS

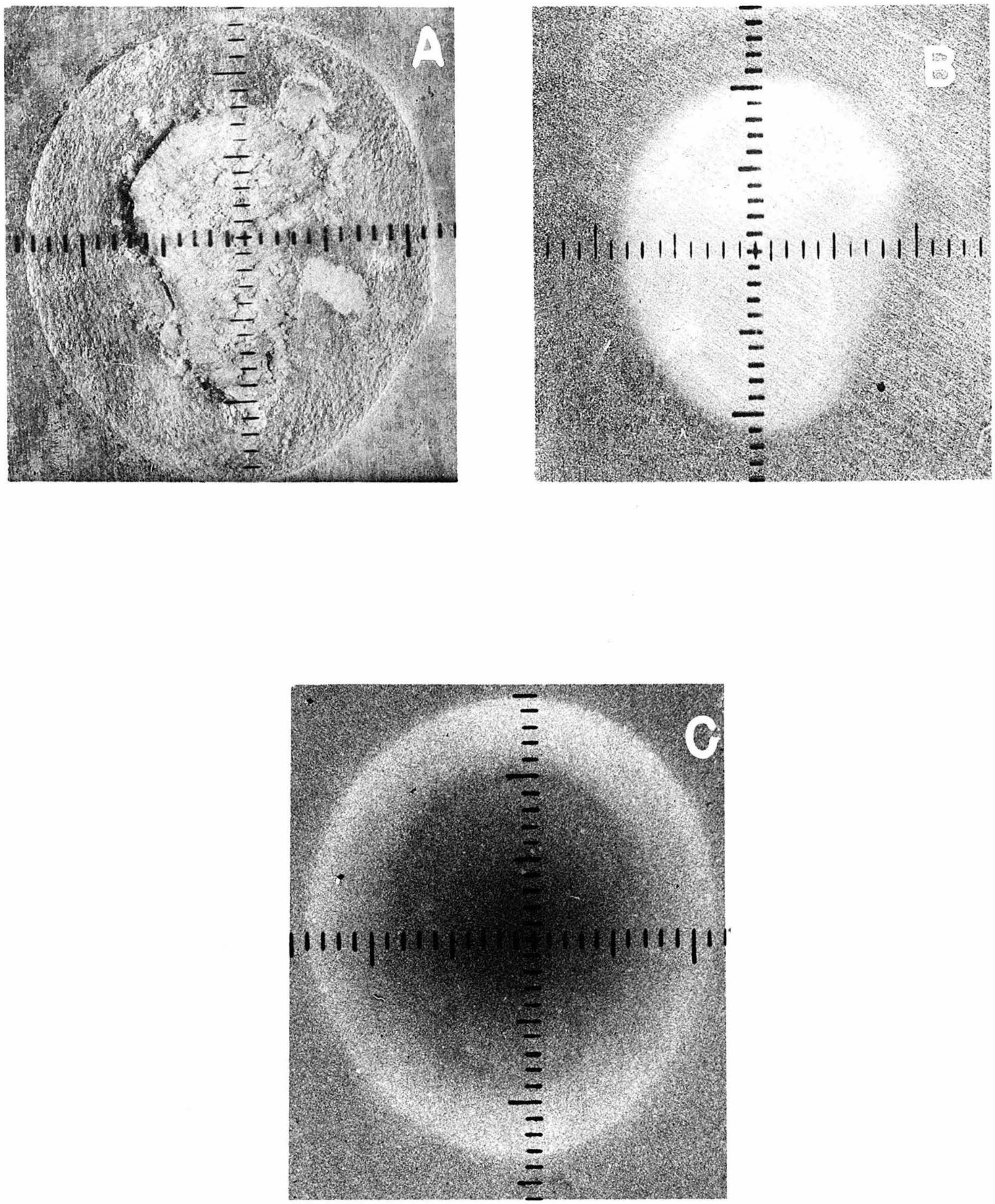
RESTRICTED

FIG. 75 - PART IV



WELD F-43 STRENGTH 310 POUNDS

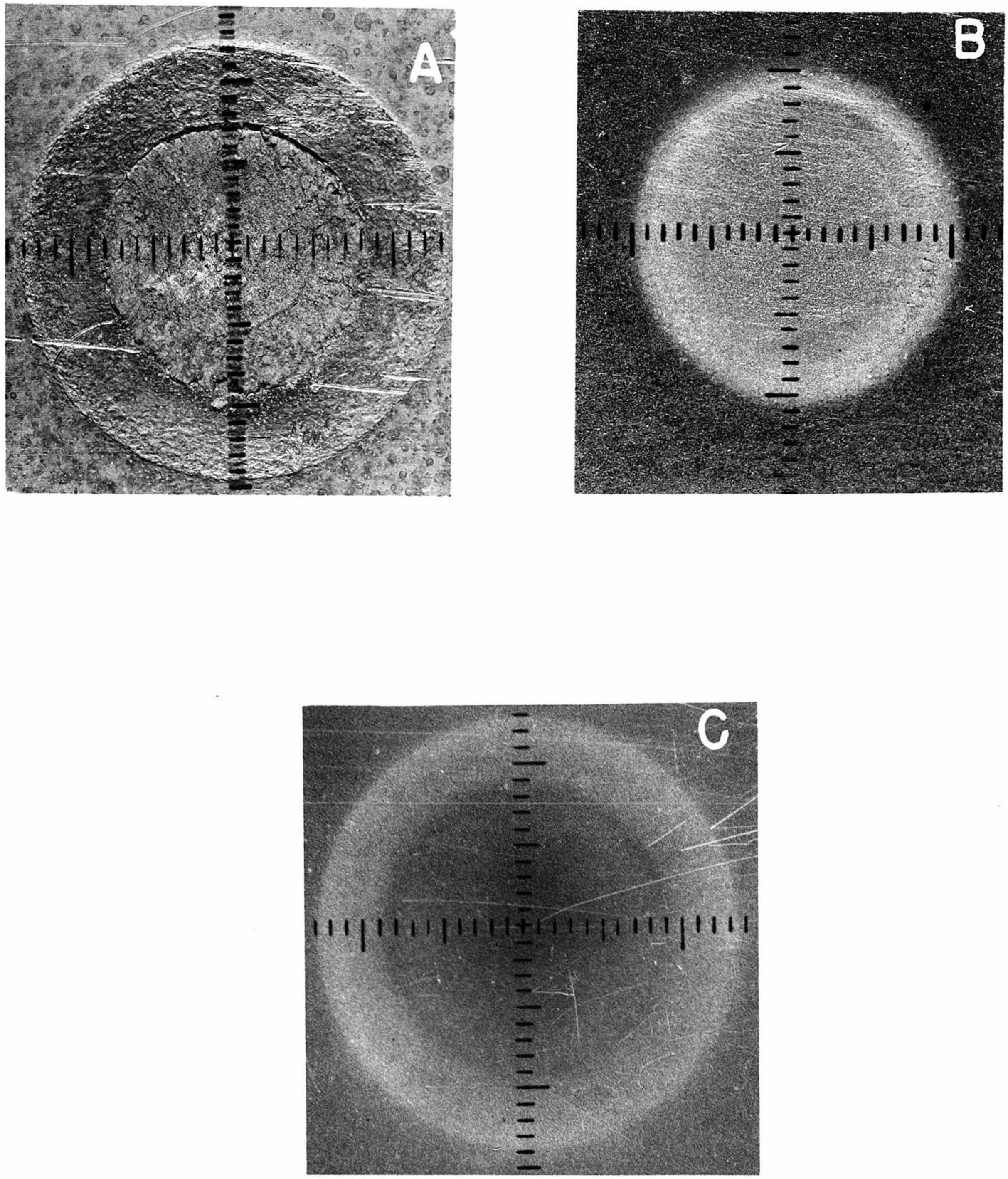
FIG. 75 - PART V



WELD F-44 STRENGTH 260 POUNDS

RESTRICTED

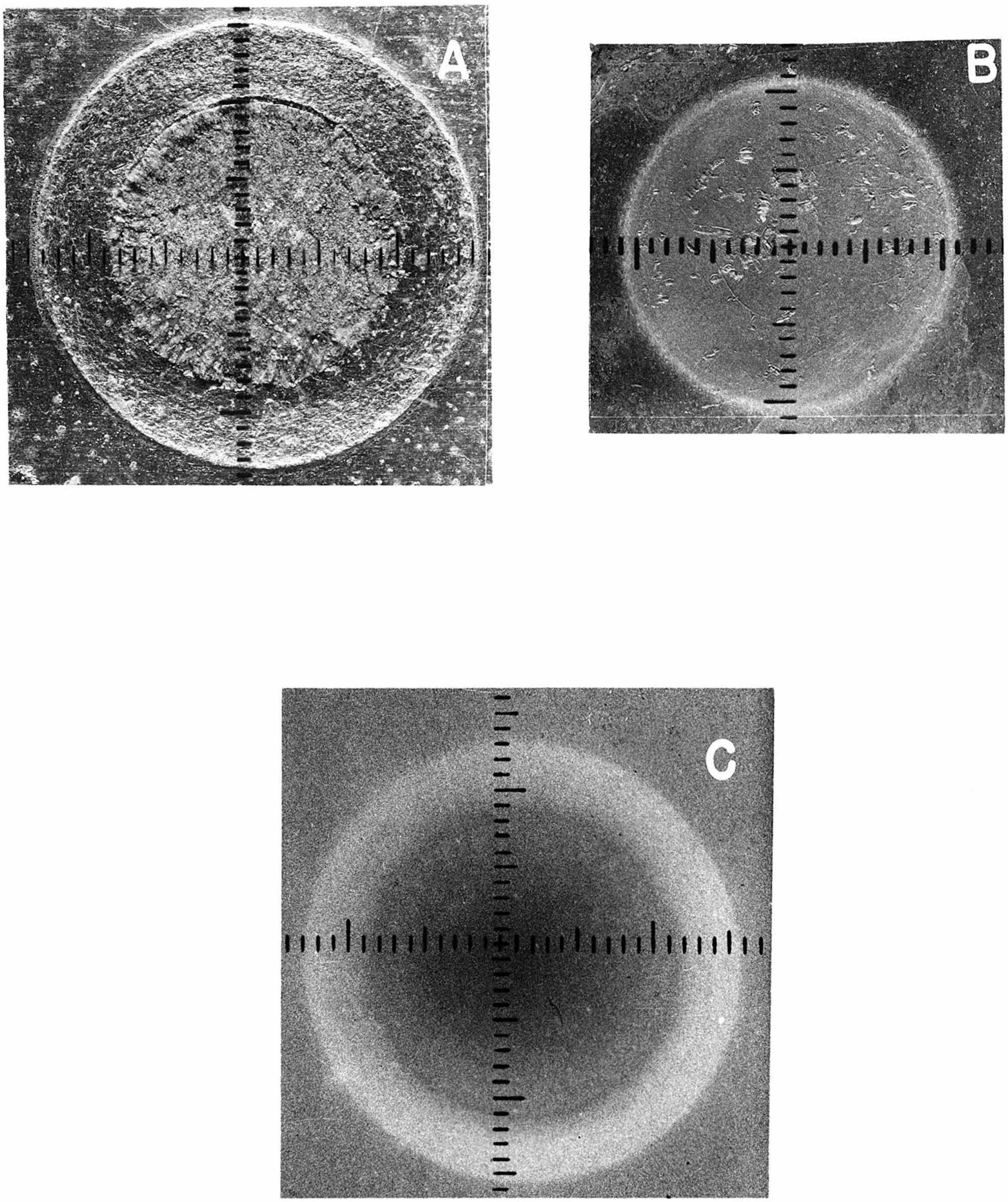
FIG. 75 - PART VI



WELD F-62 STRENGTH 460 POUNDS

RESTRICTED

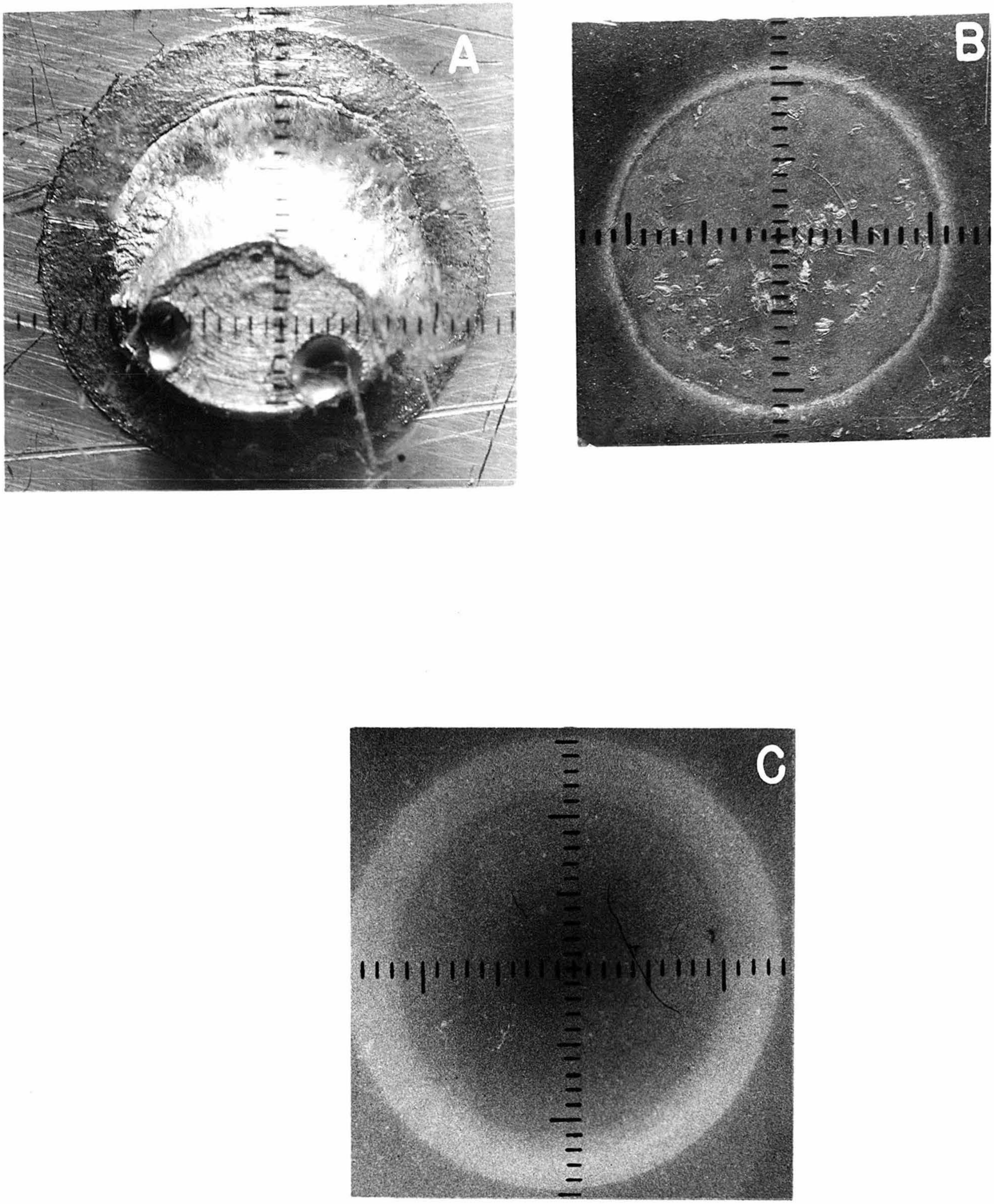
FIG. 75 - PART VII



WELD F-83 STRENGTH 575 POUNDS

RESTRICTED

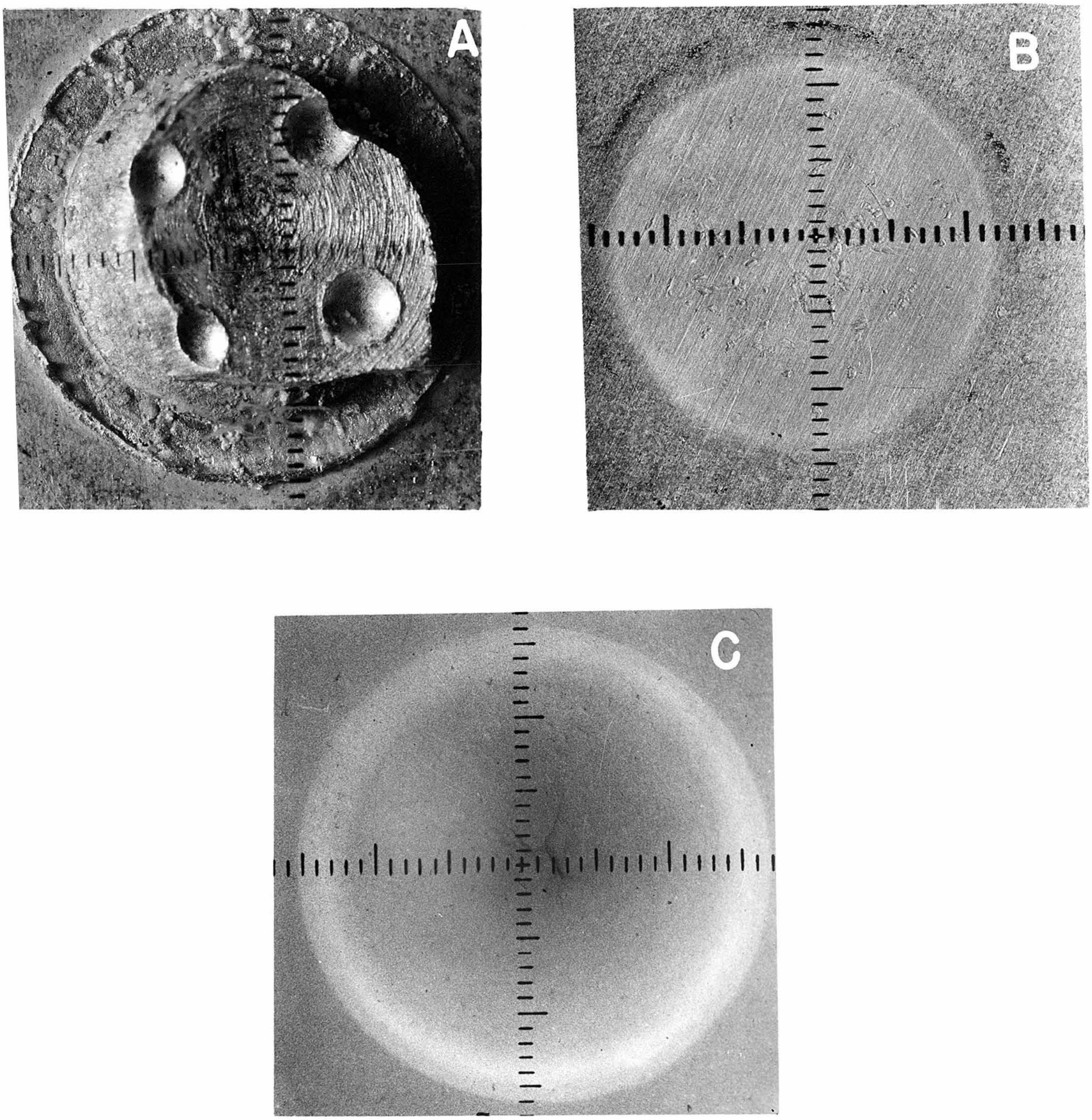
FIG. 13 - PART VIII



WELD F-100 STRENGTH 605 POUNDS

RESTRICTED

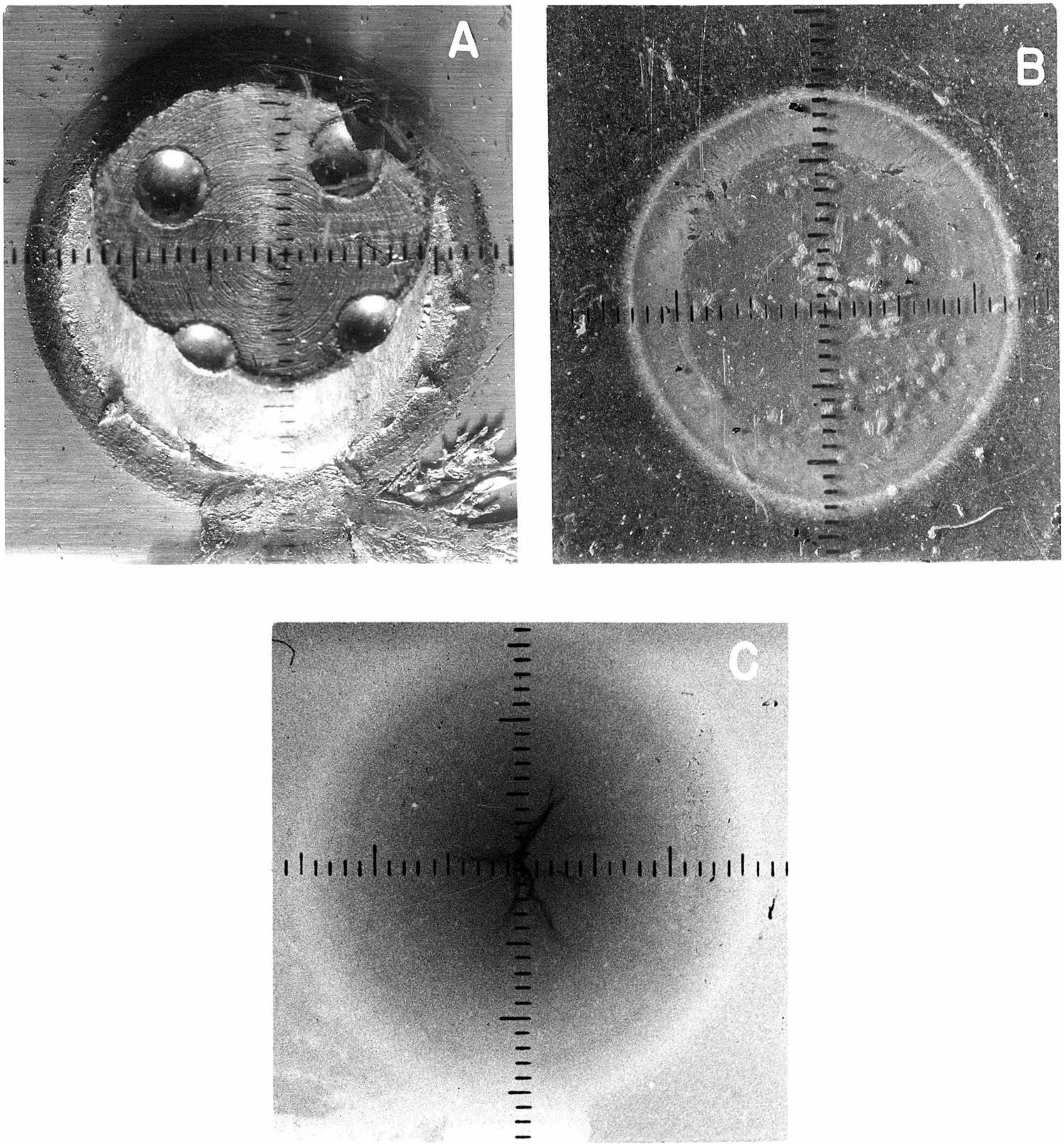
FIG. 75 - PART IX



WELD F-117 STRENGTH 850 POUNDS

RESTRICTED

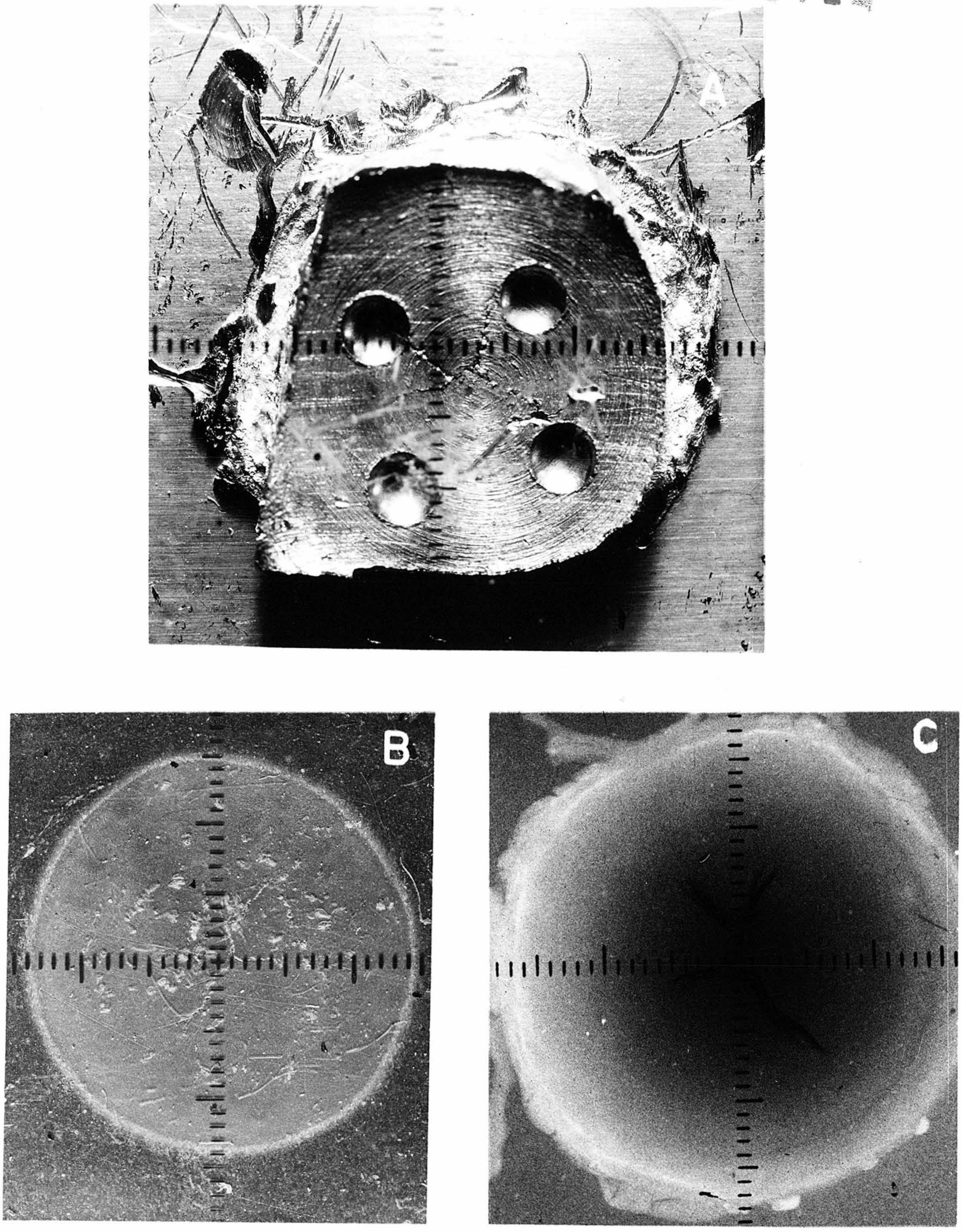
FIG. 15 - PART X



WELD F-133 STRENGTH 880 POUNDS

FIG. 75 - PART XI

RESTRICTED



WELD F-134 STRENGTH 1200 POUNDS

Fig. 75, for correspondence of shape of dark ring to shape of weld nugget just below Alclad layer at faying plane.)

b. The outer boundary B-B of the uniformly light area shown on Fig. 73 and succeeding radiographs, delineates the outer boundary of the corona region at the interface. (See entire sequence of Fig. 74.) It usually results from changes (due to heat and pressure) in the Alclad layer at the interface, and is most evident when material of the Alclad layer is pressed away from the nugget region, spreading the sheets and filling in the interfacial volume as shown in the sections of Welds F-19, F-39, F-56 and others of Fig. 74.

The boundary B-B need not necessarily be the outermost ring of the spotweld radiograph--in some cases, the scalloped white ring C-C resulting from extruded pools of eutectic may be outermost. Boundary B-B can usually be recognized by its relatively smooth contour and nearly uniform density.

