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INFLUENCE OF GEOMETRY AND RESIDUAL STRESS ON FATIGUE OF WELDED JOINTS

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UNIVERSITY OF ILLINOIS
In Cooperation With
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The purpose of this investigation was to study the factors which contribute to the relatively low fatigue strength of welded joints in high strength steel subjected to low mean stress and a large number of cycles. Fatigue tests were conducted on axially loaded specimens containing a double V butt-weld. A number of test series were devised to separate the effects of geometry and residual stress.

The significance of weld geometry was investigated by machining unwelded specimens to weld-like contours. Fatigue tests revealed that the geometry of the weld was extremely important at all levels of stress which were studied. If small irregularities or weld undercuts existed they could initiate premature failures. The stress concentration values of the weld reinforcement were evaluated by several methods including an equivalent shear method which is based primarily on the geometric properties of the weld reinforcement.

The influence of residual stress was studied by comparing the fatigue results of as-welded, stress relieved and unwelded specimens with the same geometry. Fatigue failures tended to initiate in regions of maximum tensile transverse residual stress.

Estimates of the maximum stress at the toes of a weld revealed that this stress is approximately equal to the yield stress even when the maximum nominal stress is the fatigue limit.

By subjecting the edges of the weld reinforcement to lateral pressure both the notch geometry and the residual stress pattern were altered. This process resulted in an increase in the fatigue strength.

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1 INTRODUCTION

1.1 General Consideration of Problem

Only recently quenched and tempered high strength steels have become available for structural purposes. Originally these steels were used almost exclusively for pressure vessels; however, during the last decade they have been employed in an ever increasing number of new structural applications. The combination of weldability and higher allowable stress is chiefly responsible for the growing popularity of this high strength steel.

Needless to say economy is motivating these new applications. Savings are realized when the increased allowable stress enables reductions in the cross-sections of members which more than offset the higher cost-per-pound of the quenched and tempered steel. In large structures a significant proportion of the design load represents the dead weight of the structure. By using smaller members of high strength steel the dead load is reduced, thus offering a hidden advantage. Welding combined with high yield strength steels invariably reduces erection and maintenance costs as well as making possible improved aesthetic qualities of the structure.

Recently the quenched and tempered steels have been used in the design of bridges, either as members of large trusses or even as flange material for long span girders. In bridge applications where the members are subjected to repeated loading, consideration must be given to the fatigue strength of the structure. While a structure will generally be subjected to a very large number of somewhat random stress variations, it is convenient to estimate the predominant stress cycle and the expected number of repetitions during the life of the structure. This enables a prediction of fatigue life to be made on the basis of laboratory tests which are generally conducted with a constant stress cycle.

Undercut - a groove melted into the base metal adjacent to the toe of a weld and left unfilled by the weld metal.

Weld reinforcement - weld metal on the face of a weld in excess of the metal necessary to obtain the thickness of the base plate material.

Notation

ρ	radius of curvature at the toe of weld.
θ	slope of tangent at end of initial curved section of reinforcement.
h	height of weld reinforcement at center of weld.
σ_y	yield strength of material.
$+\sigma$	tensile stress.
$-\sigma$	compressive stress.
Φ	stress function.
x	axis directed along specimen (see Fig. 5.3).
y	axis in direction of specimen thickness.
σ_{xx}	normal stress in direction of x axis.
σ_{max}	maximum value of σ_{xx} .
σ_{yy}	normal stress in direction of y axis.
τ_{xy}	shearing stress.
τ_{max}	maximum value of τ_{xy} on surface.
A_n	Fourier coefficient.
T	period of Fourier series.
$2c$	thickness of specimen.
$2L$	length of specimen.
$2w$	width of weld.
t	abscissa of τ_{max}.
s	$w - t$ (w minus t).

α	$n\pi/2L$.
K	stress concentration factor.
E	normal stress (σ_{xx}) at point (0, c+h).
A	area of shear stress triangle.
HAZ	heat-affected zone.
HABM	heat-affected base metal.
UBM	unaffected base metal.
WM	weld metal.

2 DESCRIPTION OF SPECIMENS AND STRENGTH FACTORS

2.1 Description of Material

All specimens were fabricated from N-A-Xtra 100 steel which was supplied by the National Steel Corporation in the form of 6 ft. x 12 ft. x 3/4 in. or 1 in. thick plates. This steel is a quenched and tempered steel having a minimum yield strength of 100 ksi. The particular heat treating process used for the various heats is presented in Table 1. Tables 2 and 3 contain the chemical and physical characteristics of this steel. A typical stress-strain curve for an ASTM 0.505 round specimen is shown in Fig. 2.1.

2.2 Specimen Fabrication

The following fabrication procedure is common to all specimens both unwelded and welded. Specimens have an overall length of 4 ft. and a width which is reduced from 10 in. at the ends to 4 in. in the central 5 in. of the specimens. This reduction in width is accomplished by means of a curved section of 7 in. radius (Fig. 2.2).

All specimen blanks were cut so that the direction of rolling would be the same as the direction of applied stress in the fatigue tests. No flame cutting was permitted near the test section in order to avoid altering the metallurgy. The specimens were reduced at the test section by sawing, followed by milling as indicated in Fig. 2.2. Finally the edges were draw-filed and polished in order to remove any small irregularities which might have an undue influence on failure.

2.2.1 Plain Plate Specimens All specimens which were not welded will be referred to as plain plate specimens even though they may be provided with some geometrical contour to study the effect of notch shape. In order that such plain plate specimens could be machined into the same shape as welded specimens, which were nominally 3/4 in. thick, it was necessary to use 1 in. material. Two different methods of machining this material were used, namely shaping and milling.

With the preliminary specimens it was noted that the shaper produced a considerably rougher surface than the milling process. Several exploratory tests indicated that the surface of some specimens had an excessive influence on the results. This condition occurred in specimens whose surface had been prepared by a shaper. This method of machining was therefore abandoned in favor of milling. However, since the milling machine could not produce a very sharp notch, the shaper was used to machine the motches required at the edge of simulated weld shapes. In order to produce a surface which approximated the smoothness of milling, cutting tools were made for the shaper which would produce the desired notch geometry. These tools allowed the shaper to cut without translating laterally between strokes and thus it produced a much smoother surface. To minimize any machining stresses, coolant was used and the material was removed in several layers, with a final cut of not more than 0.012 in.

2.2.2 <u>Welded Specimens</u> In fabricating the welded specimens, large plates were flame cut into blanks 10 in. by 4 ft. These blanks were then sawn into two pieces 10 in. by 2 ft. The two sawn edges were bevelled, with a 60 deg. included angle, in preparation for a double V butt-weld. On the surface of the steel adjacent to the bevelled edges the mill scale was ground off so that it would not interfere with the welding process. The mill scale remained unaltered on the rest of the surface.

Except for those studies carried out for the purpose of evaluating the effect of variations in welding procedure, the welding procedure used was the one used by Scott et al (1) in the previous tests of N-A-Xtra steel. The basic welding procedure is outlined in Section 3.2. The same welder who was qualified during these previous tests did all the welding reported herein.

E11018 electrodes were used throughout, with the exception of one series of tests in which some E7018 electrodes were used. All electrodes were baked at 800°F for one hour and stored at 350°F until used. In order that each of the six weld passes could be deposited in the flat position, the two specimen ends were securely clamped to a welding jig which could be rotated about a horizontal axis. All six passes were continuous for 7 in. with adjacent passes being in opposite directions. Preheat and interpass temperatures were controlled with the aid of a pyrometer.

After the welding had been completed, X-rays were taken of each weld in order to determine any defective specimens. The specimens were then drilled, sawn, and milled to the same standard specimen geometry as the plain plate specimens.

After a fracture has occurred it is extremely difficult to obtain accurate measurements of the surface geometry near the initiation point. In order to have this geometric information available, plaster casts were taken of all specimens which had weld-like contours. Vel Mix Stone and water were proportioned to form a thick paste which was tamped into a mold and allowed to harden. Casts, covering the reinforcement and one inch of plate material on each side, were taken of each weld face. When a specimen failed and the point of initiation was observed the appropriate cast could be sectioned at the corresponding location. The face of the cast exposed by sectioning was then magnified 50 times and the reinforcement geometry was recorded.

The point of fracture initiation was determined by observing the propagation pattern which tended to radiate from the initiation point. In the case of most fractures the initiation point or points were very well defined while occasional fractures seemed to initiate along a short length of material rather than from a point. Once the location of the fracture initiation had been established it was not difficult to section the matching cast within 1/16 in. of the corresponding point. The goemetry of the weld reinforcement does not change very rapidly along its length. Since this is the case, any small discrepancy in locating the initiation point or in finding the corresponding point on the cast would not lead to a large difference in the observed geometry of the weld reinforcement.

2.3 Test Equipment and Procedure

All fatigue tests were conducted on the University of Illinois 200,000 lb. lever type fatigue machines. Testing was carried out in a non-corrosive environment at about 200 cycles per minute. A schematic diagram of this equipment can be seen in Fig. 2.3.

The load in the specimen is determined by means of an Ames dial which measures the extension of the dynamometer. By adjusting the turnbuckle and the eccentric, the desired mean stress and stress range can be achieved.

The criterion used to determine the life of a specimen was the number of cycles at which approximately one-half of the cross-section was fractured. This condition was chosen because the microswitches generally shut the machine off by this stage. Occasionally the entire section would fracture before the machine was turned off. No adjustment was made in the number of cycles, in these cases, since the cracks were found to propagate very quickly.

All specimens were subjected to an axial load which varied from zero load to a fixed tensile load in each cycle. In order to reduce the effect of scatter, a minimum of three specimens were tested in each series. Specimens which did not fail within a reasonable number of cycles were retested at a higher stress. This new stress exceeded the initial one by at least 15 per cent where possible. It is assumed that the effect of the previous understressing is minimized by this procedure.

2.4 Factors Affecting Fatigue Strength

There is considerable difference between the fatigue strength of specimens with and without a butt-welded joint as shown in Fig. 1.3. The as-commercially produced plain plate specimens can withstand 80 per cent more stress than the welded specimens for a life of 2×10^6 cycles. Unwelded specimens fail at the end of the straight section. Failure occurs at this location because of a concentration of stress caused by the reduction in cross-section. According to Peterson (3) the width reduction cuases a stress concentration of approximately 1.14. That is, the stress at the edge of the specimen, where failure initiates, is 14 per cent higher than the nominal stress. This stress concentration means that an S-N curve for plain plate specimens, based on maximum actual stress, would be even higher than indicated on Fig. 1.1. A possible increase in stress of over 100 per cent exists at 2×10^6 cycles. While it is unlikely that all of this disparity will ever be eliminated, it should be possible to effect some changes in order to substantially reduce this difference.

In order to avoid fatigue failure it is necessary to ensure that the resistance to load exceeds the applied load at each point in the structure. In the case of a weld, both the resistance and the load vary significantly from point to point. Since fatigue failures are always accompanied by some local plastic deformation, it is convenient to think of the yield strength as the upper limit of the applied loading. In the case of a welded joint, failure initiates in an area subjected to a biaxial state of stress and thus the biaxial yield strength should be considered.

If some small portion of the material becomes overstressed for a particular loading condition this area can be very important under repetitive loading conditions. That area is then subjected to a load which at least equals its elastic resistance each time that particular loading condition, or one which is more severe is repeated. Under these conditions dislocations, which are ever present, can readily propagate into fractures.

A survey of the literature on fatigue indicates that a very large number of factors have some influence in determining the fatigue strength of a welded joint. The number of factors to be considered can be substantially reduced in the following manner. Those with relatively small effects can be excluded while others are controlled by the type of specimen and the desired loading condition. Those not being excluded or controlled can be combined into general groups leaving relatively few important factors to be studied in detail. The remainder of this section outlines the three factors which survived this elimination and grouping.

2.4.1 Metallurgical Effect In order to weld a joint it is necessary to heat the base metal adjacent to the weld to such an extent that its physical and metallurgical properties are substantially affected. Since a fatigue failure of a sound weld invariably initiates on the surface near the interface between the heat-affected zone and the weld metal, this metallurgical effect is probably quite important.

The only practical method of improving the metallurgy of this fracture initiation area is by altering the welding procedure. Any welding procedure must produce a weld which can meet the bending and tensile requirements of the weld qualification tests. It is not immediately evident that a procedure which would improve the fatigue characteristics would be capable of meeting the qualification requirements. Some tests are required to determine the extent to which both of these conditions can be satisfied.

2.4.2 Residual Stress Stress which exists in a member when it is not subjet to any external loading is called residual stress. This stress is caused by a material misfit which requires that a portion of the material be subjected to tensile stress and other areas to compressive stress in order to satisfy compatibility.

It is convenient to think of residual stress as being subdivided into micro- and macro-stresses; however, it must always be remembered that stress is the limiting value of force divided by area as the area approaches zero, and therefore there is no basic difference between these two stresses. As is implied by the names, macro-stress is associated with a considerable amount of material, such as the average stress on a large number of grains; while microstress refers to the stress acting on a much smaller area, a single grain or even a portion of a grain.

The person who is generally credited with the concept of residual stress is Heyn (4). Although his discovery occurred about fifty years ago, relatively little research was conducted on this subject until World War II. At that time, the loss of many welded ships by brittle fracture prompted a large research effort to find the origin, magnitude, and the contribution of residual stress to these failures. One might well expect that this extensive program would have greatly elucidated the problem. Unfortunately this is not the case.

Two quotations will serve to indicate the general transition of opinions which has taken place during the last two decades. In 1942, after making a comprehensive survey of the literature, Stitt and Chadsey (5) stated that "any unrelieved residual stress has little or not effect on fatigue". Trufyakov (6) concluded, in 1956, that "residual welding stresses exert a great influence on the fatigue strength of a welded joint". Finally a dominant conclusion seems to have evolved, namely that residual stress is no different than any other stress. Thus, the existence of residual stress may alter the stress cycle and therefore the fatigue strength.

Delay in achieving any unanimity of opinion, if indeed it has yet been achieved, was probably due to two main reasons. The first one is the difficulty of measuring residual stress and the second is the possibility of an unknown magnitude of mechanical stress relief when the yield strength is exceeded.

There are several main processes which can cause the formation of residual stresses, each of which could exist in the specimens used in this investigation. A brief discussion of these processes will follow.

Yielding, although it can reduce or even eliminate residual stress under some circumstances, will also produce residual stress under other conditions. Consider a specimen machined to a weld-like contour, without residual stress. Assume the specimen is now subjected to an axial load of one-half of the yield stress (σ_y) and that the notch is severe enough to cause a stress concentration of three. Instead of having the elastic stress distribution as indicated by the dotted line of Fig. 2.4a, yielding will restrict the maximum stress to the yield stress and the actual distribution will be as shown by the solid line. When the axial load is removed it will unload elastically, that is, the elastic stress distribution (dotted line) can be subtracted from the actual stress distribution (solid line) to obtain the unloaded stress distribution. Although the model is now subjected to no external loads, stress remains. Therefore a stress concentration has caused a residual stress to be induced. If this process was repeated the stress cycle based on nominal stress would be zero to one-half σ_y in tension and a modified Goodman diagram for as-commercially produced plate specimens would lead one to expect a life of almost 2×10^6 cycles. However, the true cycle at the notch would be from $-0.5\sigma_y$ (compression) to $+\sigma_y$ (tension) For this stress cycle, a life substantially less than 10^5 cycles would be predicted. Since the initiation of fatigue failures is such a local phenomenon, data presented on the basis of nominal stress is not indicative of the stress conditions which exist at the point of initiation of the fatigue crack.

Residual stress can also be produced by means of lateral pressure. A pair of dies pressed against a piece of steel, as shown in Fig. 2.4b, produce a large tensile stress perpendicular to the line of action of the applied pressure. The surface stress cannot exceed the yield stress, therefore the actual stress would be less than the elastic stress. Upon release of the die pressure the material unloads elastically and residual stress remains.

Probably the most commonly recognized source of residual stress in a welded joint is the dimensional change associated with the heating and cooling process of welding. Substantial biaxial or, in the case of thick welds, even triaxial residual stresses are developed. Stress in the direction of the weld will be referred to as longitudinal stress and that stress perpendicular to the weld as transverse stress. For a continuous pass weld the longitudinal stress builds up from zero at the ends of the weld, to a maximum tensile stress near the center (Fig. 2.5a). This stress is caused by the shrinkage of the cooling weld metal being resisted by the adjacent plate material. The transverse stress is of particular interest in this investigation since it is in the same direction as the applied loading. The transverse stress when averaged through the thickness varies from compression at the ends to tension in the central portion. Through the thickness, the transverse residual stress varies from tension at the weld surfaces to compression at mid-thickness. When the variation through the thickness is superimposed on the mean stress, it can readily be seen that the surface transverse residual stress is predominantly a tensile stress (Fig. 2.5b).

Another source of residual stress is the change in crystal structure which takes place during the transformation process. This change in crystal structure during the transformation of austenite to pearlite or martensite results in a volume change and residual stresses result.

In order to illustrate the effect of residual stress on fatigue life, several hypothetical cases will now be considered. In Fig. 2.6, a modified Goodman diagram has been drawn for a typical high strength steel without residual stress. If a specimen without residual stress was subjected to a 0 to +55 ksi stress cycle, failure would be expected at 10^6 cycles (indicated by point A on Fig. 2.6). Had a surface residual stress of +20 ksi existed, the actual stress cycle would have been +20 to +75 ksi on the surface. A specimen with this stress cycle would fall in a region where a life of 3×10^5 cycles would be indicated (point B). By increasing the residual stress to +40 ksi, point C indicates that the resulting life would be approximately one-tenth that of a specimen without residual stress. A residual compressive stress would have the opposite effect. For example, point D illustrates that a residual stress of -20 ksi will more than double the life expected with no residual stress. Since the residual stress does not alter the range of stress, various magnitudes of residual stress will merely shift the stress cycle along the dashed line of Fig. 2.6. This argument is valid so long as the load stress and the residual stress do not combine to cause yielding.

If tensile yielding does occur, this yielding tends to reduce the residual stress and thereby alter the fatigue stress cycle. Since significant stress concentrations often exist in members subjected to fatigue loading, it is quite likely that under high loads much of the residual stress developed by welding is altered by plastic deformation.

The modified Goodman diagram clearly indicates the beneficial effect of compressive residual stress in the vicinity of a potential fatigue failure. Unfortunately, it is not particularly easy to achieve this condition. Two general methods of introducing residual stress patterns have been used, namely localized heating and pressing. Heating, while very useful in the case of longitudinal welds, appears to be of little value in the case of transverse welds. Therefore, some form of pressing is available as a means of improving the residual stress distribution. The procedure used to obtain a compressive residual stress at a particular location is to yield the material in tension at that point by means of lateral pressure. Upon removal of the load, the material unloads elastically, thereby producing a compressive stress in the yielded material.

It must be noted that in any process which involves yielding of the material to effect an improvement in the ratigue strength, it is difficult to separate the effects of residual stress from those of strain hardening. However, in the case of high strength steel there is so little difference between the yield stress and the tensile strength that it is difficult to believe that strain hardening plays a major role.

Some investigation in which the processes referred to have been used are reported in the literature. Shot peening is by far the most common method of inducing compressive residual stress and the literature abounds with records of improved fatigue strength resulting from this process. One of the most interesting studies was conducted by Mattson and Robert (7). They found good correlation between residual stress and fatigue strength, tending to substantiate the concept of superpositioning of load stress and residual stress. Shot peening is not generally used because it is impractical in most cases.

Considerable work has been carried out by Gurney (8-13) in which he heated or pressed longitudinal welds to obtain a 100 per cent increase in fatigue strength. Apparently, the only research involving lateral pressure on transverse butt-welds was conducted by de Leiris (14). He obtained a 25 per cent improvement in fatigue strength by pressing with a multiple punch. De Leiris qualified his results with the statement that they could be obtained "providing the lines of welding to be hammered do now show serious irregularities which might cause an overlapping of the metal under the multiple tool, to prevent this tool from reaching some regions of the weld". This punch had a number of small rods which pressed independently and had an effect similar to peening.

2.4.3 Geometrical Notch There is no doubt that the change in plate thickness caused by the unavoidable weld reinforcement introduces a concentration of stress. The magnitude of this stress concentration (K) is substantial but it is very difficult to determine accurately.

Due to the nature of the welding process no two specimens can really be completely alike. Cross-sections of a weld a short distance apart often have significantly different shapes. The geometric properties in the immediate vicinity of the edge of the weld reinforcement are by far the most important. A study of the geometry at the fracture locations recorded in an earlier investigation of butt-welded joints revealed the following geometrical characteristics. Normally this failure region is characterized by a short curved section, with an average radius (ρ) of 0.08 in., and the slope of the tangent at the end of the curved section (θ) averaging 20 deg. While these values are normal, substantial deviations are common. Values of ρ were found to range between 0.00 and 0.60 in. and θ values ranged between 15 and 30 deg. Due to the somewhat irregular geometry at the toe of a weld both the ρ and the θ values are subject to interpretation. However, the value of ρ was generally small enough that ρ and θ were quite well defined.

Slight undercutting is not unusual. This means a groove exists near the toe of the weld with the bottom of the groove below the base metal surface. A second local influence is the effect of weld ripples. The weld electrode is pulled along as it melts producing a series of U-shaped ripples along the surface of the outer pass (Fig. 2.7a). The tips of the U coincide with the weld notches, one tip on each side. In a view of the weld cross-section, these tips appear as small grooves (Fig. 2.7c). Their size is not as important as their shape - the sharper the groove, the larger the concentration of stress. It is well known that a semi-circular groove can produce a value of K up to three and on occasions these grooves closely resemble a semi-circle.

The only attempt, known by the writer, to make an evaluation of K values for welded joints was made by Nishida (15). His photoelastic studies indicated that typical idealized weld shapes had K values between 1.4 and 1.7. However, tests on a semi-circular undercut produced a K of 3.3.

Having outlined three apparently important factors, the next step is to devise tests which will help to evaluate their contribution to the relatively low fatigue strength of high strength steel.

2.5 Factor Combinations

The only factor which can be isolated to produce significant results is the geometrical factor. By machining unwelded specimens to weld-like shapes or improved shapes, the influence of geometry alone can be determined.

Since a weld is generally accompanied by residual stress and some sort of a geometrical notch, it is desirable to study any changes to the welding procedure with specimens exhibiting all three factors. By stress relieving welded specimens and comparing the results to machined unwelded specimens of similar geometry, some idea of the contribution of the metallurgical factor can be obtained.

The effect of residual stress caused by welding can be determined by comparing the fatigue results of stress relieved and unrelieved specimens with the same geometry. This comparison will be made for both a standard and an improved weld geometry. The geometry in these two cases is controlled by machining both types of specimens to the same prescribed geometry.

Favorable residual stress could be evaluated by tests on specimens with or without a change in geometry. The shot peening process which is known to offer some improvement in fatigue strength, causes little geometrical change while developing favorable residual stress. A lateral pressing operation which would improve the geometry while inducing favorable residual stress, appears to offer all the advantages of peening plus the geometrical gain. Therefore, the pressing method will be used in this study instead of the peening process.

This investigation involves a large number of different series of tests. To aid in differentiating among the various series mnemonic specimen designation has been established. Each series is designated by two alphabetic characters which describe the residual stress conditions and the geometry, respectively, and one or two numeric digits to differentiate specimens of the same series. These designations will be explained as the particular series are introduced.

3 PRELIMINARY INVESTIGATION

3.1 Machined Plain Plate Series

The purpose of this series of tests was to determine the influence of geometry on fatigue strength. This objective was to be achieved by machining 1 in. thick plate material into 3/4 in. thick specimens with idealized weld contours. This procedure eliminated the metallurgical factor associated with welded joints and by careful machining, residual stress can be virtually eliminated to leave only the geometrical factor as a consideration. Three basic shapes were required; namely, an idealized weld contour, an improved weld contour and no weld contour at all. Two alphabetic characters are associated with each test series. For the entire machined plain plate series, the first character is "P" to indicate that the series is plain plate or unwelded. The second character indicates the geometry of the weld shape which is to be tested. Since three shapes were required for this unwelded series, three different letters are employed in the designations.

The idealized weld contour shape (Series PS) represented an attempt to match the geometry of actual welded specimens. Since it was impossible to machine a specimen to match exactly the irregular geometry of a weld, an attempt was made to match the average geometric conditions. The resulting weld shape appeared to be geometrically similar to an actual weld except that it had a smoother surface. The "S" in the series designation "PS" refers to this smooth weld shaped contour. Average values for the geometrical parameters which define the weld shape were determined from the fracture initiation points of specimens from a previous investigation. Since the same welding procedure was to be used in the subsequent tests which involved welded specimens, these average values should apply. The notch angle (θ) was found to average about 20 degrees, with individual values varying from 15 to 30 degrees. Since it was felt that this angle was quite important, machined geometry specimens were fabricated to cover this range. An average value of the notch radius (ρ) was found to be 0.08 in. Because of the difficulty in controlling such a small radius, a sharp notch with effectively zero radius was used. The influence of this slight difference in radius was checked by tests described in Section 3.3. The resulting shape is shown in Fig. 3.1b.