It is not necessarily true that the diameter of boundary B-B bears any fixed ratio to the nugget diameter--as shown in Weld F-12, Fig. 74, which has no nugget, yet has a faint boundary B-B due to small effects in the Alclad layer at the interface. (See also Fig. 42, showing measurements for a single group of welds in which the ratio of the corona diameter to the nugget diameter varies from 2:1 to 11:1)

c. The scalloped white ring C-C, shown prominently on Weld 73, Fig. 73 and on Welds F-112 and F-122 of Fig. 74, indicates the presence and location of radiographically dense pools and stringers of eutectic in the parent metal outside the weld nugget. These stringers and pools of eutectic are shown clearly on the radiograph of a vertical section of the Weld 73 of Fig. 73, and are seen to lie in the parent metal, near but not necessarily at the faying plane. Occasionally such a conducting channel for the low melting alloy breaks through to the Alclad layer at the interface, forming a blister or bubble of eutectic between the Alclad layer and the parent metal.

The pools and stringers of eutectic usually become prominent only on higher energy welds, and may be taken as evidense that the parent metal has been weakened along these channels out to the boundary C-C. The effect is probably synonomous with that of an excessively large heat affected zone outside the weld nugget. The condition is evidence of excessive heat in the weld, and usually accompanies oversize nuggets with excessive penetration.

On low energy welds the scalloped white ring C-C is usually absent, since little or no extrusion of eutectic has occurred.

d. Light Zone D-D, just inside dark ring A-A, shown on welds 37 and 73 of Fig. 73 and visible on most spotweld radiographs, seems to correlate with the columnar zone of the weld nugget. Where the dendritic zone is broad and thick in vertical section, the light zone D-D is clearly evident on spotweld radiographs.

Attempts to correlate either boundary of Zone D-D with the inner extremity of the Alclad inclusion have failed. In general, variations within zone D-D seem to mask radiographic images of the Alclad inclusion, so that the latter cannot be reliably detected.

On rare occasions, segregation of copper-rich material occurs prominently within the spotweld nugget, resulting in light radial striations. (See Weld 100 Fig. 73). This condition occurs as weld heat is increased toward the limit at which cracking occurs in the nugget.

Zone D-D has no proven significance in predicting weld strength or quality, as no correlation has yet been obtained between weld strength and differences in the cast structure within the nugget.

e. Dark Zone E-E in the center of the nugget, inside the inner boundary of the light zone D-D, shown on Welds 37 and 73 of Fig. 73, possibly correlates with the granular zone of the weld nugget. It has no proven useful significance in interpreting weld quality. The effect of sheet indentation by the electrodes of the spot welder is also occasionally evident in a gradual darkening of the image as the center of the weld is approached. However, in specimens whose outer surfaces have been ground flush and parallel, the darkening is still evident.

Zones D-D and E-E may vary greatly in shape and density.

With misshapen nuggets, such as F-42 and F-44 of Fig. 74, these variations are obviously correlated with nugget shape, apparently still following the demarkation between granular and dendritic cast structure in the nugget.

f. Cracks and Porosity in the weld nugget appear as prominent black markings F-F often radiating spokewise from the center of the nugget. They are actual voids, hence more X-rays pass through those parts of the spotweld to produce intense blackening of the radiographic film.

Cracks usually are the result of excessive heat or inadequate tip pressure during welding. There is no evidence that cracks reduce the static shear strength of spotwelds. Recent tests indicate that cracks may reduce the fatigue strength of spotwelds in stressed attachments.

g. Segregation of copper rich material within the weld nugget appears as light (usually radial) striations G-G. (See Weld 100 in Fig. 73). These light striations result because the segregated material is radiographically more dense than the surrounding cast alloy of the weld nugget.

The condition of extansive segregation within the nugget is relatively rare. It occurs in large nuggets which have been subjected to more than normal heating, often under conditions close to those producing cracking. Possibly the copper rich material gathers in incipient cracks--radiographs have been observed in which a network of black cracks (voids) connected to a network of light striations within the nugget.

There is no experimental evidence to date to show that the segregation within the nugget weakens the weld. However, the condition is undesirable, since it occurs on the borderline of excessive weld heating which produces cracking and an excessively large heat affected zone outside the weld nugget.

h. Expulsion of metal ("spit") at the faying plane H-H appears as an irregular light area outside the normal weld region (See Weld F-126, Fig. 74 and weld F-133, Fig. 75) with the characteristic shape of expelled material seen on actual welds. It is easily recognized, and occurs usually on welds made with excessive heat, insufficient electrode pressure, or improperly prepared sheet surfaces.

In general, welds with "spit" are found to be of lower strength than normal welds made under similar conditions.

i. Mis-shapen welds, characterized by irregular or oval-shaped nugget boundaries (dark ring A-A) are easily recognized. (see welds F-42 and F-44, Fig. 74, also examples in Figure 72) Such mis-shapen welds usually result from improper or non-uniform sheet surface preparation, from dirty or misshapen welding electrodes, or other local inconsistencies. Although individual mis-shapen welds may have adequate strength (if nugget area at the faying plane is adequate), the conditions producing mis-shapen welds also produce weak and defective welds. Hence this condition is undesirable.

j Excessive tip skid may be evident on the radiograph by a marked difference in the density of the uniform light area normally representing the corona and bounded by B-B, as shown on several of the two layer welds of Fig. 72. The marked lightening of this zone on one side of the weld results from the increased thickness of Alclad material on the sheet surface, pushed up as a result of tip skid. This condition should be checked by examination of the surface of the actual welded part.

Tip skid is undesirable because it may introduce inconsistent pressure conditions during welding, and usually introduces locked-up stresses in the welded part.

C. Inspection Procedure:

Radiographic inspection of spotwelds is a useful supplement to, but not a replacement for, process control and visual inspection. It provides the inspector with far more complete information concerning the weld than does visual inspection. This information should be used by the inspector in exactly the same manner as equivalent information obtained by destructively sectioning specimen welds would be used. No change in standards of weld quality and strength, as established through specifications and industrial experience, is required. Radiography simply provides more complete information on which to base judgement of weld quality.

To furnish a reference standard for the analysis of weld quality in any given factory, a series of static shear test specimens in each gauge and alloy should be prepared and radiographed, then subjected to static shear pull tests and destructive sectioning. In making these specimens, normal production conditions should be used, except that one or more welding variables, such as weld current or energy, should be varied through the widest possible range to obtain a wide range of strengths and defects. The significance of each defect and the relation of nugget size to weld strength can be determined from these specimens. A table of standard reference specimens, including welds of each nugget diameter and penetration, and specimens of each defect, can be prepared. Such a table should show, side by side, the weld section, the weld faying surface, and the radiograph for each weld type, as well as the weld strength and its acceptability. A curve can be drawn relating weld nugget size (measured by the dark ring A-A) to weld strength, from which the strength of production welds can be predicted from their radiographs. The reference table and curve should be placed where the inspector can refer to them while examining radiographs. (Fig. 74 shows such a table of data prepared from Taylor Winfield welds made at the Consolidated Vultee Aircraft Corporation of San Diego, and Fig. shows the correlation of weld strength to dark ring diameter for the welds.)

Inspection Rules

1. The weld should be rejected if the radiograph shows no image of the weld nugget.

The dark ring A-A outlining the nugget may be absent if there were no weld nugget, if the nugget were of dough-nut or crescent type with less than 10% to 20% penetration (usually possessing large Alclad inclusions), or if the radiograph were made with improper technique.

2. The weld should be rejected if the dark ring A-A outlining the weld nugget is too small in diameter to permit the required weld strength to be developed in the nugget.

Corona bonding outside the nugget should not be relied upon to provide weld strength, as poor surface preparation may result in no corona bonding. The nugget diameter required to maintain weld strength above minimum acceptable standards can be determined from the curve relating weld strength to dark ring diameter, for the given sheet thickness and alloy.

3. The weld should be rejected if excessive cracking or porosity occur in the nugget.

The limit of acceptable cracking and porosity must be established through experience, with due regard for the use for which the spotwelded structure is intended. Cracking is excessive when cracks extend to the sheet surface or the boundary of the nugget, or when they are such that they will extend to the sheet surface or beyond the nugget boundary under loading. Such extended cracks may introduce corrosion into the weld, or propagate under fatigue loading.

Cracking indicates excessive heat and inadequate electrode pressure during welding.

Limited dull porosity is probably not cause for rejection. Porosity sufficient to reduce appreciably the effective bonded area at the faying plane, will decrease weld strength and is cause for rejection. (See Weld 73, Fig. 73.)

4. The weld should be rejected if <u>nugget penetration is inadequate or excessive</u>.

Nugget penetration between 20% and 80% of the sheet thickness is usually considered acceptable.

Inadequate nugget penetration can be recognized if the dark ring A A is broad, faint, and of small diameter, fading into invisibility locally, through comparison with standard specimens with inadequate penetration. Inadequate penetration usually results in extensive Alclad inclusions into the weld nugget, with inconsistent, poor, or zero bonding.

Excessive nugget penetration can be recognized if the dark ring A A is unusually dense, of large diameter, and other evidenses of excessive heat, such as a prominent scalloped white ring C-C, are present - by comparison with standard specimens with excessive penetration. Excessive nugget penetration may be accompanied by reduced corrosion resistance or even breaking of the Alclad layer at the sheet surface, and is a definite cause of lowered sheet efficiency.

5. Depending upon quality standards and the use to be made of the spotwelded structure, the weld may be rejected if excessively large heat affected zones exist outside the weld nugget.

Excessively large heat affected zones are indicated by the presence of a prominent white scalloped ring C-C. Such zones weaken the welded joint under fatigue loading.

6. The weld may be rejected if excessive expulsion of metal ("spit") occurs at the faying plane.

A small, infrequent "spit" may occasionally occur under normal welding conditions due to an unusual local sheet surface condition. Such is not cause for rejection.

Expulsion of large amounts of metal, coupled with nugget porosity and blackening of the radiograph due to absence of metal, is cause for rejection, as such welds are usually weakened appreciably by expulsion.

7. If the weld is not subject to any of the listed causes for rejection, if it passes visual inspection, has a normal radiograph, acceptable penetration and shape, and if the

nugget diameter is sufficient to guarantee acceptable strength in the weld nugget, the weld should be accepted.

A normal weld radiograph shows clearly the nugget outline A-A, with width and density corresponding to acceptable nugget penetration, and shows no weld defects.

A nugget diameter sufficient to guarantee acceptable strength can be determined from the curve relating strength to dark ring diameter on standard specimens in the same sheet thickness and alloy.

8. The features of Zones D-D and E-E in the weld nugget, and the presence of light striations G-G (segregation) in the nugget, have as yet no proven significance in the interpretation of weld quality and strength from radiographs.

9. The frequent occurrance of misshapen welds, porosity, and spit may be taken as evidence of improper or inadequate sheet surface preparation for welding, or of bad tip conditions during welding.

10. The combination of very large nugget diameter, A-A, excessive penetration, cracking, and excessive segregation of eutectic in the parent metal is evidence of excessive current or energy (resulting in excessive heating) in the welding process.

11. The frequent occurrance of cracking and/or of porosity in the nugget, even in welds of normal size, is evidence of inadequate electrode pressure during welding, or delayed or

inadequate forging pressure.

12. In a structure containing acceptable and rejectable spotwelds, the use planned for the structure, the location and type as well as the number of defective welds, and the probable causes of the defects, must be considered in determining the acceptability of the welded structure.

Primary aircraft structures, whose failure would endanger personnel and the plane, should be welded to high standards. Secondary structures, whose failure is of little significance, do not merit the high cost of high quality welding and inspection.

Weld location is important. Failure of the end welds in a row of welds may lead to successive failure or "zippering" of the joint. On the other hand, a weak weld in the center of a large area containing hundreds of normal welds might do no harm, since usual practice is to include many more spotwelds than required by the anticipated loads.

A few defective welds among many normal welds may be harmless; but a few defective welds in a group of borderline acceptable welds might be dangerous.

The type of weld defect may be important as a result of location or of type of loading, and should be evaluated with these factors in mind.

Defective welds resulting from bad welding practice, improper sheet surface preparation, carelessness, or easily remedied causes should not be accepted. Defects which occur under optimum process control and welding conditions due to small and uncontrollable factors may be tolerated when no possible damage can result to the structure.

VII RESULTS OF TESTS ON INDUSTRIAL SPOTWELDS.

A large number of industrially made spotwelds from Southern California aircraft factories were radiographed, subjected to penetrator and ring electrode tests, and pulled to destruction as single spot static shear test strips. The welds were then sectioned, polished and etched to determine metallurgical structure and weld geometry. The radiographs and the welds were carefully inspected and measured, and the correlation between radiographic features and weld properties were determined.

The results of tests of three typical groups of industrial welds:

1. 166 Federal Spotwelds Made By The Vega Aircraft Corporation of Burbank, California.
2. 100 Taylor Winfield Spotwelds Made By Northrop Aircraft, Inc. of Hawthorne, California.
3. 138 Taylor Windfield Spotwelds Made By The Consolidated Vultee Aircraft Corporation of San Diego

and one group of laboratory welds.

4. 326 Taylor Winfield Spotwelds Made At the University of Southern California.,

are now presented in the form of graphs, photographs, and tables of data.

For each group of welds, there appear in succession:

Table I--Data On Conditions of Welding

Fig. 1. Contact Reproductions of Radiographs of Typical Weld Specimens.

Fig. 2. Correlation Between Static Shear Strength and Net Weld Nugget Area at Faying Plane (measured on Welds)

Fig. 3. Prediction of New Weld Nugget Area at the faying plane by Ring Penetrator Test.

Fig. 4. Prediction of Static Shear Strength by Ring Penetrator Test.

Fig. 5. Prediction of Net Weld Nugget Area at the faying plane by Electrical Test.

Fig. 6. Prediction of Static Shear Strength by Electrical Test.

Fig. 7. Prediction of Net Weld Nugget Area by Radiographic Dark Ring.

Fig. 8. Prediction of Static Shear Strength by Radiographic Dark Ring.

Fig. 9. Comparison of Accuracy of Static Shear Strength Measurements by Different Non-Destructive Tests.

Table II--Comparison of Accuracy of Measurement of Spotweld Static Shear Strength By Weld Nugget Diameter and By Non-Destructive Tests.

Table III--Detail of Radiographic Indications.

A. Results of Tests on 166 Federal Spotwelds Made By The Vega Aircraft Corporation of Burbank, California. .040" 24ST Alclad Aluminum Alloy Sheet.

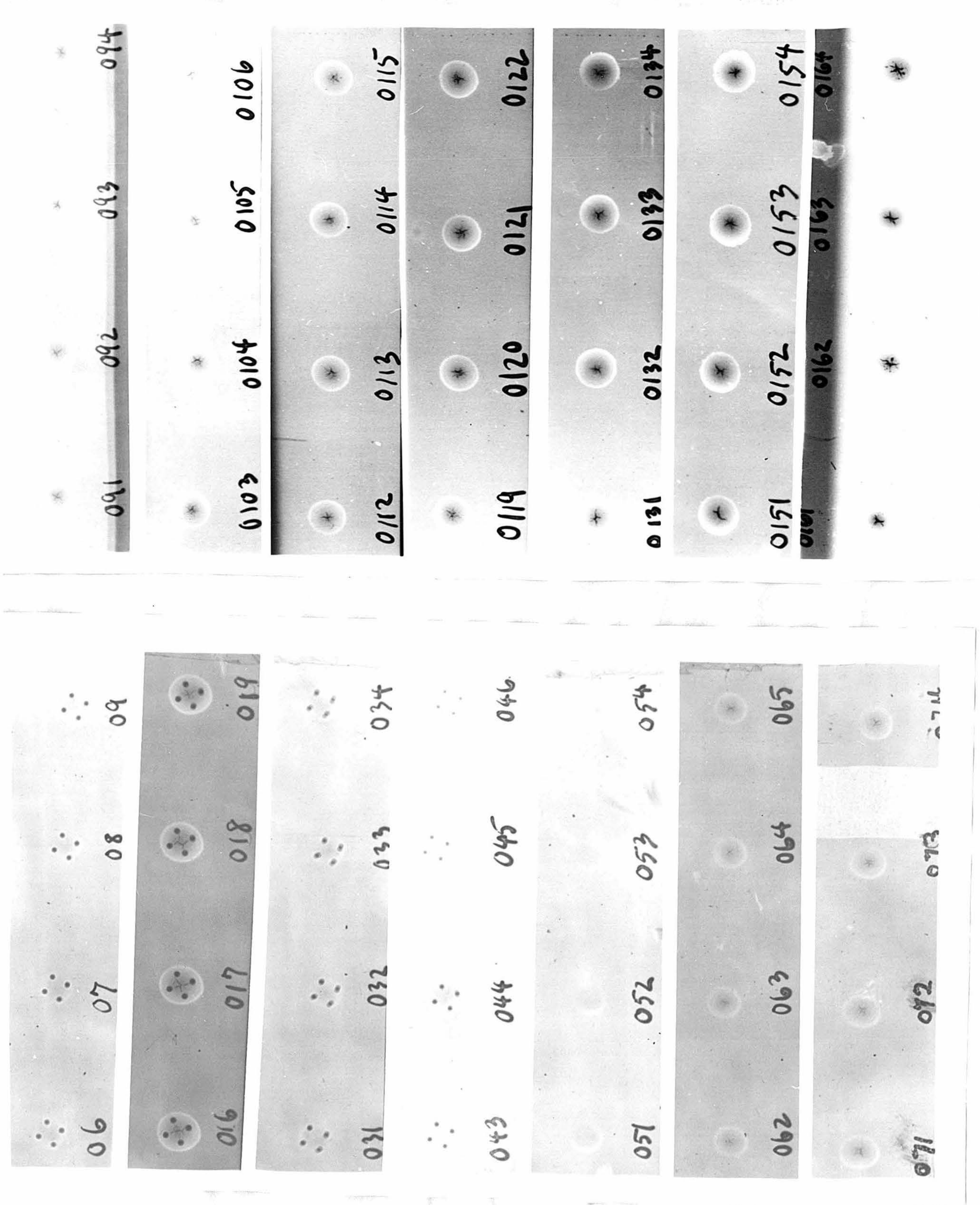
TABLE I

SPECIMEN DATA FOR SPOTWELD SPECIMENS MADE AUGUST 20, 1943 FOR CALIFORNIA INSTITUTE OF TECHNOLOGY

MATERIAL: .040 to .040 24ST Alclad
MACHINE : Federal Type P2-36-RPR-Serial 8919 Condenser Discharge
CLEANING: Oakite #84-A Time-12 minutes
MACHINE SETTINGS:

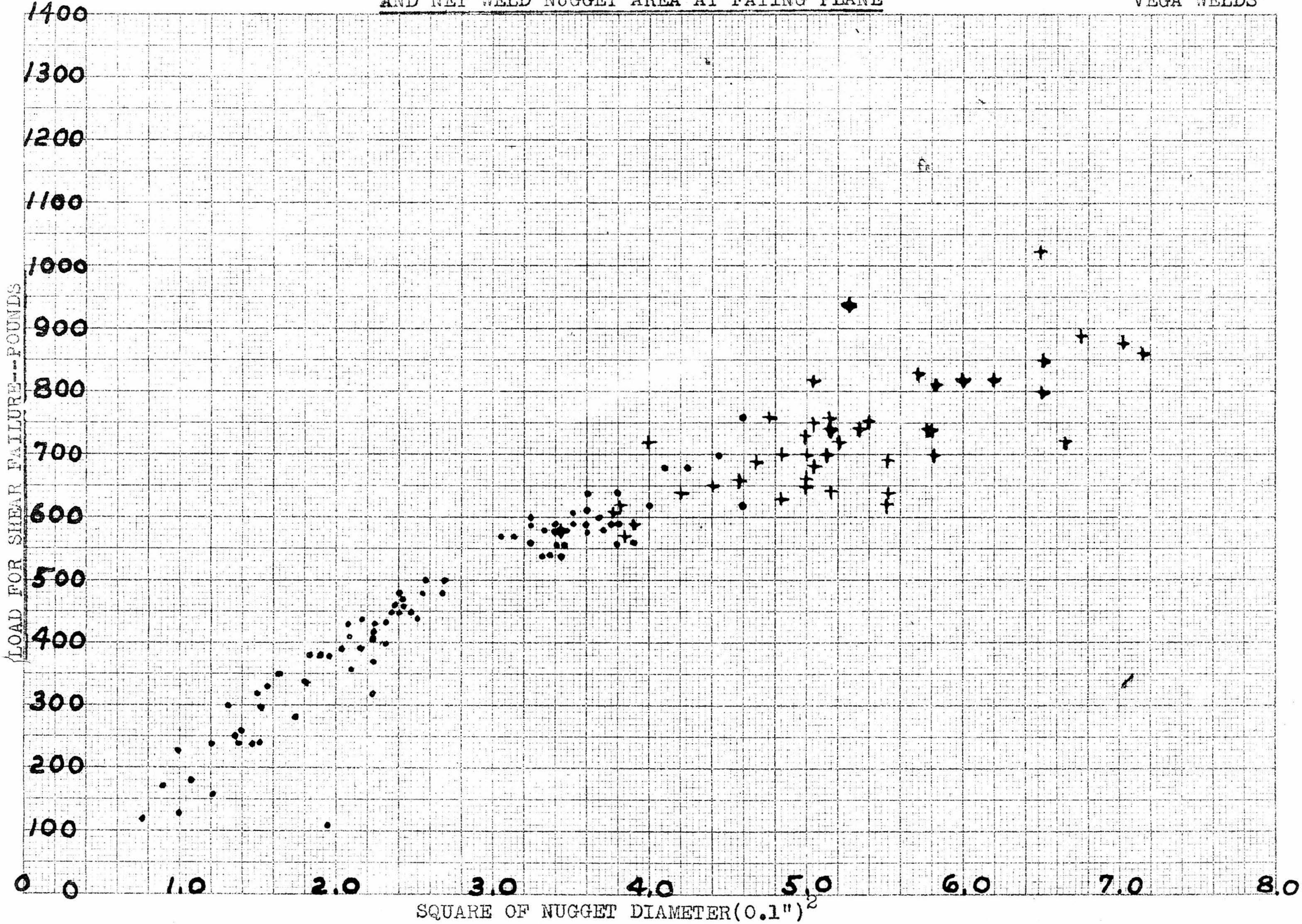
Welds No.	Spec.No.	Kilovolts	Condenser M.F.D.	Weld Press.	Forge Press.	Electrode Press.	Electrode Bottom	Approx. Shear Lb.
01-12	1	1.84	800	450	1400	5/16"D2"12	½"Flat	175
013-22	2	2.80	1000	"	"	"	"	795
023-34	3	1.86	800	"	"	"	"	229
035-46	4	1.97	800	"	"	"	"	275
047-58	5	2.05	800	"	"	"	"	320
059-70	6	2.20	800	"	"	"	"	375
071-82	7	2.30	800	"	"	"	"	425
083-94	8	2.48	800	"	"	"	"	480
095-106	9	2.50	800	"	"	"	"	495
0107-118	10	2.54	800	"	"	"	"	580
0119-130	11	2.65	800	"	"	"	"	615
0131-142	12	2.75	800	"	"	"	"	689
0143-154	13	2.80	800	"	"	"	"	725
0155-166	14	2.78	1000	"	"	"	"	740

Figure 1. Contact Radiographs of Vega Welds.