The second basic shape was used to find the effect of substantially reducing the concentration of stress at the weld. This was accomplished by the modified weld contour shape as shown in Fig. 3.1c. The modified weld contour shape (Series PM) was chosen so as to have approximately the same stress concentration factor as that which exists at the reduction in cross-section width. This means that if the stress, calculated with the stress concentration factor taken into consideration, is significant in determining the fatigue strength, the fatigue life should be about the same as that obtained on as-commercially produced plate specimens by Scott et al (1)

The third type of specimen was required to determine the effect of an additional factor which is caused by the machining, namely surface roughness. In order to evaluate the surface effect, several specimens were machined plain (Series PP), without any weld contour, so that the results could be compared to similar tests with an unaltered mill scale surface.

3.2 Alterations in Welding Procedure

There has been some indication that alterations in the welding procedure can effect improved fatigue strength. The alterations in welding procedure to be made during this investigation will be restricted to two which have given some indication of improving fatigue strength.

The basic welding procedure to be used in these tests is the one finally qualified by Scott et al (1) after several trial procedures were discarded. The details of this welding procedure can be seen in Fig. 3.2.

Tests reported by Hartman et al (16), based on a very limited number of tests of another high strength steel, have indicated improvement of fatigue strength with higher interpass temperatures. The standard welding procedure employed an interpass temperature of 250°F. Since 550°F is the practical upper limit, two groups of specimens were fabricated; one with 400°F and the other with 500°F interpass temperatures. In all cases a preheat temperature 50°F less than the interpass temperature was used. Heating was accomplished by means of an oxyacetylene torch.

The second alteration in the welding procedure involved the use of lower strength electrodes (E7018) for the outer passes. It was assumed that the E7018 eletrodes would undergo more plastic deformation at the edge of the weld reinforcement than the E11018 electrodes, thereby changing the geometry and reducing the stress concentration. Whether this would be significant enough to benefit the fatigue strength could be most easily determined by means of tests.

3.3 Machined Weld Series

The purpose of this test series was to determine the combined effect of residual stress and metallurgy on fatigue strength. The influence of these factors was to be separated by comparing welded and unwelded specimens with the same geometric characteristics. The specimens of this test series all have the letter "U" to indicate the presence of unaltered residual stress.

Welded specimens were machined to match each of the weld shapes in the machined plain plate series (Sec. 3.1) Since the geometry of specimens in each of these groups is comparable, the difference between the machined welded tests and the machined plain plate tests should indicate the metallurgical and residual stress effects caused by welding. Three tests were made on specimens machined to a smooth weld-like contour (Series US) with θ equal to 18 degrees. Five tests were conducted on welded specimens machined to the modified weld contour (Series UM). Several tests were carried out on specimens with the weld reinforcement completely milled off (Series UP). The geometry of these specimens is shown in Fig. 3.3.

By comparing the as-welded test results of reference (1), referred to in this investigation as series UA, with the results for the US series, which was machined to a smooth weld-like contour, an indication of the significance of the small difference in geometry could be obtained.

3.4 Stress Relieved Specimens

The tests of stress relieved specimens were devised to help separate the influence of metallurgy and residual stress. By comparing the results of stress relieved specimens with the machined weld test results, an indication of the influence of residual stress can be obtained. These test series all have the letter "R" to indicate that the residual stress is relieved. Three as-welded specimens, three machined weld specimens and three modified weld specimens were stress relieved. These specimens were subjected to 1100°F for one hour and then air cooled. Multiple comparisons can be made between the results for specimens of series RA, RS and RM, and the results of series UA, US, PS and PM.

3.5 Preliminary Pressed Weld Tests

The primary purpose of these tests was to evaluate the pressing apparatus and to determine the loads invovled. It was hoped that this experience would be helpful in directing later tests which involved this operation. The pressing was carried out in a 600,000 pound universal testing machine. A pair of hardened steel dies machined to the desired shape were used to apply the pressure at the required location on the specimen. The choice of die shape will determine the changes to be made in both the geometry and the residual stress. The first letter of each specimen designation is an "F" to indicate a favorable residual stress pattern.

The first pair of tests involved specimens whose weld reinforcement was completely flattened (Series FP). The effect of removing this geometrical stress raiser and the associated alteration of residual stress was to be indicated by testing these specimens in fatigue. These tests also would determine an upper bound on the pressing load. Four specimens were pressed to a modified weld contour (Series FM), in which the toes of the weld were curved with a ρ of 0.5 in. as shown in Fig. 3.4. Comparison of the fatigue results of this series with those of specimens which were machined to the same shape (Series UM) should give some indication of the effect which pressing had on residual stress. The third type of specimen (Series FG) had grooves pressed a short distance away from the toe of the weld. The purpose of these grooves was to reduce the stress at the toes of the weld. It was believed that this stress relieving effect would increase the fatigue life and possible even change the failure location to the bottom of the groove.

4 RESULTS AND DISCUSSION OF PRELIMINARY INVESTIGATION

4.1 Machined Plain Plate Results

The results of the tests on machined plain plate specimens are recorded in Table 4 and presented in Fig. 4.1 along with the S-N relationship determined previously for as-commercially produced plate for purposes of comparison. All of the points in Fig. 4.1 refer to specimens which failed at the transition section at the end of the straight portion. The effect of surface roughness on the fatigue strength can easily be observed in this figure. Surfaces prepared by a milling machine have slightly greater resistance to fatigue than mill scale surfaces. Surfaces prepared by a shaper are considerably less fatigue resistant than mill scale surfaces. These results are consistent with what would be expected on the basis of surface roughness measurements in the axial direction (Table 5). The rougher the surface the greater the stress concentration and therefore the lower the expected fatigue strength.

Because of the large difference between the fatigue results of specimens with shaped surfaces and those with mill scale surfaces, it was decided to discontinue the use of specimens prepared with the shaper after several exploratory tests. All subsequent machined surfaces were therefore made by milling, whenever possible.

Modified weld contour specimens (PM) failed where the width was reduced to 4 in. This failure location was not surprising since the geometry at the machined weld was chosen to be as severe at the point where the thickness changed as where the width changed. In Fig. 4.1 a circular symbol has been used to represent both the plain plate (PP) and the modified weld contour (PM) specimens since both groups failed at the same location. Modified weld contour results are represented by a solid circle to distinguish them from the plain plate results.

All failures in the series PS, idealized weld contours, occurred in a manner similar to failures of actual welded joints. Failures initiated at the edge of the simulated reinforcement anywhere across the entire width of the specimen, always starting at the surface. The number of initiation points varied from one to four and averaged two. Similar as-welded specimens were characterized by fewer fracture initiation points. In the case of welded specimens the geometry would vary along the weld notch and, in general, only one fracture would occur where the geometry was very severe.

As has been mentioned in Sec. 2.2.2 the geometrical conditions at fracture initiation points were determined by means of plaster casts which were made before the specimens were tested. Once the initiation point was noted the appropriate cast could be sectioned and the notch geometry revealed by magnifying the cross-section 50 times.

The machined weld contour (PS) results were found to be very dependent upon the notch angle θ. The test results are plotted in Fig. 4.2 and listed in Table 6. Results for θ of 15 degrees fell midway between the results for as-commercially produced plate and the results obtained for the as-welded joints. By increasing θ to 25 degrees, the fatigue strength was reduced to that of the as-welded specimens. Since the average θ for the fracture initiation points of as-welded specimens was 20 degrees, this means, specimens exhibiting only the geometrical influence (no welding and essentially no residual stress) have the same fatigue strength as welded specimens with a 5 degree less severe weld notch angle. This certainly indicates that geometry is a very significant factor.

4.2 Results of Altered Welding Procedure

In order to assess the contribution of metallurgy to any changes in fatigue strength, several specimens were examined metallurgically. The fatigue results and the metallurgical results have been separated into the following two sections.

4.2.1 Fatigue Results Seven of eight specimens prepared with higher interpass temperatures did not have a life as great as the specimens prepared with the standard welding procedure. For this series of tests the fatigue strength averaged 20 per cent less than the fatigue strength of standard as-welded specimens. Those specimens welded with an interpass temperature of 550°F appeared to be at least as resistant to fatigue as those prepared with a 400°F interpass temperature. These results are listed in Table 7 and plotted in Fig. 4.3.

The use of E7018 electrodes on the outer passes consistently reduced the life of the specimens when compared to similar specimens with E11018 electrodes on all passes. The lower strength electrodes appear to reduce the fatigue strength by approximately 20 per cent (Fig. 4.4 and Table 8).

Two specimens on Fig. 4.3 and one specimen on Fig. 4.4 have been plotted with a "d" to indicate that they were defective specimens. Normally a failure of a welded specimen initiates on the surface near the interface between the weld metal and the heat-affected zone. It requires a substantial defect to move the failure location elsewhere. Only three other failure locations were observed. Failures can initiate in the weld metal itself, starting at such defects as excess porosity, an inclusion, or lack of penetration. These failures can generally be spotted easily by observing the fracture surface. A second type of failure occurred near a nick or a protrusion in a specimen. Specimens were handled enough that they occasionally received nicks. If such stress raisers were located in a relatively highly stressed area they could cause a failure. For example, protrusions occasionally resulted from improper removal of the metal filings produced by milling and in several cases caused a failure where the specimen width was reduced to 4 in. The final type of failure was a fretting failure which generally started at the bolt holes in the pullheads of the specimen. When these failures occurred, new pullheads were welded on and the test continued. In the cases of the first two types of failure it was impossible to repair the defective portion and continue the test. Instead the result is plotted and accompanied by the symbol "d" to indicate that the true life would be somewhat in excess of the observed one had the defect not been present.

4.2.2 Metallurgical Results Three specimens with different interpass temperatures (250°F, 400°F and 550°F) and one specimen with low strength electrodes on the outer passes were examined metallurgically. Hardness surveys were made across the weld near the surface between the heat-affected zones.

250°F Interpass Temperature: Since this was the basic welding procedure, it was used as a standard with which to compare the other metallurgical results. The fatigue crack initiated at the interface between the weld metal (WM) and the heat-affected zone (HAZ). Along this WM-HAZ interface the martensite grains are large and the angle of crack penetration is about 45° to the surface. The fracture progressed along this interface for a very short distance and then crossed the martensite in the HAZ and proceeded almost straight across the specimen through the unaffected base metal.

Typical microstructures for the basic welding procedure are presented in Fig. 4.5. Photomicrographs revealed some porosity in the weld metal. The average hardness at the location of the notch was 270 D.P.H. (Depth Penetration Hardness).

400°F Interpass Temperature: The fracture started at the HAZ-WM interface where the average hardness was 271 D.P.H. and soon intersected a coarse martensite having a rather high hardness, the highest value reaching 624 D P.H. The crack intersected a larger than average number of inclusions and also excessive porosity. Hardness surveys are shown in Fig. 4.6.

550°F Interpass Temperature: The average notch hardness of 292 D.P.H. was considerably higher than the hardness of the lower interpass specimens. Microscopic examination revealed an exceptionally rough fracture with many hairline fractures occurring in some areas. It appears likely that internal cracks were formed in the large grained tempered martensite before the final crack propagated from the surface inward. Close examination of the photomicrographs indicated that some of the cracks followed the tempered martensite grain boundaries, while others progressed along continuous ferrite stringers. The ferrite nucleated at the old austenite grain boundaries when the rate of cooling was too slow to produce 100 per cent martensite.

Low Strength Outer Passes: This weld differed from the standard welds only in that the outer passes were made with E7018 electrodes instead of E11018. While the average hardness across the outer pass was 30 D.P.H. points lower than the preceding specimens, the average notch hardness was 376 D.P.H. or almost 100 points higher than the other notches. A fatigue crack initiated in the weld metal near the heat-affected zone. A second crack started about one-hundredth of an inch from the one which ultimately led to failure.

4.3 Machined Weld Results

A study of Fig. 4.7 reveals that the welded specimens which were machined to an idealized weld contour (US) exhibited the same resistance to fatigue as the as-welded specimens. The metallurgical structure of these US specimens was unaltered, the geometry was consistent across the width of the specimen but still comparable to the average geometry of an as-welded joint, and the residual stresses were virtually unaffected by the machining process and, therefore, this result is not surprising. These tests help to confirm that the PS series with the machined weld contour adequately represents the geometry of as-welded specimens.

A total of five modified weld contour specimens (UM) were tested at two different stress levels. Three UM specimens were tested at 0 to +55 ksi. The results show little or no improvement over as-welded results. Since these specimens had a substantially improved geometry this result was somewhat unexpected. It is felt that the relatively high nominal stress (+55 ksi), multiplied by the stress concentration factor and added to the residual stress must still have been producing considerable plastic deformation at the toe of the weld which resulted in an early fatigue failure. In order to check this reasoning, two specimens were tested with a maximum nominal stress of +40 ksi. It seemed unlikely that this stress level would cause plastic deformation. Both of these specimens had a life of 2×10^6 cycles without failure. This was a great improvement over the as-welded results as can be seen in Fig. 4.7.

Eight specimens were tested with the weld reinforcement completely removed (Series UP). The results which are recorded in Table 9 display considerable scatter. These specimens invariably had fatigue lives which were greater than the lives of as-welded joints and less than the lives of as-commercially produced plate specimens.

Examination of the failure surfaces of the seven specimens which failed revealed that five failures had initiated at weld defects and the other two failures had occurred a considerable distance away from the weld. Since five failures initiated at weld defects, it is not surprising that so much scatter was observed in the fatigue results. The geometry of the weld reinforcement of as-welded specimens varies with each specimen; however, the range of variation is fairly small. Thus, each as-welded specimen has a fairly severe stress raiser at the toes of the weld and therefore failures generally initiate at this location. Once the reinforcement is removed, internal defects, which are not controlled with respect to location or severity generally determine the initiation of a fatigue failure. Since there is a large variation in the severity of these weld defects, substantial scatter in the fatigue results of specimens with reinforcement removed is not unexpected. With the reinforcement in place, such minor internal defects could easily go undetected since the failure would occur at the edge of the reinforcement.

The combined results of the series UM and UP indicate that an improvement in weld geometry can increase the fatigue strength as long as two conditions are fulfilled. The first condition is that the external geometry is still severe enough to control the location of fracture. A second requirement appears to be that the fatigue stress cycle is low enough that the actual notch stress is somewhat below the yield strength of the material. It is difficult to know whether this second condition has been satisfied unless the residual stress pattern and the stress concentration values are known.

4.4 Results of Stress Relieving

Since the discussion of the effect of the stress relieving heat treatment relates to all three types of specimens, this discussion is deferred until the data have been presented. These results are listed in Table 10 and plotted on Fig. 4.8. Stress relieved specimens with weld shaped cross-sections (Series RA and RS) produced considerable scatter with only a small improvement over the as-welded results. The modified weld series (RM) also showed a slight improvement. All three specimens in the series (RM) were tested at 0 to +55 ksi. For the same reason as discussed in Section 4.3 it is felt that a much larger improvement would have been observed had the specimens been tested at 0 to +40 ksi.

Although the heat treating process, which was used to stress relieve these specimens, was not supposed to alter the material properties there is evidence that some changes have occurred. For example, the yield stress and the tensile strength (ultimate stress) of the stress relieved material has been increased while the ductility has been slightly reduced (Table 3). A stronger indication of the changes caused by stress relieving was obtained by observing the fracture surfaces. All stress relieved specimens had failures which initiated at the edge of the weld reinforcement; however, there was a strong tendency for the crack to propagate along the edge of the base metal-weld metal interface through the plate thickness, thus forming a V-shaped failure surface. This type of failure was not typical of any other test series. The shape of the failure surface tended to indicate that the stress relieving process had weakened the heat-affected zone.

The various initiation points were well spread out across the width of the specimen. Since this was in contrast to the as-welded specimen results, it appeared that the residual stress remaining in the stress relieved specimens was not dictating the location of fracture initiation.

The results for this RM series did not exhibit as much scatter as was observed in the RS and RA series. The only explanation which might account for this difference is the fact that only three tests were conducted with a 0 to +55 ksi stress cycle. It is quite possible that the sample is not large enough to properly indicate the scatter which could be expected.

4.5 Preliminary Pressed Weld Results

It should be recalled that the pressing tests in this group were strictly of an exploratory nature. The failure, in all cases, occurred at the same location as would have been observed in as-welded specimens, namely at the edge of the reinforcement. The entire series averaged a ten per cent increase in life; however, in all cases it could readily be seen that the pressing operation had not been carried out most advantageously. Furthermore, the pressing loads required to deform the metal into the desired shapes were excessive. To press the reinforcement level with the base metal required a load of 500 kips; while even the specimen with the smallest grooves required a load of 150 kips.

Both specimens which were pressed flat (Fig. 3.4a) had welds with undercuts. The pressing operation did not alter the geometry in the immediate vicinity of the undercut. It is also doubtful whether any significant change was made in the residual stress in the undercut region. Since failure occurred in the region of the undercut, it is not surprising that little improvement in fatigue strength was observed (Table 11).

The same situation which occurred in the specimens which were pressed flat, prevailed for those pressed to a modified weld shape (Fig. 3.4b). Some observable undercut was present in all specimens and this undercut could not consistently be pressed smooth. The slight improvement in fatigue strength could be attributed to the overall improvement in geometry. However, the improvement was small because geometry slightly removed from the notch has only a small effect. The local geometry is much more significant.

In the case of specimens with pressed grooves, the dies were machined so that the grooves were too far apart. The geometry at the point of initiation was not altered and the fatigue life was 15 per cent lower than for as-welded specimens. It is quite possible that pressing outside of the notch location increased the existing residual tensile stress at the notch. This increased residual stress could easily account for the reduced fatigue life.

The tests did show that specimen geometry can be conveniently changed by means of lateral pressing with dies. Furthermore this series emphasized the importance of conditions in the immediate vicinity of a fracture. Alteration of geometry and residual stress a short distance away from the point had only a small influence on the fatigue life.

4.6 Factor Contribution

It is convenient to examine these various test series simultaneously to assist in determining the relative significance of residual stress, metallurgy and geometry.

4.6.1 Residual Stress In order to evaluate the effect of residual stress it is necessary to compare geometrically similar specimens. This comparison will be made for two different shapes, namely the machined weld contour

(Fig. 4.9) and the modified weld contour (Fig. 4.10).

In the case of the machined weld contour, all specimens had very small notch radii while there was considerable variation in the notch angles. A number which represents the notch angle (θ) of the specimen, in degrees, accompanies each test result in Fig. 4.9. In order to evaluate the effect of metallurgy and residual stress collectively it is necessary to compare specimens with the same notch angle. Since only two of the welded specimens of the series US were free of defects and each of these specimens had a notch angle (θ) of 18 deg. it is convenient to make a comparison for this geometry. The close proximity of these results to the S-N relationship for as-welded specimens would seem to indicate that the same relationship would apply and a separate curve has not been drawn.

If one examines the results for unwelded specimens, represented by the circles in Fig. 4.9, for which the values of θ range from 15 to 30 deg. an S-N relationship would probably lie in the vicinity of the dashed line.

At a life of 10^6 cycles the dashed line representing the unwelded specimens (PS) indicates a fatigue strength of 40 ksi or approximately 20 per cent greater than the welded (US) specimens. The series PS differs from the series US only in the absence of the metallurgical and residual stress factors. These two factors, therefore, combine to decrease the fatigue strength by 20 per cent.

It would be desirable to determine the individual contribution, of both metallurgy and residual stress, to this decrease in fatigue strength. In order to evaluate the individual contribution it is necessary to examine the results for a group of specimens in which one of these parameters has been radically reduced. The stress relieved specimens (RS) which were intended to provide such a comparison exhibited an unreasonable amount of scatter.

In the case of the specimens with the modified weld contour the results were more consistent. It was immediately evident that the unwelded (PM) test series is considerably more fatigue resistant than the welded (UM) or welded-relieved (RM) series. Again this indicates the contribution of residual stress and metallurgy in lowering the fatigue strength. Examination of the data presented in Fig. 4.10 reveals that no improvement in fatigue life was obtained by stress relieving three of the specimens which were tested at 0 to +55 ksi. One might tend to conclude that residual stress was not important since stress relieving did not improve the fatigue life. However, two significant changes occurred in the stress relieved specimens which tend to contradict this conclusion. One is that unusual V-shaped failure surfaces were formed (Sec. 4.4) suggesting that the heat-affected zone had been weakened by the stress relieving process. The second factor tending to support the influence of residual stress was the fact that the failure initiation points were more randomly spread across the toe of the weld in the stress relieved specimens.

4.6.2 Geometry The importance of geometry has been clearly indicated by the machined plain plate tests. Unwelded specimens (PS) machined to match the weld geometry had lives only slightly greater than as-welded specimens while specimens machined to a modified weld contour (PM) proved slightly more fatigue resistant than as-commercially produced specimens.

The preliminary pressed tests (Sec. 3.5) showed the importance of the notch geometry. In many of these tests major changes in geometry were achieved a short distance away from the notch without altering the notch. These distant geometrical improvements were not reflected in the fatigue strength.

5 NOTCH STRESS DETERMINATION

5.1 Residual Stress Contribution

In order to estimate the actual stress in a loaded specimen at the toe of a weld it is necessary to determine the residual stress distribution at this location. Although the general distribution of residual stress in butt-welded joints has been determined by several researchers, it was felt that the stress magnitude would be highly dependent upon the welding procedure employed and any subsequent edge machining of the specimen (Fig. 2.2). It was therefore decided to measure the residual stress across the toes of a welded specimen.

5.1.1 Method of Measurement Foil strain gages of 1/16 in. grid were used to measure the surface residual stress of one as-welded fatigue specimen at seven different locations. The strain gages were attached to the specimen as close to the toe of the weld as possible and initial readings of the gages were taken. Next the residual stress was released by sawing so as to remove a small piece of metal with the strain gage attached. Another reading was taken when the sawing was complete. The difference between final and initial readings gives a measure of the strain caused by the residual stress in the direction of the gage. By placing a pair of perpendicular gages in locations of biaxial residual stress, the strains determined could be converted to stress.

A graph showing the relationship between yield strength and temperature, for the type of steel under study, was found in reference (17). This diagram indicated that there is negligible reduction in the short time yield strength for temperatures up to 800°F. This means that the residual stress would not be altered by temperature unless 800°F was exceeded. Only when the yield strength is less than the residual stress would any thermal relaxing of the residual stress take place.

Since the solder on the strain gage leads melted at about 300°F this became the controlling factor. A band saw was used to do most of the cutting, as temperatures could be held to just over 100°F with the aid of compressed air. The band saw was used to cut within 1/8 in. of the gages on the sides remote from the lead wires as indicated in Fig. 5.1c. In the next operation, a hand saw was used to cut approximately 1/16 in. below the surface under the entire area covered by the gages. The gages along with 1/16 in. of surface material were then removed by means of a cut perpendicular to the surface. Where two perpendicular gages were involved, one was trimmed closely and then a reading was taken. Next the first gage was destroyed as the second gage was trimmed as closely as possible before a reading was recorded.

5.1.2 Residual Stress Pattern The as-welded specimen was found to have the following surface residual stress distribution along the edge of the reinforcement. The longitudinal residual stress (parallel to the weld) increased from zero at the edges of the specimen to +48 ksi in the central portion. Transverse residual stress (perpendicular to the weld) had values as high as -55 ksi in the central portion (Fig. 5.2a). The lack of symmetry observed is not surprising because the temperature would be substantially different at each end of the weld when the final pass is completed. The resulting residual stress pattern is highly dependent upon this temperature distribution and the subsequent rate of cooling.

Many investigators have measured localized residual stress values up to the yield strength of the material, thus the observed value of +67 ksi does not seem excessive. It is strongly suspected that local residual stress values up to the yield strength exist in the weld before any machining takes place. The average transverse residual stress is compressive at the ends of the weld and tensile in the central portion. Equilibrium necessitates that the transverse compressive forces near the ends of the weld balance the central tensile force. When a fatigue specimen is sawn and milled to reduce it to its final dimensions, all of the material is removed from the compressive zone. The remaining residual stress must be in equilibrium, therefore the magnitude of this stress must be reduced in the specimen to be subjected to fatigue loading.

A study of the location of fracture initiation indicates the significance which residual stress plays in this initiation. Of those sepcimens in which residual stress was not purposely altered, over 90 per cent had failures which initiated in the central half of the cross-section where the measurements indicate a maximum transverse tensile residual stress. In the other 10 per cent of the specimens failure invariably initiated near the quarter points where substantial tensile residual stress existed. In no case was a failure observed to initiate at the edge of the specimen in the zone of compressive residual stress. In stress relieved specimens only 50 per cent of the failures initiated in the central portion. Since the stress relieving process substantially reduces the residual stress, the maximum stress at the notch becomes fairly uniform along the length of the weld causing failure initiation points to occur in a random manner.

5.2 Stress Concentration Factor

The nominal stress applied to a specimen is altered in the vicinity of the weld reinforcement because of the change in specimen cross-section associated with this reinforcement. In order to determine the notch stress of a loaded specimen it is necessary to know how this nominal stress is affected. Therefore the stress concentration factors at a number of typical fracture locations were evaluated.

There has been a great deal published on the theoretical calculation of stress concentration values (18). However, almost without exception, the studies have been concerned with grooves rather than projections. Considerable effort was expended in an attempt to develop a general closed form solution for the stress concentration values of weld-shaped projections; however, no success was achieved. The evaluation of stress concentration factors at the toe of the weld was made in the following three ways.

5.2.1 Strain Gages Stress concentration values were determined at seven locations along the notch of an as-welded specimen by means of strain gages. Using strain gages for this purpose undoubtedly yields a lower bound of the stress concentration value for two reasons. One is that strain gages average the strain over the length of the gage, which was 1/8 in. The second factor is that it is necessary to grind a small area smooth in order that the gage will properly adhere to the metal. This smoothing operation inevitably reduces the peak stress. The stress concentration values were found to range from 1.08 to 1.42 and to average 1.27.

Strain gages were also placed on one specimen which had been machined to a modified weld contour. Again the results of these measurements would be expected to be a lower bound of the stress concentration value; however, because of the smoothness of the machined surface and the short gage length (1/16 in. in this case), the observed strain should be close to the peak strain. An average stress concentration value of 1.22 was obtained for this modified weld contour specimen.

5.2.2 Photostress In order to determine the average stress concentration value along the entire notch, one specimen was coated with Photostress. Two methods of covering curved surface, such as weld reinforcement, are commonly employed. In one case liquid Photostress plastic is brushed directly on the test piece, while in the other case liquid plastic is poured into a mold forming a thin sheet. When the sheet is partly solidified it is glued onto the test section. Since it is flexible, it can be closely contoured to surface of fairly large curvature.

Preliminary tests of contoured sheets revealed that it was impossible to properly match the small notch radii. Brushing liquid plastic on a test specimen caused a variation in the thickness of the Photostress material over the surface. This variation proved to be a drawback because it complicated any stress concentration calculations. The procedure which was adopted consisted of applying sheet plastic to the flat portions next to the weld reinforcement and brushing liquid plastic over the reinforcement. By placing the flat sheets as close to the notch as possible, the thickness of the brushed plastic adjacent to these sheets could be maintained equal to the sheet plastic thickness. The material used had a strain sensitivity constant of 0.08 and a thickness of 0.0475 in.

A special procedure is required to ensure that the polarized light is properly reflected from the weld area. The light coming from the polariscope is normally reflected by the glue used to bond the plastic to the specimen. In the case of the brushed on material, no glue is used so it is necessary to sandblast the weld reinforcement to make it more reflective.

Once the photostress was in place, the specimen was loaded and unloaded and colored photographs were taken at regular intervals of load. The maximum load was large enough so that plastic deformation could be expected in the notch area.

Stress concentration values were determined for an as-welded specimen at three different levels of stress (30, 45, and 60 ksi). The mean value of K was 1.41 and the range was from 1.39 to 1.43. These very consistent results were achieved by optical compensation. By rotating the Photostress analyser a well defined color called "tint of passage" could be made predominant along the notch. The true birefringence in the plastic coating could then be determined by subtracting the artificial birefringence from that observed. The true birefringence can then be converted to stress. The tint of passage was chosen as the predominant color and thus it represents an average notch stress. Some small areas would be more highly stressed and others not stressed as much. While these differences could be seen through the Photostress instrument it would be difficult to accurately evaluate the range of stress concentrations along the notch.

The K value determined by Photostress is greater than that determined by strain gage measurements (1.41 vs. 1.27). This difference is to be expected since the use of Photostress does not alter the specimen geometry and there is no averaging over a gage length as in the case of strain gages. However, in case of Photostress the polarized light passes through the Photostress thereby averaging the strain through the thickness of the material (0.0475 in.).

When the applied load on the unloading cycle was made to match those loads at which the stress concnetration values had been determined, slight differences in the birefringence of the notch could be observed. This was doubtless due to the small amount of plastic deformation which must have occurred at maximum load.

5.2.3 Equivalent Shear Experimental evaluations of stress concentration factors are quite valuable; however, it is difficult to predict the effect of a slight change in geometry on such results. For this reason it is desirable to have some means of studying the effect of altering the significant geometric properties.

An "equivalent shear" method originally devised by Weinel (19) and later improved by Hetenyi and Liu (20) can be altered to permit the determination of approximate values of K for a wide variety of weld shapes. Weinel proposed that the shoulder portions of axially loaded notched bars be replaced by the stresses acting on the edges of the remaining portion. When reasonable assumptions as to the distribution of these stresses are made, stress concentration values can be obtained. Since the normal and shearing stresses represent boundary conditions on a member of constant thickness, the internal stress distribution can be determined by expressing the boundary loads by Fourier series and solving with the aid of a stress function. Weinel assumed that the normal stress would have negligible effect on the stress concentration factor. Furthermore, he assumed that the shear stress was proportional to the slope of the notch within the range of the notch and zero elsewhere. Equilibrium on the removed shoulder was used to determine the constant of proportionality.

Hetenyi et al (20) made a further contribution to this method. By observing the exact stress distributions in the vicinity of notches and fillets, determined by Neuber (18), a more realistic assumption as to the distribution of the shearing stress was made. A triangular distribution of shear stress seemed to represent closely the true distribution for grooved and filleted bars subjected to tensile loadings. Theoretical solutions further revealed that the apex of the triangle was approximately 0.5ρ from the notch. The magnitude of the maximum shear stress was found to be a function of the S/ρ ratio for shallow grooves and of $\sqrt{a/\rho}$ for deep notches ("S" is the thickness of the shoulder portion and "a" is one-half of the minimum thickness). Exact values obtained for elliptical notches were used for shallow grooves and the results obtained for hyperbolic notches were used for deep notches and fillets. The final dimension of the triangle (the base length) was chosen so as not to violate equilibrium.

It appears that this general approach can be applied to determine stress concentration values of welds as follows. Consider an axially loaded weld as shown in Fig. 5.3a. Because of the short width of the weld, the axial stress would not be uniformly distributed at the centerline. Instead, the stress would be somewhat reduced near the surface as shown in Fig. 5.3b.

If the reinforcement were imagined to be removed, the free body diagrams shown in Fig. 5.3c would result. The total shear force on a surface boundary between the weld reinforcement and the base plate would have to equal that portion of the axial load carried by the reinforcement. Geometric symmetry would necessitate zero shear at the center of the weld - the shear therefore varies from zero at the edge of the weld to a maximum near the edge and then decreases to zero at the center of the reinforcement. A triangular shear stress distribution would appear to produce a good approximation to the true distribution. The normal stress which Weinel (19) found to have negligible effect on the stress concentration of fillets, would be even smaller in the case of welds since the height of the reinforcement (h) is so small.

The boundary stress values would be completely defined if the coordinates of the apex of the shear stress distribution were known. It is strongly suspected that these coordinates are functions of the geometric properties θ, ρ and h. For example, in filleted or grooved members the location of maximum shear is highly dependent on ρ . It is reasonable to expect a similar dependence would exist for weld shapes. Equilibrium of one-half of the reinforcement would establish the maximum shear value. Since the axial stress is not uniformly distributed at the center line, the axial load in the reinforcement must be known before the equilibrium condition can be applied.

In the absence of precise knowledge of the apex coordinates, the problem can be set up for a shear stress triangle of unit area and an entire range of values for the location of the apex. As further experiments indicate reasonable methods of determining the apex, the appropriate values may be read from a chart. When tests indicate the proper manner of evaluating the shear triangle area, the value in the chart may be multiplied by the approximate area. The resulting number would be the amount by which the stress concentration value exceeds unity.

A more detailed explanation of how this equivalent shear approach was applied to weld shapes follows. The shear stress was assumed to have a triangular distribution for a distance w on either side of the centerline and to be zero elsewhere. It was desired to know the internal stress caused by the boundary loads acting on this equivalent member. Elasticity solutions of problems of this nature require the boundary loads to be single continuous functions along the entire edge. Thus one way such solutions could be used was to express the shear stress as a Fourier series where each term was continuous along the entire edge. By superposition, the sum of the series would yield the correct boundary loads and also the correct internal stresses.

It was decided to consider the boundary loading in two parts since this resulted in a more useful solution to the problem. The internal stresses caused by the shear loading alone were solved separately for a unit area shear triangle. These stresses could then be multiplied by the true shear area and added to the stress caused by the axial load, to obtain the true internal stress distribution. A schematic representation of this procedure is shown in Fig. 5.4.

The problem amounts to finding a solution which satisfies the boundary conditions for a two dimensional stress function. A solution of this type of problem is outlined by Timoshenko and Goodier (21). The equation for the stress function (ϕ) is

$$\frac{\partial^4\phi}{\partial x^4} + \frac{2\partial^4\phi}{\partial x^2 \partial y^2} + \frac{\partial^4\phi}{\partial y^4} = 0 \tag{5-1}$$

This equation can be satisfied by a function ϕ of the form

$$\phi = \sum_{n=1}^{\infty} \cos\alpha x . f(y) \tag{5-2}$$

where

$$\alpha = \frac{2n\pi}{T}$$

This leads to the following stress function:

$$\phi = \sum_{n=1}^{\infty} \cos\alpha x . (C_1 . \cosh\alpha y + C_2 . \sinh\alpha y + C_3 . y . \cosh\alpha y + C_4 . y . \sinh\alpha y) \tag{5-3}$$

The equation for the stress function is formed so that the following relations are satisfied:

$$\sigma_{xx} = \frac{\partial^2\phi}{\partial y^2} \qquad \sigma_{yy} = \frac{\partial^2\phi}{\partial x^2} \qquad \tau_{xy} = \frac{-\partial^2\phi}{\partial x \partial y} \tag{5-4}$$

Since the member is loaded with shear stress only, σ_{xx} must be zero at the end of the specimen. This necessitates $\cos\alpha x$ being zero at the ends of the specimen and therefore $\sin\alpha x$ is one. The shear stress is anti-symmetrical so it can be represented by a Fourier sine series of the form

$$\tau_{xy} = \sum_{n=1}^{\infty} A_n \cdot \sin \ \alpha x \ dx \tag{5-5}$$

where

$$A_n = 2/T \int_0^T (\tau_{xy}) \sin\alpha x \ dx \tag{5-6}$$

Since the sine terms must all be zero at $n = \pm 2L$ the period T of the series is 4L or twice the length of the specimen.

The shear stress has the following values when the apex coordinates are chosen to make the area of one shear triangle equal to unity.

$$\tau_{xy} = -2x/wt \qquad 0 < x < t$$

$$\tau_{xy} = 2(x-w)/ws \qquad t < x < w$$

$$\tau_{xy} = 0 \qquad w < x < L$$

Substituting the preceding shear stress expressions into the expression for A_n, Equation 5-6, results in the following:

$$A_n = \frac{-2}{wL\alpha^2} \ \{ (\frac{1}{s} + \frac{1}{t}) \sin\alpha t - (\frac{1}{s}) \sin\alpha w \} \qquad \text{if } s \neq 0 \text{ and } t \neq 0$$

$$A_n = \frac{-2}{wL\alpha^2}\{(\frac{1}{t})\sin\alpha t - \alpha\cos\alpha t\} \qquad \text{if } s = 0$$

$$A_n = \frac{-2}{wL\alpha^2}\{\alpha - (\frac{1}{s})\sin\alpha w\} \qquad \text{if } t = 0$$

The boundary conditions on the upper and lower surfaces are:

$$\sigma_{yy} = 0 \qquad \text{at} \qquad y = \pm c$$

$$\tau_{xy} = \pm\sum_{n=1}^{\infty} A_n . \sin\alpha x \qquad \text{at} \qquad y = \pm c$$

These four conditions permit the evaluation of the unknown constants C_1 through C_4 in Equation 5-3. By substituting these C values into the expression for σ_{xx}, evaluated at y = c, the following expression results:

$$\sigma_{xx} = 2\sum_{n=1} A_n \frac{\cosh^2 \alpha c}{(\alpha c + \sinh \alpha c \ . \ \cosh \alpha c)} \ . \ \cos \alpha x \qquad (5-7)$$

Since the butt-welds have a 60° included angle and the bevelled ends are placed 1/8 in. apart before welding, w can be expressed as a function of c; namely $w = 1/16 + c \ . \ \cot 60°$.

A sufficient number of terms must be taken to ensure adequate convergence; however, the number of terms required depends on the length of the specimen. If the member is made too long an excessive number of terms are required for adequate convergence. On the other hand if the member is too short the proximity of the ends will result in erroneous stress values near the centerline. By checking specific stress conditions for members of various lengths it was determined that for a length, L = 4w, adequate convergence was achieved with

300 terms.

The σ_{xx} expression was evaluated for several thicknesses. For each thickness σ_{xx} maximum was determined for many different positions of the apex of the shear stress triangle (i.e. many values of s). The results of these calculations are plotted in Fig. 4.11. If the coordinates of the apex of the shear triangle are known for a particular weld this diagram can be used to calculate the stress concentration value of the weld.

It was observed by Mathews (22) that the location of the peak stress was at a distance of 0.4 ρ from the notches of grooves and fillets rather than at 0.5 ρ as used by Hetenyi et al (20). Since the geometry in the vicinity of the notch is by far the most important in determining the location of the maximum shear stress, a similar relation would be expected for weld reinforcement. Until evidence indicates otherwise it will be assumed that $s = 0.4\ \rho$.

Next, the appropriate value of the shear triangle area must be evaluated. Since this area as used in the calculations is equal to the axial load in the reinforcement some bounds on its value can be determined. The axial stress would not be uniformly distributed at the centerline and therefore the reinforcement must carry less load than $h \cdot c/(h+c)$ on each side (assuming a unit tensile stress at the specimen ends). It is felt that the shear triangle area (A), because it is equal to the load in the reinforcement, depends upon ρ, h and θ. An extensive investigation would be necessary to determine the contribution of these factors. For two specimens a number of strain gages were placed on the top of the reinforcement at different locations to determine the axial stress (E) at this location. At each of these locations the geometry (ρ, h and θ) was recorded.

If the stress distribution at the centerline is assumed to be uniform over the middle 2c inches and to vary linearly to a value of E at the surface of the reinforcement, the stress concentration value can be evaluated. With this stress distribution A is equal to $\frac{hc}{h + 2c}(1 + E)$. Since the apex of the shear stress triangle is assumed to be 0.4ρ from the notch, the s/w ratio can be easily calculated. Having obtained the appropriate s/w ratio, the maximum stress for a unit shear area can be read from Fig. 5.5. This value when multiplied by A and added to 1.0 yields the stress concentration value of the notch.

Calculation of a typical stress concentration value would proceed as follows: assume that the member is 3/4 in. thick and has the following reinforcement characteristics $\rho = 0.21$ in., $h = 0.05$ in., and $E = 0.70$. Then,

$$w = 0.0625 + 0.375 \cot 60^\circ = 0.279 \text{ in.}$$

and

$$s/w = \frac{0.4 \times 0.21}{0.279} = 0.301 \text{ or } 30.1\%$$

For $s/w = 30.1$ per cent and $2c = 0.75$ in.

the maximum stress for a shear triangle of unit area can be read from Fig. 5.5.

$$\sigma_{max} = 8.4 \text{ in this case}$$

Next, the true value of A can be determined:

$$A = \frac{hc}{h + 2c}(1 + E) = \frac{0.05 \times 0.375}{0.05 + 0.75}(1 + 0.70) = 0.040$$

and thus

$$K = (8.4 \times 0.040) + 1 = 1.34$$

This procedure was followed at seven cross-sections of an as-welded (UA) specimen. The resulting K values averaged 1.40 and ranged from 1.26 to 1.53. Photostress results on a different as-welded specimen indicated an average K value of 1.41 (Sec. 5.2.2).

Three cross-sections of a modified weld contour specimen (UM) were evaluated by this equivalent shear method. The average K value was 1.27 and the range was from 1.24 to 1.30. The K value of this same specimen was evaluated by means of strain gages (Sec. 5.2.1) with an average K of 1.22 resulting. In light of the difficulty in placing the strain gages at the point of maximum stress and the inherent averaging over the gage length, these results are felt to be quite consistent.

Because of the consistency of the results, it is felt that this equivalent shear method of determining stress concentration values is adequate for a large range of geometric parameters. Conservative values for K can be obtained by assuming the stress to be uniformly distributed over the gross area. The true value of E is related to the values ρ, h and θ. The manner in which these values contribute to E requires a separate study.

5.3 Notch Stress Values

Having determined the residual stress distribution and typical stress concentration values it is now possible to estimate the stress occurring at the notches of loaded specimens.

When as-welded specimens were tested with a 0 to +34 ksi stress cycle there could be no certainty that failure would occur. A maximum stress concentration of 1.53 was evaluated for this type of specimen (Sec. 5.2.3) and a maximum transverse surface residual stress of +67 ksi was measured on another as-welded specimen (Sec. 5.1.2). If these two effects are combined a nominal stress of 34 ksi would represent a maximum notch stress of $(34 \times 1.53) + 67 = 119$ ksi. This stress is approximately equal to the biaxial yield stress of the material.

It can be seen in Fig. 4.10 that the UM specimens had lives over 2×10^6 cycles when cycled from 0 to +40 ksi. Since short lives were observed for specimens tested with 0 to +55 ksi stress cycles this value of 40 ksi must be approximately the fatigue limit. Stress concentration values were found to be approximately 1.27 for this type of specimen (Sec. 5.2.4). The residual stress values which were determined for the as-welded joints would not be appreciably changed by the machining process necessary to produce the modified weld contour. Therefore the maximum notch stress for a 0 to +40 ksi stress cycle would be (40 x 1.27) + 67 = 118 ksi or approximately the yield stress. The apparent absence of plastic deformation would seem consistent with the observed life. A 0 to +55 ksi stress cycle would appear to cause approximately 20 ksi of residual stress to be relieved mechanically. This could well be the reason that the stress relieved specimens (RM) were no more fatigue resistant than the unrelieved specimen (UM) at this stress level.

The relieving process would not completely eliminate the residual stress but rather reduce the stress to the value of the yield stress of the material at the relieving temperature. The stress relieved specimens were heated to 1100°F. It is indicated in Reference (17) that the yield strength of N-A-Xtra steel is approximately 30 ksi at this relieving temperature. This means that residual stress up to 30 ksi could remain in the relieved specimen. Assuming that 30 ksi of residual stress did remain the (RM) specimens, which were tested at 0 to +55 ksi, would have a maximum notch stress of (55 x 1.27) + 30 = 100 ksi. Since this notch stress is substantially below the yield stress it can only be concluded that the low observed life was caused by weakening of the heat-affected zone. It should be recalled that these specimens formed grooved shaped failure surfaces since the fatigue crack propagated along this heat-affected zone. Similar welded specimens (UM) tested at 0 to +55 ksi would have a maximum elastic notch stress of (55 x 1.27) + 67 = 137 ksi. This value is large enough to ensure considerable plastic deformation which is doubtless responsible for the short fatigue lives of these specimens. These calculations would seem to indicate the importance of keeping the notch stress low in order to avoid plastic deformation.

6 PRESSED WELD TESTS

6.1 Pressing Procedure

The test data indicate that both residual stress and geometry may have a major influence on fatigue behavior; therefore, any pressing procedure should attempt to make both of these factors more favorable. To ensure compressive residual stress along the toe of the weld the pressing should be carried out with a die having small diameter projections. However, if the diameter is too small the irregular geometry along the toe of the weld will cause part of the notch to remain unpressed. Obviously some compromise must be made in the choice of the projections.

Results presented in Sec. 5.2.3 indicate that as-welded specimens have average K values of 1.40 and modified weld contour specimens have average K values of 1.27. The preliminary pressing results of Sec. 4.5 showed that excessive die loads were required to change the geometry from as-welded to the modified weld contour. It appears that the most beneficial geometric effect of pressing will be the elimination of small irregularities at the notches. After proper pressing no cross-section will have a K value significantly above the mean. However, the main purpose of the pressing operation is to convert the tensile transverse residual stress into compressive stress.

A die with two 1/4 in. diameter projections was chosen. The 1/4 in. diameter dimension would be large enough to take care of the irregularities in the weld width yet small enough to achieve adequate alteration of the residual stress at loads that would not be excessive. These projections were machined 0.60 in. center to center on one face of a block of tool steel. A pair of these dies was machined from blocks which were 2 in. square in cross-section and 4.5 in. long. The dies were hardened by heat treatment before they were used. One pair of dies was employed to press all four notches simultaneously.

6.2 Pressed Weld Results

Eleven pressed specimens were tested with a 0 to +50 ksi stress cycle. The results which are presented in Table 12 show considerable scatter. All specimens had a life equal to or better than similarly tested as-welded specimens. The improvement based on life ranged from no effect to lives over three times as great as as-welded specimens.

A number of conditions are probably responsible for the large scatter in the results. Believed to be of prime importance is the fact that the plate material from which this series of specimens was fabricated was found to be badly warped. Four foot specimen blanks were bowed up to three-eighths of an inch. Prior to welding, these blanks were straightened as well as possible by bending them in the opposite direction until plastic deformation occurred. While this procedure eliminated most of the warping it was impossible to straighten the plate to the extent necessary to produce plane specimens. The remaining curvature made it difficult to properly align the bevelled ends which were to be welded. This condition resulted in small offsets which caused two of the notches to occur at small re-entrant corners. Failure invariably initiated at one of these two notches.

Three specimens (F13, F15, and F19) were tested when the machine was improperly adjusted. One of the pullheads could not rotate freely thereby inducing a bending moment. After this condition was detected the bending stress was measured by instrumenting a specimen with strain gages. The edge stress was found to differ from the nominal stress by ten per cent. The notch stress at the edge of the specimen would show an even greater discrepancy due to the stress concentration of the weld reinforcement. In each case failure initiated at the end of the weld notch which had the increased stress due to bending. When the results of these three specimens are compared to the results of as-welded specimens tested at a stress level equivalent to that caused by bending they are found to have over three times as long a fatigue life.

Several specimens had observable undercuts which prevented the dies from properly pressing the notch across the entire width. In these cases failure was found to initiate at that part of the notch which was undercut and where the deformation caused by pressing was either minimal or non-existent.

Two of the specimens (F18 and F111), which exhibited the longest lives, failed at a slight burr some distance from the weld. These burrs should have been removed during the draw-filling process. For these specimens all that can be said is that the true life is in excess of that which was observed.

Since several specimens achieved lives in excess of 4 x 10^5 cycles, compared to a life 1.5 x 10^5 for as-welded specimens, it is apparent that the pressing process offers a considerable advantage to fatigue resistance. It appears as though an increase in fatigue strength as great as 25 per cent can be obtained at lives of 4 x 10^5 cycles if compressive stresses can be induced along the entire notch.

Since specimen F18 failed about 4 in. away from the pressed notches this specimen was used after the fatigue test to determine the residual stress achieved by the pressing operation. The same procedure which was discussed in Sec. 5.1.1 was employed to determine this residual stress distribution. The transverse residual stress was found to be compressive along the entire notch. A minimum compressive residual stress of 14 ksi was measured at one edge while a maximum value of 30 ksi was recorded at the center. The lack of symmetry which was present in the as-welded specimen was again observed (Fig. 5.2b). It would be expected that the lack of symmetry observed in as-welded specimens would be maintained since the pressing operation would do nothing to alter this condition. It is interesting to note that while 90 per cent of the failures of as-welded specimens were observed to initiate in the central half of the specimen only one of the nine pressed specimens failing at the notch had a failure initiate in the central half of the specimen cross-section. Since the minimum transverse residual compressive stress occurred at the edges of the specimen these failure locations offer further evidence of the influence of residual stress in determining the location of fracture initiation.

6.3 Implementation of Pressing Methods

Pressing loads of approximately 300 kips were used to press the FI series. Such a substantial load would be difficult to obtain on a construction site. If one pair of notches was pressed at a time the required load would be halved. Furthermore if each inch of the notch length was pressed independently the load could be divided by eight. This could reduce the load to less than 40 kips which is well within the capacity of a squeeze riveting machine. This reduced pressing length would offer two additional advantages. Slight undercuts could be pressed since this would not involve excessive yielding of adjacent material. It would also be more convenient to accomodate slight changes in the width of the weld. While the toe of the weld is approximately linear over a one inch length wider variations can be expected over longer intervals. It therefore seems quite reasonable that the loads could be reduced substantially and an improvement in the effectiveness of the pressing procedure could be accomplished at the same time. While such a pressing process might appear to involve a significant amount of labor, it must be recalled that this would only have to be applied to a small proportion of the welded joints in a structure. Only those subjected to a large number of cycles and possessing a small dead load stress would likely need any improvement in fatigue strength.

7 SUMMARY

7.1 Preliminary Investigation

All of the fatigue tests reported herein have been conducted at one stress cycle (zero-to-tension), with one type of steel (N-A-Xtra 100) and at relatively long lives. Great care should be exercised when applying these results to conditions different from those under which the tests were conducted. Furthermore many of the test series contained as few as three specimens. Because of the inherent scatter associated with fatigue data it is quite possible that individual tests would deviate considerably from those tested.

The object of the preliminary investigation was to determine which factors were most significant in causing fatigue failures of butt-welded joints in high strength steel. Axial loaded fatigue tests on unwelded specimens, machined to simulate welds, indicated that the geometry of the weld reinforcement was very important in determining the resistance to fatigue at all levels of stress. The change in specimen cross-section associated with the weld reinforcement introduces a substantial stress concentration at this location. Although the exact manner in which the shape of the reinforcement contributes to this concentration of stress is somewhat in doubt the notch radius (ρ), the tangent slope (θ) and the height of the reinforcement (h) all appear to be of prime importance. The geometrical properties in the immediate vicinity of the notch are considerably more important than those at points a short distance away from the notch.

An equivalent shear method was developed which enabled the approximate calculation of stress concentration values for weld-shaped sections of known geometry. At present this method requires a strain gage to estimate the axial load being carried by the weld reinforcement. It is hoped that further study of the geometrical influence on stress flow will permit determination of the load in the reinforcement by geometrical properties alone. Applying this equivalent shear method to a typical as-welded specimen revealed stress concentration values which averaged 1.40 and ranged from 1.26 to 1.53.