PROJECT 43
GROUP O
VEGA WELDS

FIGURE 2 -CORRELATION BETWEEN STATIC SHEAR STRENGTH AND NET WELD NUGGET AREA AT FAYING PLANE



PROJECT 43
GROUP 0
VEGA WELDS

FIGURE 3--PREDICTION OF NET WELD NUGGET AREA AT THE FAYING PLANE BY RING PENETRATOR TEST

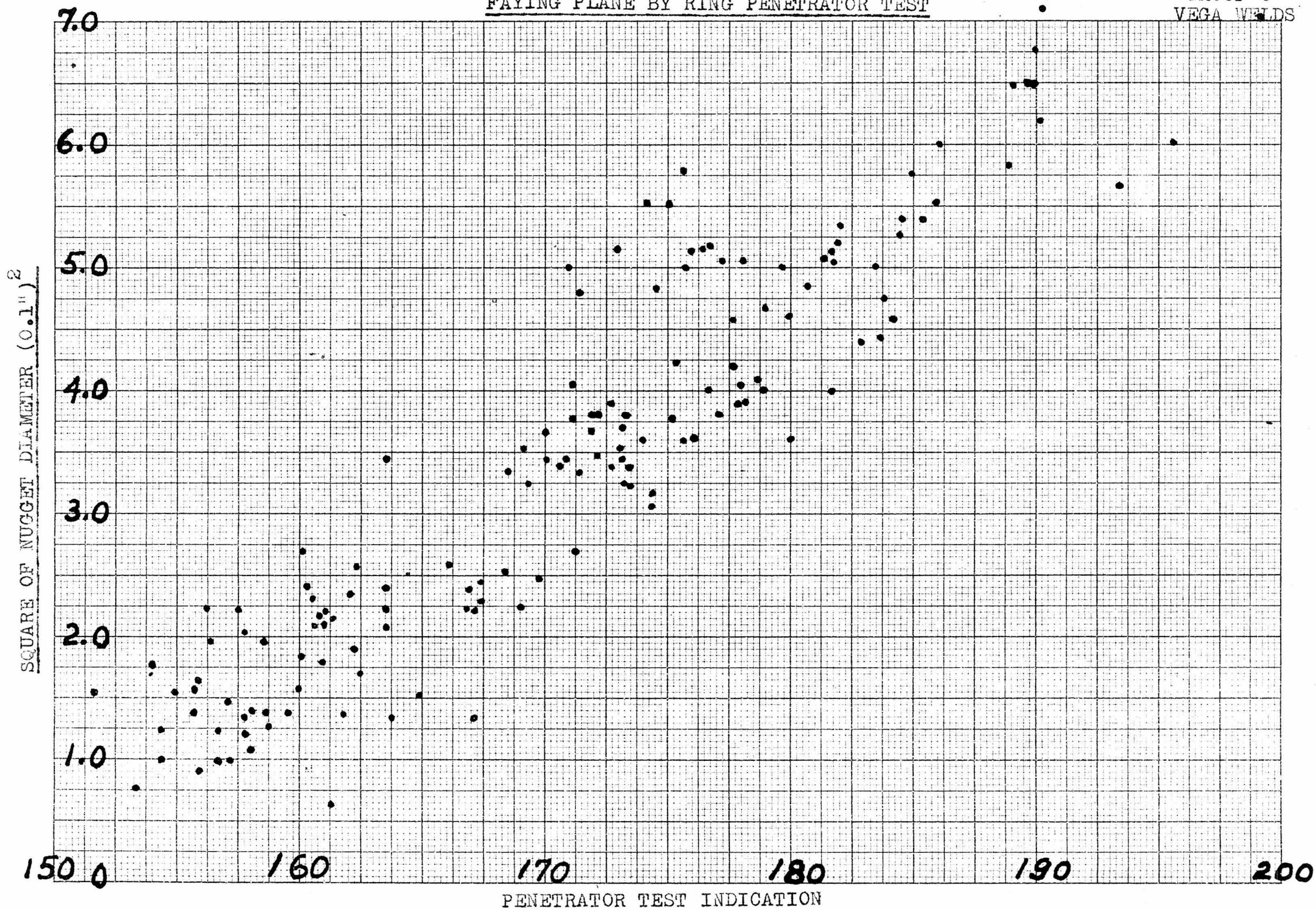


FIGURE 4-PREDICTION OF STATIC SHEAR STRENGTH
BY RING PENETRATOR TEST

PROJECT 43
GROUP O
VEGA WELDS

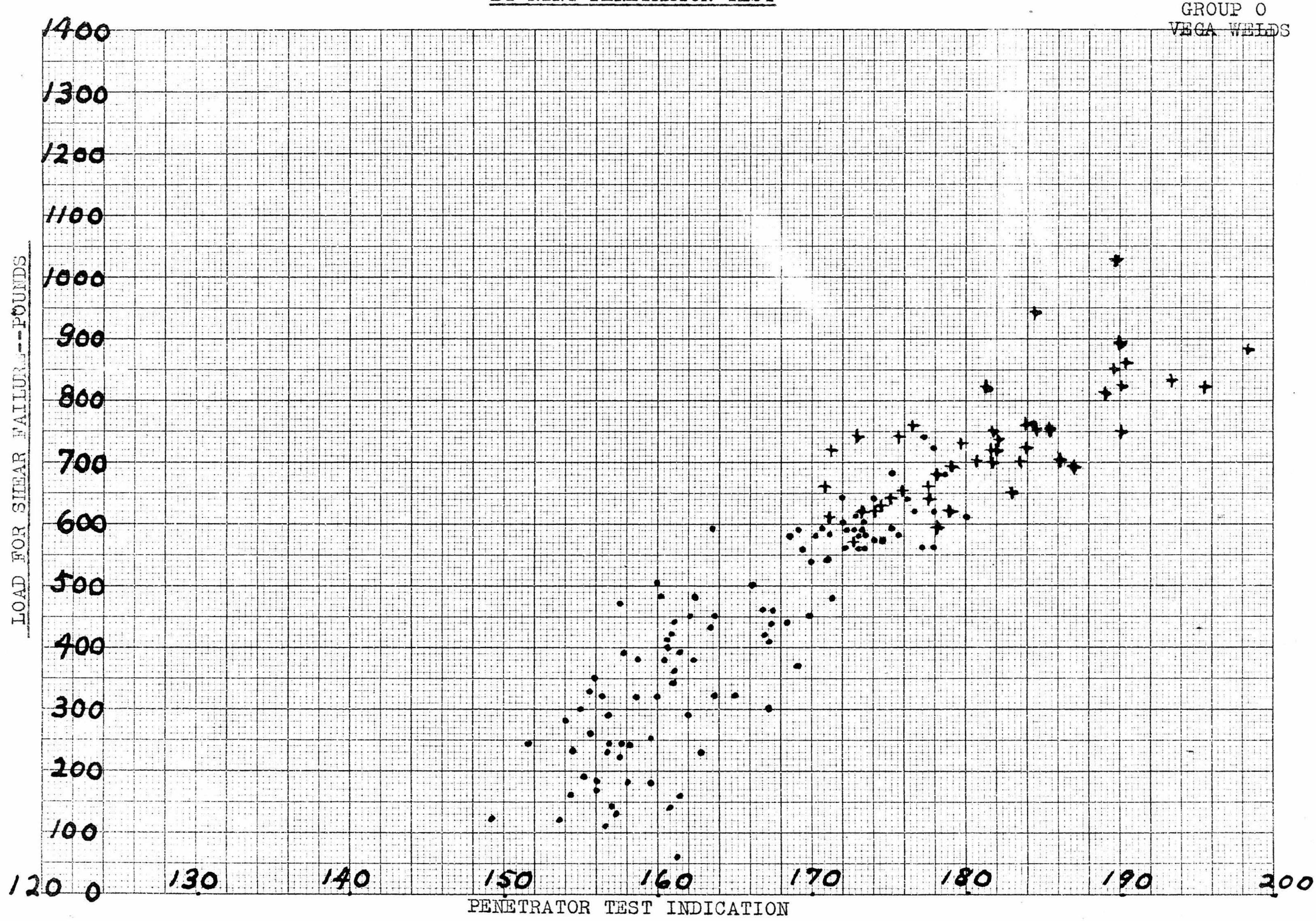
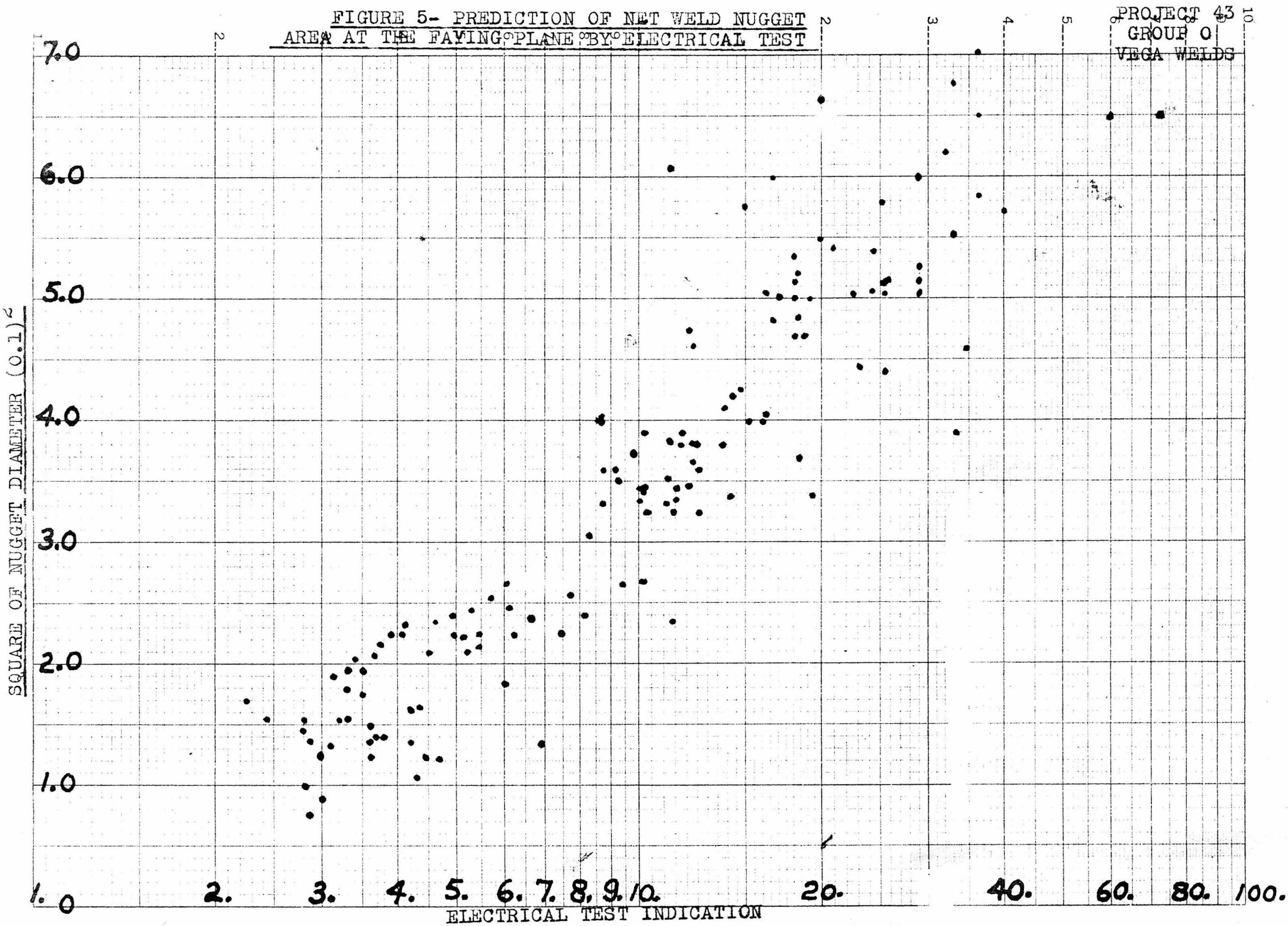


FIGURE 5- PREDICTION OF NET WELD NUGGET AREA AT THE FAYING PLANE BY ELECTRICAL TEST



PROJECT 43
GROUP O
VEGA WELDS

FIGURE 6--PREDICTION OF STATIC SHEAR STRENGTH BY ELECTRICAL TEST

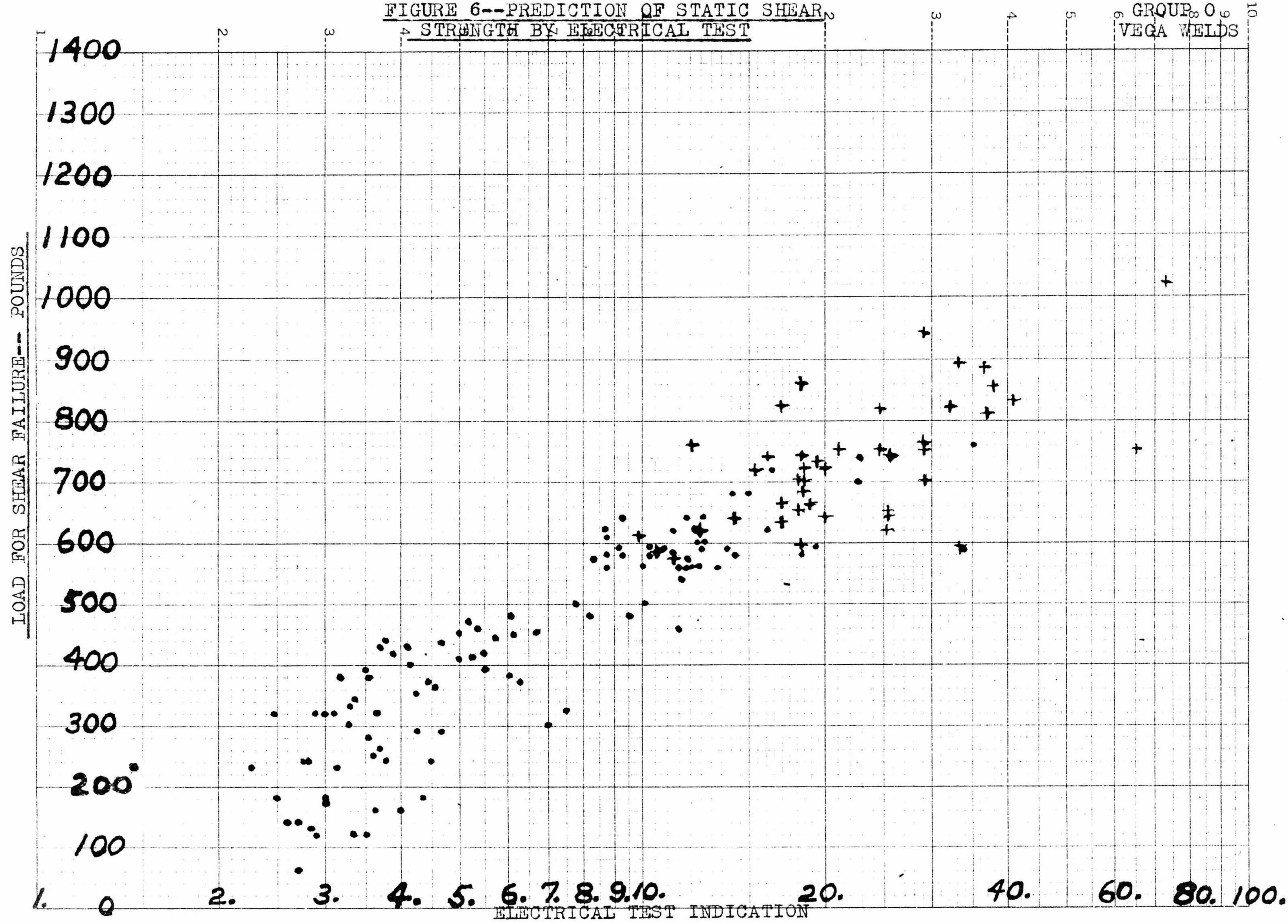


TABLE II

Comparison of Accuracy of Measurement of Spotweld Static Shear Strength by Weld Nugget Diameter and by Non-destructive Tests.

Test Method	Error in Prediction		
	Median Error	Maximum Error For 90% Welds	Maximum Error For 100% of Welds
Weld Nugget Diameter	25 Pounds	65 Pounds	205 Pounds
Ring Penetrator Test	55 Pounds	145 Pounds	255 Pounds
Electrical Test	55 Pounds	145 Pounds	305 Pounds
Radiographic Dark Ring	25 Pounds	75 Pounds	185 Pounds

TABLE III

RADIOGRAPHIC INDICATIONS

Weld No.	Actual Strength	Predicted Strength	Acceptable Penetration and Normal Size	Low Penetration or Undersize	High Penetration and Oversize	Defects: Cracks	Spit	Porosity	Misshapen	Other	Accepted	Rejected
1	230	-		x								
2	370	-		x								
3	320	-		x								
4	320	-		x								
5	290	-		x								
6	230	-		x								
7	180	-		x								
8	220	-		x								
9	290	-		x								
10	-	-		x								
11	320	-		x								
12	320	-		x								
13	650	838			x	x						
14	640	795			x	x						
15	740	758			x	x						
16	620	810			x	x						
17	720	765			x	x						
18	660	730			x	x						
19	640	783			x	x						
20	-	740			x	x						
21	740	740			x	x						
22	820	812			x	x						
23	330	-		x								
24	180	-		x								
25	140	-		x								
26	180	-		x								
27	60	-		x								
28	170	-		x								
29	160	-		x								
30	-	-		x								
31	320	-		x								
32	300	-		x								
33	240	-		x								
34	340	-		x								
35	280	-		x								
36	250	-		x								
37	230	-		x								
38	160	-		x								
39	110	-		x								
40	-	-		x								
41	260	-		x								
42	240	-		x								
43	350	-		x								
44	130	-		x								
45	240	-		x								
46	140	-		x								

RADIOGRAPHIC INDICATIONS

Defects

Weld No.	Actual Strength	Predicted Strength	Acceptable Penetration and Normal Size	Low Penetration or Undersize	High Penetration and Oversize	Cracks	Spit	Porosity	Misshapen	Other	Accepted	Rejected
148	650	690			x	x						
149	630	715			x	x						
150	-	730			x	x						
151	680	730			x	x						
152	740	758			x	x						
153	820	768			x	x						
154	740	730			x	x						
155	820	740			x	x	x					
156	810	800			x	x	x					
157	890	825			x	x						
158	830	800			x	x	x					
159	940	783			x	x	x					
160	-	730			x	x	x					
161	850	810			x	x	x					
162	860	825			x	x						
163	750	865			x	x	x					
164	700	740			x	x	x					
165	1020	945			x	x						
166	880	927			x	x	x					

Note: Where no Actual Strength is given, the specimen was sectioned.
Where no Predicted Strength is given, no dark ring was visible.

B. Results of Tests on 100 Taylor-Winfield Spotwelds Made By the Northrop Aircraft Corporation of Hawthorne California In .040" 24ST Alclad Aluminum Alloy Sheet.

TABLE I

Specimen data for spotweld specimens made July 13, 1943 for California Institute of Technology.

Material	:	.040 to .040 24ST Alc.	
Machine	:	Taylor-Winfield	
Electrode Weld Pressure	:	980 lbs.	
Electrode Forge Press	:	1500 lbs.	(Constant)
Capacitance	:	600 Mfd.	(Constant)
Voltage	:		(Variable)
Radius top elec.	:	4"	(Constant)
Radius bottom elec.	:	10"	(Constant)

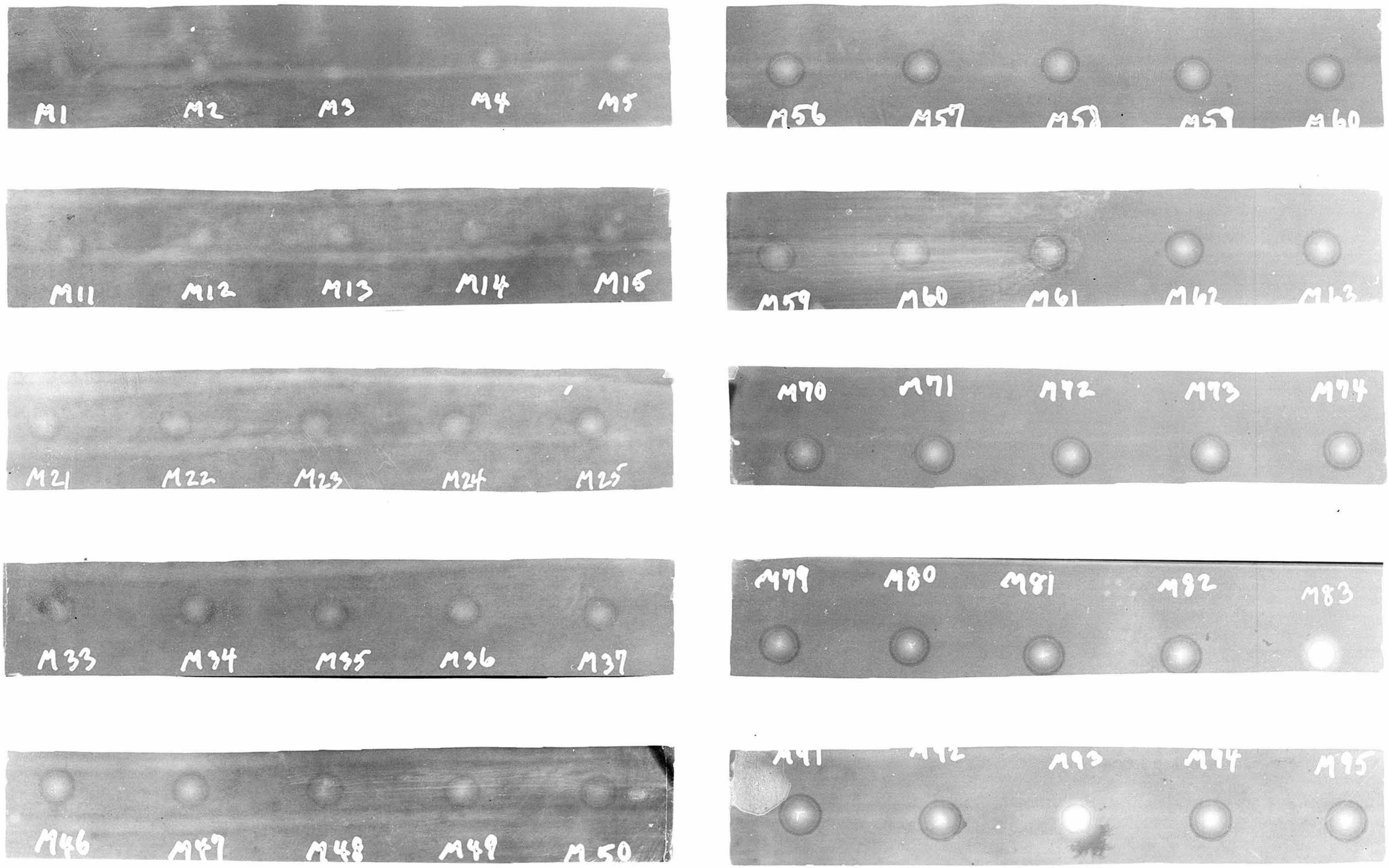
Material cleaned in Eelite for 16 minutes

Welds No.	D.C. Voltage
M1-10	1875
M11-20	1975
M21-30	2150
M 31-40	2275
M 41-50	2420
M 51-60	2550
M 61-70	2660
M 71-80	2790
M 81-90	2900
M 91-100	3000

TABLE II

Comparison of Accuracy of Measurement of Spotweld Static Shear Strength by Weld Nugget Diameter and by Non-destructive Tests.

	Error in Prediction		
Test Method	Median Error	Maximum Error For 90% Welds	For 100% of welds
Weld Nugget Diameter	25 Pounds	75 Pounds	160 Pounds
Ring Penetrator Test	35 Pounds	75 Pounds	230 Pounds
Electrical Test	25 Pounds	75 Pounds	130 Pounds
Radiographic Dark Ring	35 Pounds	85 Pounds	125 Pounds



CONTACT REPRODUCTIONS OF RADIOGRAPHSOF TYPICAL WELDS IN THIS GROUP

PROJECT 41
GROUP M
NORTHRUP WELDS

FIGURE 2 - CORRELATION BETWEEN STATIC SHEAR STRENGTH AND NET WELD NUGGET AREA AT FAYING PLANE

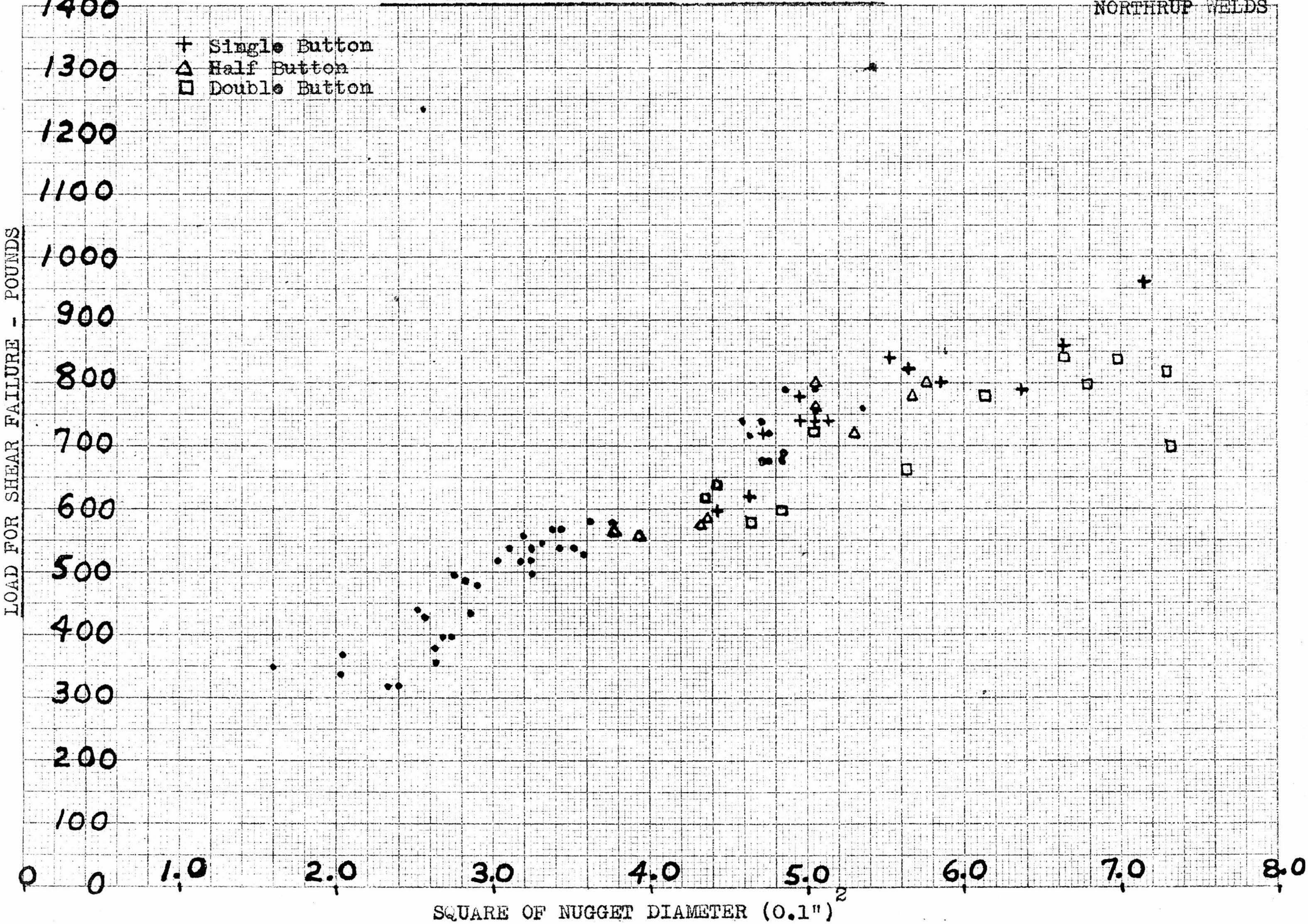
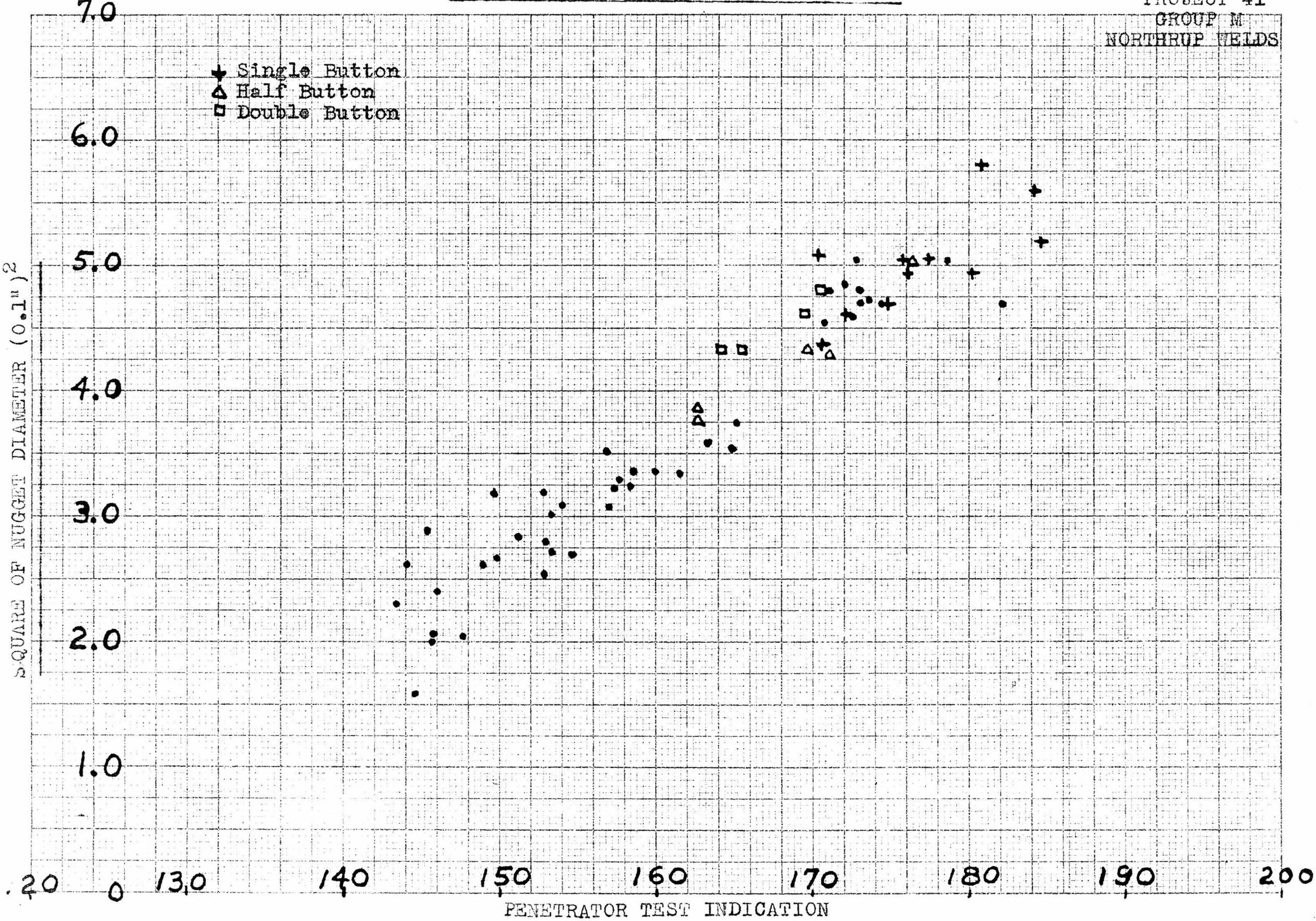