Two changes were made in tne welding procedure in an attempt to improve the fatigue strength by altering the metallurgy. Neither increasing the interpass temperature nor reducing the electrode strength of the outer passes improved the fatigue strength.

There was a strong tendency for fatigue failures to initiate in areas containing a large amount of residual stress. A transverse surface residual stress (perpendicular to the weld) of 67 ksi was measured even though the process of machining the specimen edges (Fig. 2.2) must relieve a great deal of the initial residual stress.

Stress relieving proved to be of no value at higher stress levels and of only limited value in other cases. Failure surfaces of stress relieved specimens followed the edge of the weld metal forming a V-shaped failure surface. Since failure surfaces of unrelieved specimens were primarily perpendicular to the surface it appears that the stress relieving process weakened the heat-affected zone.

Most fatigue data are presented on a nominal stress basis. This is doubtless done because of the difficulty in determining the maximum stress in a member. However, evaluation of transverse residual stress and typical stress concentration values permitted estimates of the maximum stress in the specimens used in this investigation. These values seemed to indicate that the fatigue limit of welded joints is the nominal stress which causes the maximum notch stress to reach the yield stress of the material.

7.2 Pressed Weld Tests

The purpose of the final investigation was to improve the factors which had been found to have a significant effect on the fatigue strength of the specimens being tested. Geometry and residual stress had both proved to play important roles in the observed fatigue failures. Omitting metallurgy from the list of important factors is not an indication that it is not important but rather that no practical way of improving it is known.

The toes of the welds were pressed with dies in order to alter the residual stress across the entire notch and to produce an improvement in the geometry of the notch. Residual stress measurements revealed that the pressing operation had produced transverse compressive residual stress varying from 14 to 30 ksi across the entire weld notch.

Although the fatigue results were somewhat clouded by several factors which could not be adequately controlled it was obvious that an improvement in the fatigue strength of the high strength welded joints had been achieved by pressing the toes of the welds. The pressing method which was used can certainly be improved and this would probably result in even greater increases in fatigue resistance. Changes in the pressing procedure could be made to reduce the pressure required to such an extent that economical pressing equipment could be located on a construction site. These same changes would make it easier to control the amount and location of applied pressure.

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TABLE 1

HEAT TREATMENT CYCLES

Heat No.	Austentizing Treatment		Tempering Treatment	
	Temperature °F	Time Minutes	Temperature °F	Time Minutes
5M-15629	1650	70	1260	60
5MB-15103	1650	70	1240	60
5MB-05579	1650	90	1260	70

TABLE 2

CHEMICAL COMPOSITION OF PLATE MATERIAL

Chemical Content (per cent)	Heat 5M-15629		Heat 5MB-15103		Heat 5MB-05579	
	Manu.*	Check**	Manu.	Check	Manu.	Check
C	0.19	0.21	0.17	0.17	0.18	0.20
Mn	0.97	0.98	1.04	1.05	0.99	0.96
P	0.008	0.010	0.0.8	0.041 0.039	0.012	0.016
S	0.020	0.017	0.021	0.019	0.017	0.015
Si	0.78	0.75	0.85	0.51	0.52	0.43
Cr	0.68	0.68	0.82	0.70	0.68	0.57
Mo	0.25	0.26	0.24	0.26	0.20	0.20
Zr	0.10	0.10	0.10	0.03	0.09	0.05
Cu	--	0.03	--	0.14	--	0.14

* Information supplied by the manufacturer
** Check analysis

TABLE 3

PHYSICAL CHARACTERISTICS OF PLATE MATERIAL

(a) Information supplied by the manufacturer

Heat No.	Direction	Yield Stress* (ksi)	Ultimate Stress (ksi)	Elongation 2-in. (per cent)	Brinell Hardness No.
5M-15629 3/4-in.	Long.	104.0	116.4	28	---
	Trans.	106.1	119.2	22	
5MB-15103 3/4-in.	Long.	109.4	120.8	30	255
	Trans.	109.4	121.7	28	
5MB-05579 1-in.	Long.	108.3	118.7	36	255
	Trans.	110.0	119.4	34	

* 0.2 per cent offset.

(b) Based on 0.505 in. round specimens**

Heat No.	Direction	Yield Stress*** (ksi)	Ultimate Stress (ksi)	Elongation in 2-in. (per cent)	Reduction in area (per cent)
5M-15629	Long.	96.3	111.3	23.1	65.1
5MB-15103	Long.	111.2	121.0	20.8	61.5
5MB-15103 Stress Relieved	Long.	116.0	125.3	20.2	59.9
5MB-05579	Long.	110.8	119.9	21.0	61.6

** Results are averages of at least three tests.
*** Halt of the pointer method.

TABLE 4

RESULTS FOR MACHINED SPECIMENS FAILING AS PLAIN PLATES*

Specimen**	Machining Method	Stress (ksi)	Life (cycles)
PP1	milled	0 to +75	330,000
PP2	milled	0 to +65	610,000
PP3	milled	0 to +60	2,040,000^{u}
PP3	milled	0 to +65	900,000^{r}
PM1	milled	0 to +65	390,000
PM2	milled	0 to +65	430,000
PM3	milled	0 to +65	2,120,000
PS10	shaped	0 to +50	370,000
PS11	shaped	0 to +40	660,000
PS12	shaped	0 to +40	950,000

* Plotted in Fig. 4.1
** See Fig. 3.1

u Specimen did not fail.
r Rerun of unfailed specimen.

TABLE 5

SURFACE ROUGHNESS MEASUREMENTS*

Type of Surface	Axial Direction	Transverse Direction
Milled	20	40
Mill Scale	100	100
Shaped Single Pass	120	50
Shaped Multi Pass	230	80

* Expressed as a per cent of mill scale roughness.

TABLE 6

RESULTS FOR MACHINED SPECIMENS FAILING AT MACHINED WELD CONTOUR*

Specimen**	Stress (ksi)	Life (cycles)	Notch Angle (degrees)
PS1	0 to +65	70,000	30
PS2	0 to +40	3,340,000[u]	15
PS2	0 to +50	500,000[r]	15
PS3	0 to +45	2,520,000[u]	15
PS3	0 to +55	360,000[r]	15
PS4	0 to +45	190,000	25
PS5	0 to +34	2,700,000[u]	15
PS5	o to +45	700,000[r]	15
PS6	0 to +34	1,170,000	25

* Plotted in Fig. 4.2

** See Fig. 3.1b

[u] Specimen did not fail.

[r] Rerun of unfailed specimen.

TABLE 7

FATIGUE RESULTS FOR VARIATION IN INTERPASS TEMPERATURE*

Specimen	Interpass Temperature (°F)	Stress (ksi)	Life (cycles)
UA1	400	o to +30	555,000
UA2	400	0 to +34	510,000[d]
UA3	400	0 to +34	390,000
UA4	400	0 to +34	360,000
UA5	550	0 to +30	2,690,000[u]
UA6	550	0 to +30	490,000[d]
UA7	550	0 to +34	600,000
UA8	550	0 to +34	380,000

* Plotted in Fig. 4.3
d Defective specimen.
u Specimen did not fail.

TABLE 8

FATIGUE RESULTS FOR LOW STRENGTH ELECTRODES ON OUTER PASSES*

Specimen	Stress (ksi)	Life (cycles)
UA9	0 to +34	440,000
UA10	0 to +34	350,000
UA11	0 to +34	310,000
UA12	0 to +34	200,000[d]

* E7018 electrodes used on outer passes, E11018 elsewhere-results plotted in Fig. 4.4
d Defective specimen.

TABLE 9

RESULTS OF SPECIMENS WITH WELD SHAPE ALTERED BY MACHINING*

Specimen**	Stress (ksi)	Life (cycles)
US1	0 to +34	900,000
US2	0 to +34	790,000
US3	0 to +34	520,000[d]
UM1	0 to +55	150,000
UM2	0 to +55	170,000
UM3	0 to +55	250,000
UM4	0 to +40	2,500,000[u]
UM5	0 to +40	1,980,000[u]
UP1	0 to +55	490,000
UP2	0 to +55	1,430,000
UP3	0 to +40	560,000
UP4	0 to +40	1,360,000[u]
UP5	0 to +55	60,000
UP6	0 to +55	120,000
UP7	0 to +55	140,000
UP8	0 to +40	2,010,000

* Plotted in Fig. 4.7
** See Fig. 3.3
d Defective specimen
u Specimen did not fail

TABLE 10

RESULTS OF STRESS RELIEVING*

Specimen	Stress (ksi)	Life (cycles)
RA1	0 to +34	480,000
RA2	0 to +34	2,900,000^{u}
RA2	0 to +40	400,000^{r}
RA3	0 to +40	140,000
RS1	0 to +34	2,500,000^{u}
RS1	0 to +40	1,820,000^{ru}
RS2	0 to +34	2,290,000^{u}
RS2	0 to +40	590,000^{r}
RS3	0 to +40	280,000
RM1	0 to +55	160,000
RM2	0 to +55	140,000
RM3	0 to +55	100,000

* Plotted in Fig. 4.8
u Specimen did not fail
r Rerun of unfailed specimen

TABLE 11

PRESSED WELD RESULTS

Specimen*	Stress (ksi)	Life	r (in)	f (in)	g (in)
FG1	0 to +40	340,000	0.25	0.18	0.01
FG2	0 to +40	350,000	0.25	0.18	0.06
FG3	0 to +40	400,000	0.25	0.18	0.02
FP1	0 to +40	380,000			
FP2	0 to +40	710,000			
FM1	0 to +40	400,000			
FM2	0 to +40	480,000			
FM3	0 to +40	500,000			
FM4	0 to +40	660,000			

* See Fig. 3.5

TABLE 12

FINAL PRESSED WELD RESULTS

Specimen	Stress (ksi)	Life (cycles)
FI1	0 to +50	160,000[d]
FI2	0 to +50	180,000
FI3	0 to +50	180,000[b]
FI4	0 to +50	210,000
FI5	0 to +50	240,000[b]
FI6	0 to +50	270,000
FI7	0 to +50	280,000
FI8	0 to +50	340,000[u]
FI9	0 to +50	430,000[b]
FI10	0 to +50	440,000
FI11	0 to +50	530,000[u]

[b] Bending caused by machine
[d] Defective specimen
[u] Specimen did not fail at weld

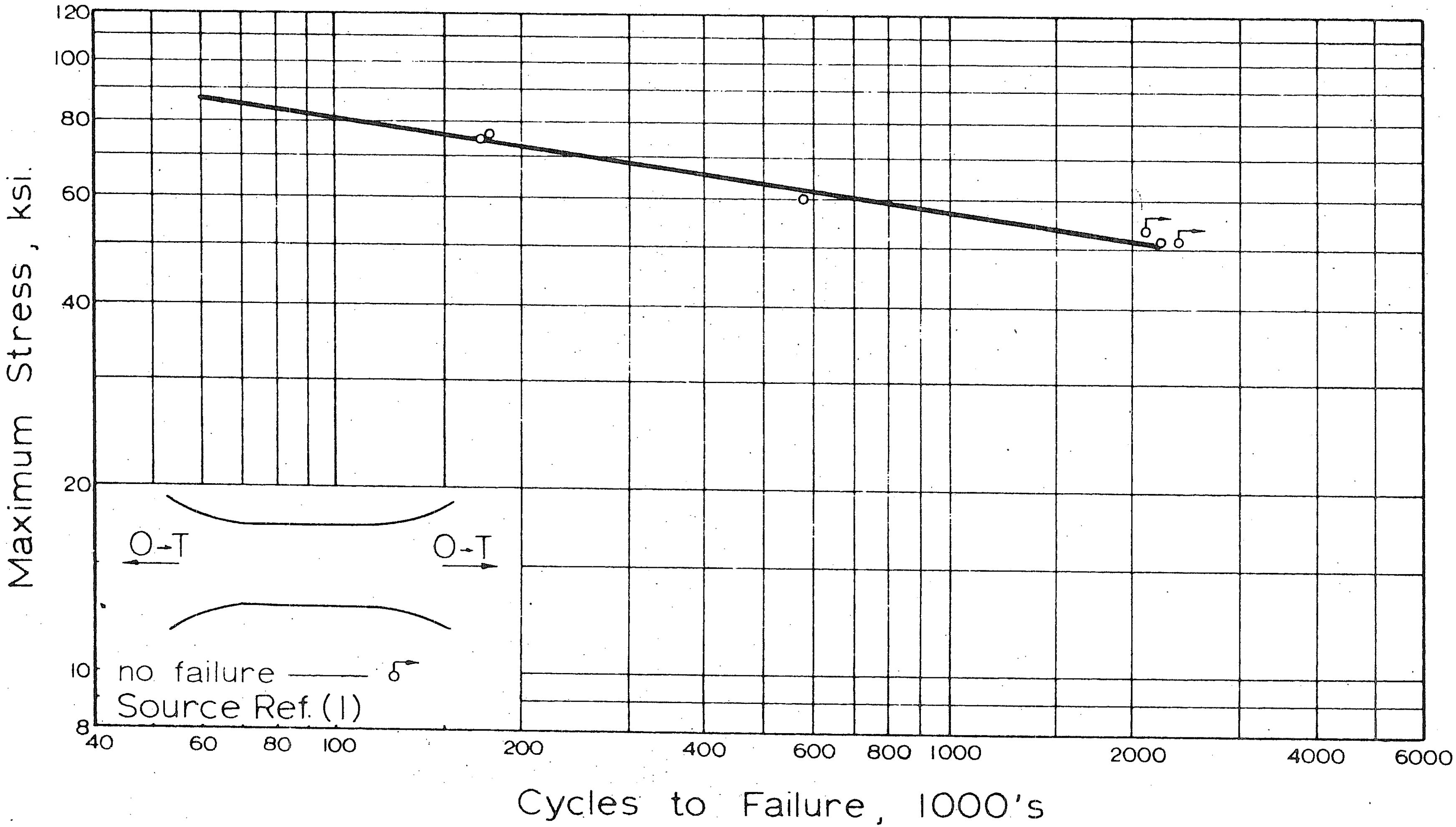
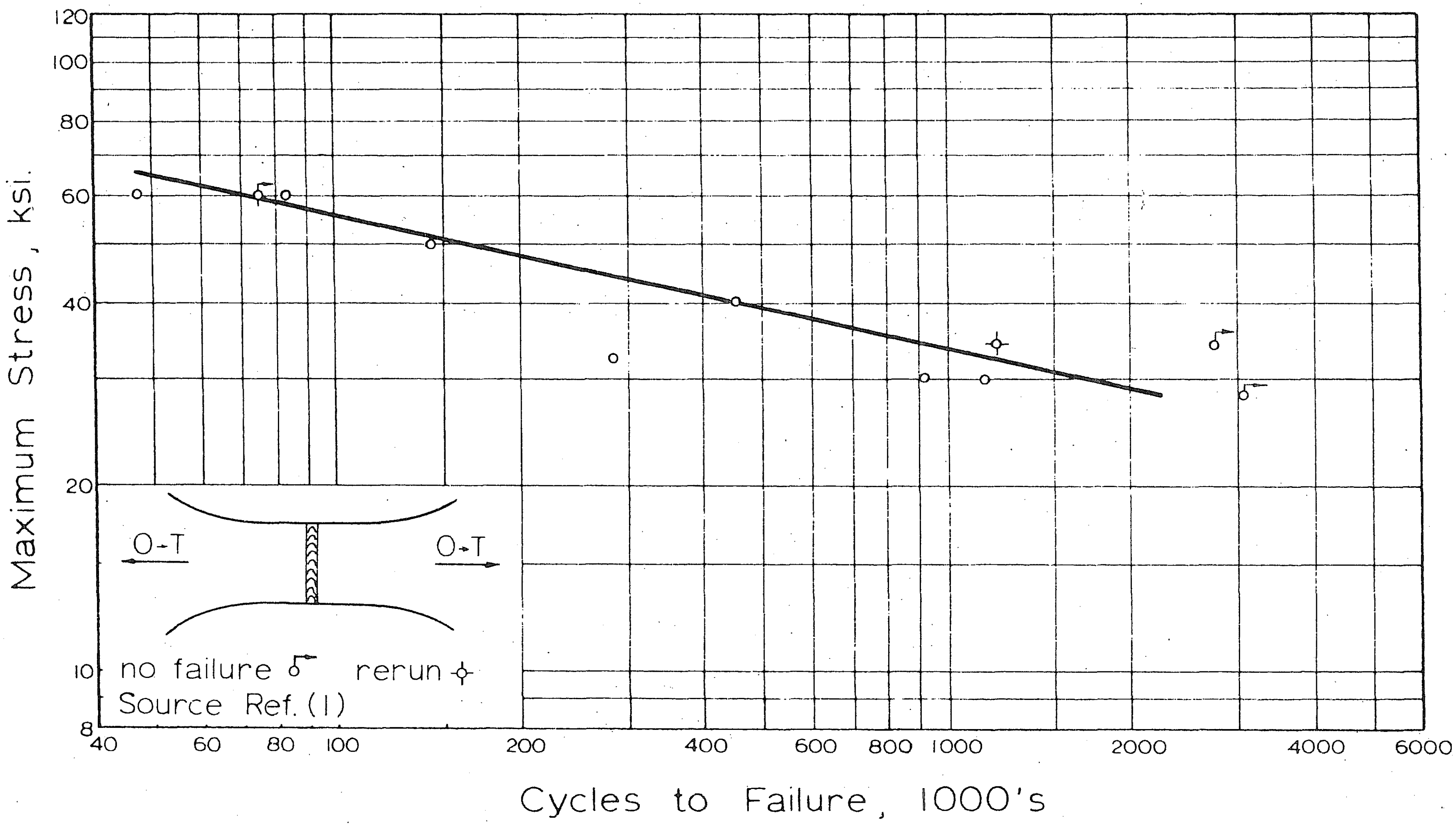


FIG. 1·1 RESULTS OF FATIGUE TESTS OF AS-COMMERCIALLY PRODUCED SPECIMENS

AXIAL TENSION



Source Ref. (1)

FIG. 1·2 RESULTS OF FATIGUE TESTS OF TRANSVERSE BUTT-WELDS IN AS-WELDED CONDITION AXIAL TENSION

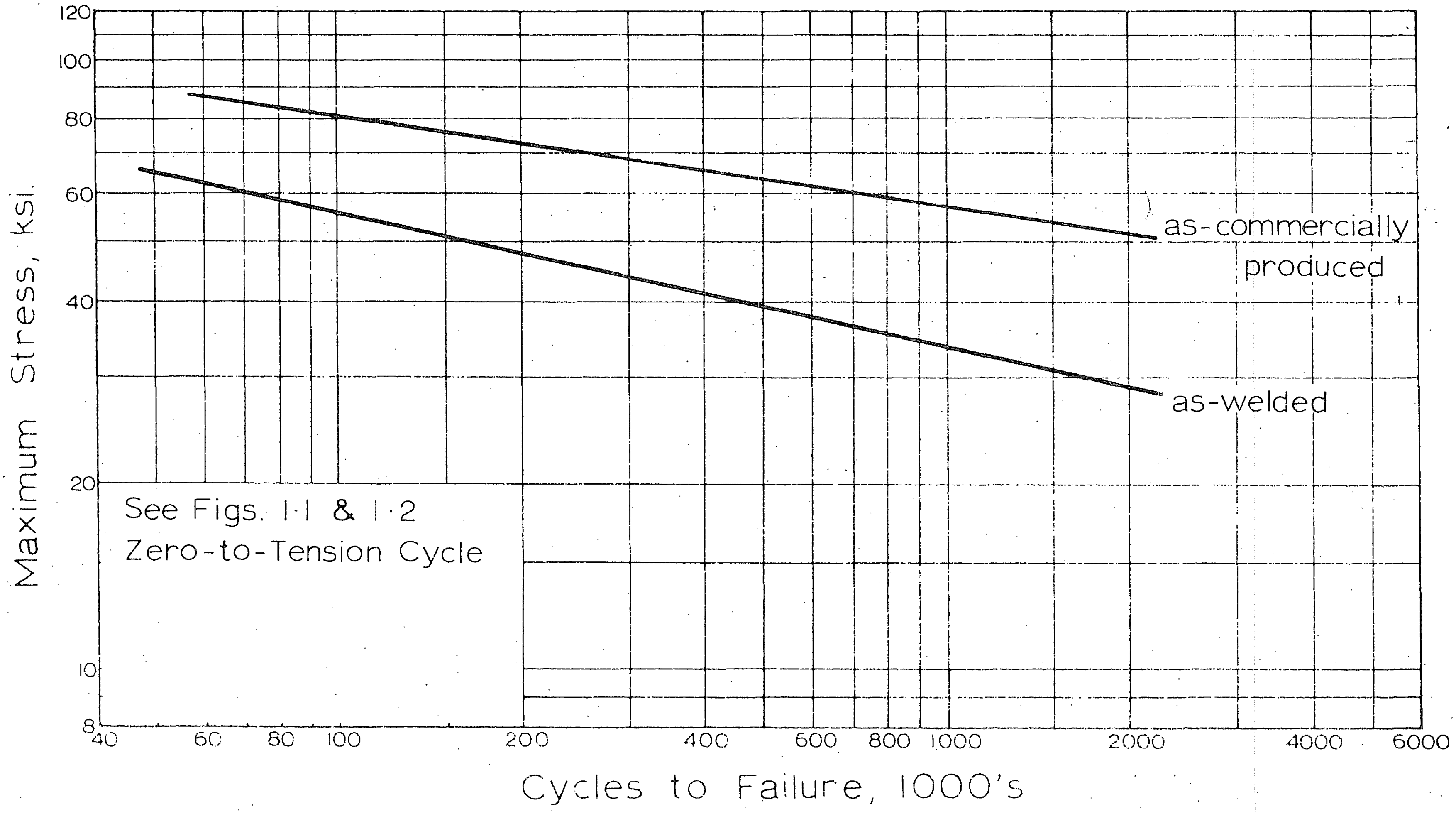


FIG. 1·3 COMPARISON OF FATIGUE RESULTS OF WELDED AND UNWELDED SPECIMENS AXIAL TENSION

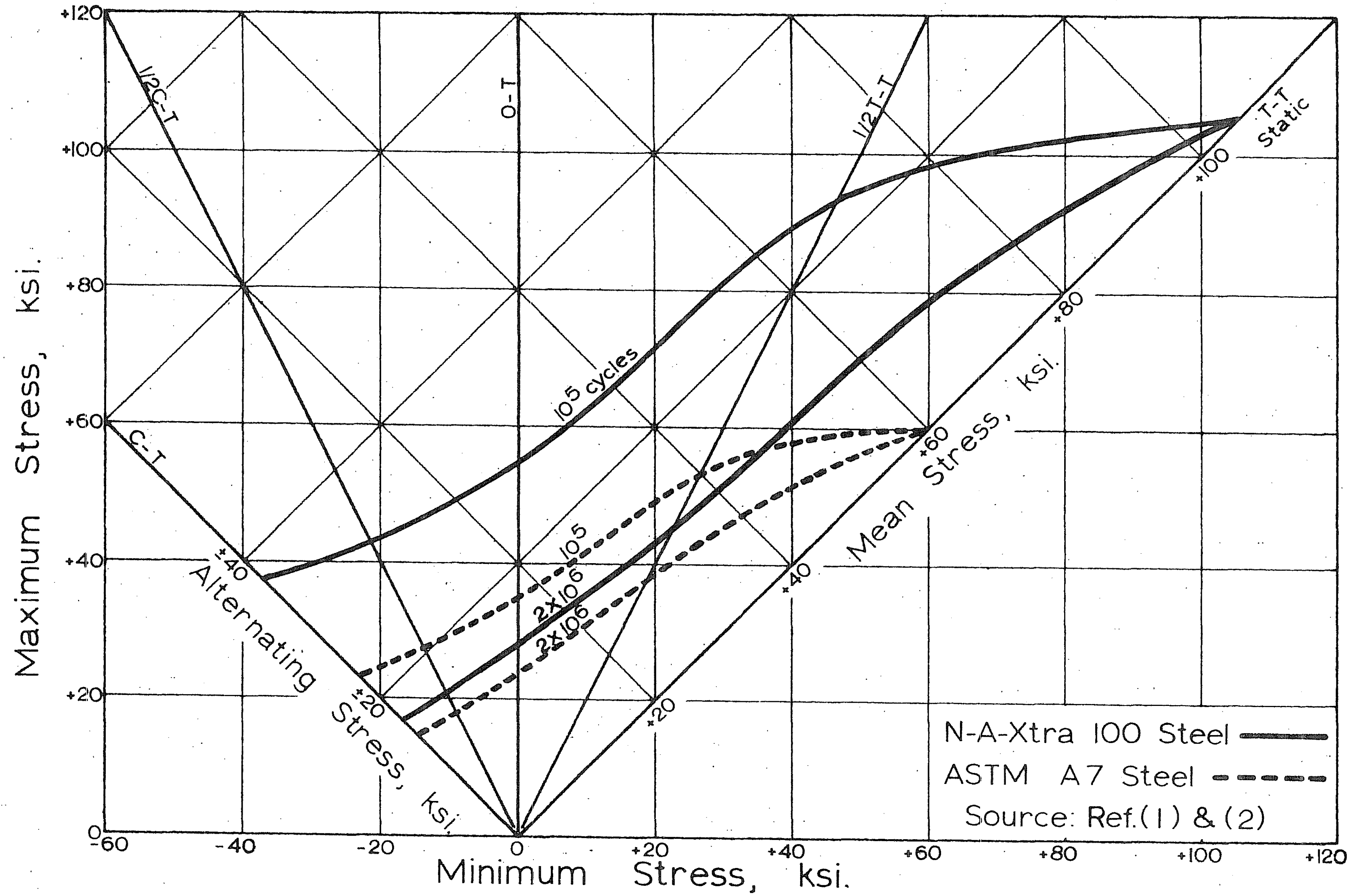


FIG. 1·4 MODIFIED GOODMAN DIAGRAM FOR AXIALLY LOADED TRANSVERSE BUTT-WELDED JOINTS

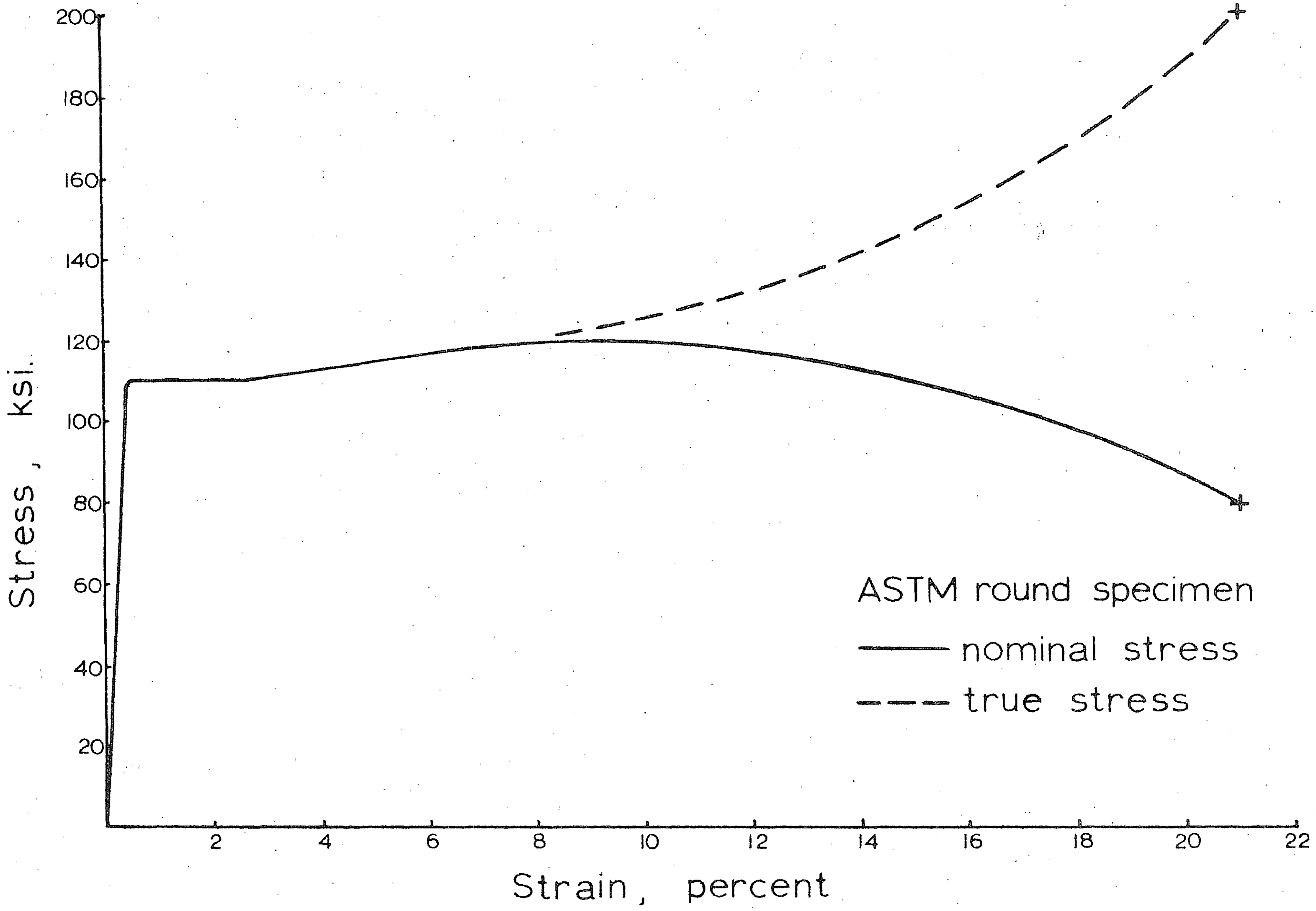


FIG. 2·1 STRESS - STRAIN CURVE FOR N-A-XTRA 100 STEEL

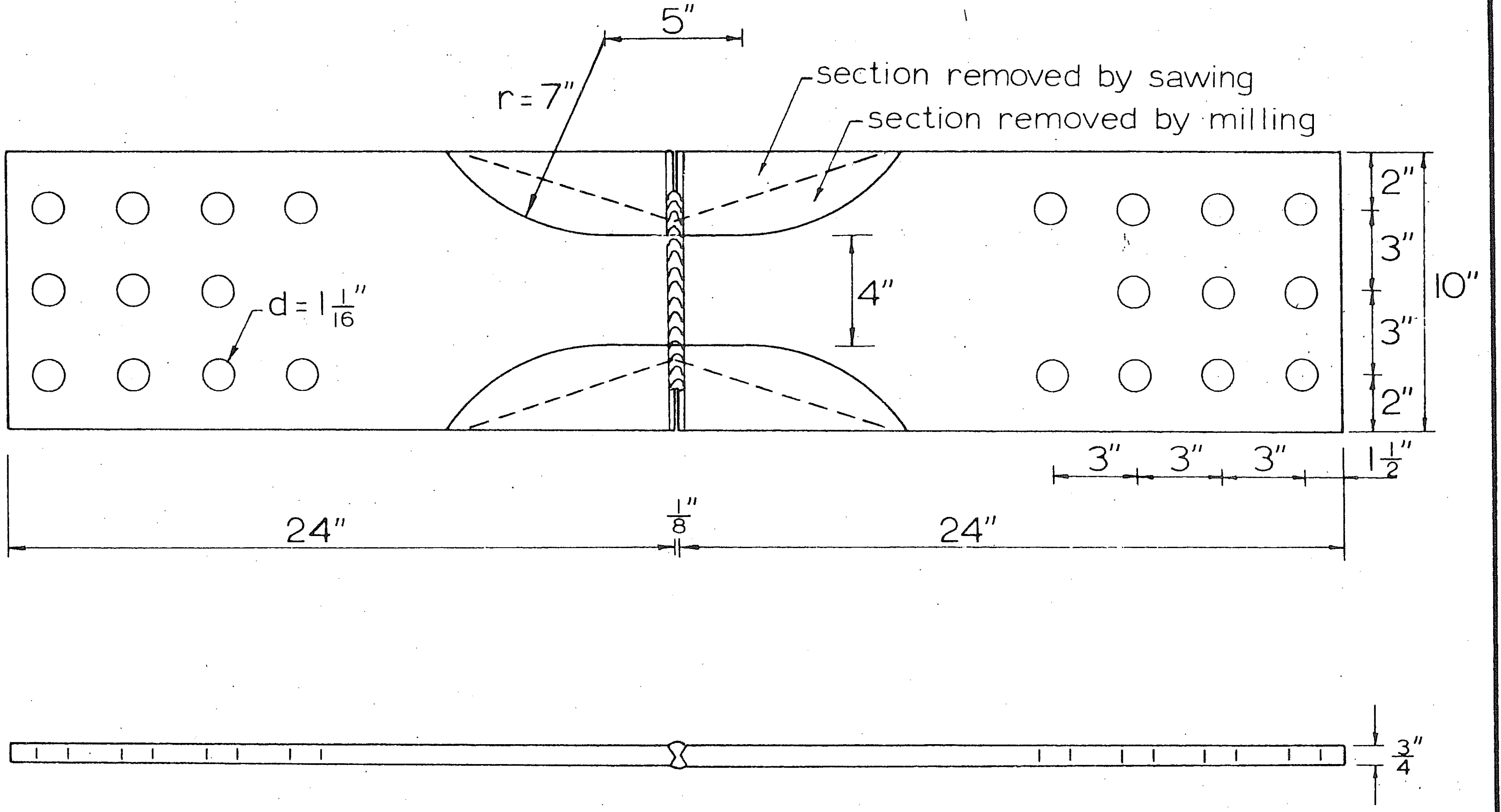


FIG. 2·2 SPECIMEN DETAILS

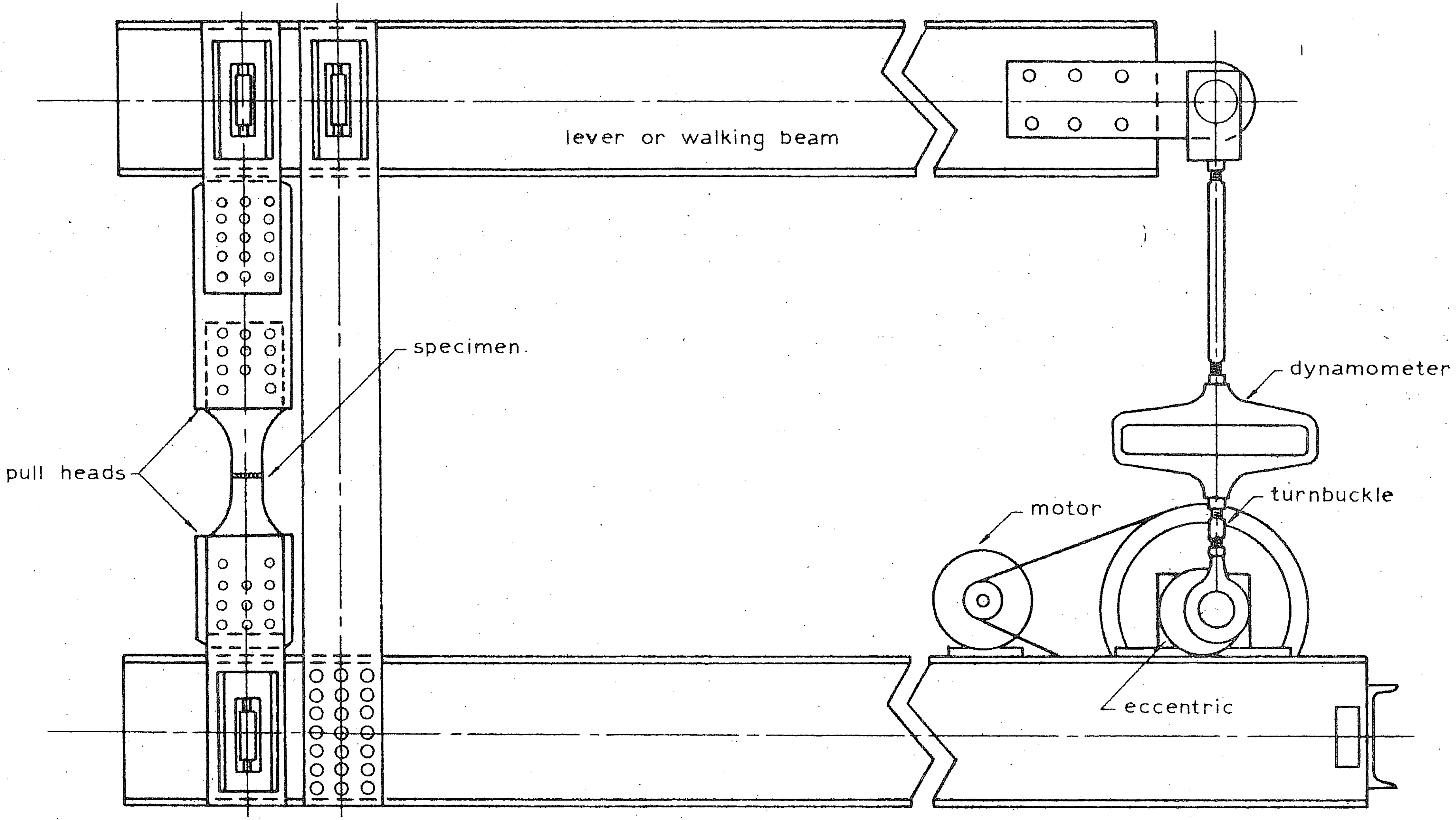
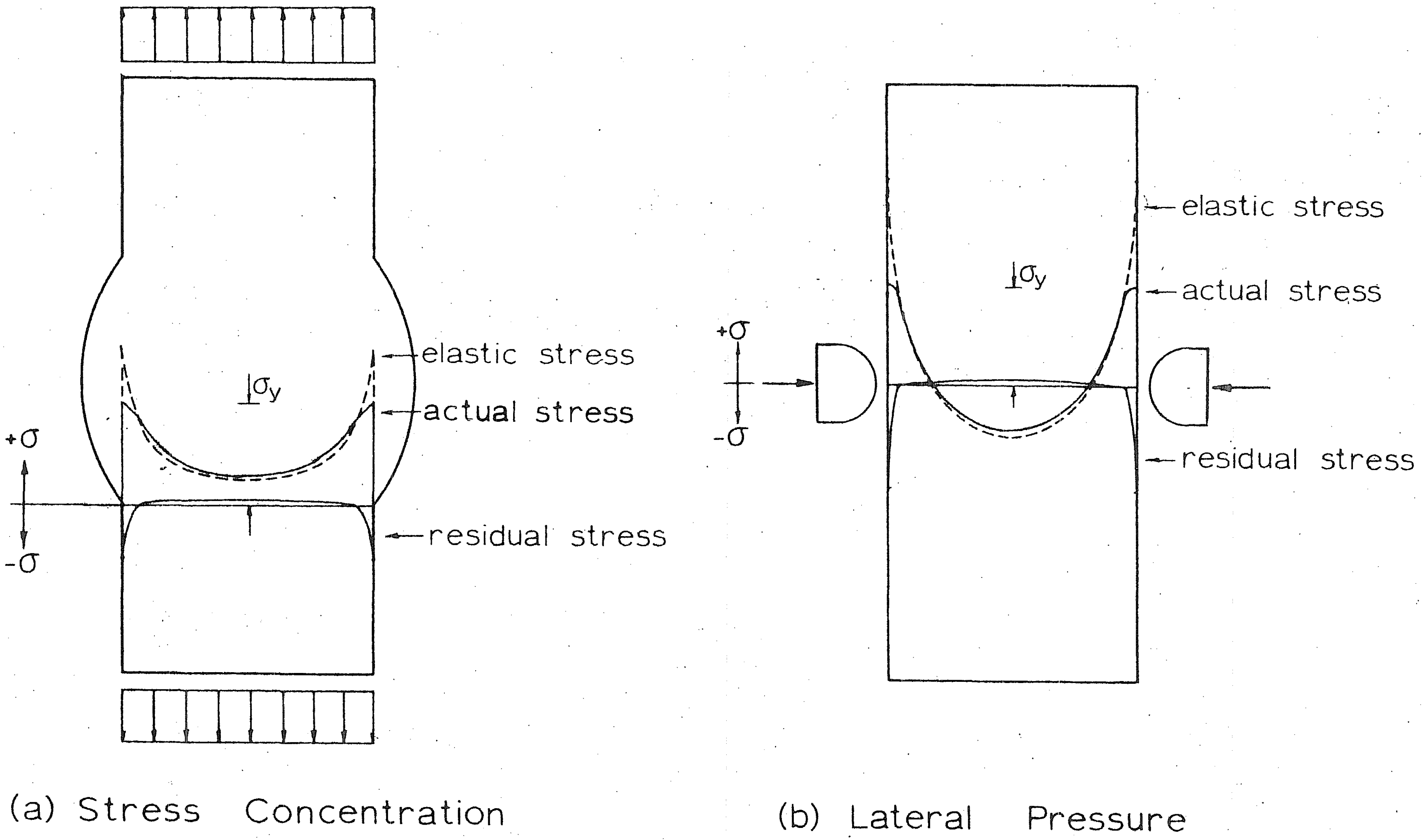


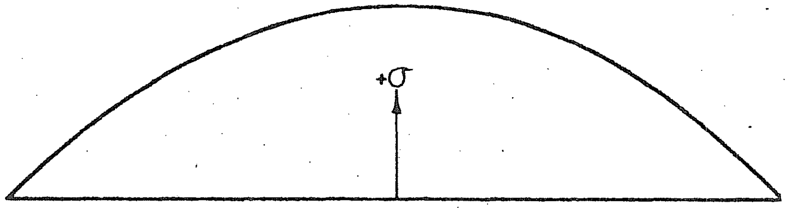
FIG. 2·3 LEVER TYPE FATIGUE TESTING MACHINE AS USED FOR AXIAL LOADING



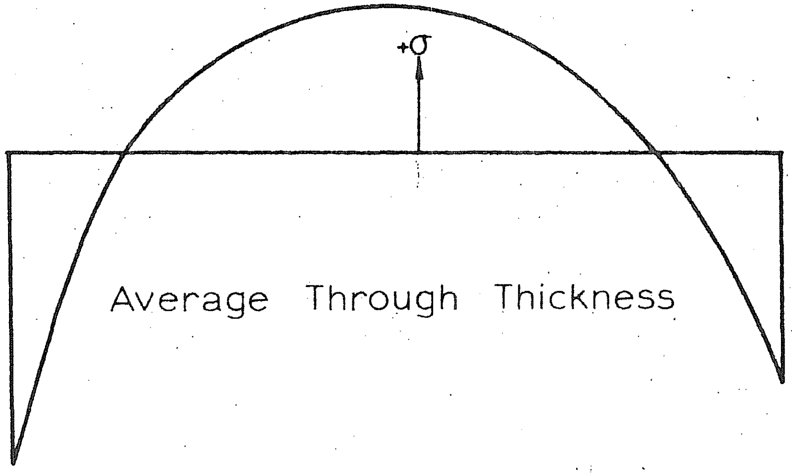
(a) Stress Concentration

(b) Lateral Pressure

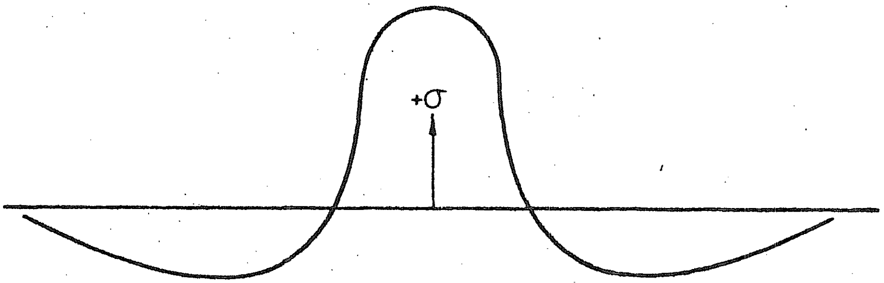
FIG. 2·4 RESIDUAL STRESS CAUSED BY LOCAL YIELDING



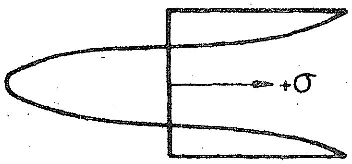
Distribution Along Weld



Average Through Thickness



Distribution Across Weld

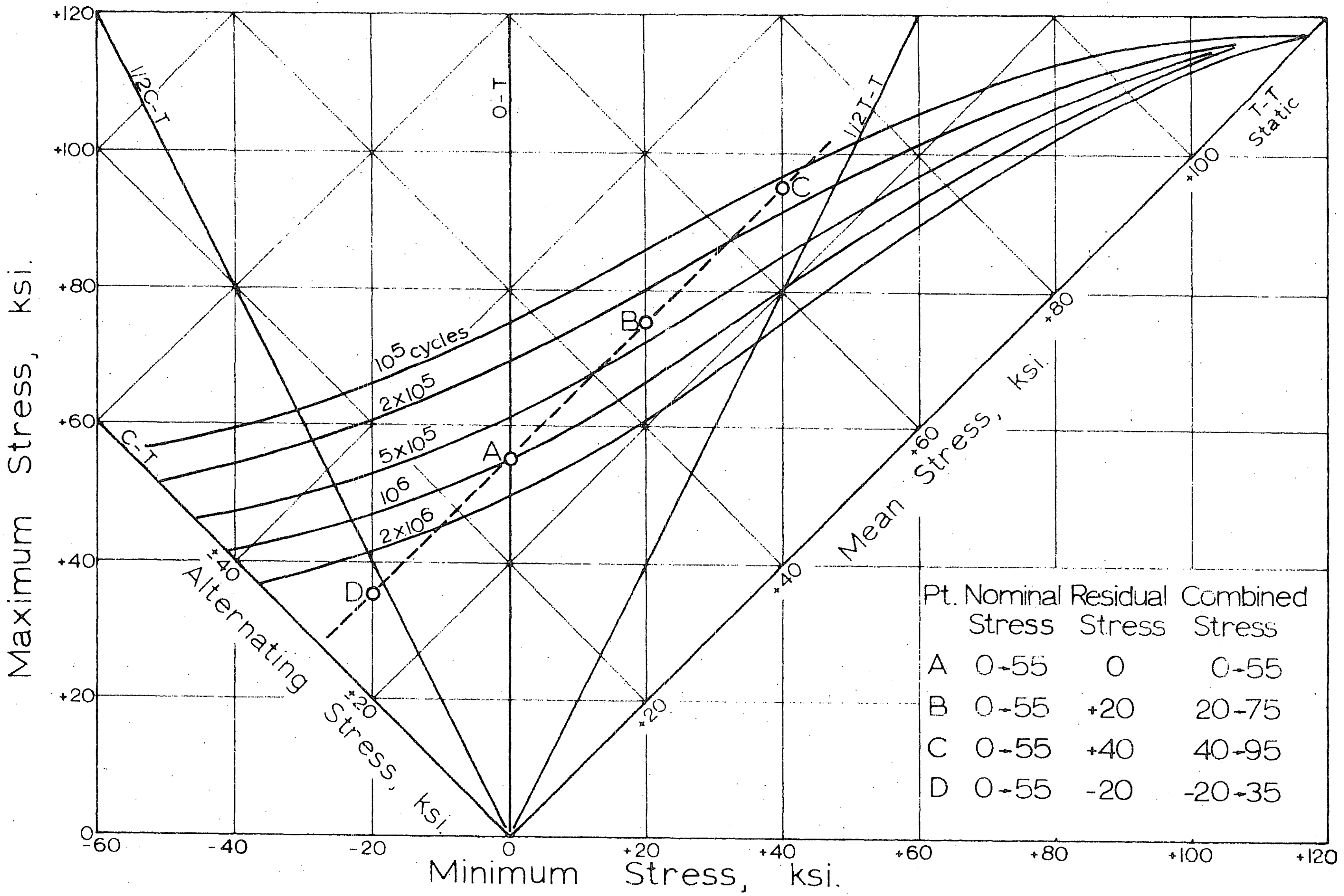


Distribution Through Thickness

(a) Longitudinal Residual Stress

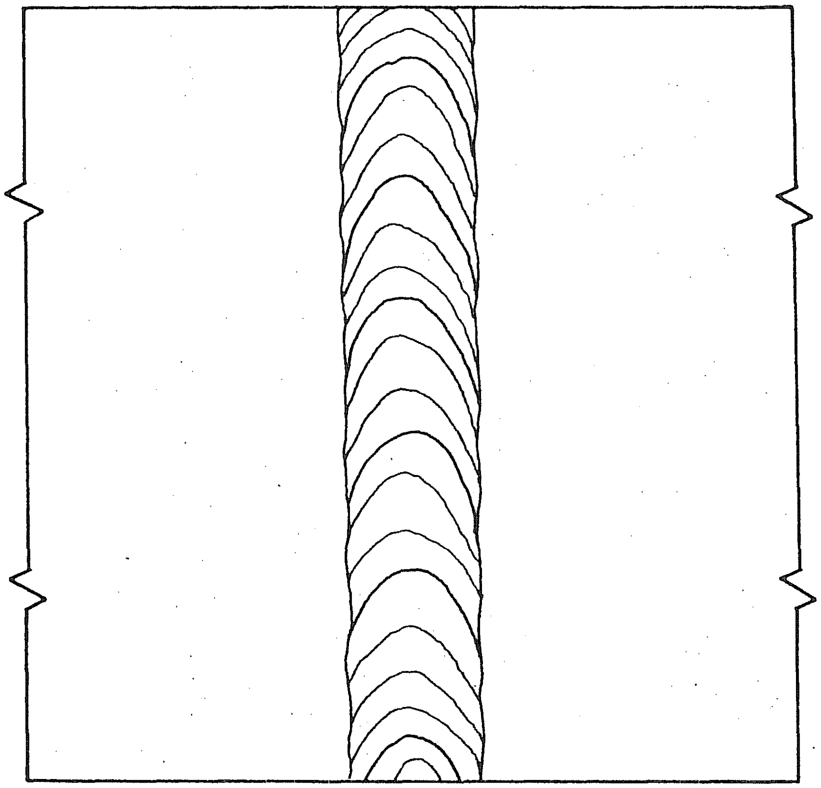
(b) Transverse Residual Stress

FIG. 2·5 RESIDUAL STRESSES IN DOUBLE V BUTT-WELD

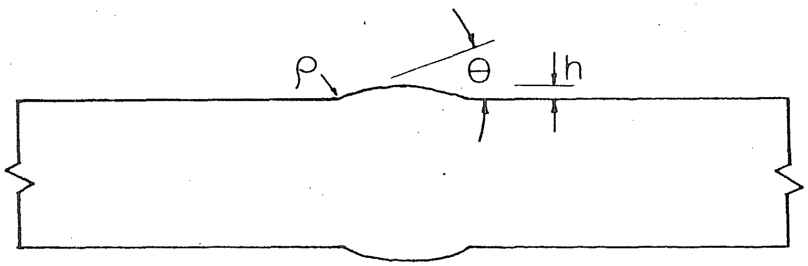


Pt.	Nominal Stress	Residual Stress	Combined Stress
A	0-55	0	0-55
B	0-55	+20	20-75
C	0-55	+40	40-95
D	0-55	-20	-20-35