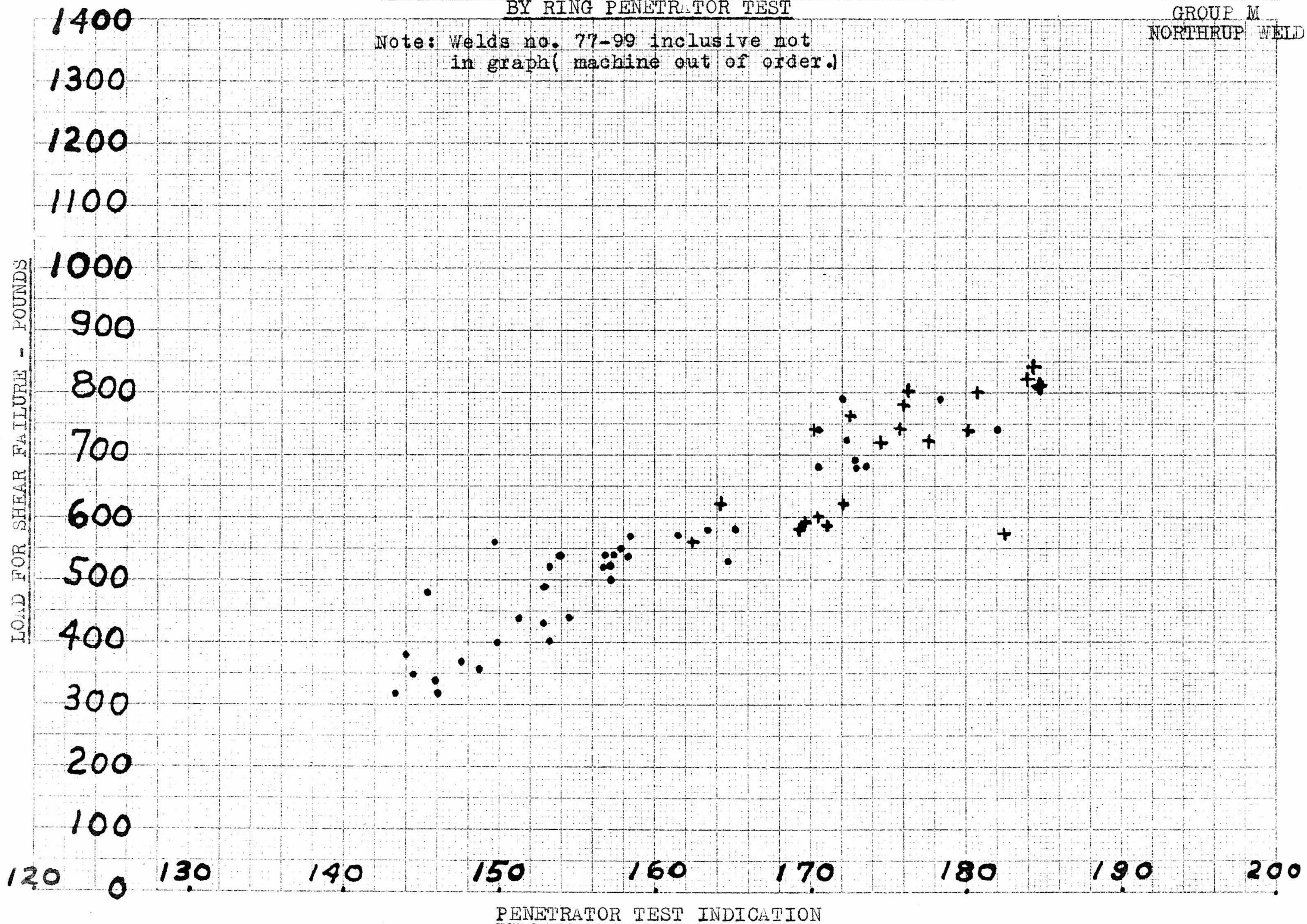
FIGURE 3 - PREDICTIONOF NET WELD NUGGET "AREA" AT THE FAYING PLANE BY RING PENETRATOR TEST



PROJECT 41
GROUP M
NORTHRUP WELDS

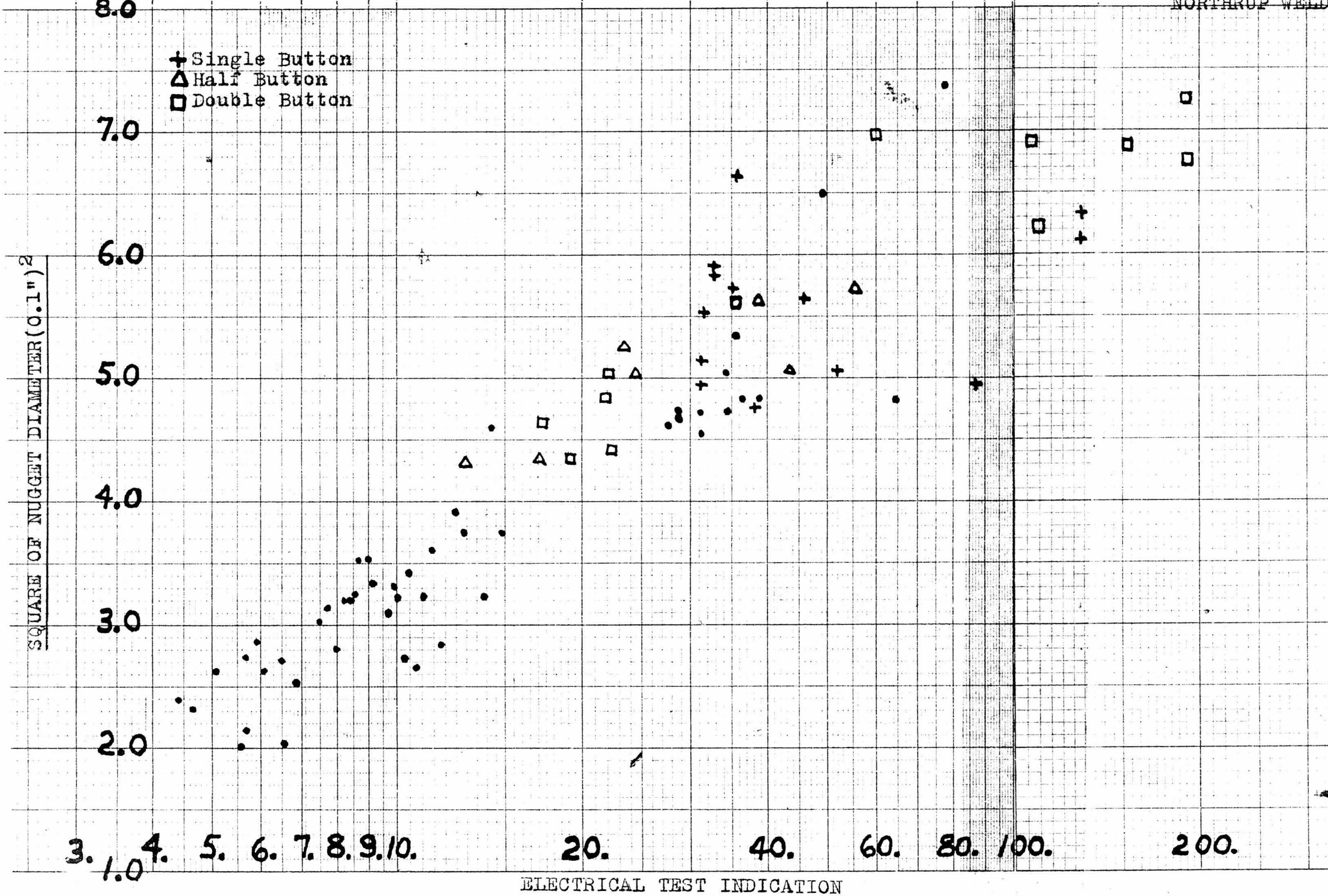
FIGURE 4 - PREDICTION OF STATIC SHEAR STRENGTH BY RING PENETRATOR TEST

Note: Welds no. 77-99 inclusive mot in graph(machine out of order.)



PROJECT 41
GROUP M$_\omega$
NORTHRUP WELD

FIGURE 5- PREDICTION OF NET WELD NUGGET AREA AT THE FAYING PLANE BY ELECTRICAL TEST



PROJECT 41
GROUP M -
NORTHRUP WELDS

FIGURE 6 -PREDICTION OF STATIC SHEAR STRENGTH BY ELECTRICAL TEST

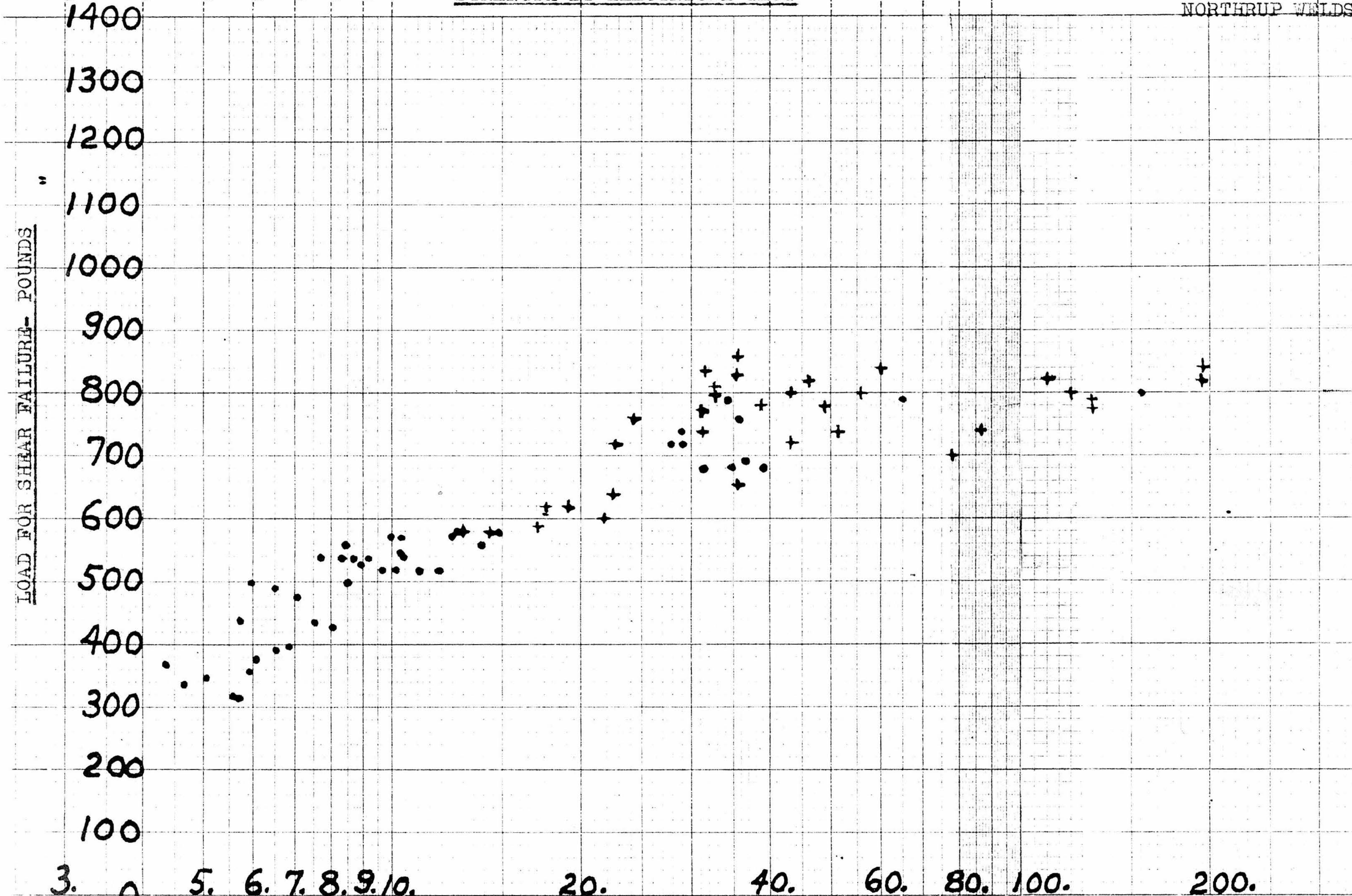
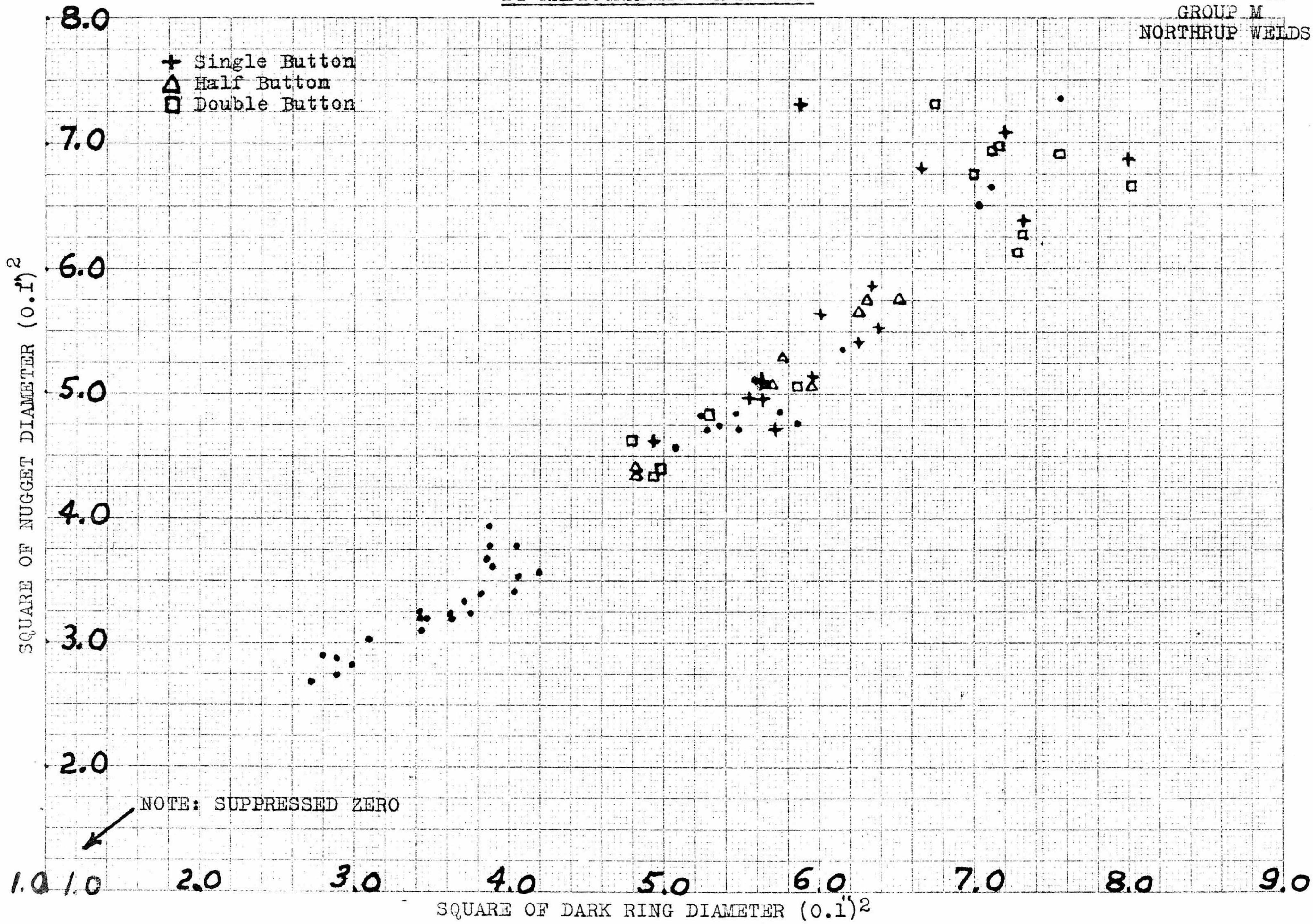


FIGURE 7-PREDICTION OF NET WELD NUGGET AREA
BY RADIOGRAPHIC DARK RING

PROJECT 41
GROUP M
NORTHRUP WELDS



PROJECT 41
GROUP M
NORTHRUP WELDS

FIGURE 8- PREDICTION OF STATIC SHEAR STRENGTH BY RADIOGRAPHIC DARK RING.

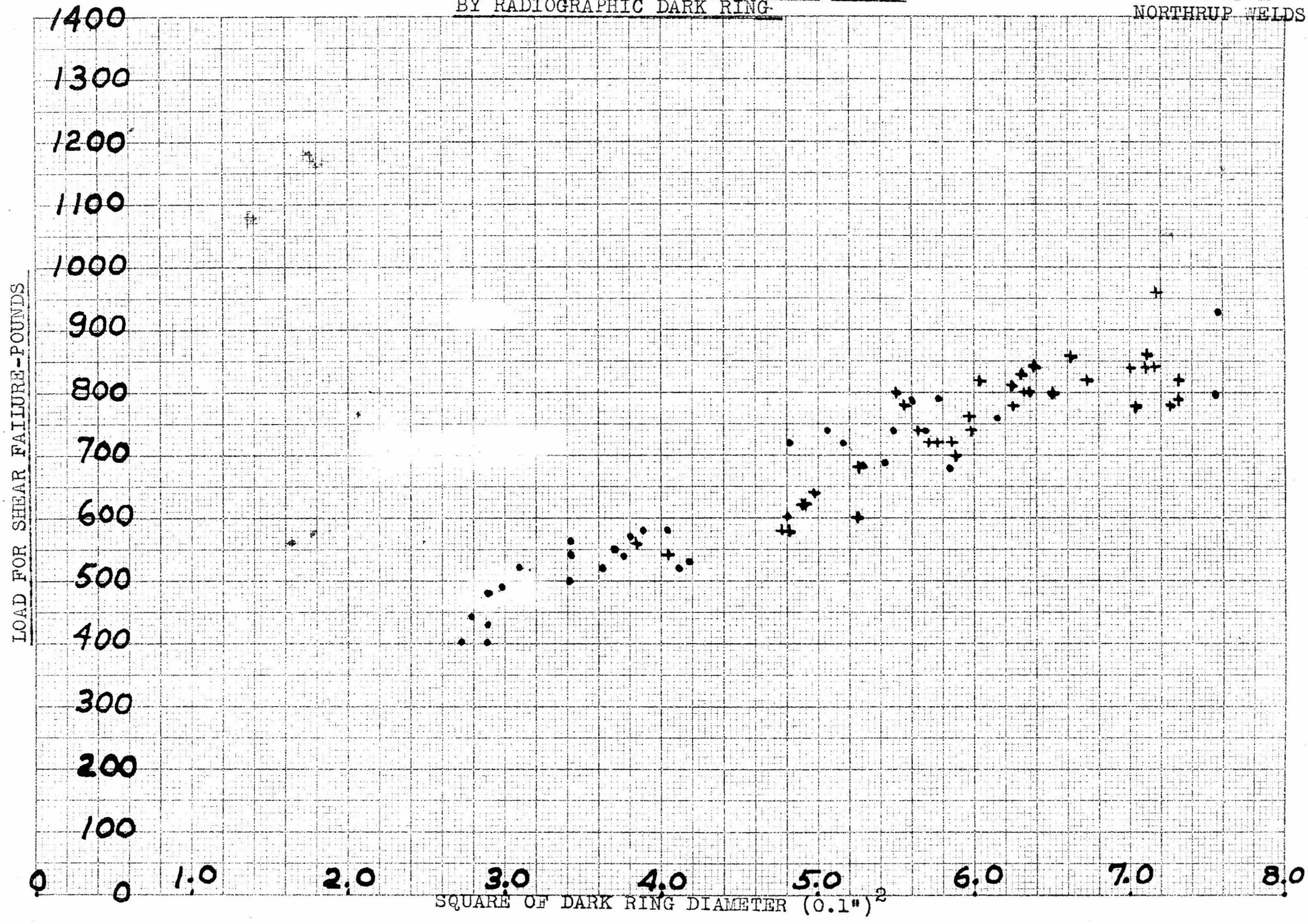


FIGURE 9 - COMPARISON OF ACCURACY OF STATIC SHEAR STRENGTH MEASUREMENTS BY DIFFERENT NON-DESTRUCTIVE TESTS

PROJECT 41
GROUP M
NORTHRUP WELDS

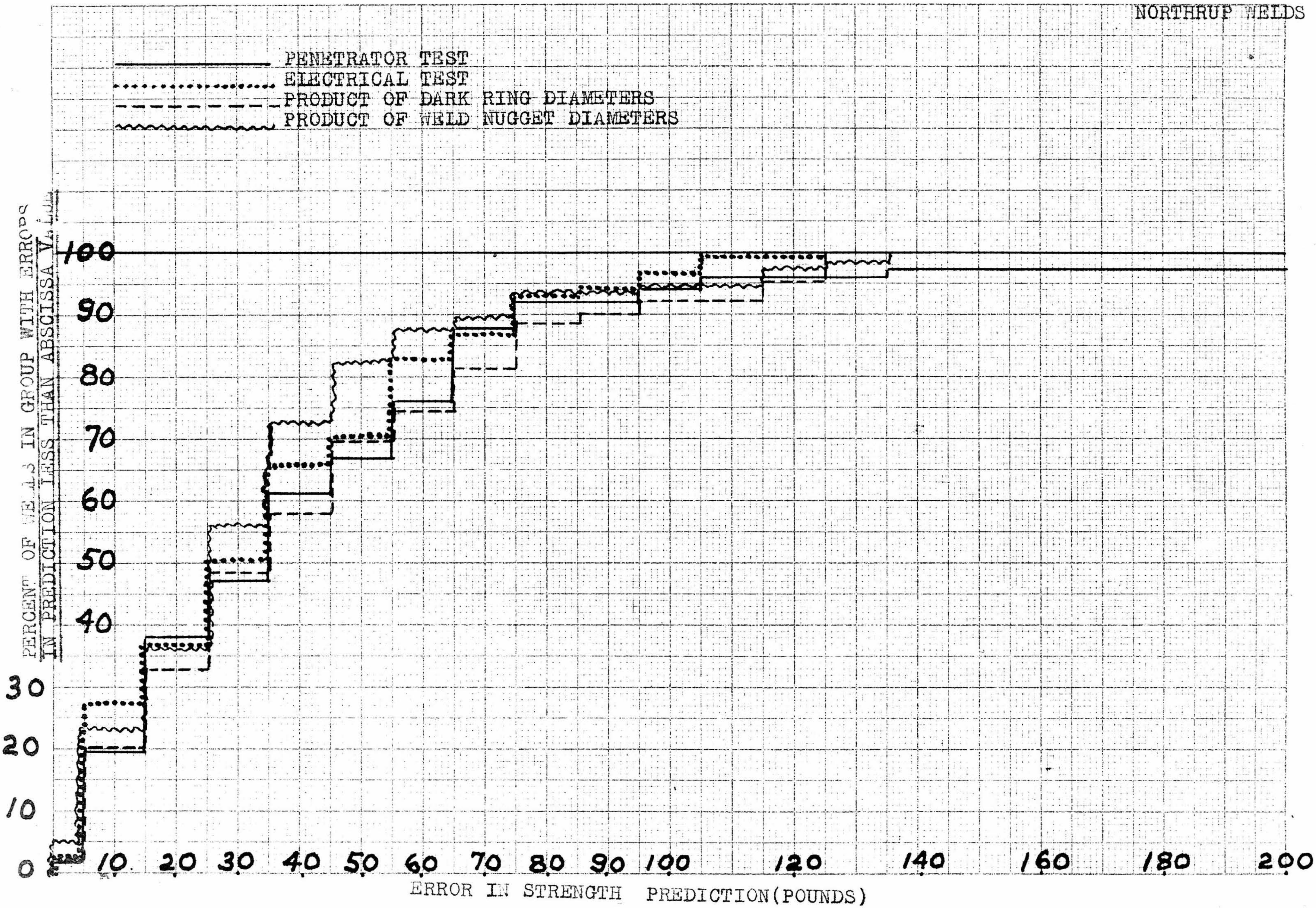


TABLE III
Radiographic Indications

Weld No.	Actual Strength	Predict Strength	Acceptable Penetration and Normal Size	Low Penetration or Under Size	High Penetration and Oversize	Defects						
						Cracks	Spit	Porosity	Misshapen	Other	Accepted	Rejected
1	-	-		x								
2	360	-		x								
3	380	-		x								
4	350	-		x								
5	-	-		x								
6	-	-		x								
7	320	-		x								
8	340	-		x								
9	320	-		x								
10	370	-		x								
11	400	470		x								
12	490	430		x								
13	430	470		x								
14	400	450		x								
15	-	-		x								
16	430	470		x								
17	500	-		x								
18	440	460		x								
19	520	490		x								
20	440	-		x								
21	550	550		x								
22	570	560		x								
23	540	555		x								
24	520	540		x								
25	-	525		x								
26	560	520		x								
27	540	520		x								
28	520	544		x								
29	540	520		x								
30	500	520		x								
31	560	565	x									
32	570	565	x									
33	580	580	x									
34	580	665	x									
35	-	595	x									
36	520	590	x									
37	530	597	x									
38	540	580	x									
39	570	568	x									
40	540	535	x									
41	620	670	x									
42	590	660	x									
43	600	700	x									
44	580	660	x									
45	-	673	x									
46	640	673	x									
47	620	670	x									
48	600	660	x									

Radiographic Indications Cont.

Weld No.	Actual Strength	Predict. Strength	Acceptable Penetration and Normal Size	Low Penetration or Under-Size	High Penetration and Over-size	Defects: Cracks	Spit	Porosity	Misshapen	Other	Accepted	Rejected
49	580	660	x									
50	-	682	x									
51	-	742	x									
52	680	760	x									
53	740	725	x				x					
54	680	702	x									
55	-	670	x									
56	690	720	x									
57	680	702	x									
58	740	682	x									
59	720	690	x									
60	720	660	x									
61	740	738	x									
62	790	750	x									
63	800	725	x									
64	780	730	x									
65	-	725	x									
66	740	770	x									
67	760	770	x									
68	720	747	x									
69	740	738	x									
70	790	735	x									
71	820	775	x									
72	800	808				xx						
73	840	812			x	x						
74	810	800			x	x						
75	-	825	x		x	x						
76	720	763				xx						
77	860	838			x	x						
78	780	800				xx						
79	800	825			x	x						
80	830	805			x	x						
81	840	880			x	x						
82	840	870			x	x						
83	660	-	x			xx						
84	780	872			x	x						
85	-	885			x	x						
86	790	900			x	x						
87	780	898			x	x						
88	820	845			x	x						
89	850	900			x	x						
90	840	885			x	x						
91	800	922			x	x						
92	840	970			x	x						
93	760	790	x		x	x						
94	860	880				xx						
95	-	922			x	x						
96	700	763	x		x	x						
97	720	752	x			xxx						
98	960	835				xx						
99	930	967			x	x						
100	-	922			x	x						
					x	x						

C. Results of Tests on 138 Taylor Winfield Spotwelds Made By the Consolidated Vultee Aircraft Corporation of San Diego in .040" 24ST Alclad Aluminum Alloy Sheet.

Note: Macrographs of Sections of unpulled welds in this group were given in Figure 56. Enlargements of radiographs of typical welds in this group were given in Fig. 74. The electrical test was omitted, for these welds.

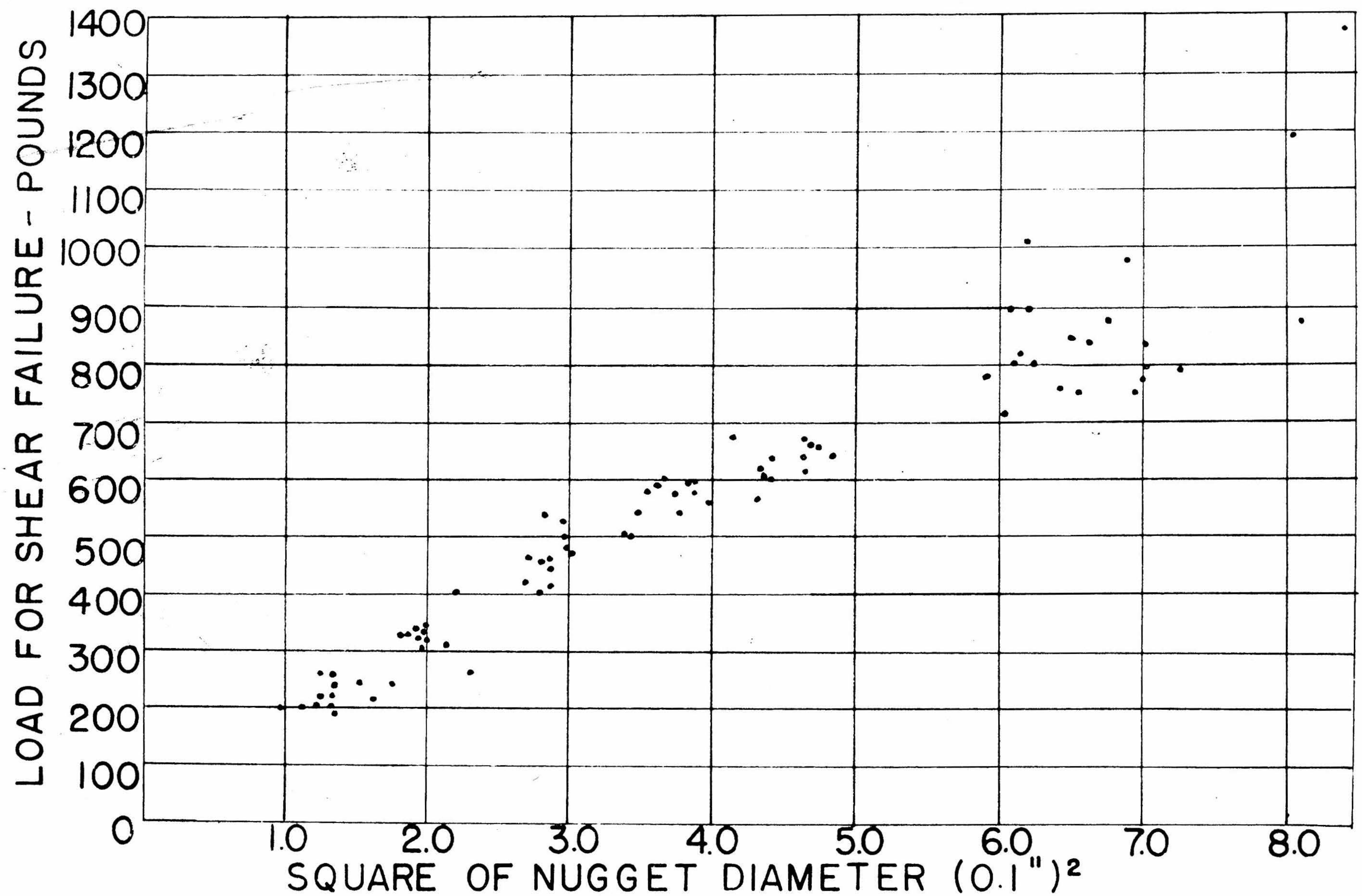


FIG. 4. CORRELATION BETWEEN STATIC SHEAR STRENGTH AND WELD NUGGET AREA AT FAYING PLANE.