FIG. 2·6 INFLUENCE OF RESIDUAL STRESS ON FATIGUE LIFE

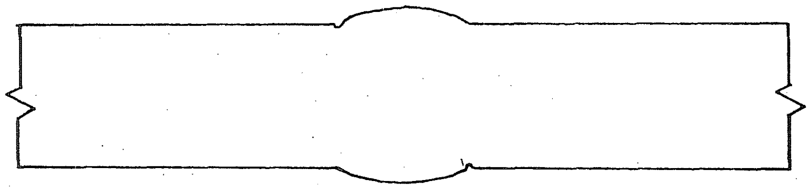


(a) Weld Ripples



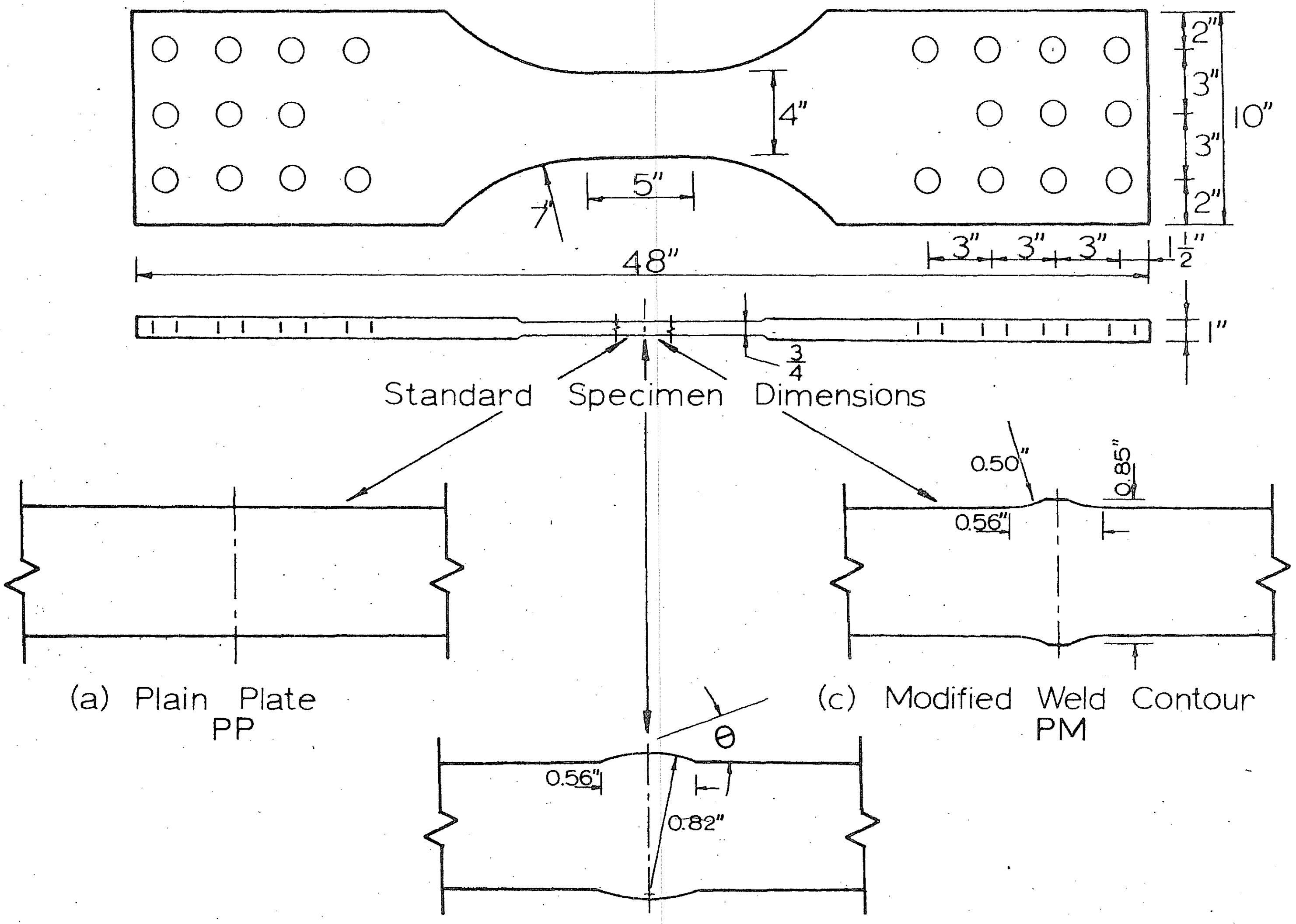
Average Values: ρ = 0.08″
θ = 20 deg.
h = 0.07″

(b) Typical Cross-Section



(c) Ripple Effect

FIG. 2·7 WELD GEOMETRY

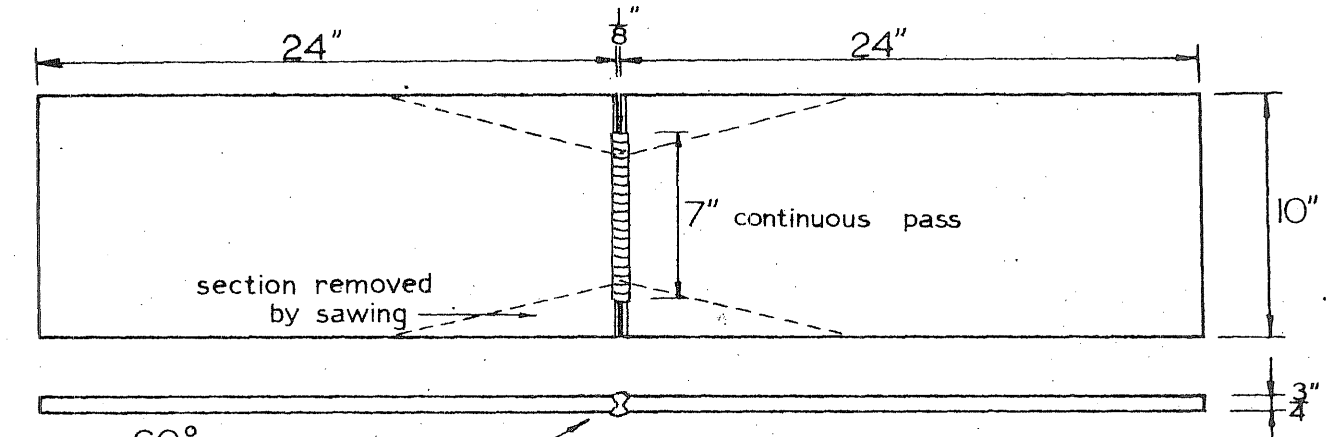


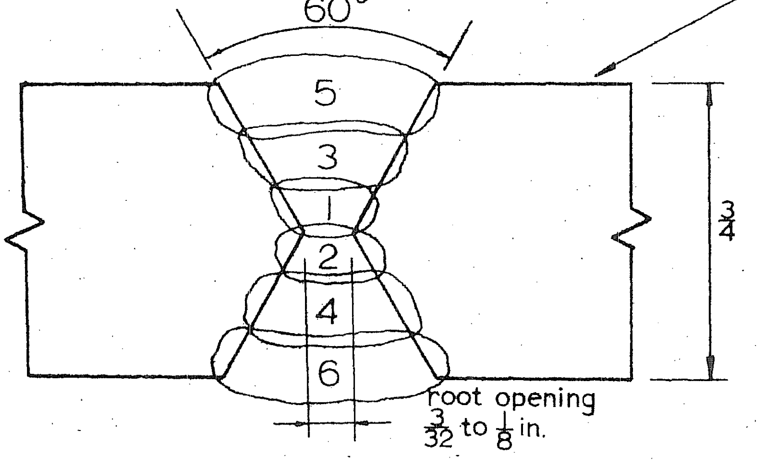
(a) Plain Plate
PP

(c) Modified Weld Contour
PM

(b) Machined Weld Contour
PS

FIG. 3·1 MACHINED PLAIN PLATE SPECIMENS





Pass	Electrode dia. in.	Current amps.	Rate of Travel in./min.
1	5/32	150	5.5
2	5/32	140	7.5
3	3/16	230	8.0
4	3/16	220	7.0
5&6	3/16	210	5.0 to 7.0

Voltage : 21 volts

Polarity : D.C. reversed

Preheat : 200° F

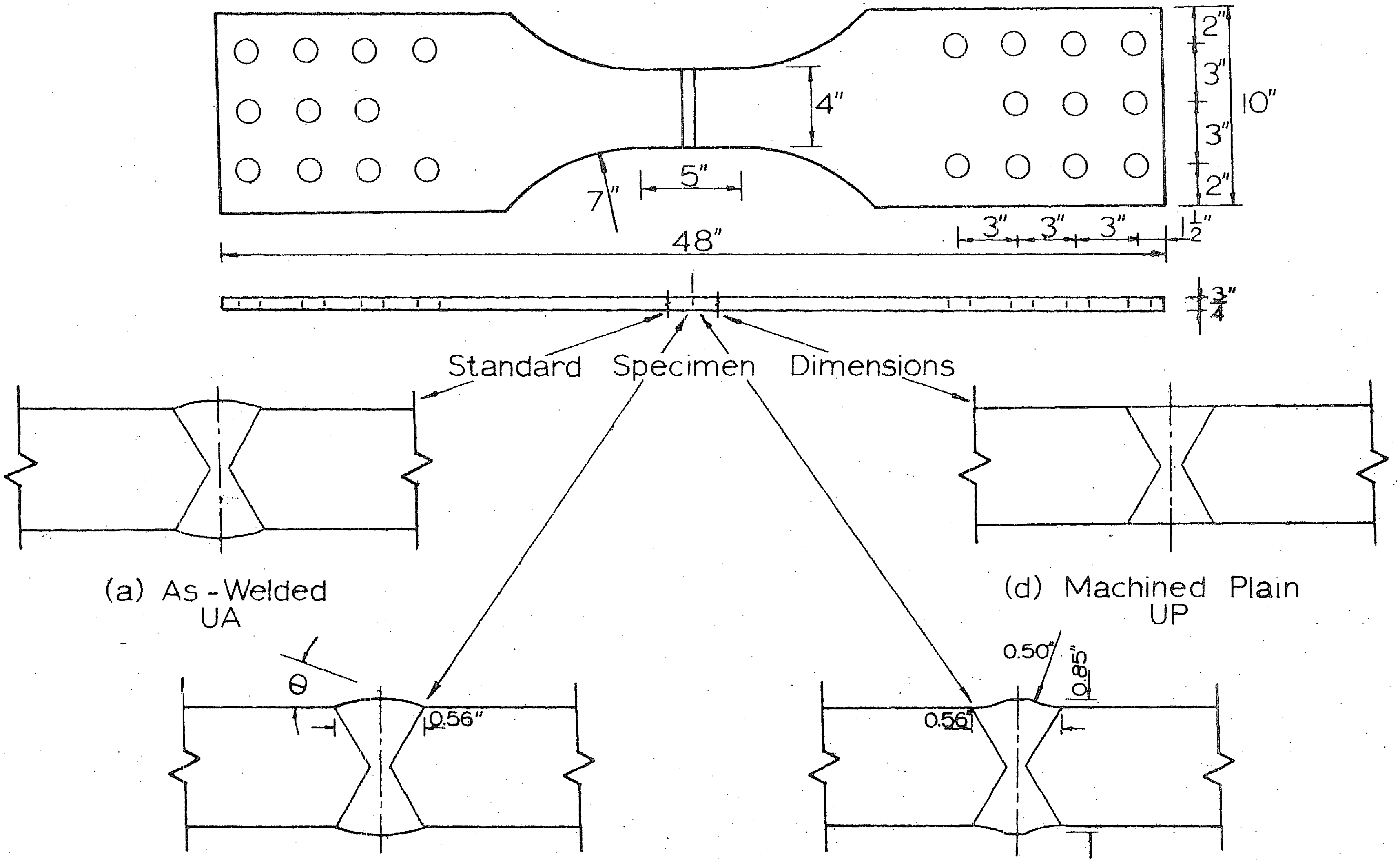
Electrode : E 11018

Interpass Temperature : 250° F (maximum)

All welding in flat position

Underside of pass 1 back-gouged with air arc before pass 2.