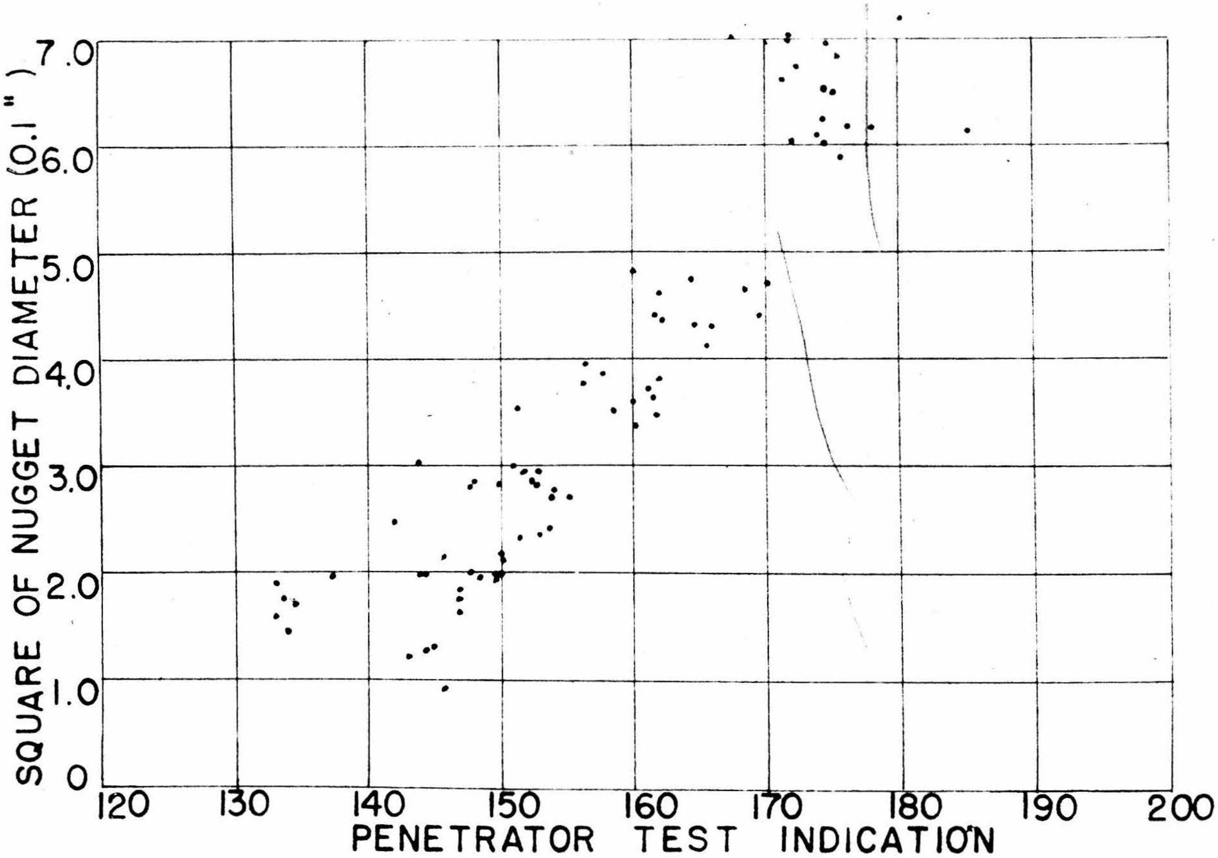


FIG. 5. PREDICTION OF WELD NUGGET AREA
BY RING PENETRATOR TEST.

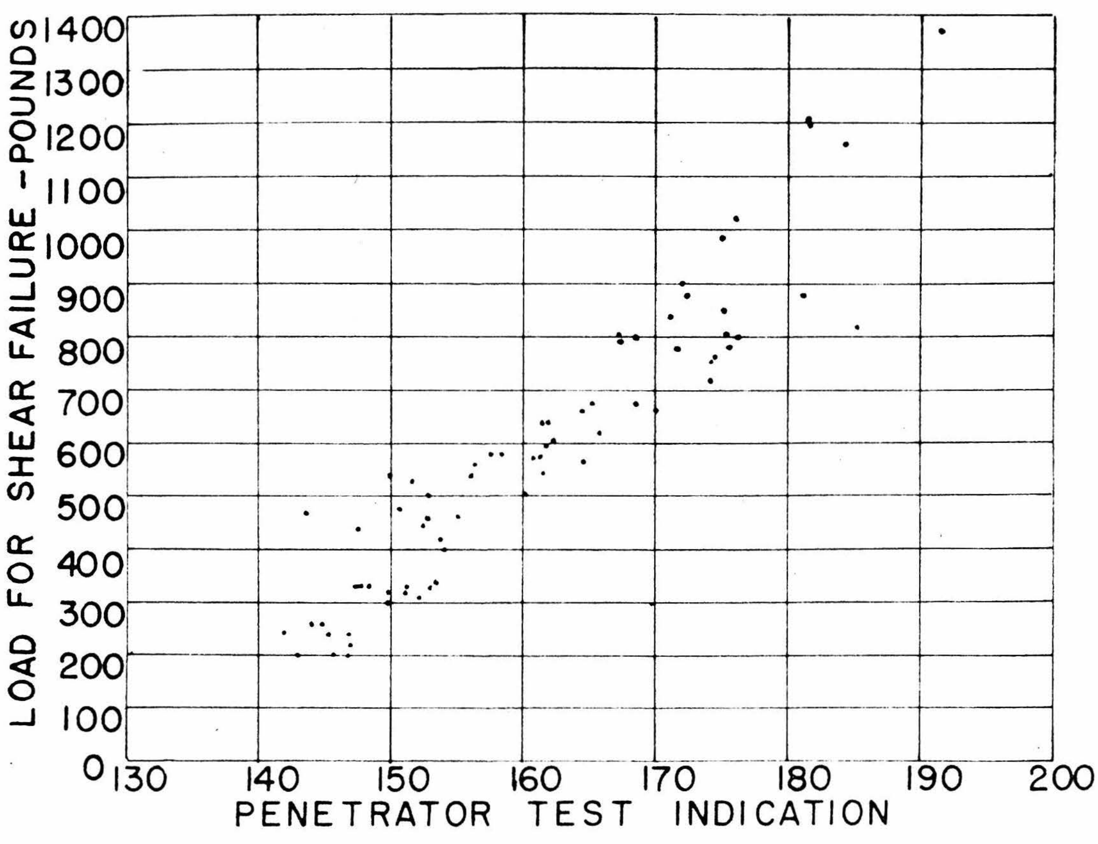


FIG. 6. PREDICTION OF STATIC SHEAR
STRENGTH BY RING PENETRATOR TEST.

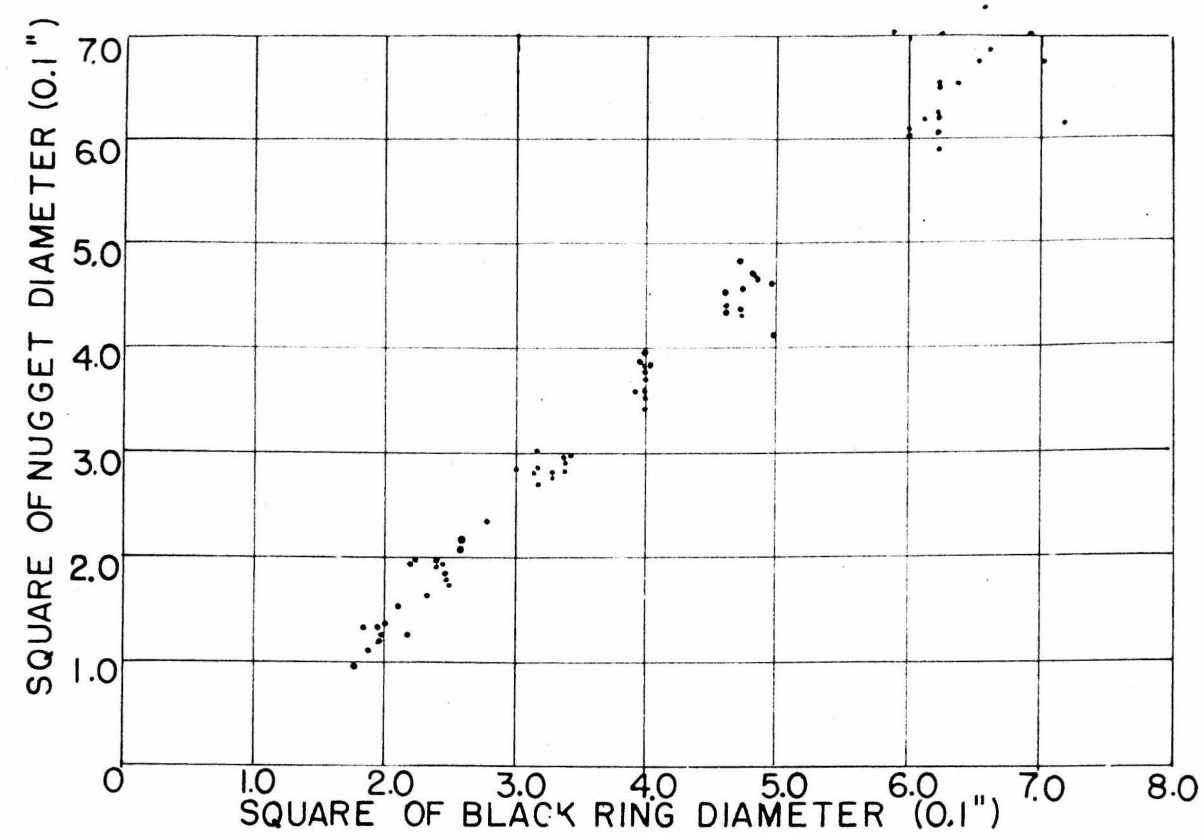


FIG. 7. PREDICTION OF WELD NUGGET DIAMETER BY RADIOGRAPHIC DARK RING.

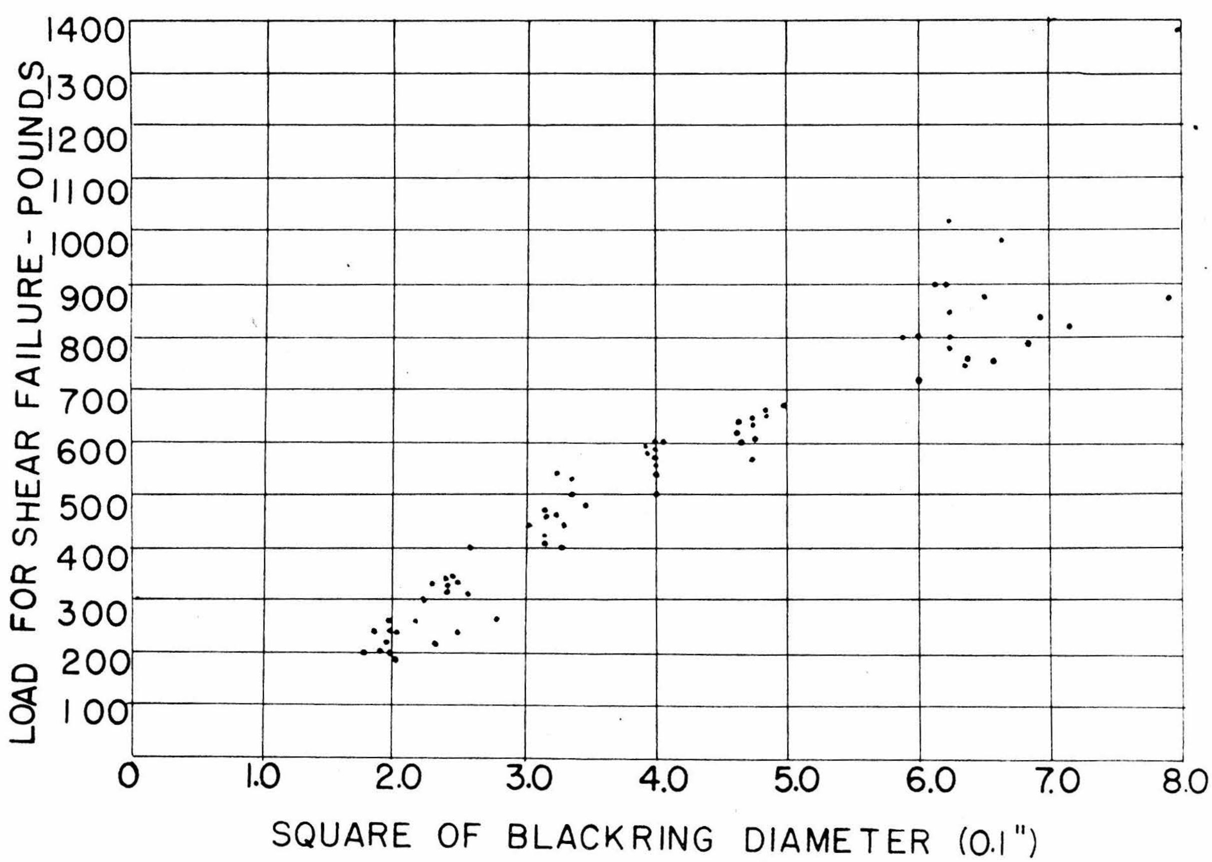


FIG. 8. PREDICTION OF STATIC SHEAR STRENGTH BY RADIOGRAPHIC DARK RING.

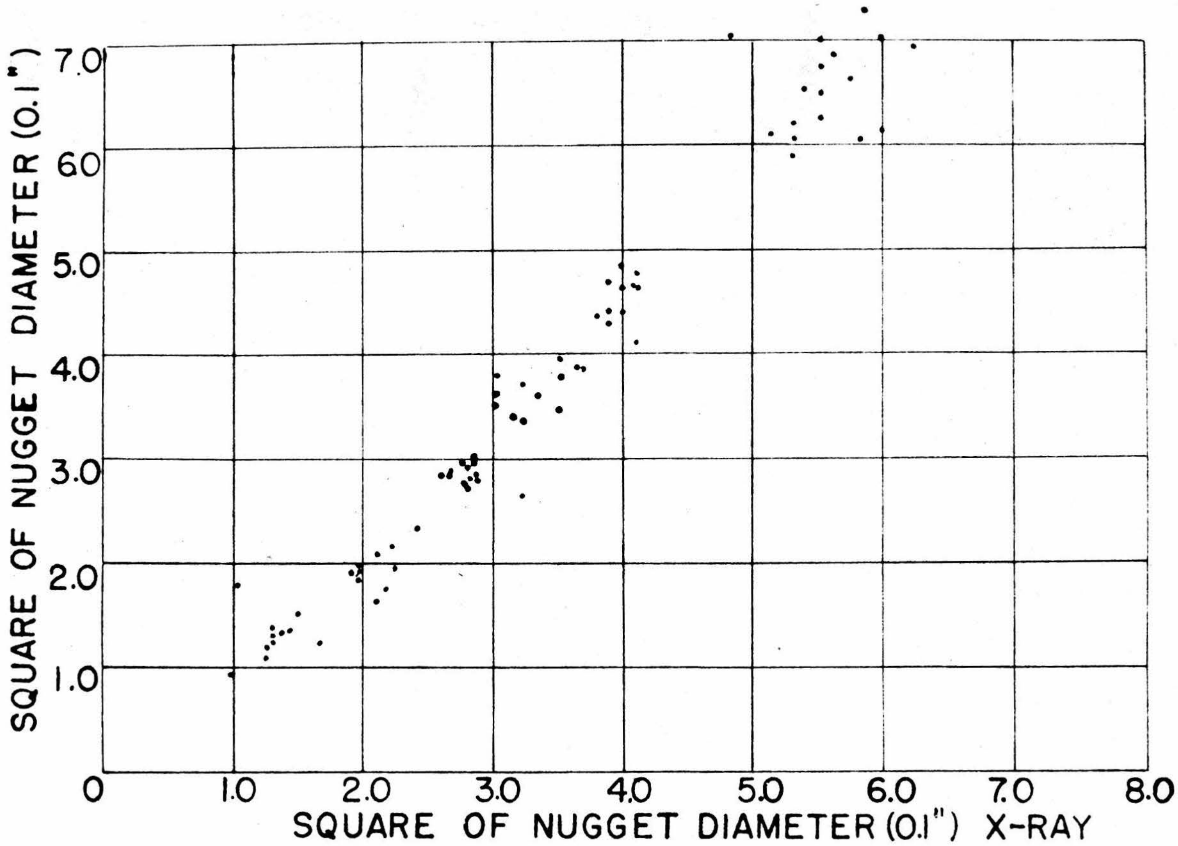


FIG. 9. PREDICTION OF WELD NUGGET AREA BY RADIOGRAPHIC FAINT RING.

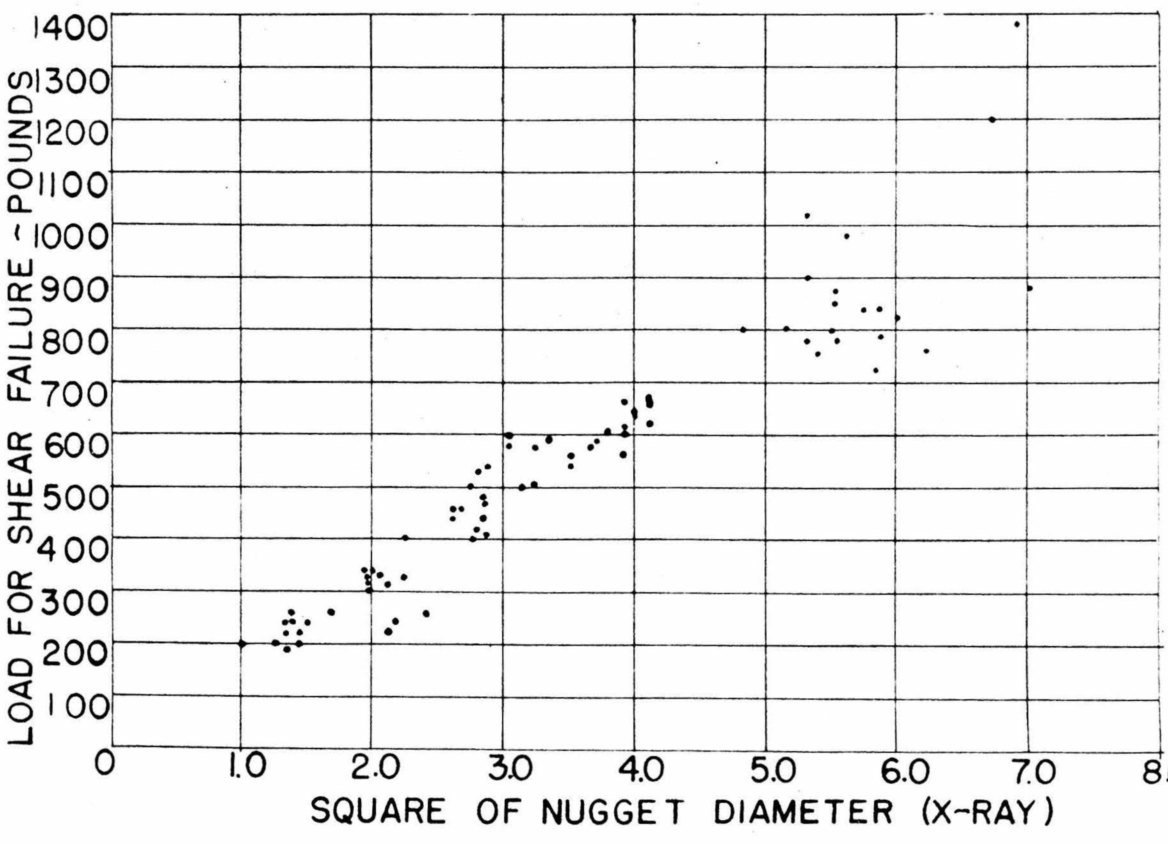


FIG. 10. PREDICTION OF STATIC SHEAR STRENGTH BY RADIOGRAPHIC FAINT RING.

THE ORDINATES IN THIS CURVE MEASURES THE PERCENTAGE OF THE GROUP OF WELDS WHOSE STRENGTH WAS MEASURED WITH AN ERROR GREATER THAN THAT INDICATED BY THE ABSCISSA.

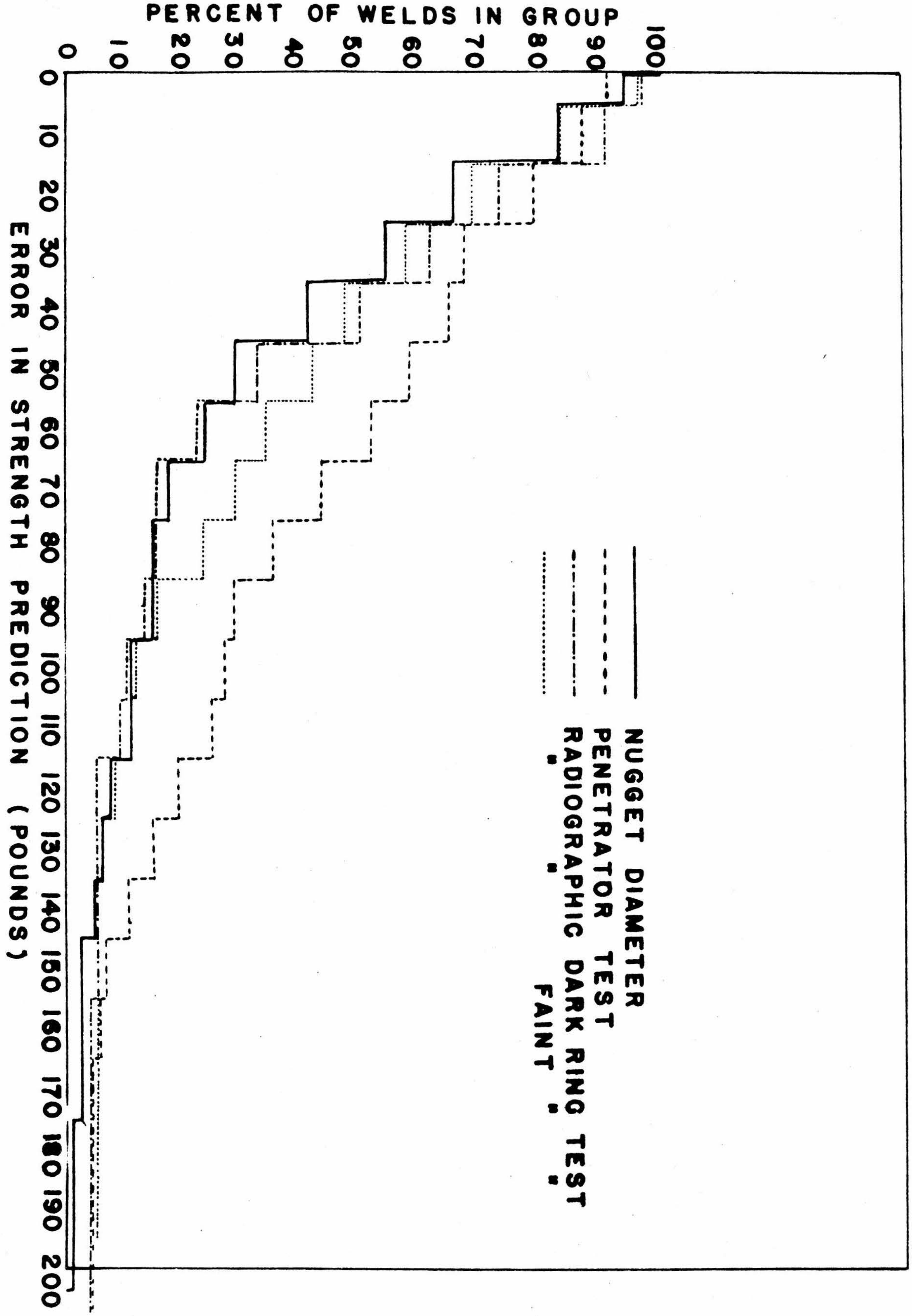


FIG. 11. COMPARISON OF ACCURACY OF STATIC SHEAR STRENGTH MEASUREMENTS BY DIFFERENT NON-DESTRUCTIVE TESTS.

D. Results of Tests on 326 Taylor Winfield Spotwelds Made on the Laboratory Welder At the University of Southern California in .040" 24ST Alclad Aluminum Alloy Sheet.

Note: The electrical test was omitted. A selection of typical results is included.

TABLE I

Specimen data for spotweld specimens made May 28, and June 19, 1943 at University of Southern California for California Institute of Technology.

Material	:	.040 to .040 24ST Alc.
Machine	:	Taylor-Winfield Hi-Wave Welder 440 line volts
Electrode Pressure	:	(variable)
Capacitance	:	(variable)
Voltage	:	(variable)
Radius top electrode	:	3"
Radius bottom elec.	:	3"

Material cleaned in Oakite #63 at 180° F for 4 minutes and wire brushed.

Panel No.	Welds No.	Electrode Pressure	Capacitance	Voltage
1	B1-11	1100	240	1800
2	12-24	1100	360	1716
3	25-36	1100	480	1680
4	37-48	1100	480	2060
5	49-60	1100	600	1960
6	61-70	1100	720	1900
7	71-82	1100	840	1840
8	83-94	1175	960	1800
9	95-104	1175	960	2000
10	105-116	1175	960	2200
11	H1-11	1400	960	1800
12	12-21	1400	960	2000
13	22-31	1400	960	2200
14	32-43	1400	960	2400
15	44-53	1400	960	2600
16	54-63	1400	960	2800
17	64-75	1400	1200	2200
18	76-85	1400	1200	2400
19	86-95	1400	1200	2600
20	96-105	1400	1200	2800
21	I1-11	1400	960	1800
22	12-21	1400	960	2000
23	22-31	1400	960	2200
24	32-44	1400	960	2400
25	45-54	1400	960	2600
26	55-64	1400	960	2800
27	65-76	1400	1200	2200
28	77-86	1400	1200	2400
29	87-96	1400	1200	2600
30	97-105	1400	1200	2800

TABLE I

Specimen data for spotweld specimens made June 4, 1943 for California Institute of Technology.

Material	:	.040 to .040 24 ST Alc.	
Machine	:	Taylor-Winfield Hi-Wave Welder. 440 line Volts.	
Electrode Press	:	1225 lbs.	(Constant)
Capacitance	:	2280 Mfd.	(Constant)
Voltage	:		(Variable)
Throat	:	13	(Constant)
Arm	:	36"	(Constant)
Radius top elec.	:	5"	(Constant)
Radius bottom elec.	:	3"	(Constant)

Material cleaned in Oakite #63 and Oakite #84A

Panel No.	Welds No.	D.C.Voltage
1	F1-17	1400
2	F18-34	1500
3	F35-52	1600
4	F53-70	1650
5	F71-87	1800
6	F88-105	1900
7	F106-121	2050
8	F122-138	2275

TABLE II

Comparison of Accuracy of Measurement of Spotweld Static Shear Strength by Weld Nugget Diameter and by Non-destructive Tests.

		Error in Measurement	
		Minimum Error	
Test Method	Median	For 90% of Welds	For 100% of Welds
Weld Nugget Diamgter	35 Pounds	115 Pounds	210 Pounds
Ring Penetrator Test	65 Pounds	145 Pounds	290 Pounds
Radiographic Dark Ring	35 Pounds	105 Pounds	380 Pounds
Radiographic Faint Ring	35 Pounds	105 Pounds	290 Pounds

FIG. 6. CONTACT REPRODUCTIONS OF SPOTWELD RADIOGRAPHS. WELDS IN .040" 24ST ALCLAD SHEET.

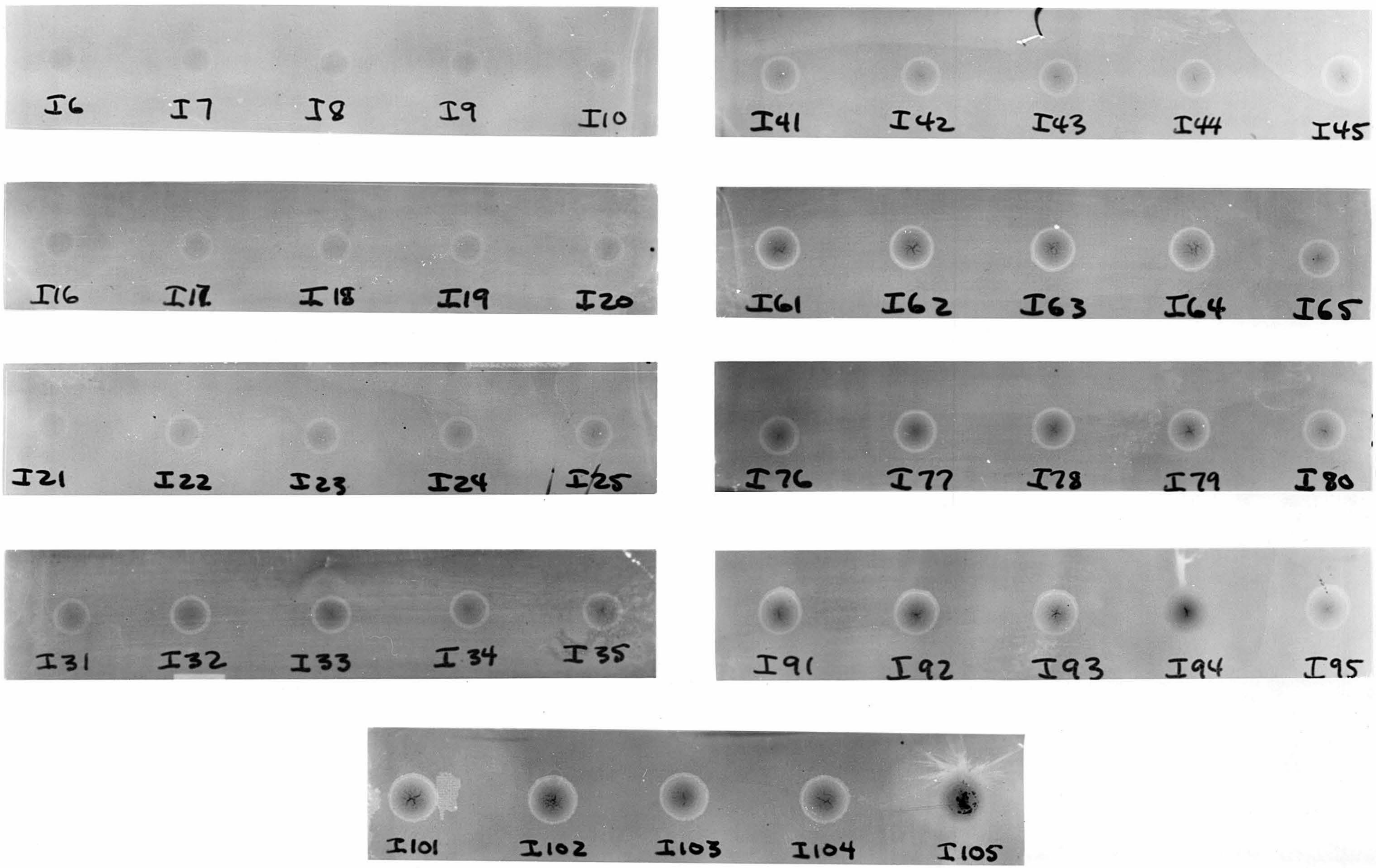
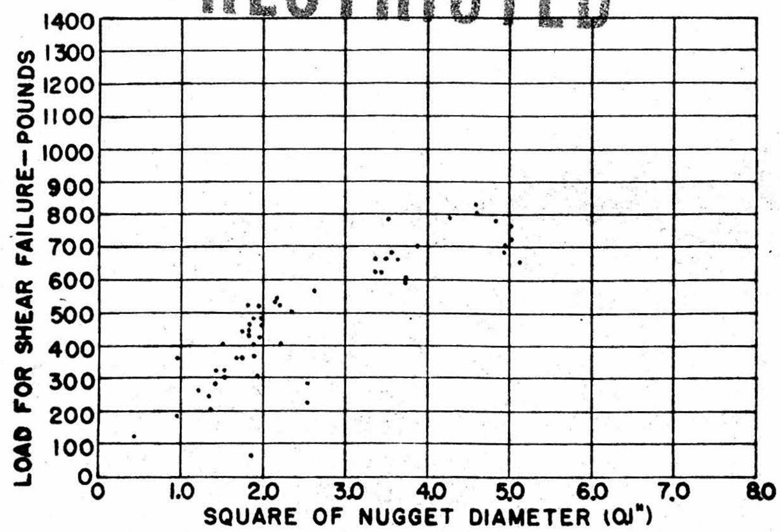
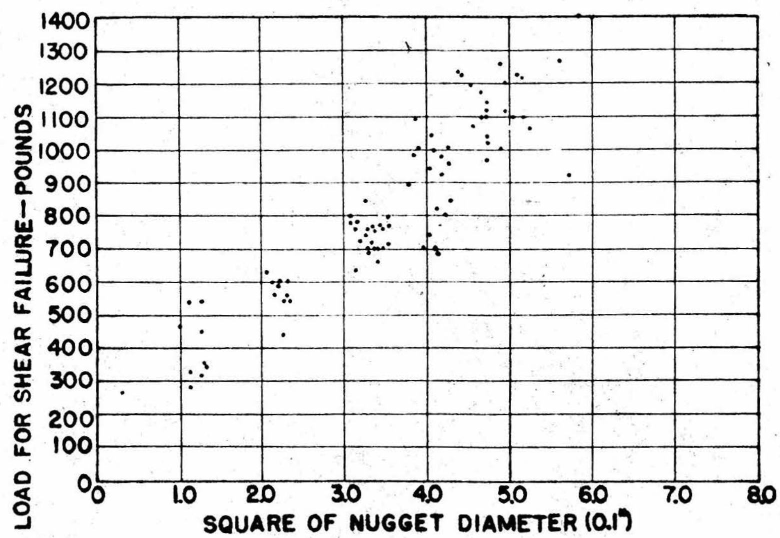


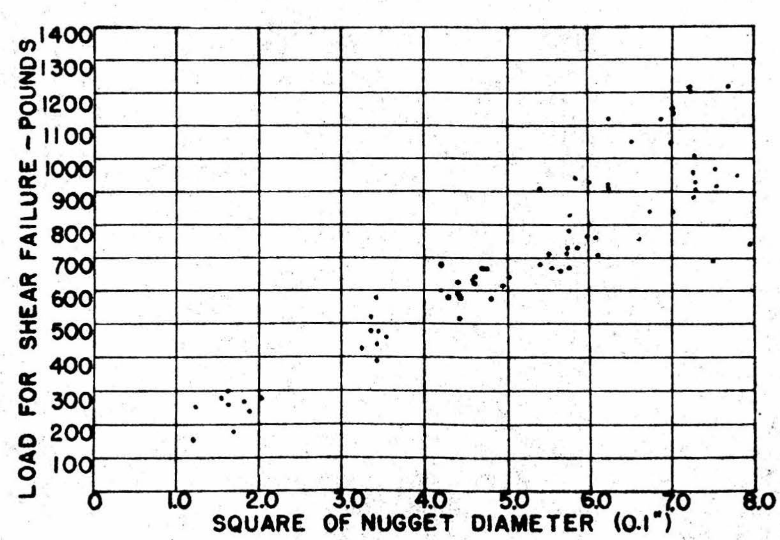
FIG. 1. CORRELATION BETWEEN STATIC SHEAR STRENGTH AND WELD NUGGET AREA AT FAYING PLANE.



GROUP B – 115 WELDS

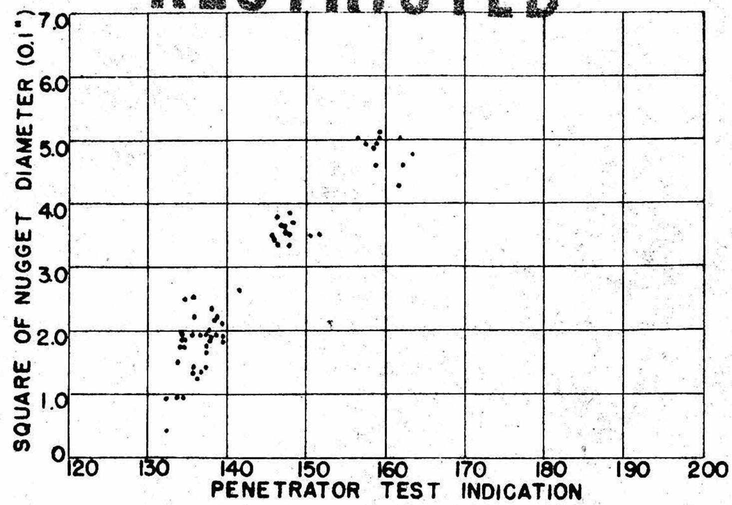


GROUP H – 105 WELDS

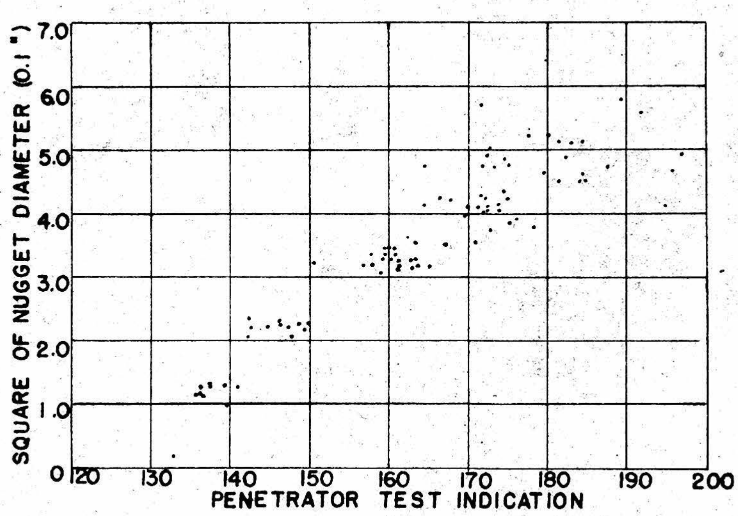


GROUP I – 105 WELDS.

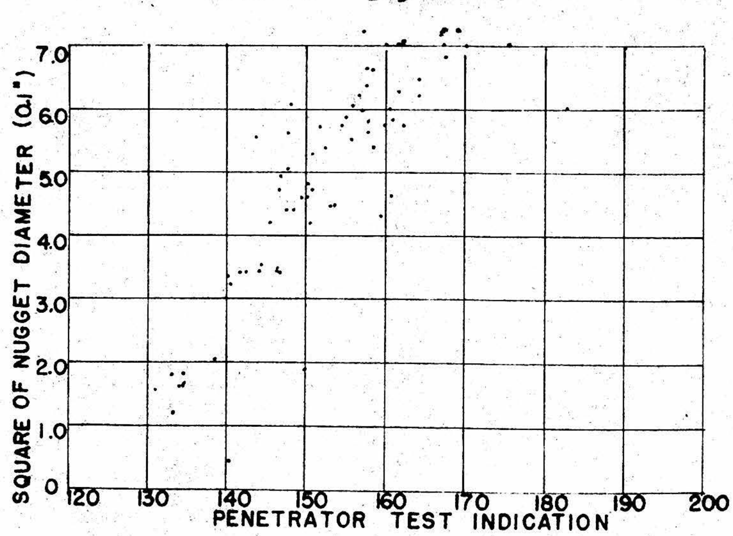
Fig. 2. Prediction of weld nugget area at faying plane by ring prnetrator test.



Group B - 115 welds

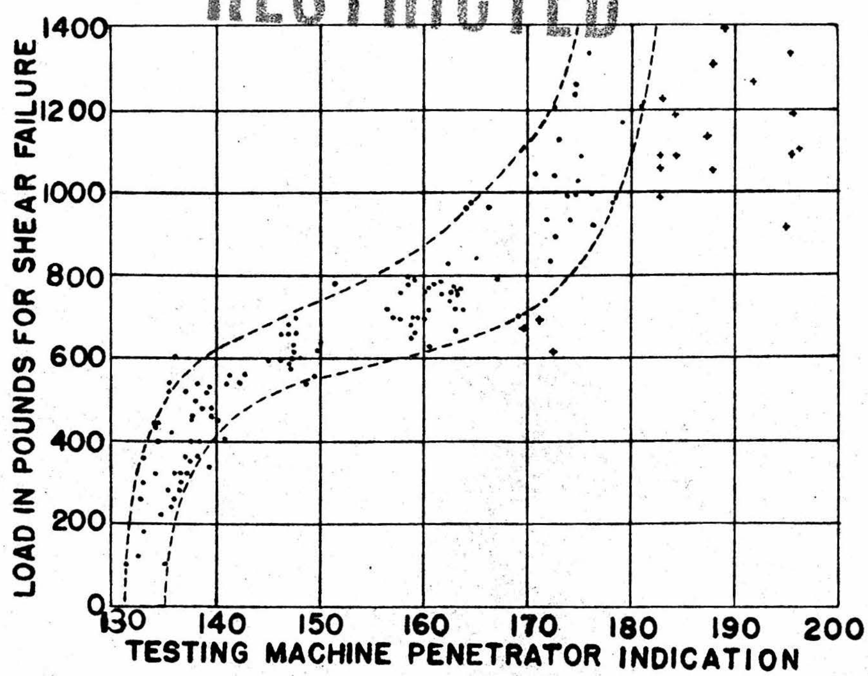


Group H - 105 welds

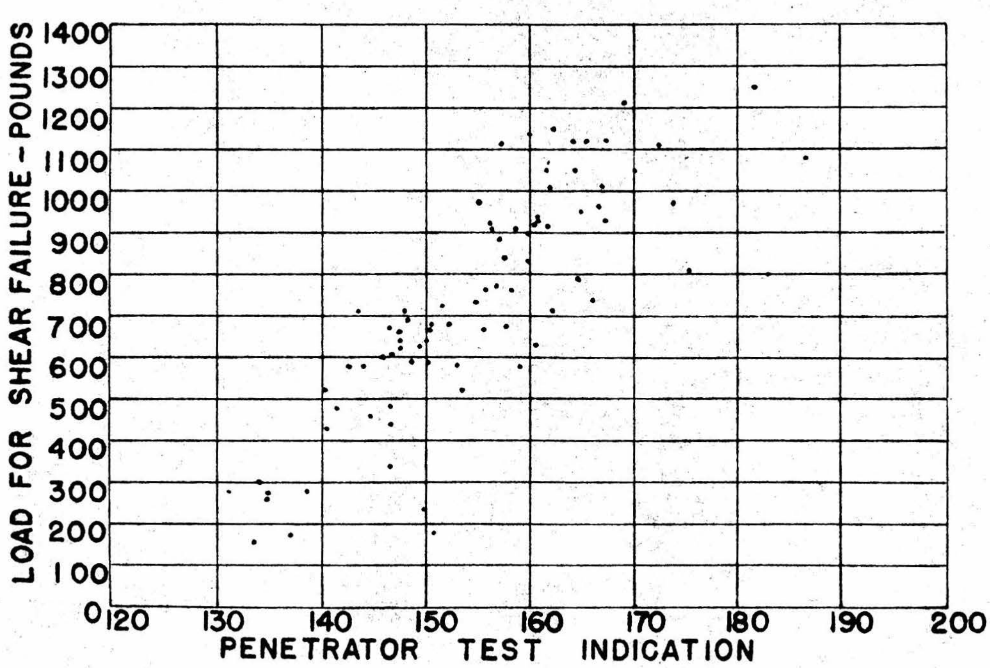


Group I - 105 welds

FIG. 3. PREDICTION OF SPOTWELD STATIC SHEAR STRENGTH BY RING PENETRATOR TEST.



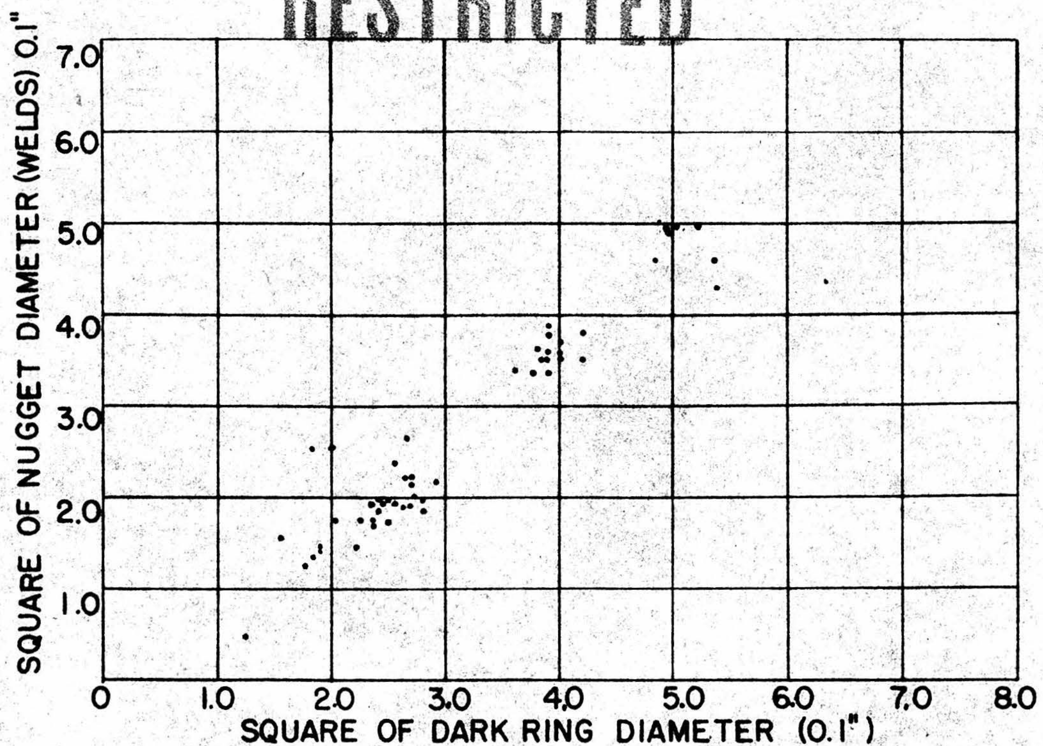
COMBINATION OF GROUP B (115 WELDS) AND GROUP H (105 WELDS). (+) INDICATES BADLY CRACKED WELD.



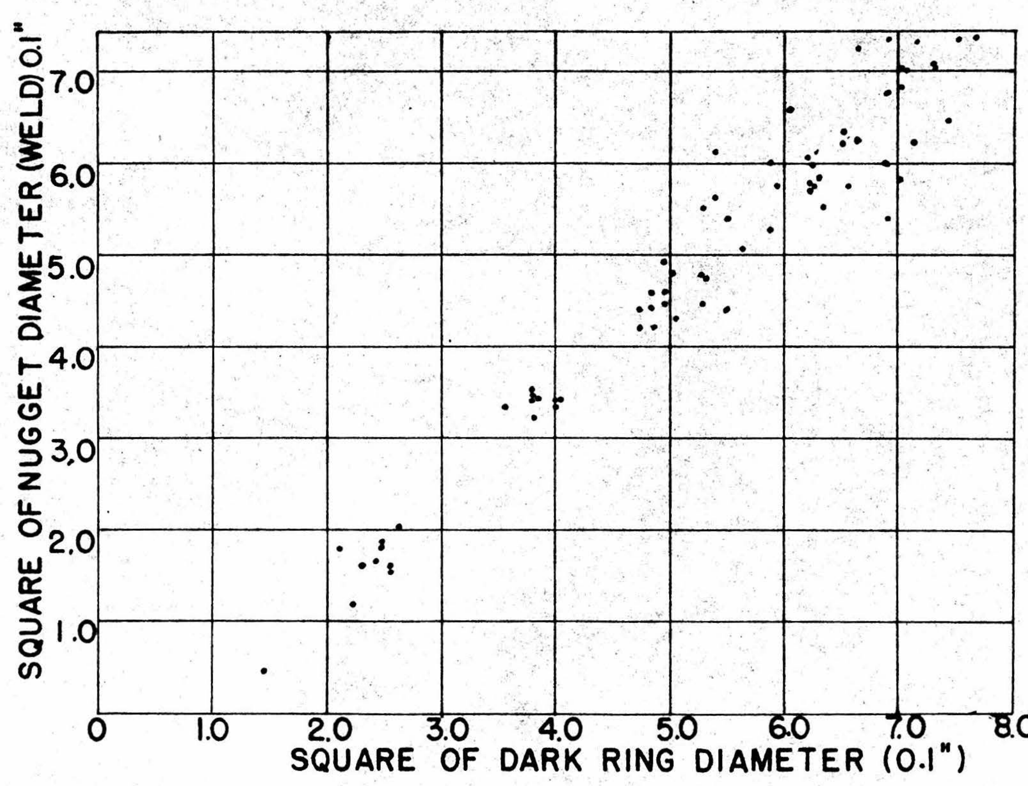
GROUP I - 105 WELDS

FIG. 4. PREDICTION OF WELD NUGGET DIAMETER BY RADIOGRAPHIC DARK RING.

RESTRICTED



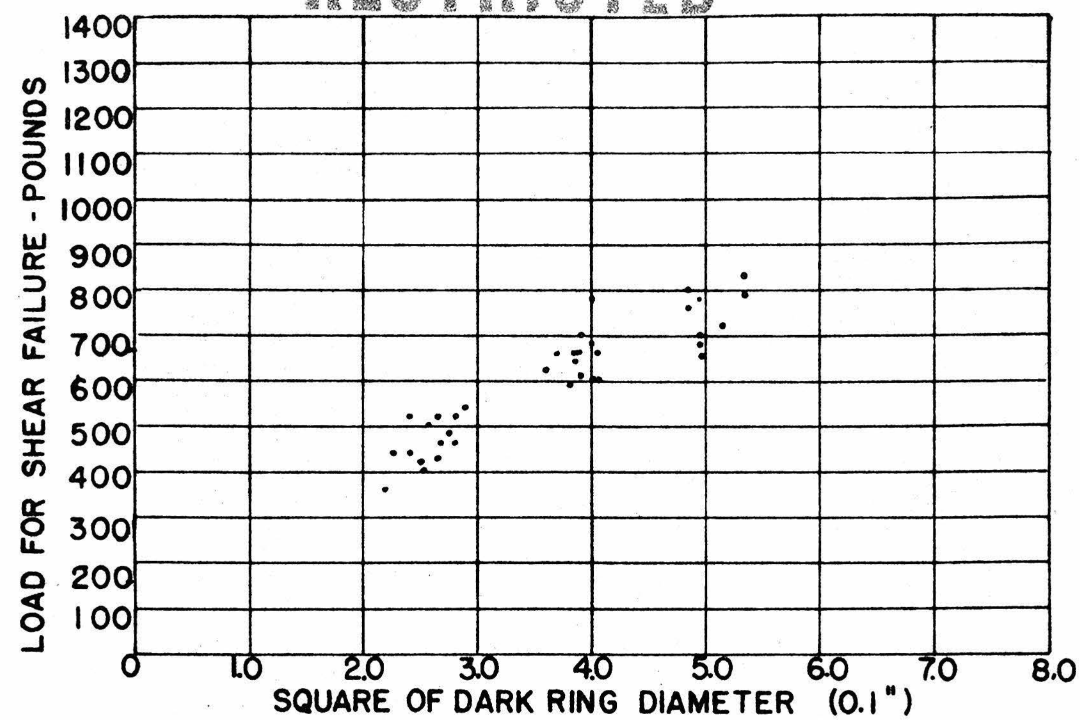
GROUP B – 115 WELDS



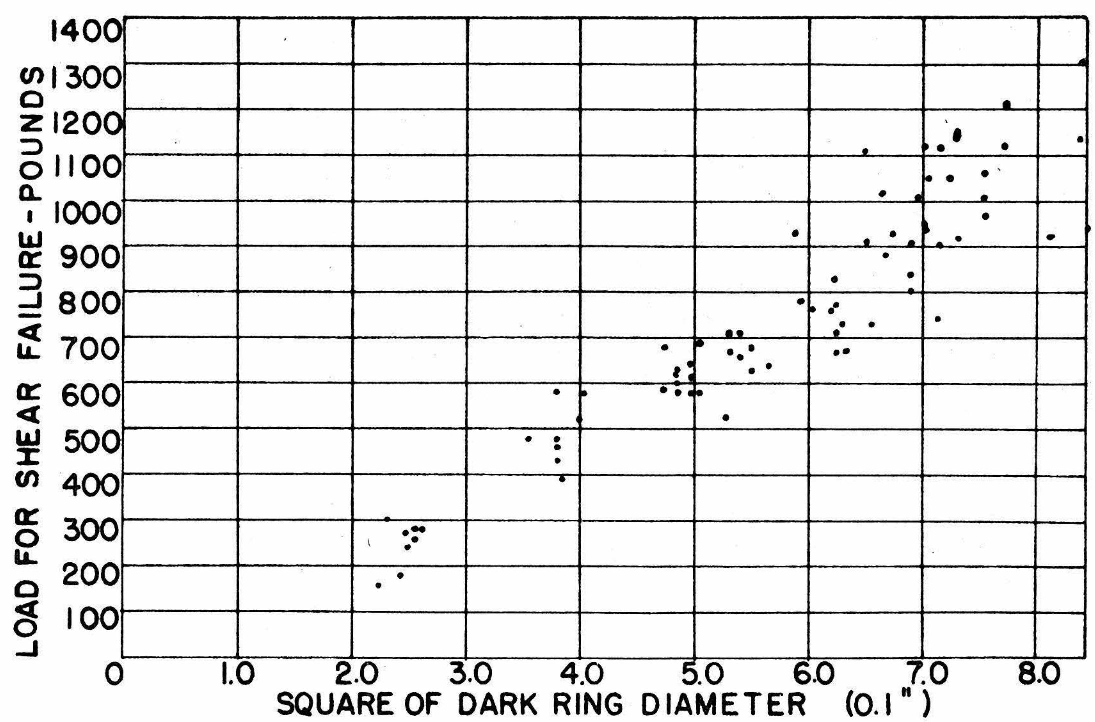
GROUP I – 105 WELDS

FIG. 5. PREDICTION OF SPOTWELD STATIC SHEAR STRENGTH BY RADIOGRAPHIC DARK RING.