FIG. 3·2 BASIC WELDING PROCEDURE



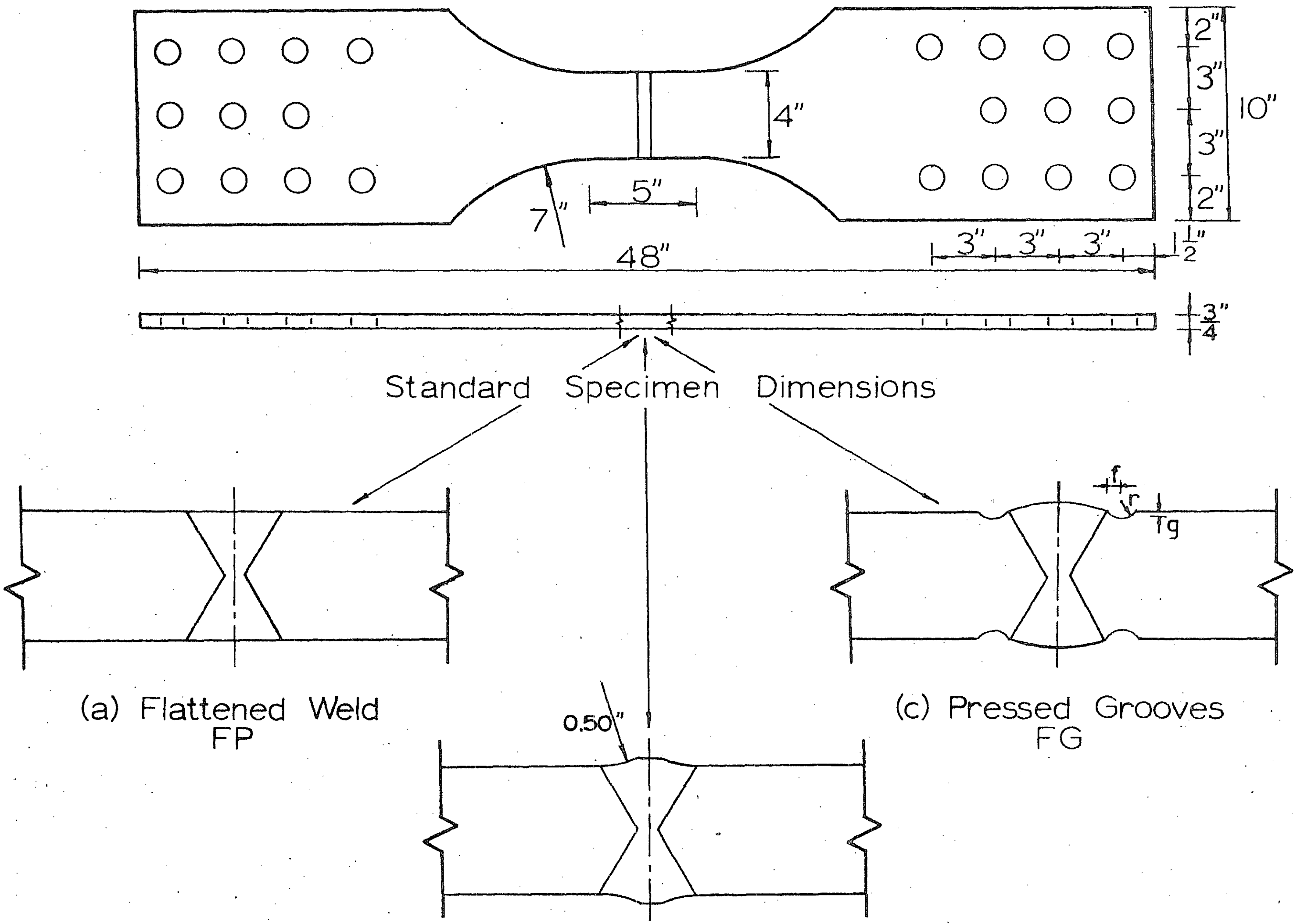
(a) As-Welded
UA

(d) Machined Plain
UP

(b) Machined Weld
US

(c) Modified Weld
UM

FIG. 3·3 MACHINED WELD SPECIMENS



(a) Flattened Weld
FP

(c) Pressed Grooves
FG

(b) Pressed Modified Weld
FM

FIG. 3.4 PRESSED WELD SPECIMENS

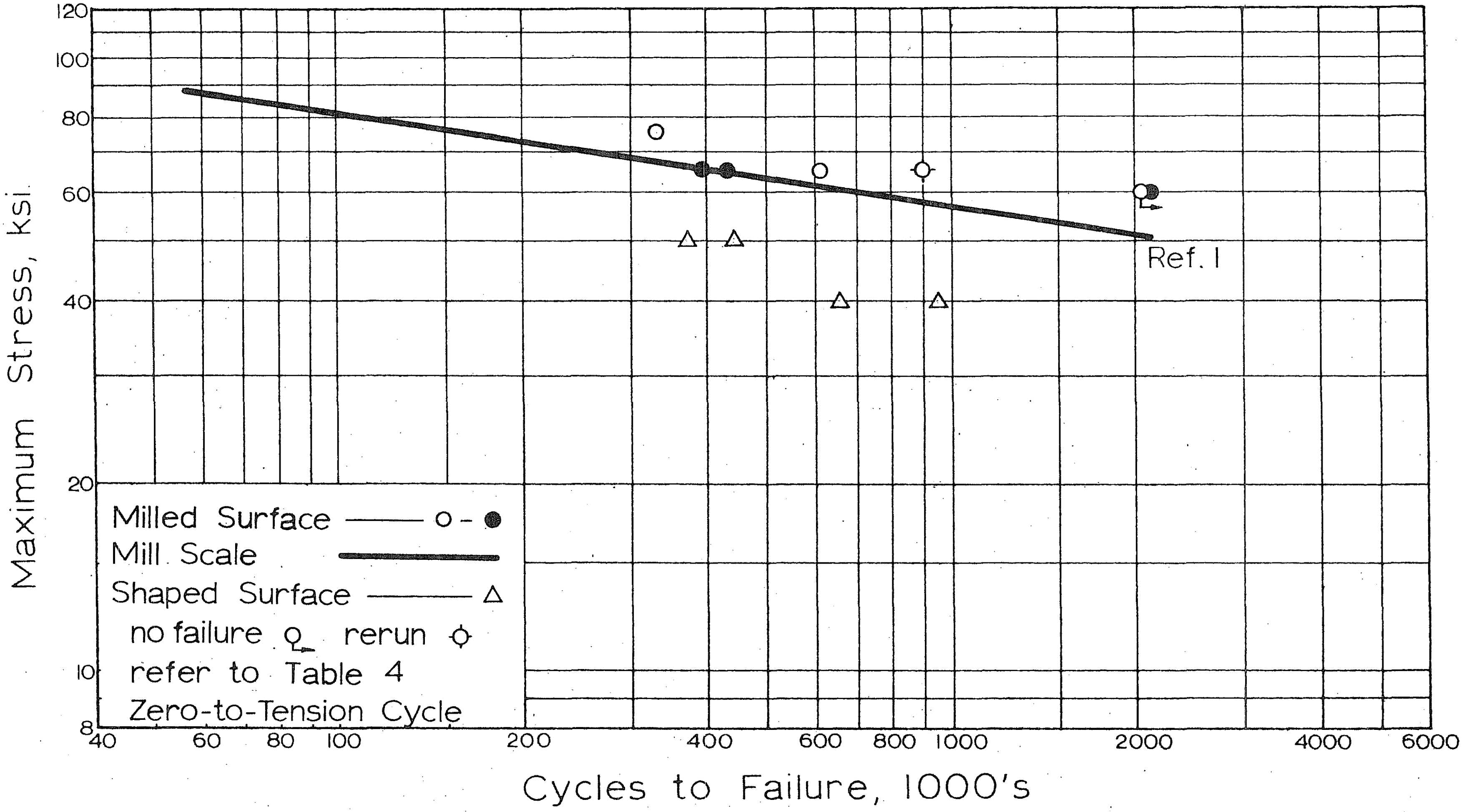


FIG. 4·I EFFECT OF MACHINED SURFACE ON PLAIN PLATE TESTS

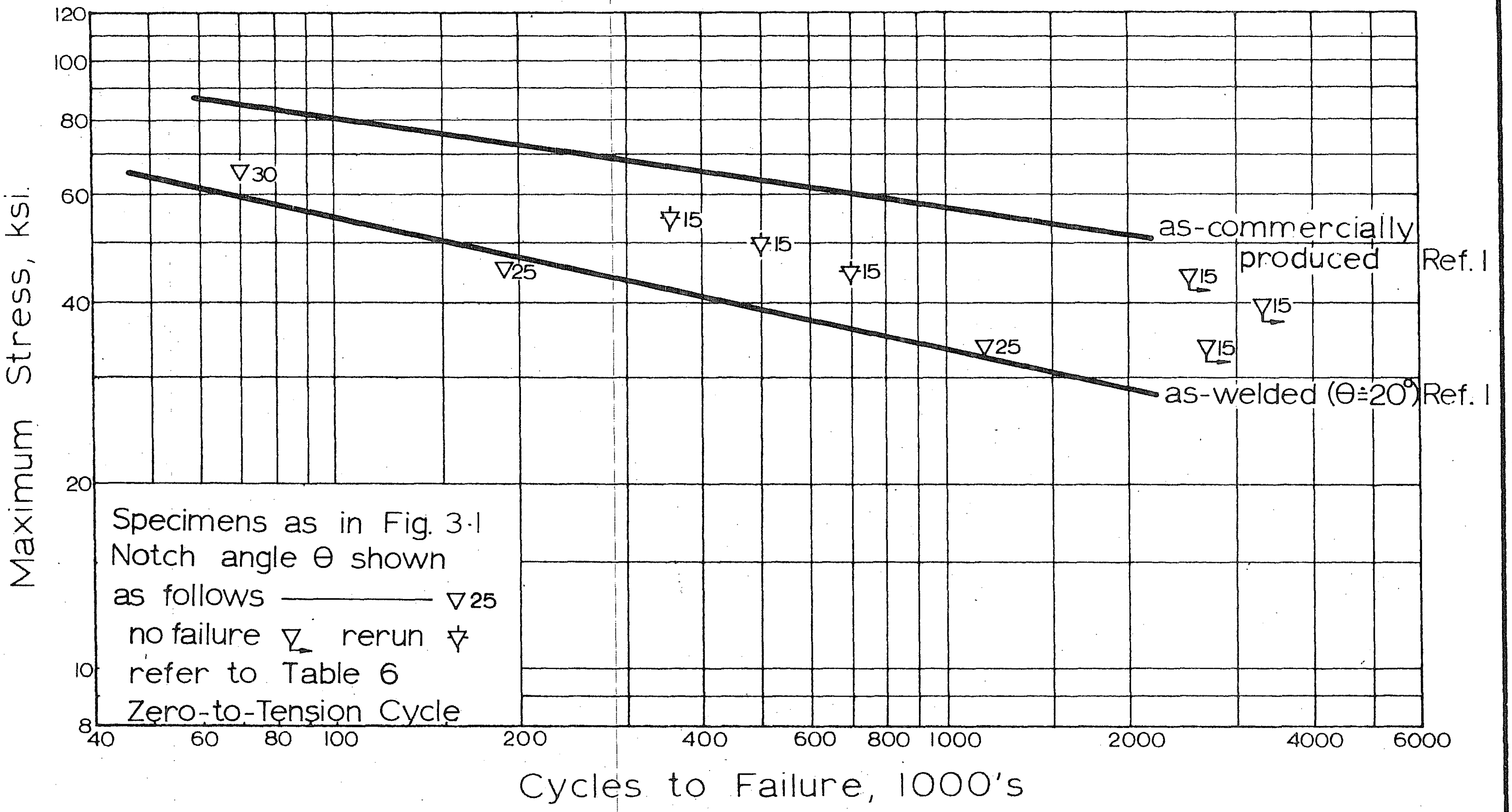


FIG. 4·2 GEOMETRICAL INFLUENCE ON FATIGUE STRENGTH OF MACHINED WELD CONTOURS

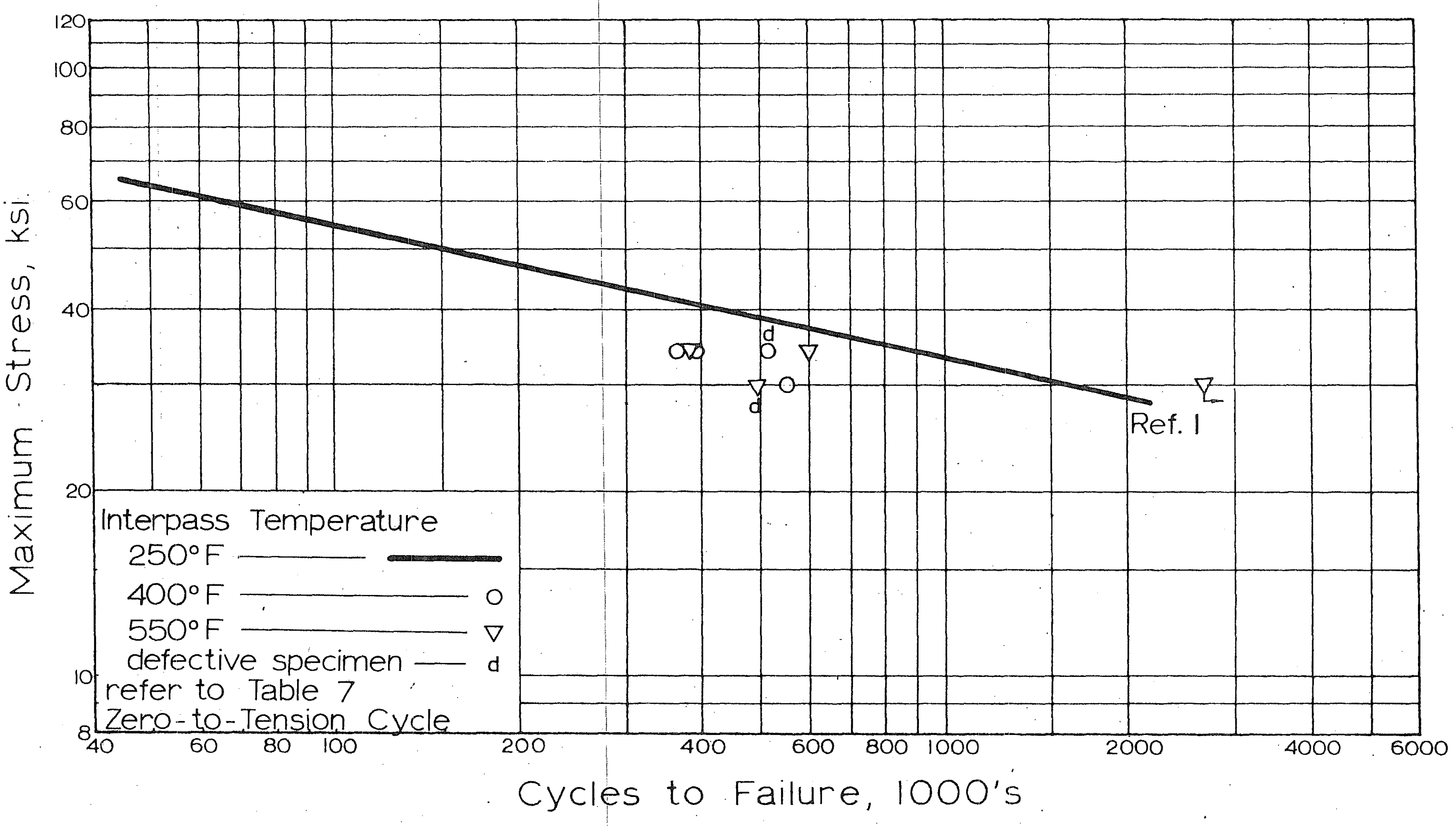


FIG. 4·3 EFFECT OF INTERPASS TEMPERATURE ON FATIGUE STRENGTH

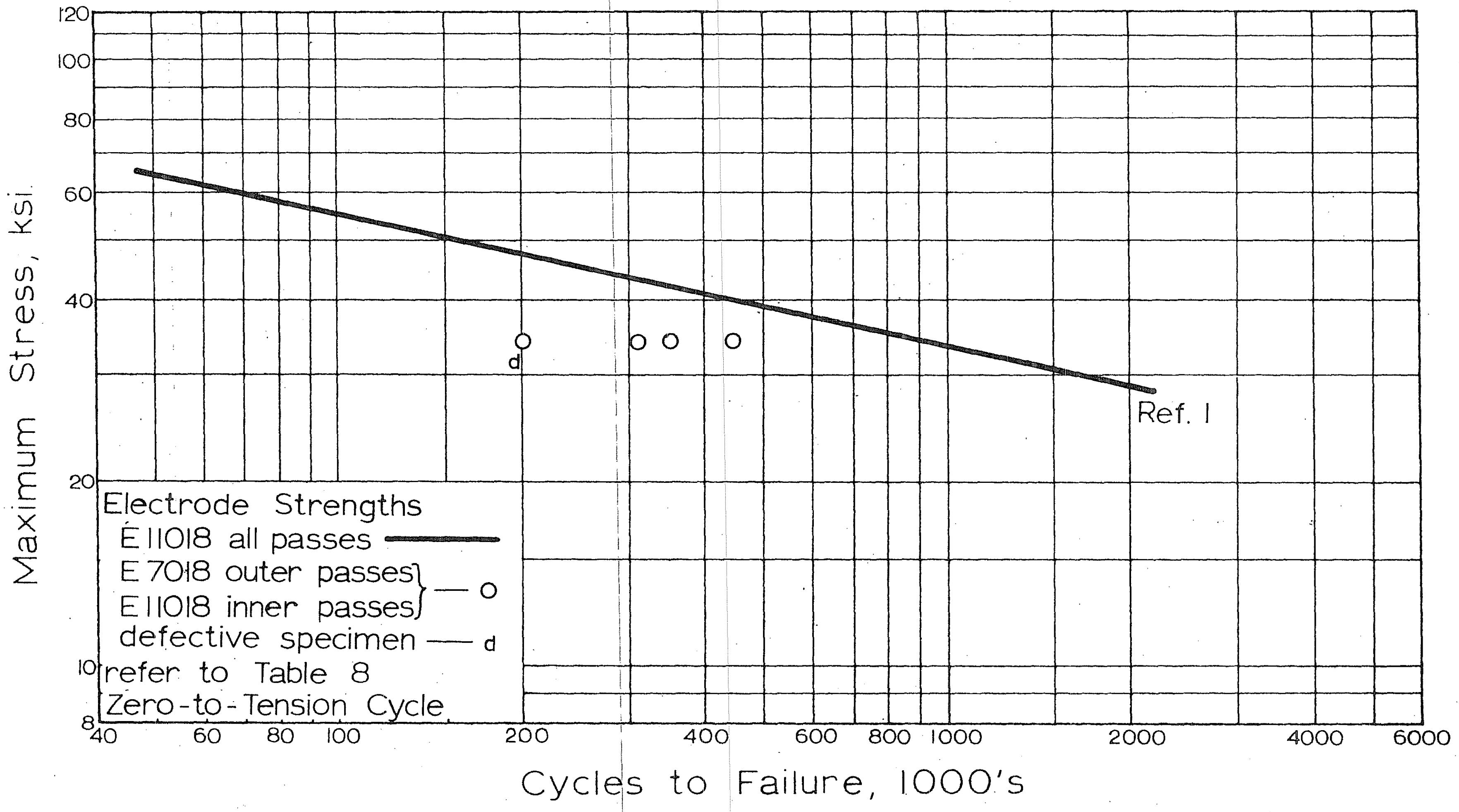
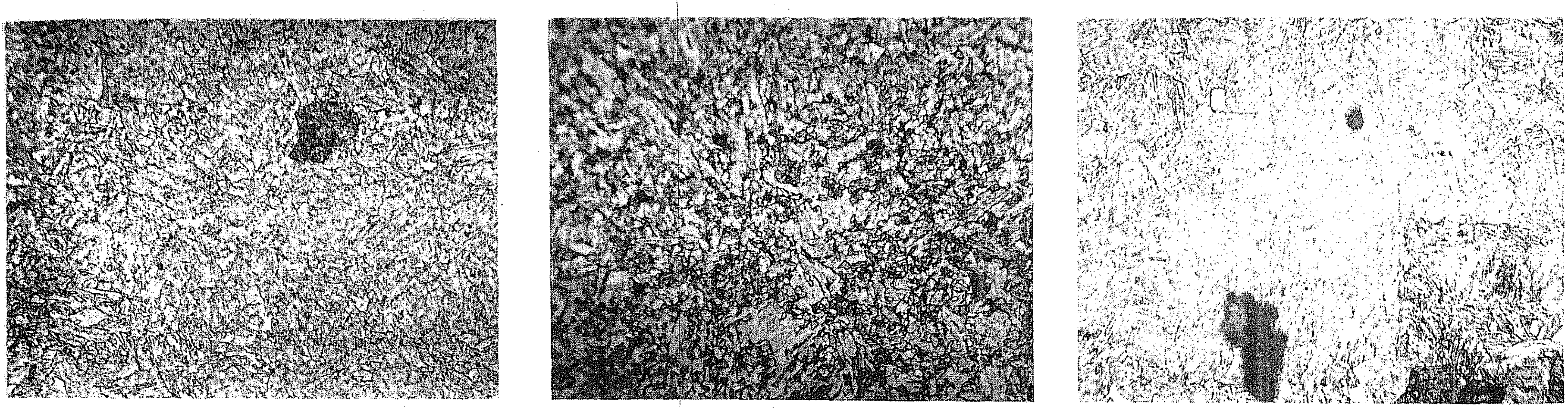
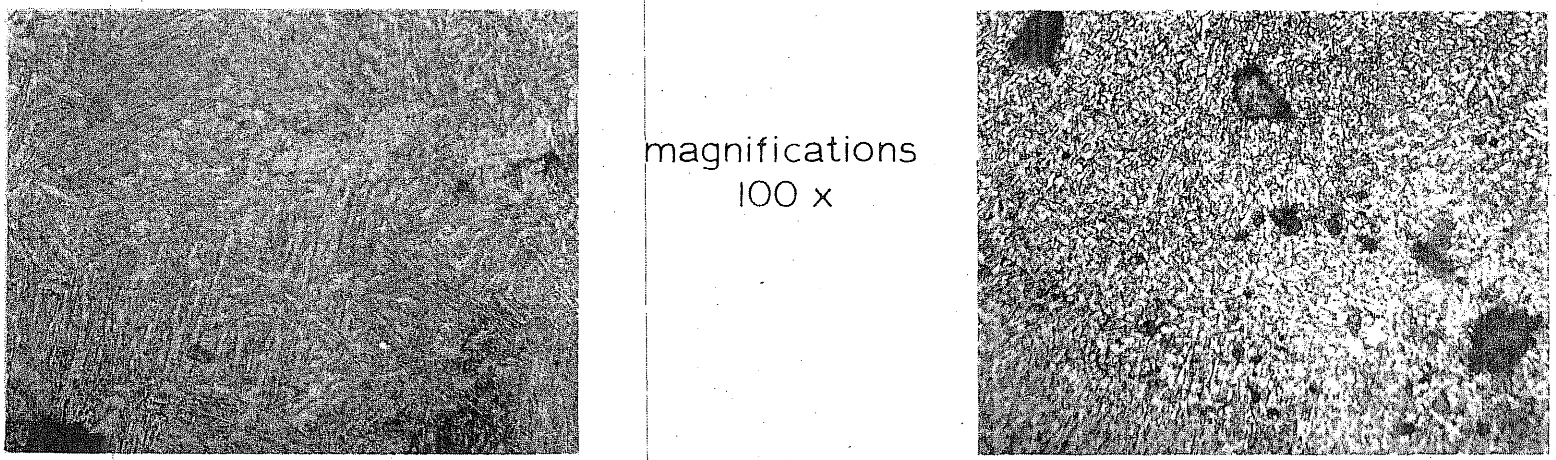