RESTRICTED

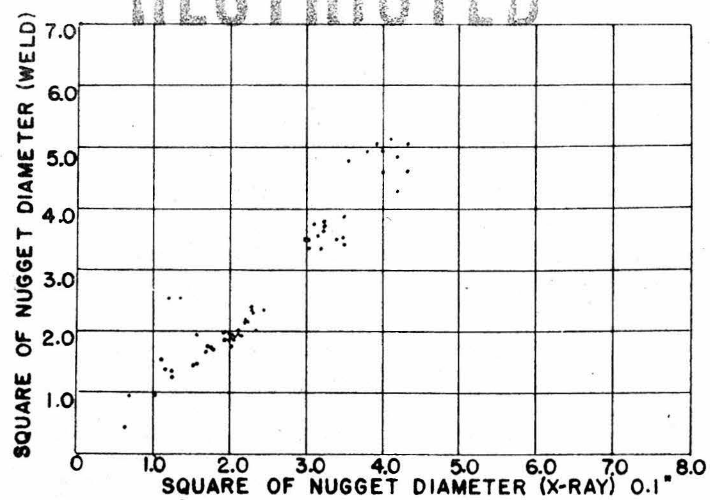


GROUP B – 115 WELDS. WELDS B 1 THROUGH B 50 FELL APART, SHOWED NO DARK RING ON RADIOGRAPH.

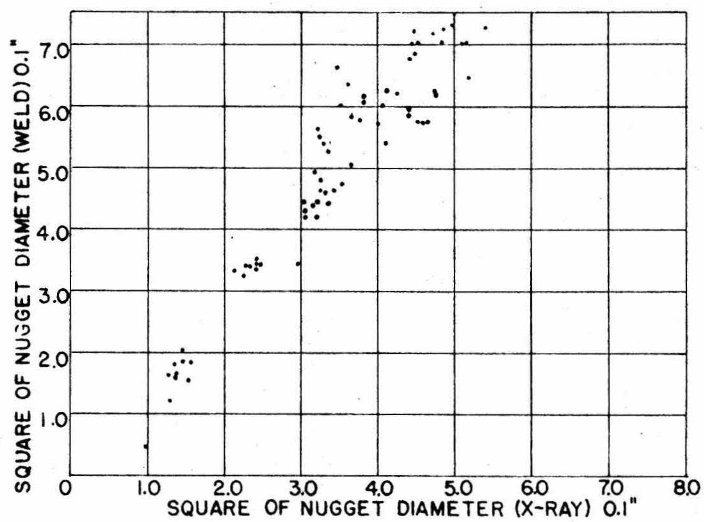


GROUP I – 115 WELDS

FIG. 6. PREDICTION OF WELD NUGGET AREA BY RADIOGRAPHIC FAINT RING.

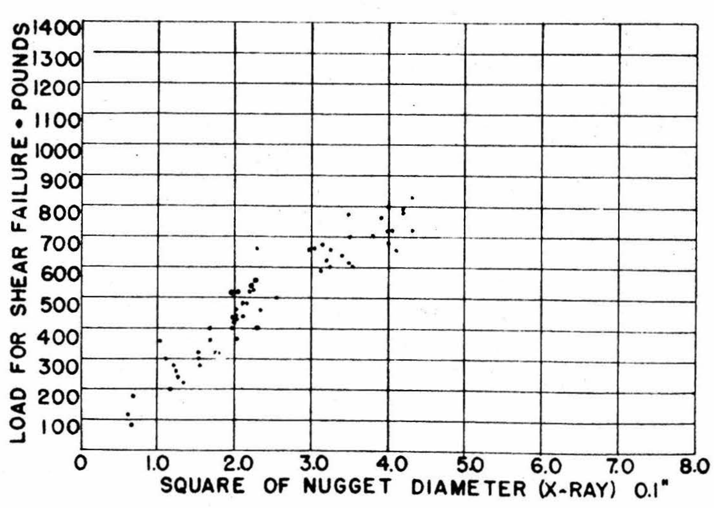


GROUP B – 115 WELDS



GROUP I – 105 WELDS

FIG. 7. PREDICTION OF SPOTWELD STATIC SHEAR STRENGTH BY RADIOGRAPHIC FAINT RING.



GROUP B – 115 WELDS

FIG. 8A CORRELATION OF RADIOGRAPHIC IMAGE WITH BONDED CORONA AREA.

RESTRICTED

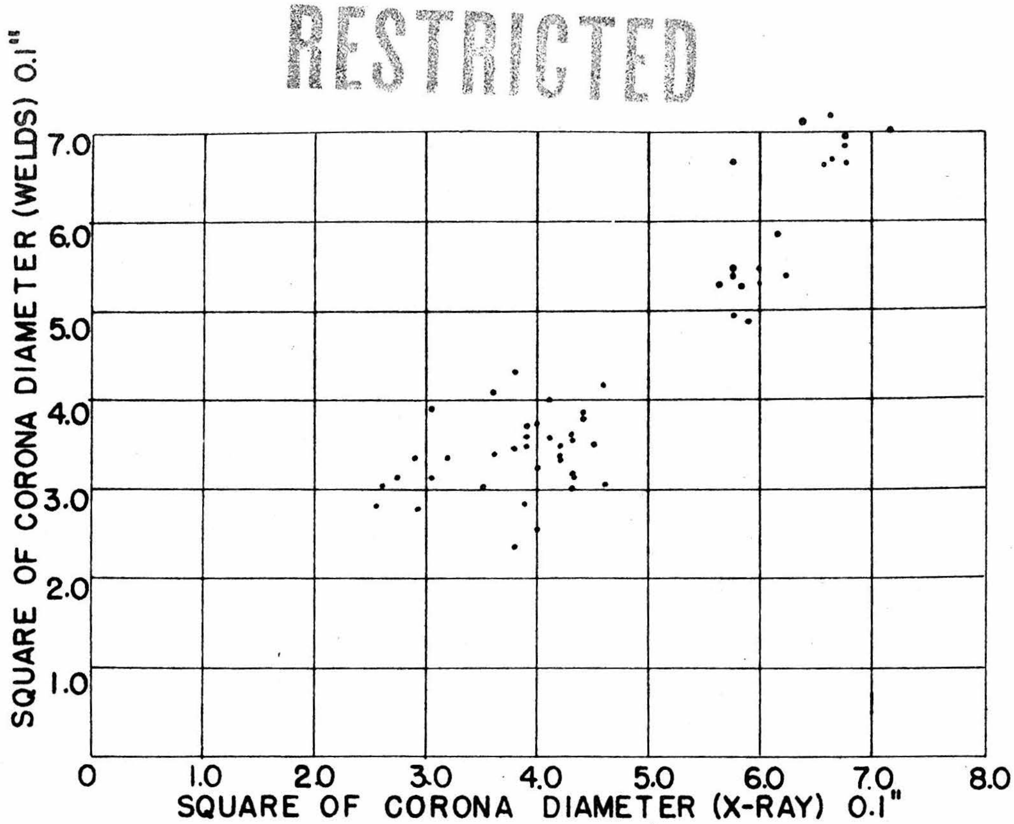
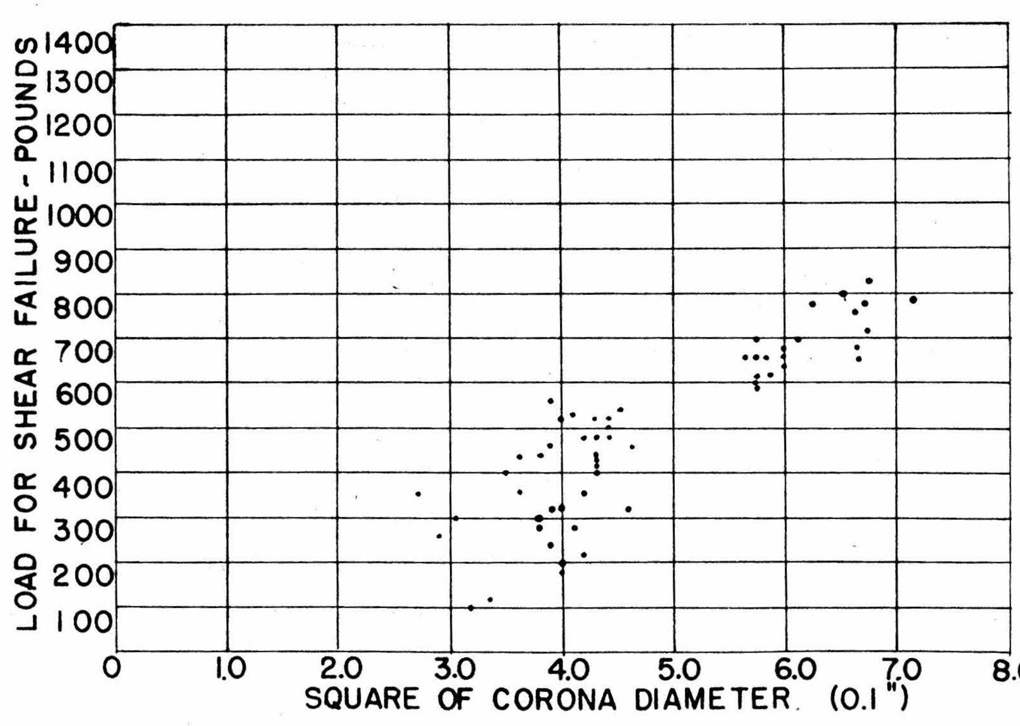


FIG. 8B CORRELATION OF BONDED CORONA AREA WITH SPOTWELD STATIC SHEAR STRENGTH.



E. Summary of Results of Tests on Industrial Welds.

On the typical groups included in this thesis, and on groups of welds from four other aircraft factories, the radiographic test measured weld strength and nugget size more accurately than the penetrator or electrical tests. Median error for the radiographic test was from 25 to 45 pounds, for welds whose strengths ranged from 200 to 1300 pounds, with normal weld strength 500 to 600 pounds. Median error with the penetrator test varied from 35 to 85 pounds, with the electrical test from 25 to 95 pounds. Each of these tests would serve for industrial inspection, since 80 to 90% of the welds would be measured to within 20% of actual weld strength.

The additional information on weld geometry, structure, and defects provided by the radiographic test, in addition to its superior accuracy and reliability, make it preferable to the penetrator and electrical non-destructive tests.

VIII CONCLUSIONS:

It is possible to measure spotweld nugget size and static shear strength by the penetrator and electrical non-destructive tests, for spotwelds in equal thickness two layer aluminum alloy joints. The accuracy and reliability of measurement are sufficient to make the methods useful in industrial inspection. The chief disadvantage of both of these methods is the necessity for accurately centering the test assembly over the spotweld, to avoid large errors in indication. The penetrator test also has the disadvantage that it marks the sheet surface, but in tests on thousands of welds, no case of failure resulting from the penetrator indentations has been observed.

Correlation of radiographic details with weld geometry and structure showed that, for spotwelds in equal thicknesses of 24ST Alclad aluminum alloy sheet:

1. Spotweld static shear strength, nugget size, geometry, and defects can be determined reliably and accurately from the radiographs of production spotwelds.

2. Spotweld defects such as inadequate nugget penetration (with possible lack of bonding or excessive Alclad inclusion into the nugget), excessive penetration in oversize nuggets, cracking, porosity, spitting, or excessively large heat-affected zones are clearly evident in the spotweld radiographs.

3. In groups including hundreds of industrially-

made spotwelds in .040" 24St Alclad sheet, with uniform distributions of static shear strength from 0 to 1300 pounds, the nugget diameter in the 24ST alloy was determined with a median error of only .01 ", and strength predicted with a median error of from 25 to 45 pounds, by visual examination and measurement of the spotweld radiographs.

On production spot welds, the penetrator, electrical, and radiographic tests each measured spotweld static shear strength with a reliability and accuracy well above the requirements of practical industrial spotweld inspection.

The radiographic test offers advantages over the penetrator and electrical tests by providing not only a measure of weld strength, but by showing in clear and unquestionable form the presence of defects such as lack of penetration, cracks, porosity, spitting, misshapen nuggets, excessive penetration, and excessively large heat affected zones. It makes possible complete weld inspection in a single operation which is absolutely not damaging to the weld.

Three necessary prerequisites to the general acceptance of radiography as a reliable non-destructive test for spotwelds in equal thicknesses of 24ST Alclad sheet have been met by research:

1. The method of interpreting weld geometry, structure, strength, and defects from radiographs has been established.

2. The technique of radiographing spotwelds, using available production X-ray equipment and commercial film, has

been developed to give excellent radiographs, with exposure times as low as 5 seconds per weld. Low cost portable X-ray equipment for spotweld radiography could be manufactured of commercially available components.

3. The reliability and adequacy of radiographic inspection has been proven by the results of tests on thousands of industrially made spotwelds from many factories. The accuracy of prediction of weld strength and size was well above industrial inspection requirements.

IX ACKNOWLEDGEMENTS:

The author wishes to express his sincere appreciation of the guidance and inspiration given by Professors Lindvall, Sorensen, and Clark, of the cooperation and achievements of Mr. Vance Danford and Dr. L.W. Ball and the firm of Triplett and Barton, Inc., and of the very great help in carrying out this research of Mr. J.F. Manildi, Mr. C.C. Woolsey, and each of the members of the Welding Research Group of California Institute of Technology.

REFERENCES AND BIBLIOGRAPHY

(1) " Alcoa Aluminum and Its Alloys", a data and information pamphlet published by the Aluminum Company of America, Pittsburgh, Pennsylvania, 1942.

(2) "Revealing the Microstructure of 24S Alloy", by F. Keller and R.A.Bossert--"Metal Progress" Vol. 41 No. 1 January, 1942.

(3) "Structural and Metallurgical Properties of Condenser Discharge Spot Welds", by G.S.Mikhalapov and T.F. Falls, in "The Welding Journal" Vol. 21 No. 4 April, 1942.

(4) "Radiography of Spot Welds" by Robert C. Woods, John C. Barrett and T.W. Dietz, in "Metals and Alloys" for September, 1942: also "Metals and Alloys", December, 1942, pages 1080-1083.

(5) "Standards and Recommended Practices and Procedures For Spotwelding of Aluminum Alloys" by Aircraft Welding Standards Committee of the American Welding Society, February 1, 1942, Revised April 15, 1942--Section I-STANDARDS OF WELD QUALITY (5) Weld Penetration.

(6) "Correlation of Metallographic and Radiographic Examinations of Spotwelds in Aluminum Alloys" by D.W.Smith and F. Keller, in "Welding Journal" of December, 1942.

(7) "Metallurgical Aspects of Spotwelds in Aluminum Alloys" by J.R.Heising and E.H.Burkhart, in "Metals and Progress", December, 1942.

(8) "Examination of Spotwelds in Alclad 24S-T" by W.F. Hess, R.A.Wyant and B.L.Averbach, in "Welding Journal" of July, 1942.

(9) "Radiography of Light Alloys" by Robert C.Woods and V. C. Cetrone - in "Iron Age", March 25, 1943.

(10) "Microradiography" in "Iron Age", July 22, 1943, Volume 152 #4.

(11) Navy Department Third Partial Report on Eddy-current Type Flaw Detectors - Tests of Spotwelds in Aluminum Alloys, by Naval Research Laboratory, Anacostia Station, Washington, D.C., NRL Report No. o-1792 (RESTRICTED).

(12) "An Eddy-Current Method of Flaw Detection in Non-magnetic Metals" by Ross Gunn, Anacostia, D.C. in "Journal of Applied Mechanics", March, 1941.

(13) "Modulus of Elasticity and Damping in Relation to the State of the Material" by F.Forster, Dr. Phil., and Professor W. Koster, Dr. Phil., in "Journal of the Institution of Electrical Engineers", London, B.I., Volume 84, January-June, 1939, Pages 558-564.

(14) "New Methods of Spotweld Inspection by X-ray" - by Natalie Godalsky - Paper furnished by Sciaky Brothers, 4915 W. 67th Street, Chicago, Illinois.

(15) "Fatigue Characteristics of Spotwelded 24ST Aluminum Alloy" by H.W.Russell, L.R.Jackson, H.J.Grover, and W.W. Beaver, Battelle Memorial Institute, for National Advisory Committee for Aeronautics, Copy No. 150 ARR No. 3F16, June, 1943 (RESTRICTED).

SOURCES OF PROPOSED TEST METHODS

(a) Two Side Direct Current Test. A form of test similar to the two side direct current test was developed by Andrew and Perillo for the Glenn Martin Aircraft Company of Baltimore, Maryland. (Refer to Mr. Paul Merriman for details.).

(b) One Side Direct Current Test. A preliminary form of this test was developed in the Electrical Research Section of the Lockheed Aircraft Corporation, Burbank, California. (Refer to Mr. Fred Bowden for details).

(c) Lap Joint Induction Test. A test which may be similar to the lap joint induction test was developed by Mr. Norman Bonn, of Philadelphia, Pennsylvania.

(d) Pick-Up Coil Eddy Current Test. Developed in the Naval Research Laboratory and reported by Ross Gunn in "An Eddy-Current Method of Flaw Detection in Non-Magnetic Materials" in the "Journal of Applied Mechanics", March, 1941.

(e) Spotweld Eddy Testing Unit. Developed in the Naval Research Laboratory and reported in a pregress report, July, 1942.

(f) Lockheed Eddy Current Test Unit. Developed in the Electrical Research Section of the Lockheed Aircraft Corporation by Dr. Philip Carlson.

(g) Heat Reservoir Thermal Test. Developed by the General Electric Company, Schenectady, New York, and tested in the Lockheed Aircraft Corporation Research Laboratory, Burbank, California.

(h) Vibration Damping Test. Method is discussed in "Modulus of Elasticity and Damping in Relation to the State of the Material" by F. Forster, Dr. Phil, and Professor W. Koster, Dr. Phil., in Journal of the Institution of Electrical Engineers", London, B.I. Volume 84, January-June, 1939, pages 558-564.

(i) Wave Reflection Test. Proposed by Professor F.A. Firestone of the University of Michigan, in connection with the Supersonic Reflectoscope.

(j) Weld Outline Test. Mlle. Natalie Godalsky in a paper furnished by Sciaky Brothers, Chicago, Illinois.

Note: Proposed test methods identified by the sign ∉ were independently proposed and developed by the Welding Research Group of the California Institute of Technology.

RADIOGRAPHIC FILM TERMS USED

SPEED

Film speeds for comparison purposes are sensitometric measurements under specified conditions. These conditions have been so chosen as to be representative of a large percent of production work. Speed is espressed as the MAS necessary to produce a density of 2.50 through .50" of 24 ST rolled aluminum alloy. The film is in a paper envelope and exposed on x-ray unit number 6 at 79 primary volts (approximately 100 KVP). The exact MAS value is obtained from a plot of density versus exposure time for .50" of material.

CONTRAST

The quantitative expression of radiographic contrast as indicated in this report by digits along the various plots, is the percent of the total thickness that will produce a density difference of .02. This percent represents the percent of the total thickness that would be just detectable in the interpretation of a radiograph. The human eye can only differentiate a minimum density value. Under ideal laboratory conditions this minimum value is about .005. For calculating contrast applicable to production conditions the conservative density difference of .02 is used.

This contrast value is calculated by assuming a straight line relationship between two densities, usually those produced by a thickness difference of .10" of material. The thickness represented by a density difference of .02 is calculated and divided by the total average thickness over which the density difference was measured. This is multiplied by 100 to express it in percent.

For example, if .10" of material will produce a density difference of .20, then a density difference of .02 will represent .01" of material. If the average thickness over which the density was measured was 1.00", then .01" would represent 1% of the total thickness. This percent is used to express the radiographic contrast.

When it is necessary to apply a single contrast value to a film for comparison purposes, the value used is that found for .50" of 24 ST rolled aluminum alloy, at a density of 2.50, exposed for 424 MAS and variable voltage on x-ray unit number 6. This is generally supplimented by the value found for the same thickness of material at the same density exposed at 79PV and variable time on the same x-ray unit. Contrast values for given thicknesses are found by a plot of contrast versus thickness. These plots are not limited to any thickness, voltage or material.

QUANTITIES AND VALUES USED IN DATA COLUMNS

DATA TITLE	QUANTITY AND VALUE
Speed	MAS (see definition)
Fog	Density units or hundredths of density units
Grain	Code number
Film	Code number
Development	1 - Machine development 2 - Hand development with agitation 3 - Hand development without agitation
Developer	Code number
Dev. Time	Minutes or tenths of minutes
Dev. Temp.	Degrees Fahrenheit
Part	1 thru 5 or 48 - aluminum alloy 6 thru 9 or 46 - steel 10 thru 13, 47 or 178 - copper or brass 37 or 177 - lead
Machine	Type of x-ray machine 1 - 220 KVP T & B equipment 2 - 220 KVP commercial equipment 3 - 250 KVP commercial equipment 4 - 400 KVP commercial equipment 5 - 150 KVP T & B equipment (without rectifier) 6 - 150 KVP T & B equipment (with rectifier) 7 - 140 KVP commercial equipment 8 - 100 KVP commercial medical equipment 9 - Miscellaneous equipment 10- Radium (quantity given under MA) 11- 1000 KVP commercial equipment
Tube Dist.	Inches
Time	Exposure time - seconds or tenths of seconds
MA	Milliamperes or tenths of milliamperes
Voltage	Primary voltage
Screen	Type of screen or film holder used 1, 31 or 32 - Paper holder (no intensifying screens) 2, 3 or 38 -- Front and back lead screens 5 ----------- Tungstate screens
Filter	Code number
Film No.	Identification number on film test strips
W. O.	Project number
Former Date Space	Project division number
Em. No.	Part of film emulsion number
Subject	See special sheet if these values are used
V1	
V2	
V3	
V4	
V5	X-ray machine number unless otherwise stated
Thickness	Inches or hundredths of inches
Density	Density units or hundredths of density units
Contrast	Percent or hundredths of percent (see definition)

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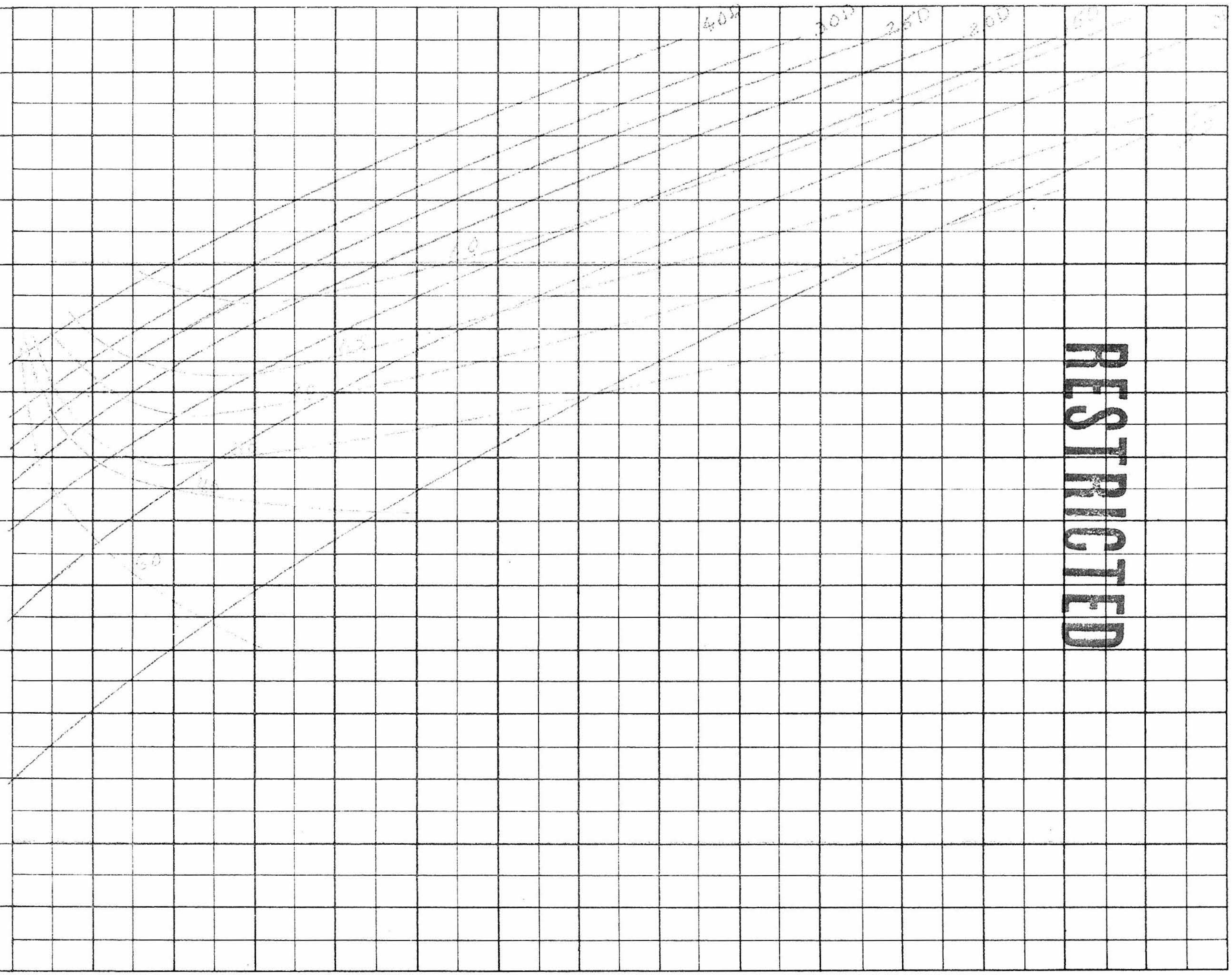
BURBANK, CALIFORNIA

Report No. ___ Page No. ___

Form 1716

Speed	
Fog	17
Grain	
Film	60
Development	1
Developer	15
Dev. Time	47
Dev. Temp.	68
Part	3
Machine	6
Tube Dist.	36
Time	4
MA	10
Voltage	30
Screen	31
Filter	-
Film No.	-
W. O.	472
Date	657
Em. No.	56
Subject	
V-1	
V-2	
V-3	
V-4	
V-5	13
Thickness	
Density	
Contrast	

Remarks



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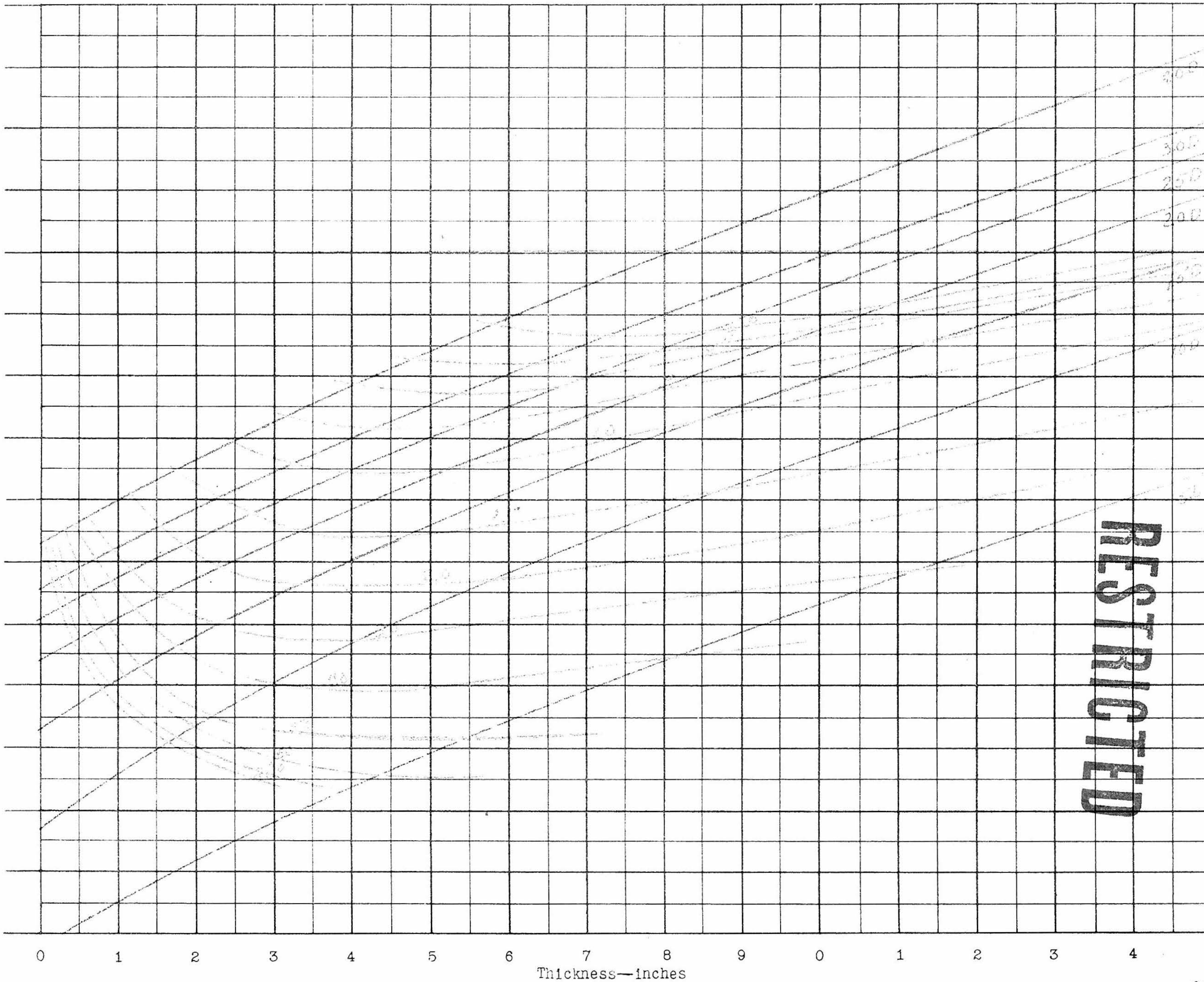
Report No. ___ Page No. ___

Form 1716

Speed	
Fog	17
Grain	
Film	60
Development	1
Developer	15
Dev. Time	47
Dev. Temp.	68
Part	3
Machine	6
Tube Dist.	36
Time	Y
MA	10
Voltage	35
Screen	31
Filter	-
Film No.	-
W. O.	477
Date	652
Em. No.	56
Subject	
V-1	
V-2	
V-3	
V-4	
V-5	13
Thickness	
Density	
Contrast	

Remarks

— Contrast



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METALLURGICAL DIAGNOSIS

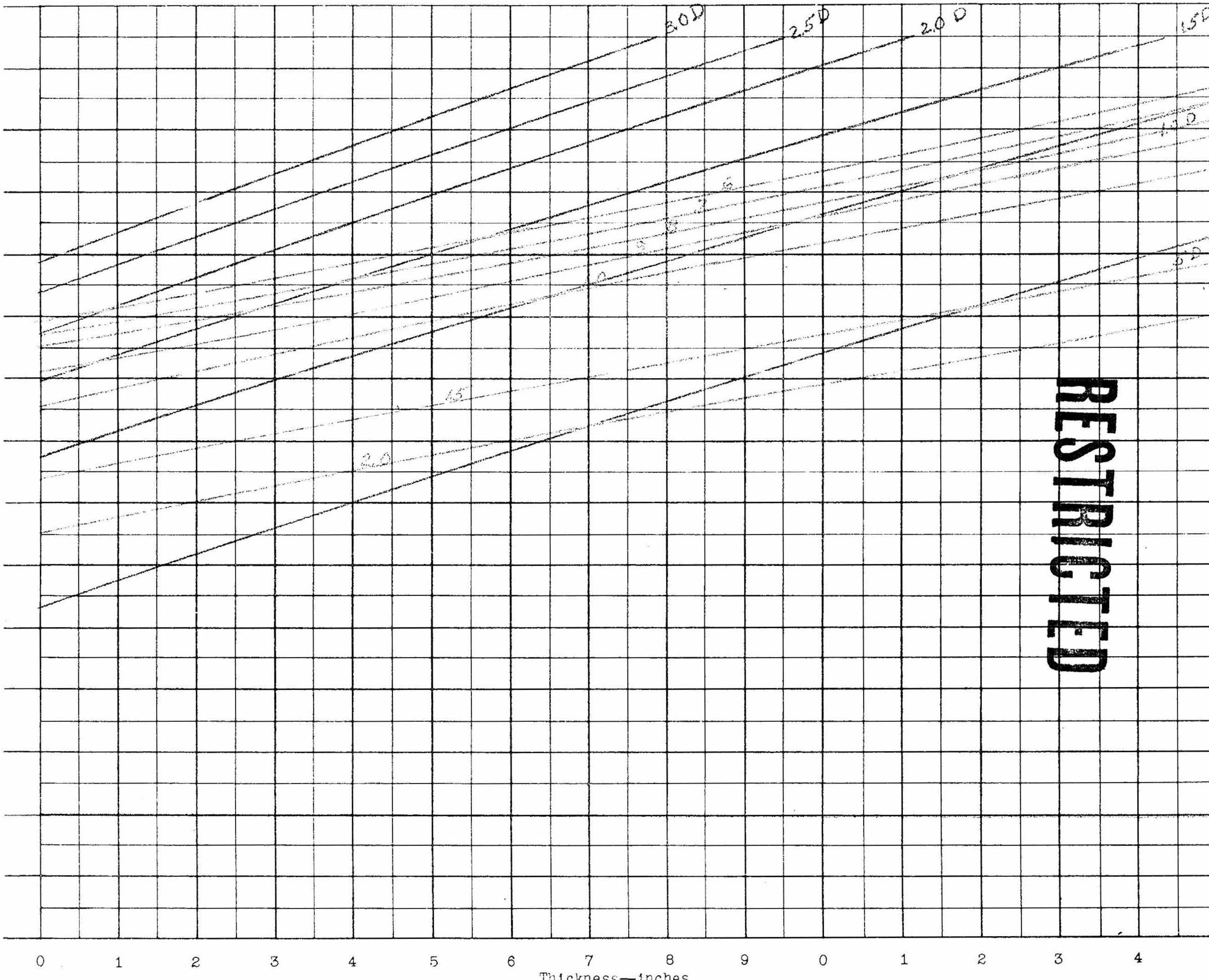
BURBANK, CALIFORNIA

Report No. ___ Page No. ___

Form 1716

Speed	
Fog	17
Grain	
Film	60
Development	1
Developer	15
Dev. Time	47
Dev. Temp.	68
Part	3
Machine	6
Tube Dist.	36
Time	V
MA	10
Voltage	35
Screen	31
Filter	-
Film No.	-
W. O.	472
Date	652
Em. No.	56
Subject	
V-1	
V-2	
V-3	
V-4	
V-5	13
Thickness	
Density	
Contrast	

Remarks
— Contrast



RESTRICTED

6

TRIPLETT & BARTON INC.
METALLURGICAL DIAGNOSIS

BURBANK, CALIFORNIA

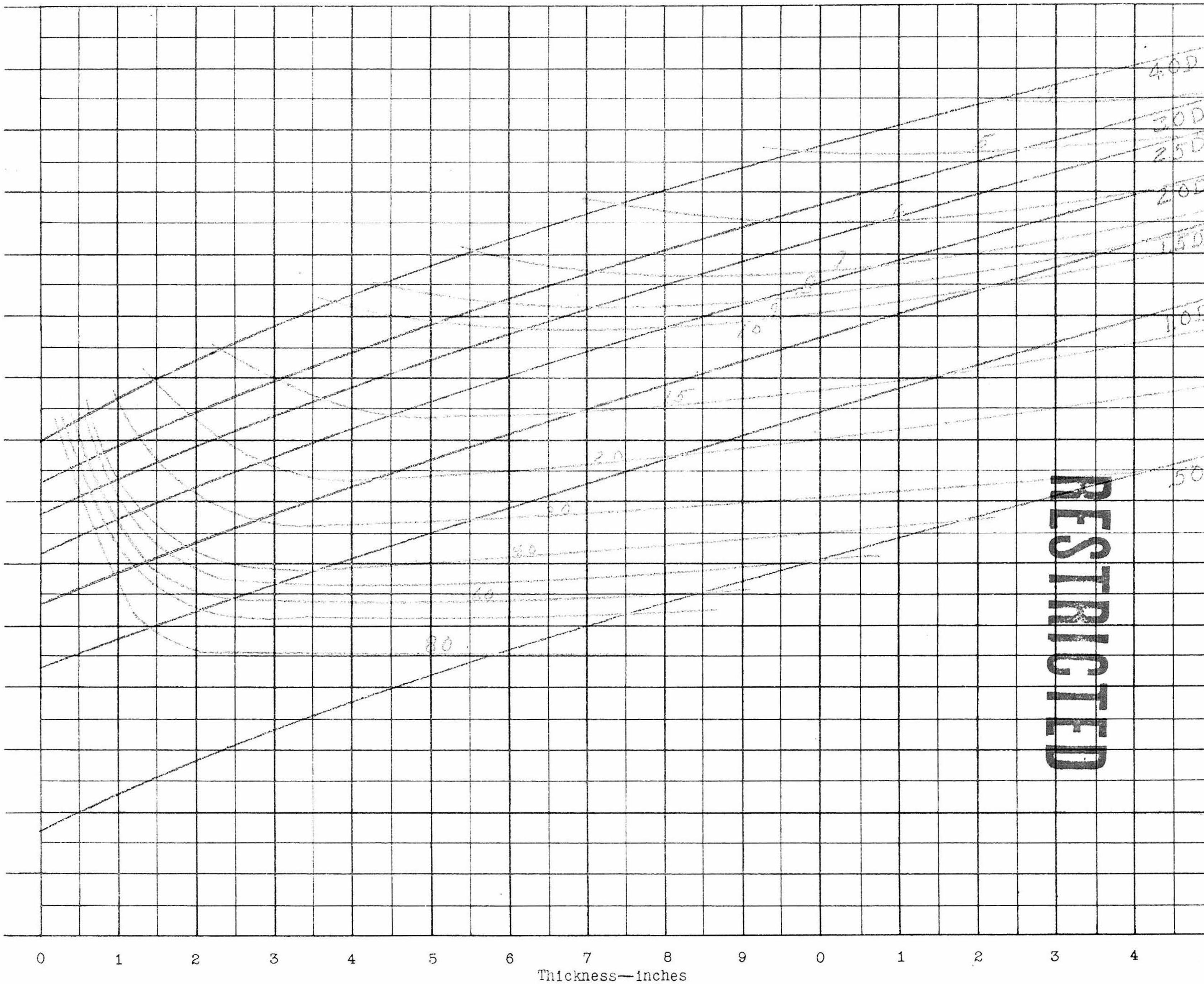
Report No. ___ Page No. ___

Speed	
Fog	17
Grain	
Film	60
Development	1
Developer	15
Dev. Time	47
Dev. Temp.	68
Part	3
Machine	6
Tube Dist.	36
Time	V
MA	10
Voltage	40
Screen	31
Filter	-
Film No.	-
W. O.	472
Date	654
Em. No.	56
Subject	
V-1	
V-2	
V-3	
V-4	
V-5	13
Thickness	
Density	
Contrast	

Remarks

— Contrast

Form 1716



TRIPLETT & BARTON INC
METALLURGICAL DIAGNOSIS
BURBANK, CALIFORNIA

Report No. ___ Page No. ___

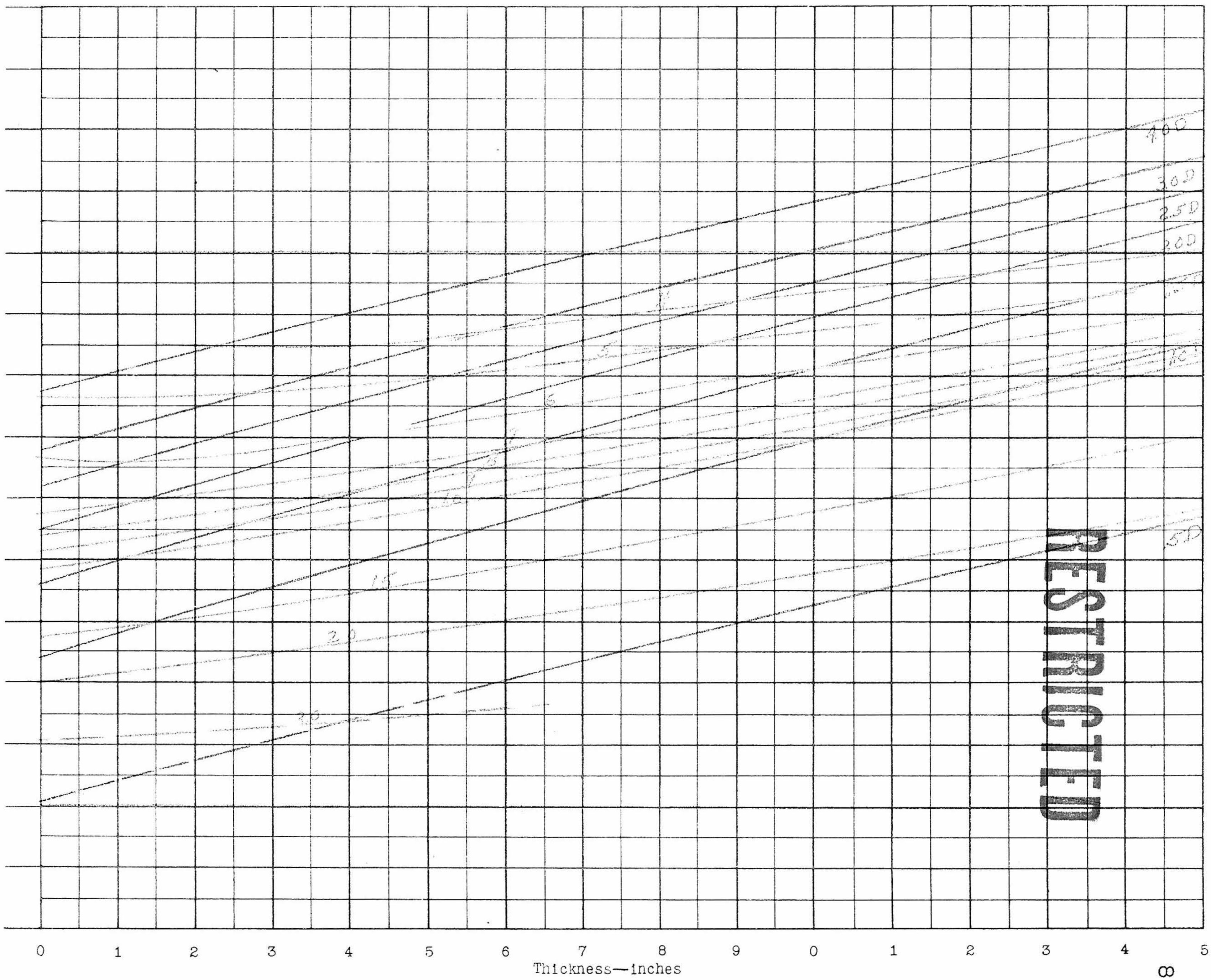
Speed	
Fog	17
Grain	
Film	60
Development	/
Developer	15
Dev. Time	47
Dev. Temp.	68
Part	3
Machine	6
Tube Dist.	36
Time	Y
MA	10
Voltage	40
Screen	31
Filter	–
Film No.	–
W. O.	472
Date	655
Em. No.	56
Subject	
V-1	
V-2	
V-3	
V-4	
V-5	13
Thickness	
Density	
Contrast	

Remarks

— Contrast

Form 1716

RESTRICTED



TRIPLETT & BARTON INC.
METALLURGICAL DIAGNOSIS

BURBANK, CALIFORNIA

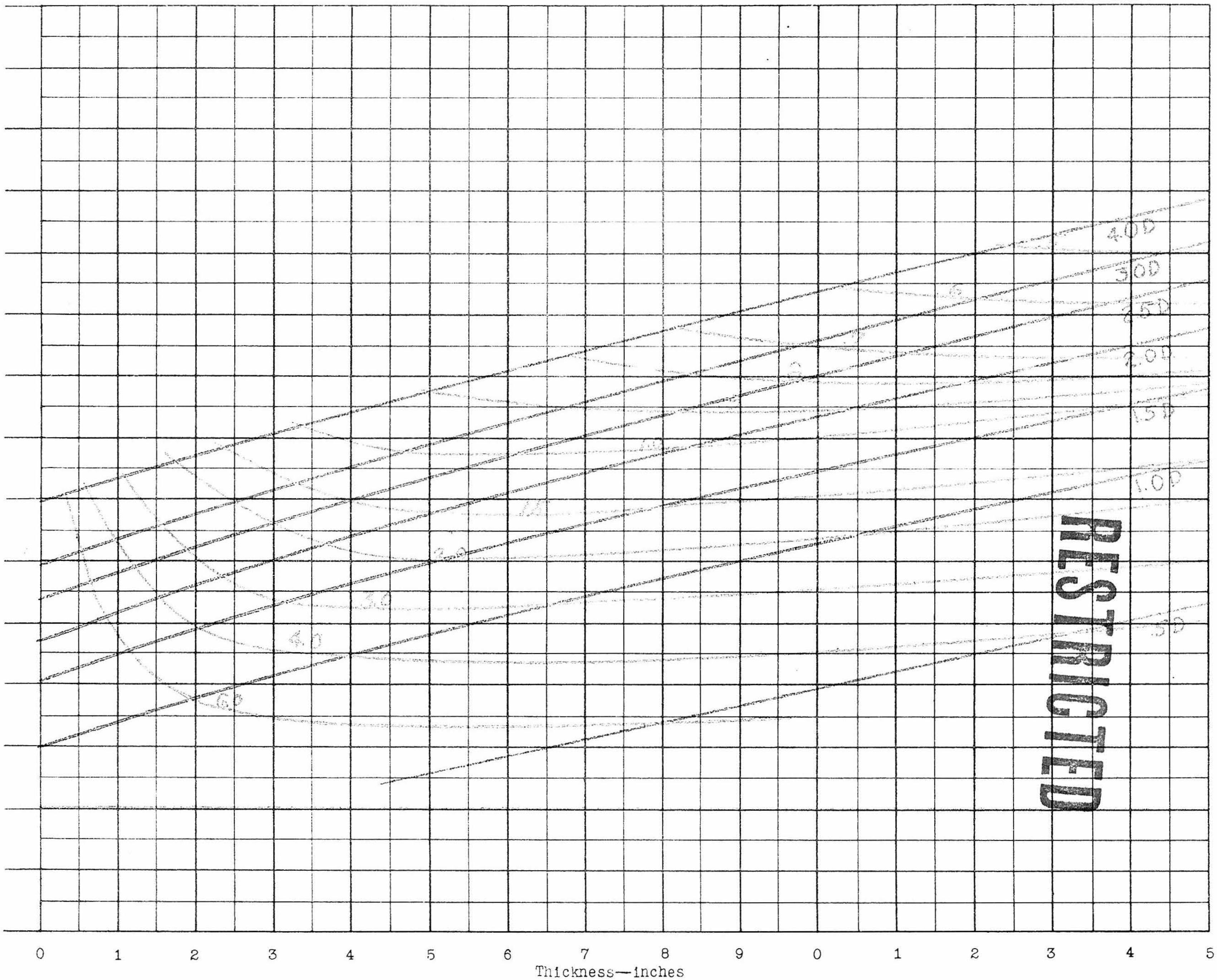
Report No. ___ Page No. ___

Form 1716

Speed	
Fog	17
Grain	
Film	60
Development	1
Developer	15
Dev. Time	47
Dev. Temp.	68
Part	3
Machine	6
Tube Dist.	36
Time	V
MA	10
Voltage	45
Screen	31
Filter	—
Film No.	321-8
W. O.	472
Date	656
Em. No.	56
Subject	
V-1	
V-2	
V-3	
V-4	
V-5	13
Thickness	
Density	
Contrast	

Remarks

— Contrast



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METALLURGICAL DIAGNOSIS

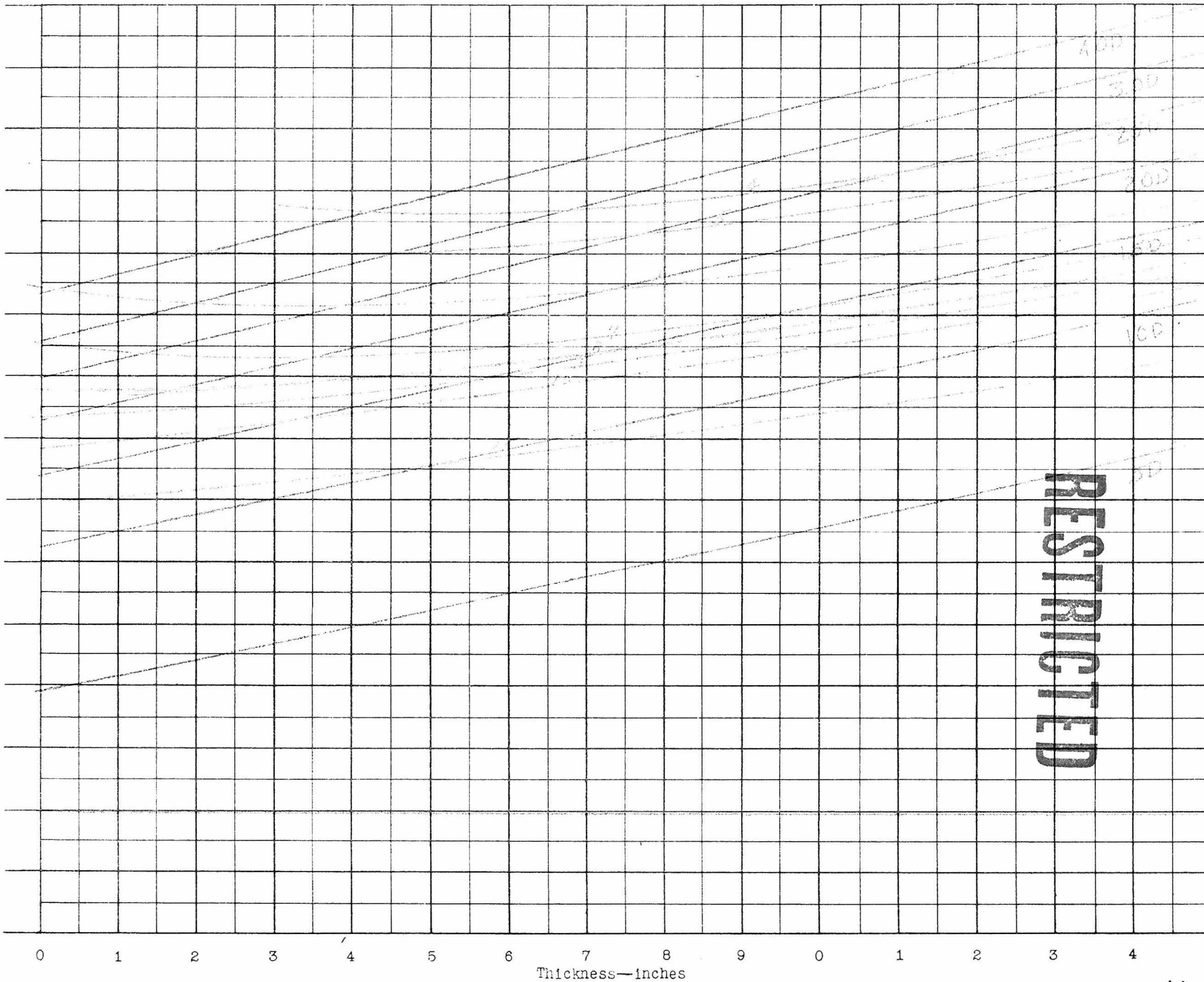
BURBANK, CALIFORNIA

Report No. ___ Page No. ___

Speed	
Fog	17
Grain	
Film	60
Development	1
Developer	15
Dev. Time	47
Dev. Temp.	68
Part	3
Machine	6
Tube Dist.	36
Time	V
MA	10
Voltage	45
Screen	31
Filter	-
Film No.	-
W. O.	472
Date	657
Em. No.	56
Subject	
V-1	
V-2	
V-3	
V-4	
V-5	13
Thickness	
Density	
Contrast	

Remarks

Form 1718



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METALLURGICAL DIAGNOSIS

BURBANK, CALIFORNIA

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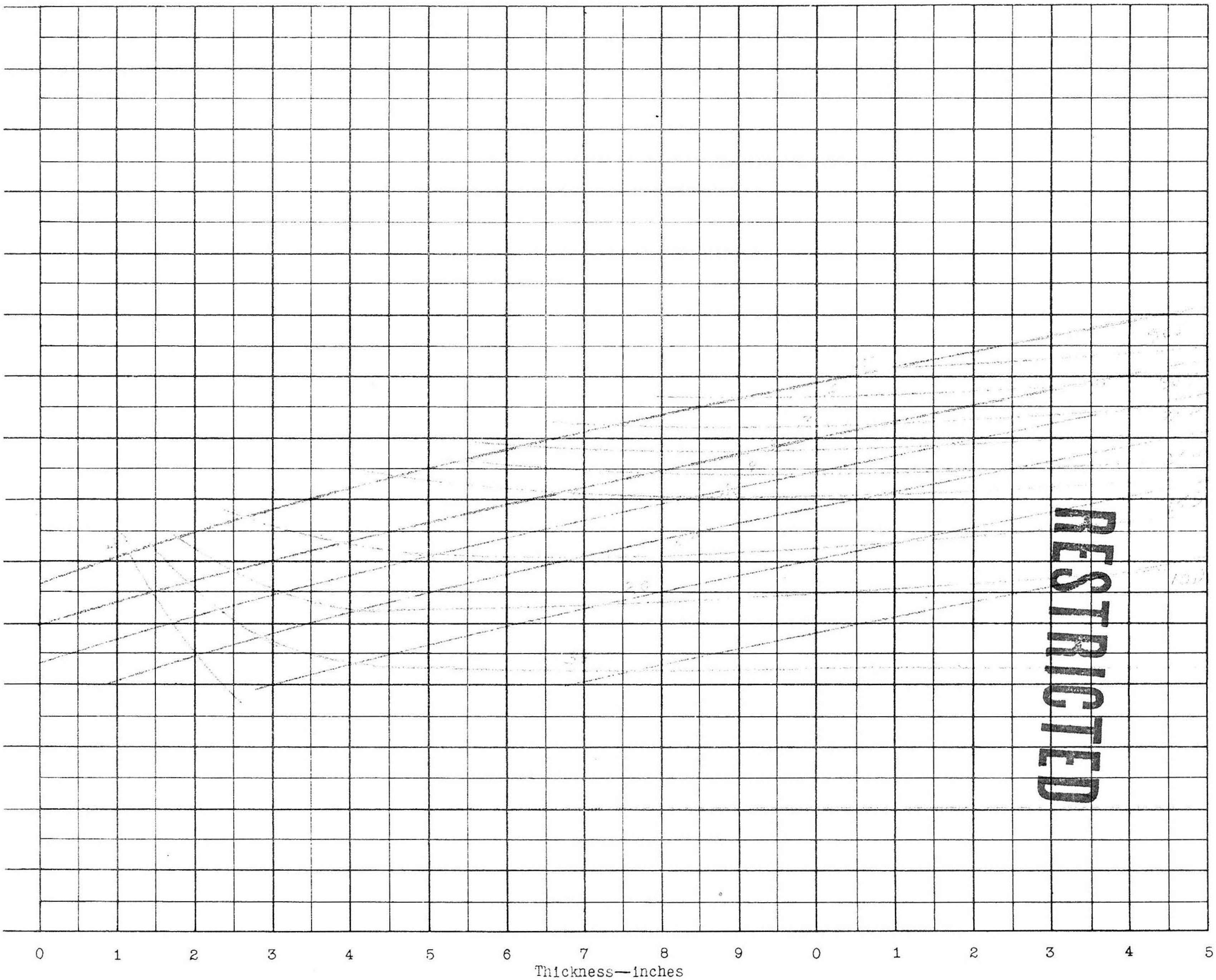
Form 1716

Speed	
Fog	17
Grain	
Film	60
Development	/
Developer	15
Dev. Time	47
Dev. Temp.	68
Part	3
Machine	6
Tube Dist.	36
Time	4
MA	10
Voltage	50
Screen	31
Filter	–
Film No.	–
W. O.	472
Date	658
Em. No.	56
Subject	
V-1	
V-2	
V-3	
V-4	
V-5	13
Thickness	
Density	
Contrast	

Remarks



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METALLURGICAL DIAGNOSIS

BURBANK, CALIFORNIA

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Form 1716

RESTRICTED

Speed	
Fog	
Grain	
Film	
Development	
Developer	
Dev. Time	
Dev. Temp.	
Part	
Machine	
Tube Dist.	
Time	
MA	
Voltage	
Screen	
Filter	
Film No.	
W. O.	
Date	
Em. No.	
Subject	
V-1	
V-2	
V-3	
V-4	
V-5	
Thickness	
Density	
Contrast	

Remarks

0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5

Thickness—inches