FIG. 4.4 INFLUENCE OF ELECTRODE STRENGTH ON FATIGUE STRENGTH



UBM UBM-HABM HAZ

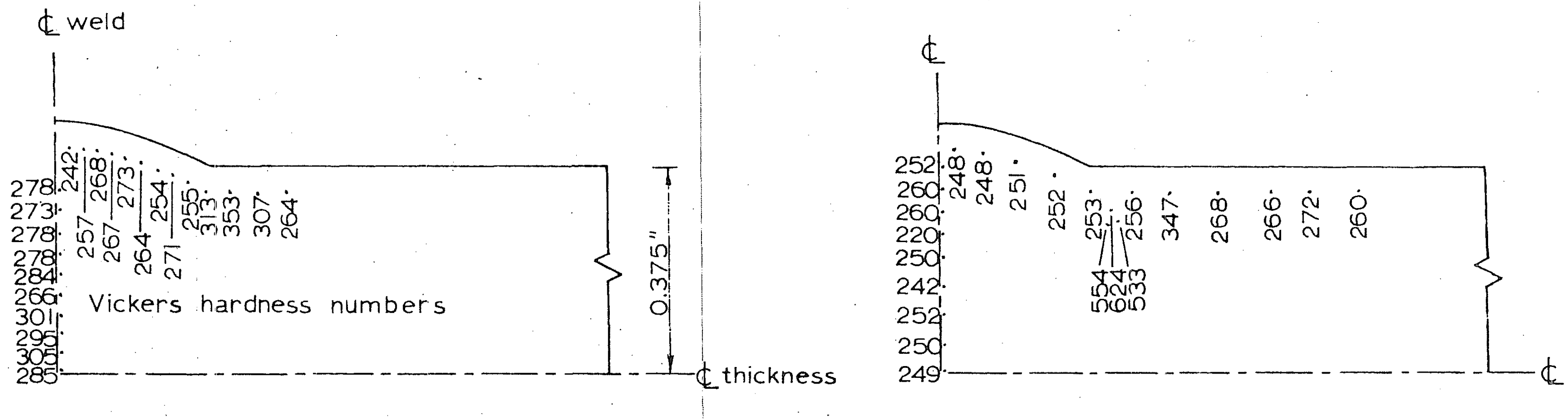


HAZ-WM WM

magnifications
100 x

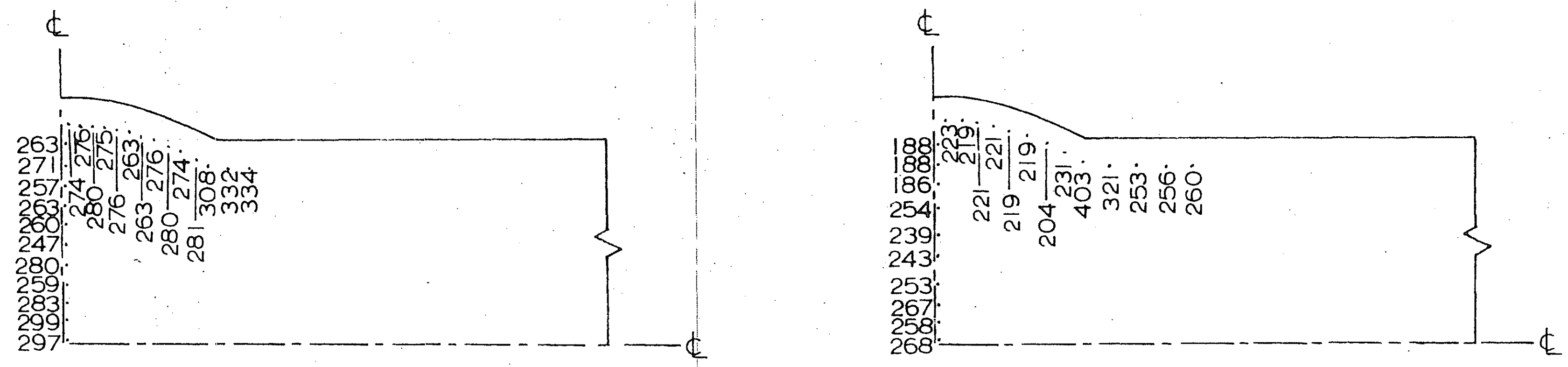
FIG. 4.5

MICROGRAPHS OF STANDARD WELD



(a) 250° Interpass Temperature

(b) 400° Interpass Temperature



(c) 550° Interpass Temperature

(d) Low Strength Electrode

FIG.4·6 HARDNESS SURVEYS FOR VARIOUS WELDING PROCEDURES

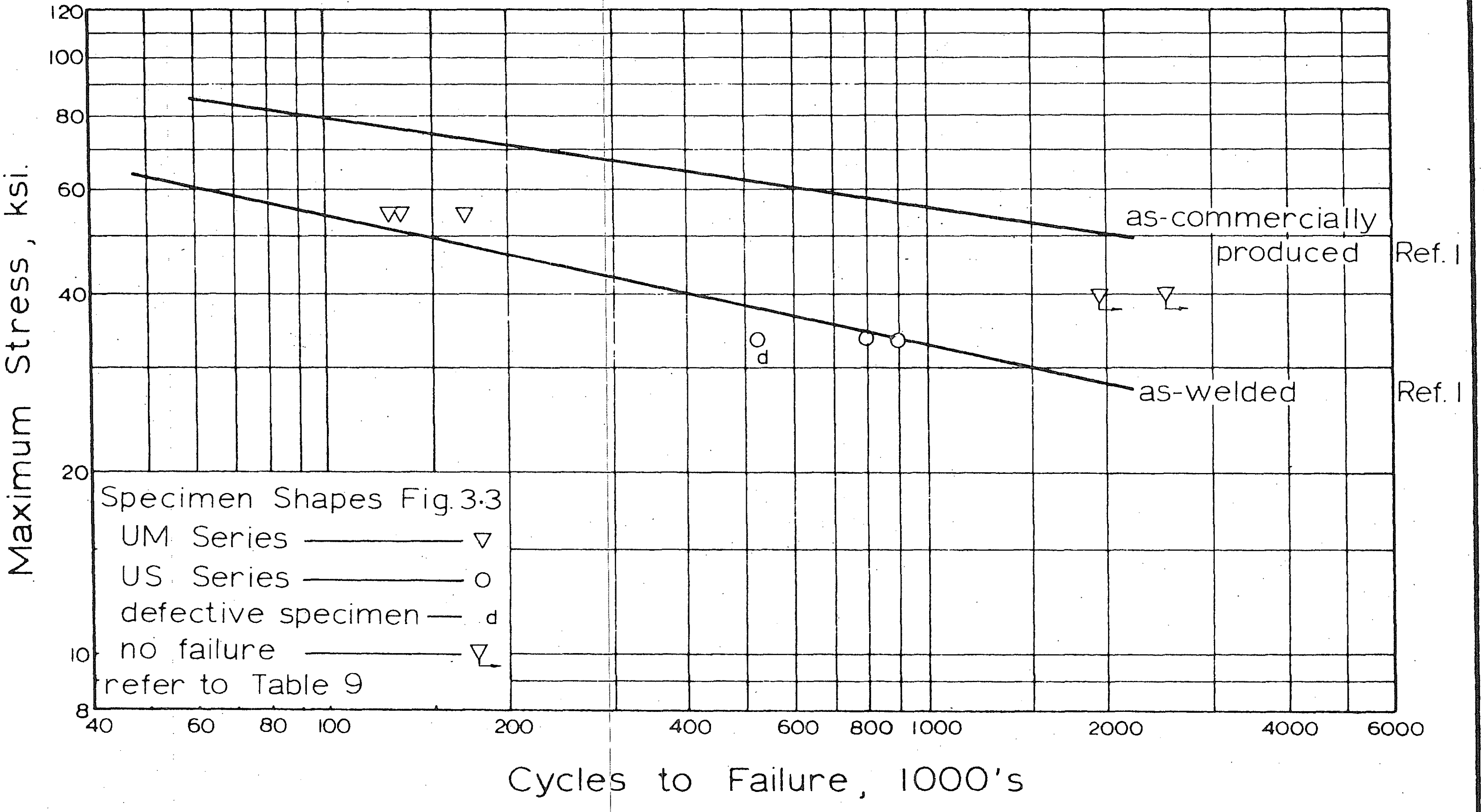


FIG. 4·7 RESULTS OF MACHINED WELD TESTS

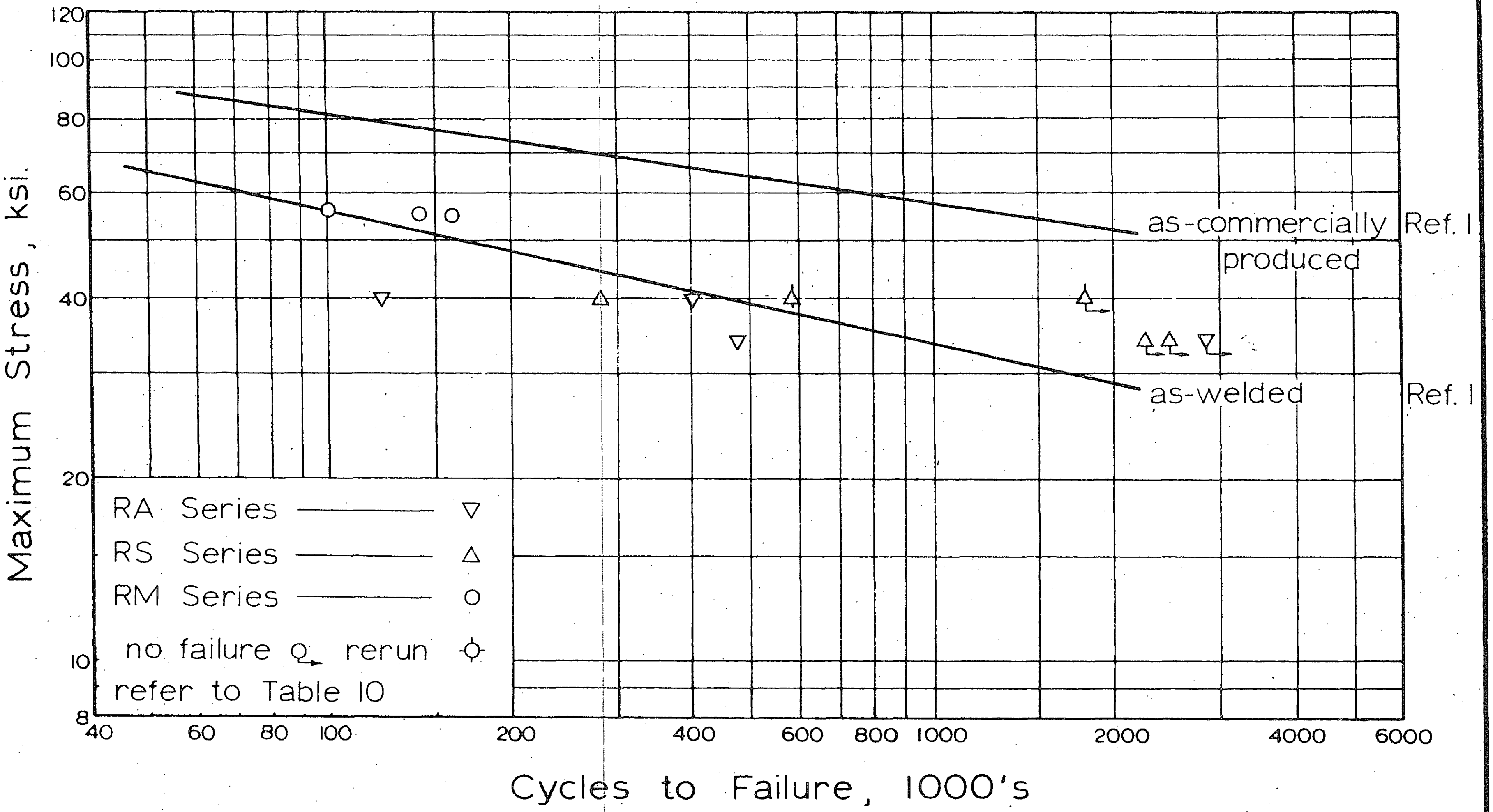


FIG. 4·8 RESULTS OF STRESS RELIEVED TESTS

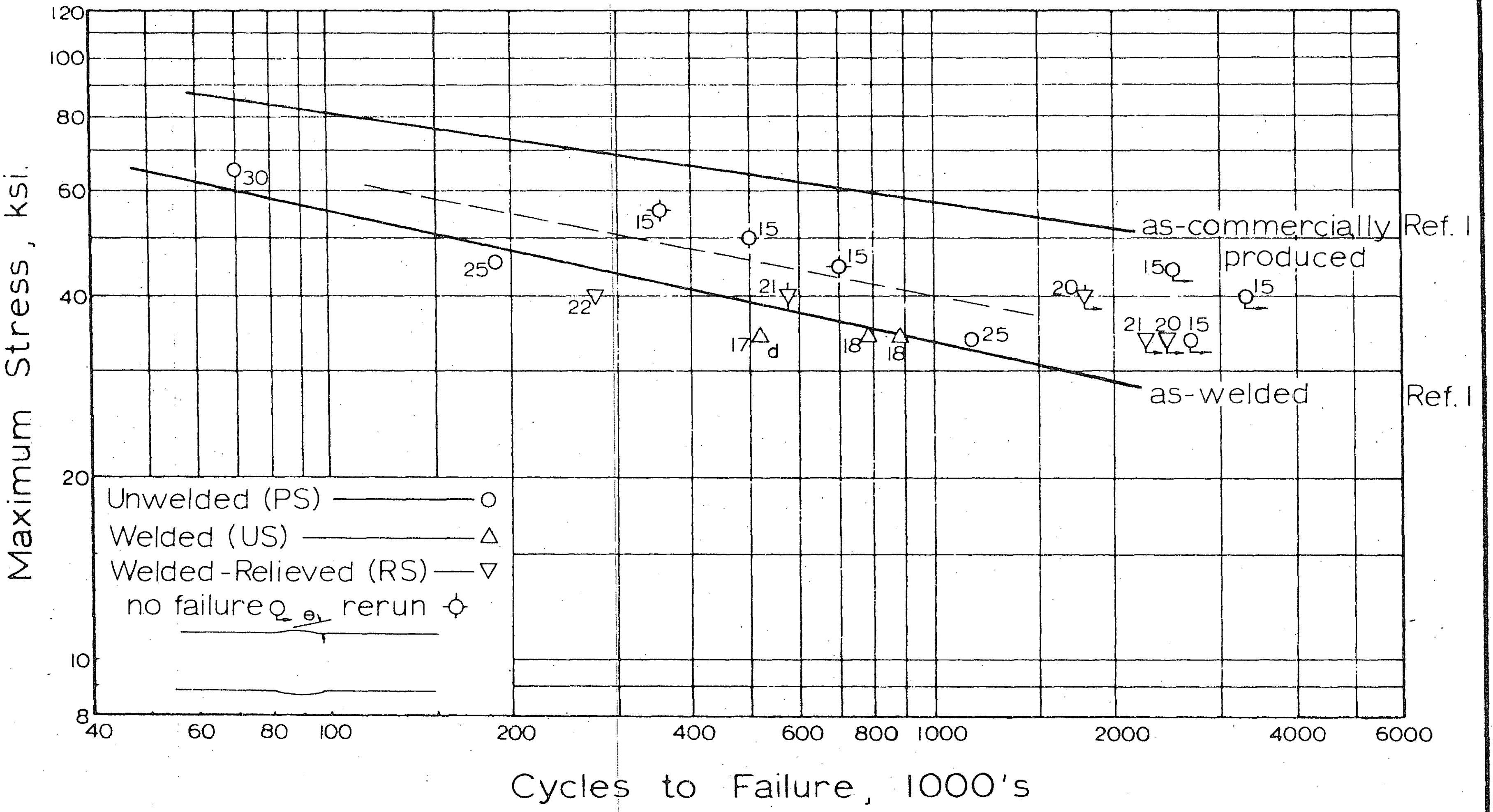


FIG. 4·9 RESULTS OF GEOMETRICALLY SIMILAR SPECIMENS

MACHINED WELD CONTOUR

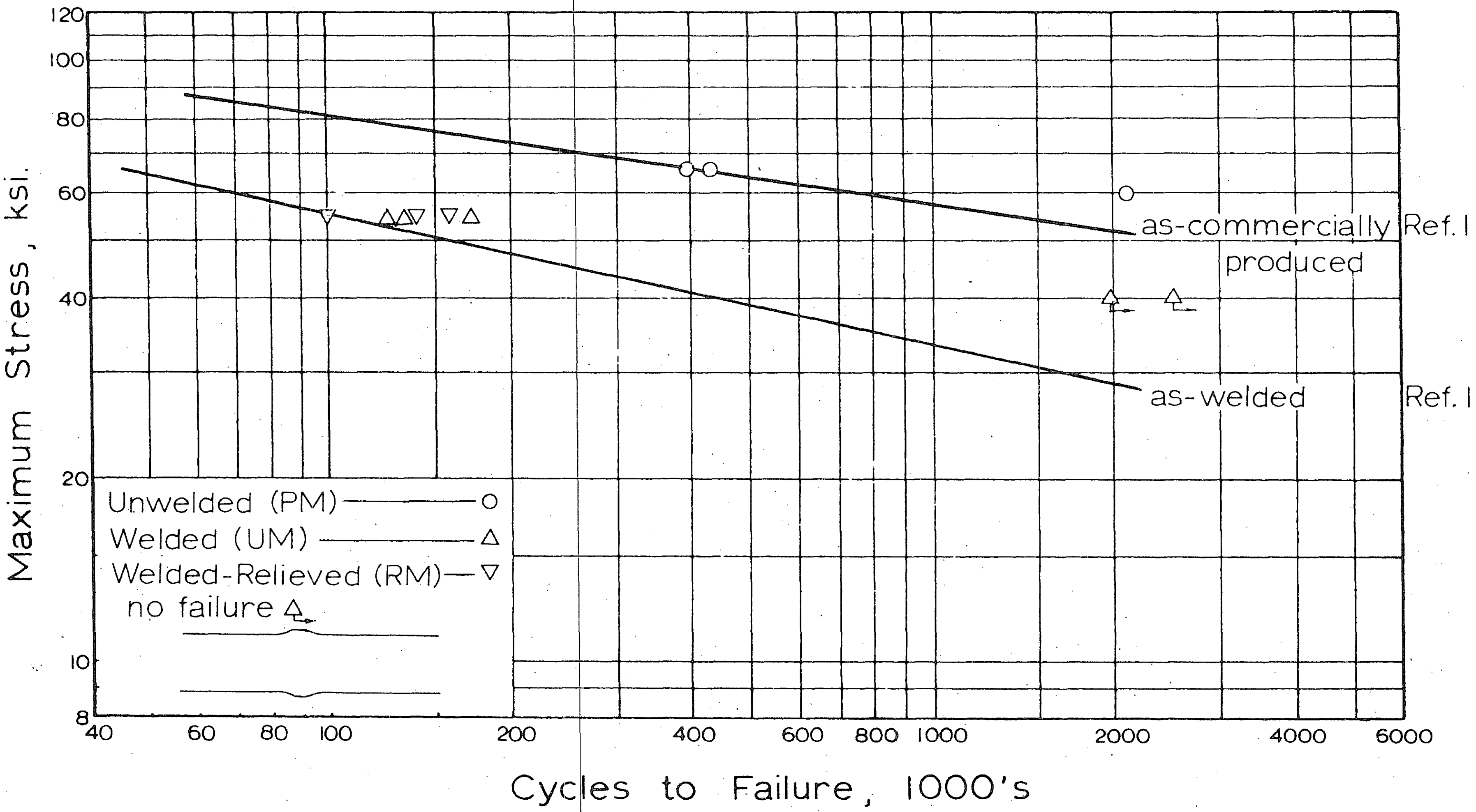
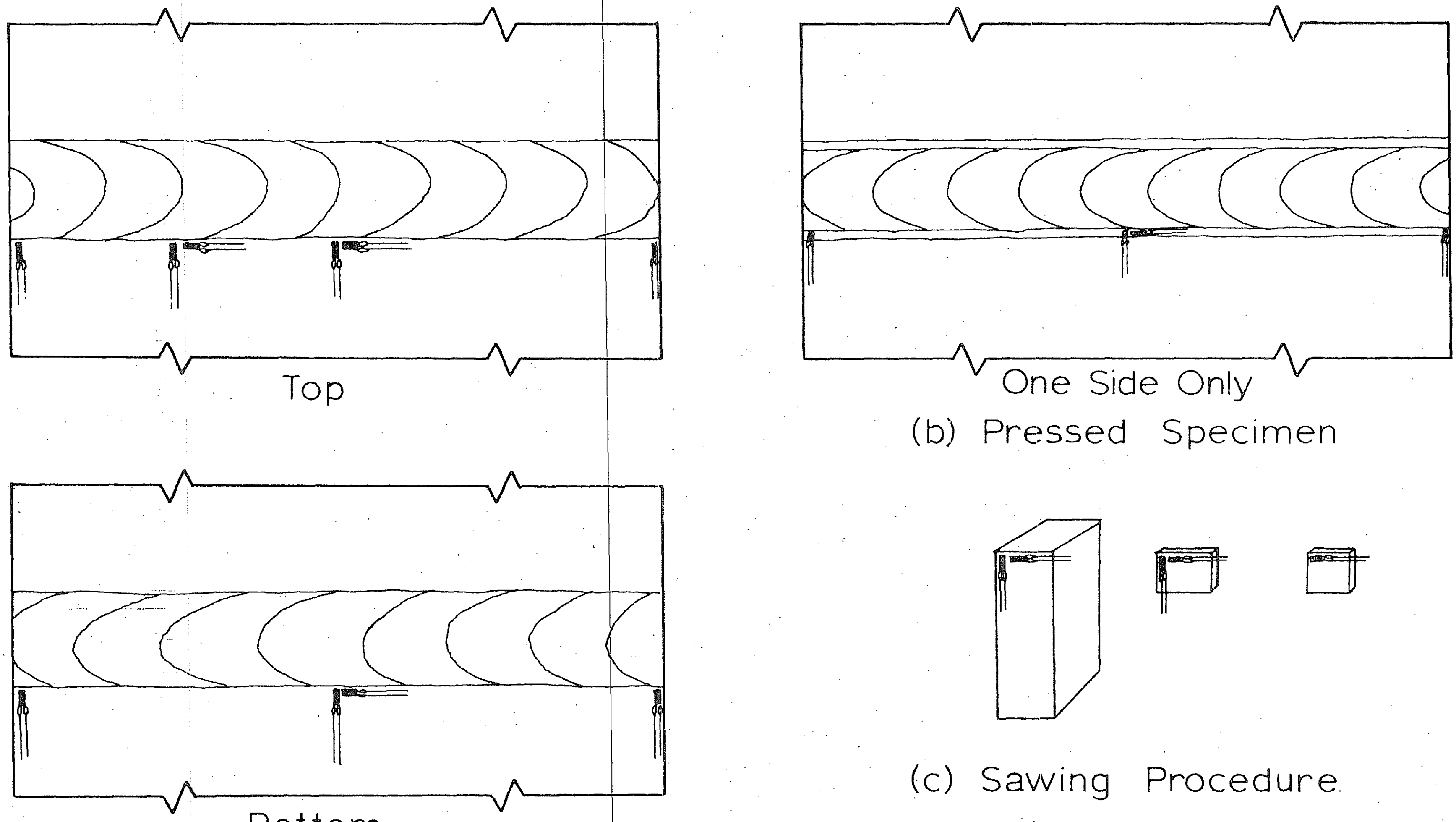


FIG. 4·10 RESULTS OF GEOMETRICALLY SIMILAR SPECIMENS

MODIFIED WELD CONTOUR



Top

Bottom

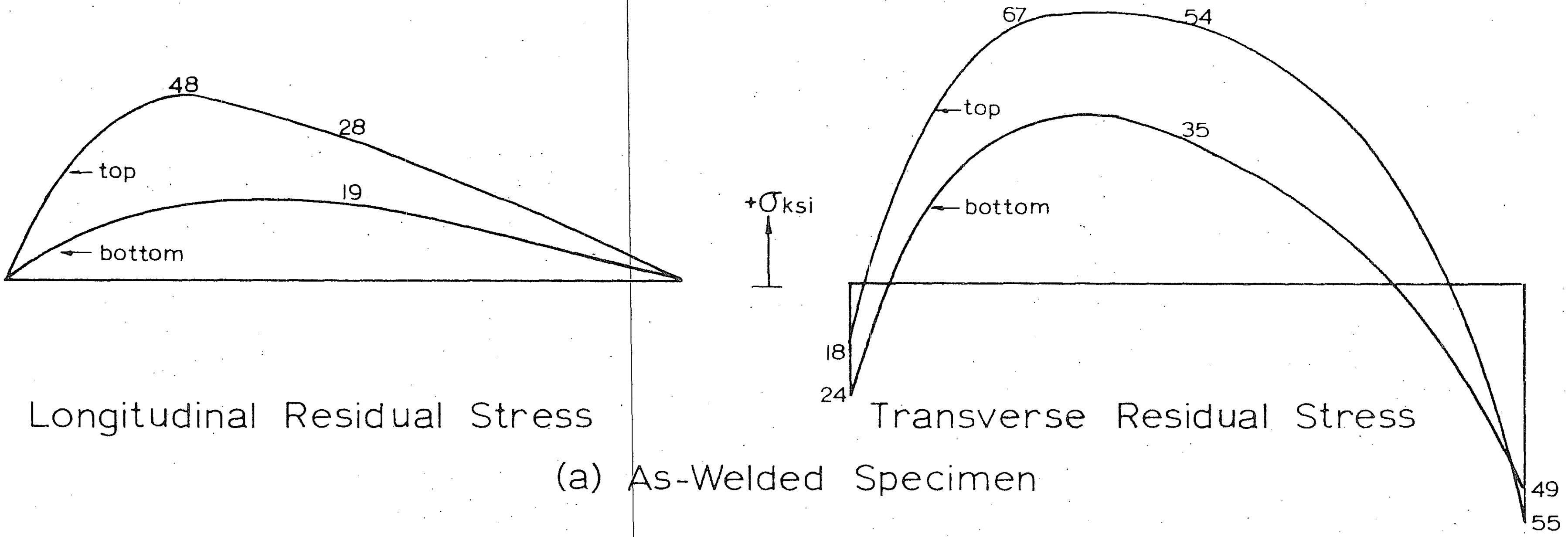
(a) As-Welded Specimen

One Side Only

(b) Pressed Specimen

(c) Sawing Procedure

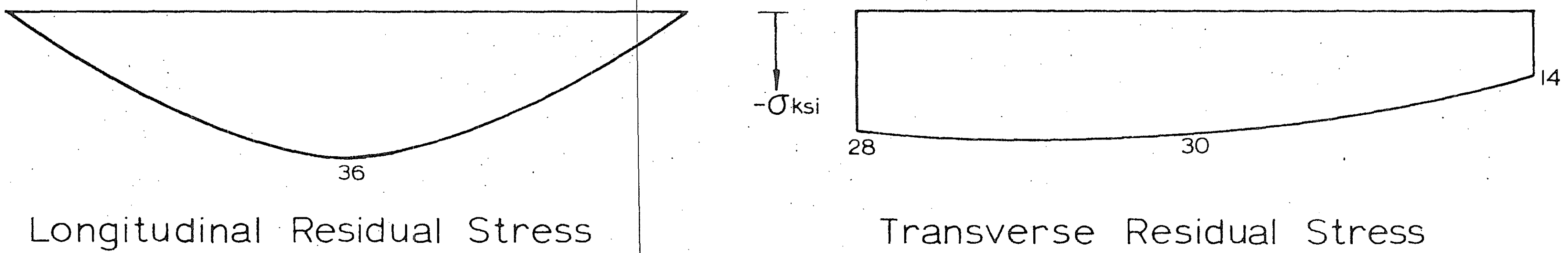
FIG. 5·1 RESIDUAL STRESS SPECIMENS



Longitudinal Residual Stress

Transverse Residual Stress

(a) As-Welded Specimen

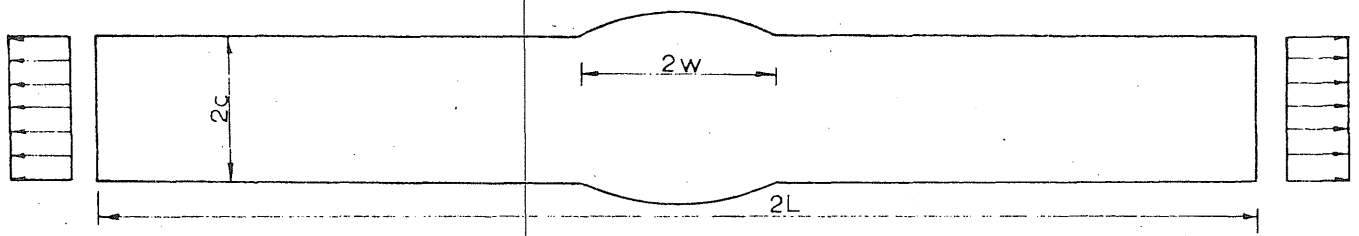


Longitudinal Residual Stress

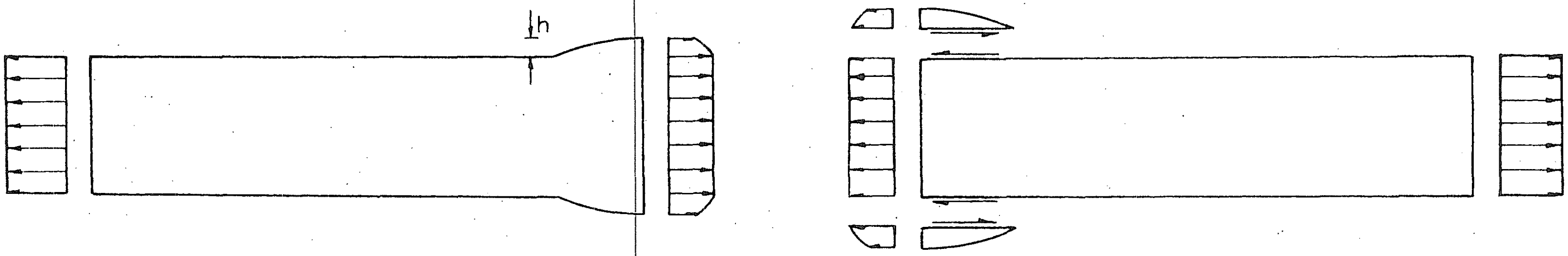
Transverse Residual Stress

(b) Pressed Specimen

FIG. 5·2 RESIDUAL STRESS RESULTS

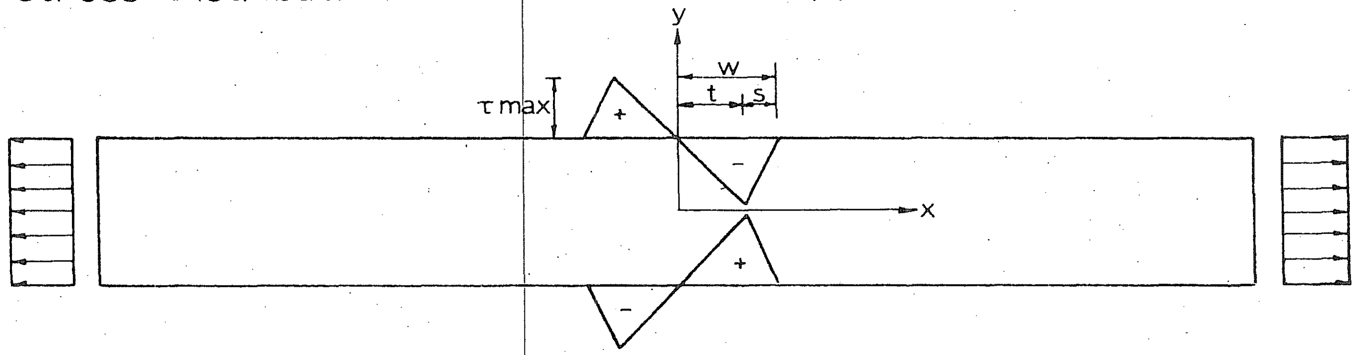


(a) Axially Loaded Weld



(b) Stress Distribution at Center

(c) Reinforcement Removed



(d) Approximate Shear Stress Distribution

FIG. 5·3 EQUIVALENT SHEAR LOADING

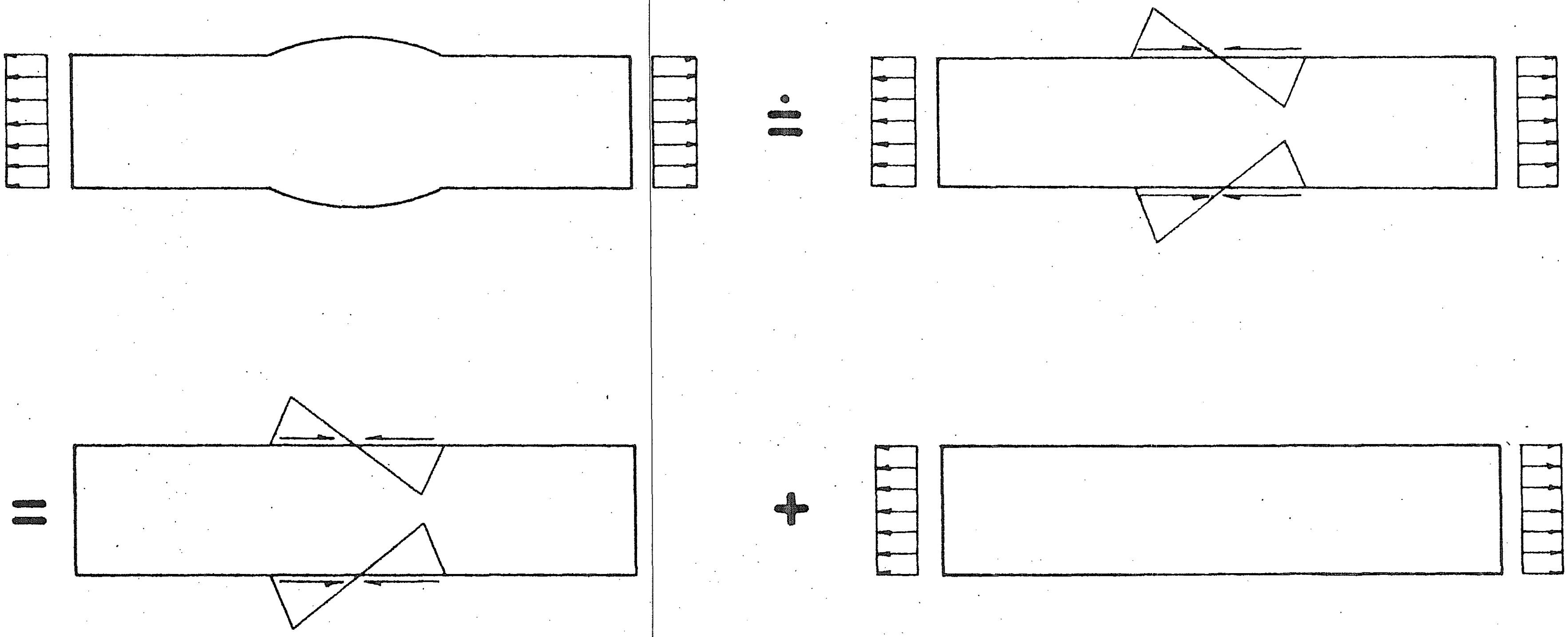


FIG. 5·4 SUPERPOSITION OF BOUNDARY LOADS

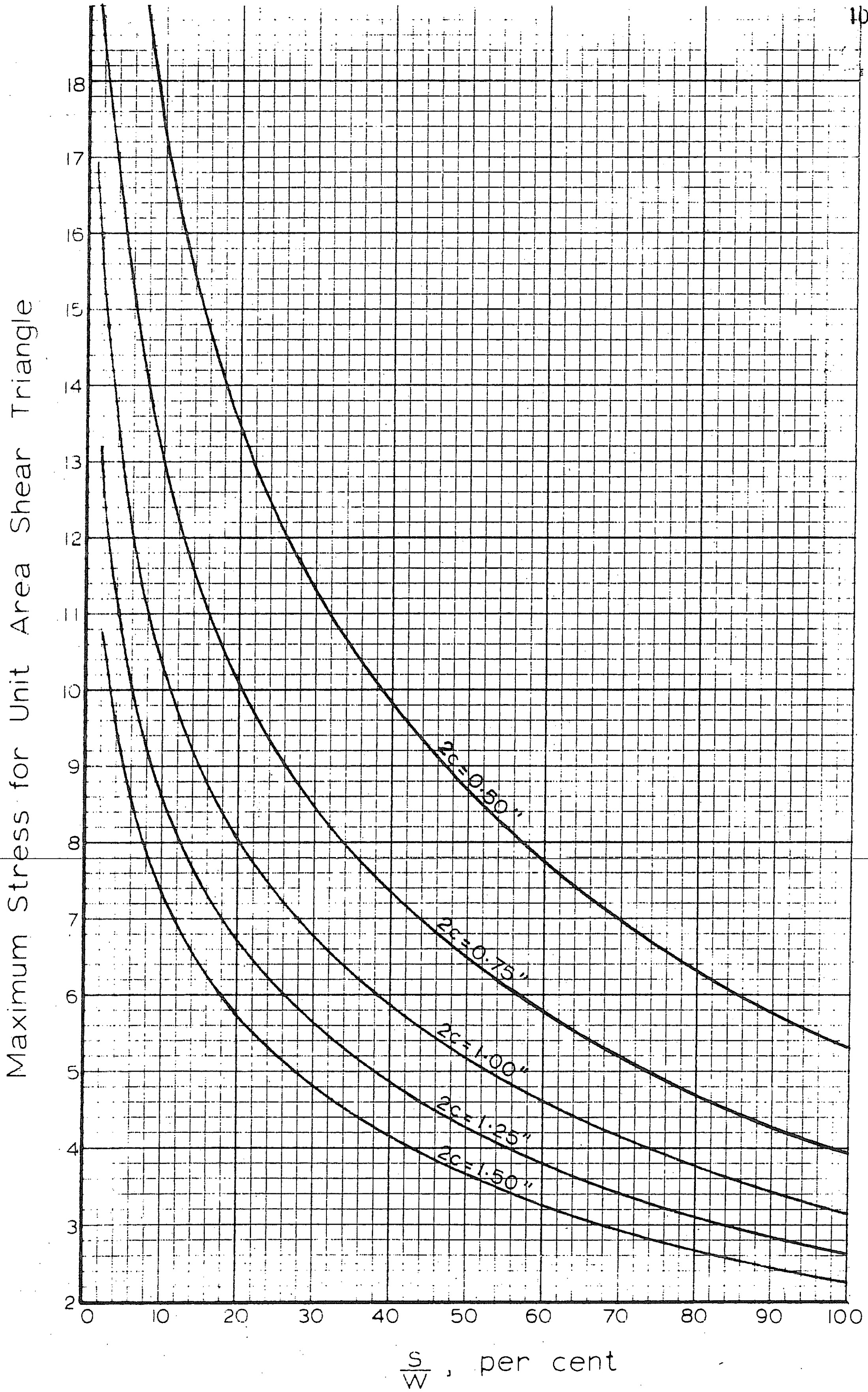


FIG. 5·5 SHEAR CONCENTRATION FACTOR