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THE FATIGUE STRENGTH OF BUTT-WELDED AND PLAIN SPECIMENS OF 18(250) MARAGING STEEL PLATE

by

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SUMMARY

Fatigue tests in pulsating tension on samples of 18(250) maraging steel plate, both with and without central transverse butt welds, are reported. Tests are also described in which the weld bead was removed by grinding. The results obtained from the plain plate, which was tested as rolled and aged, were inferior to those reported by other investigators for specimens machined from bar stock. To investigate this discrepancy, plain plate specimens were also tested with the surfaces ground before aging and after aging.

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THE FATIGUE STRENGTH OF BUTT-WELDED AND PLAIN SPECIMENS OF 18(250) MARAGING STEEL PLATE

1.0 INTRODUCTION

The maraging steels are an attractive group of materials because they are capable of developing very high strength by a simple heat treatment. In the condition normally supplied by the mill i. e., solution annealed, they are readily machineable, yet by a treatment as straightforward as heating to 900°F (482°C) for three hours, followed by air cooling, they can develop static tensile strengths well in excess of 250 ksi. These high strengths are accompanied by adequate ductility, impact strength, and fracture toughness for many design purposes. Furthermore, there is little distortion during heat treatment and problems of scaling and quench cracking do not arise.

An added attraction is that they can be welded fairly readily so that complex structures and components can be built up in which the elimination of quench cracking and minimal distortion during heat treatment are very considerable virtues.

Thus, in spite of the high basic material cost, it may be expected that an increasingly wide range of applications will be found for the maraging steels.

It is well known that the fatigue strength of welds is, in general, considerably lower than that of the base material. The reasons may lie in the stress concentration due to the weld bead, residual stresses, metallurgical changes in the heat-affected zone, or to weld imperfections. In a fatigue test in this laboratory on a particular component made of welded 18(250) maraging steel plate, the fatigue strength was found to be considerably lower than would have been expected from consideration of the data available at that time (Ref. 1 and 2). In order to investigate this phenomenon the manufacturer was requested to prepare simple butt-welded samples that were subsequently subjected to fatigue tests. Similar samples were prepared by the Experimental Workshops of the National Research Council, and tests were also performed on the basic plate. This report presents the results of these and related experiments, the latter being concerned with some of the effects of surface preparation on the welds and on the basic plate.

2.0 TEST SPECIMENS

The test specimens were made from three separate heats of vacuum melted - vacuum cast $\frac{1}{4}$-in (6.35 mm) thick, 18(250) grade maraging steel plate. The material from the first two heats, which will be designated heats A and B for convenience, was used by the manufacturer to prepare butt-welded samples only. Heat C was used for both the weld samples prepared in the NRC Workshops and for the plain material specimens.

The butt-welded specimens from heats A and B were made by cutting and rejoining a plate approximately 12 in × 36 in (300 mm × 900 mm), the cut being made transverse to the rolling direction. For the welded specimens from heat C the plate size was 12 in × 12 in (300 mm × 300 mm). Each plate was then cut and machined to the dimensions shown in Figure 1a to form the fatigue specimens containing a central transverse butt weld. All welds were made manually, using the tungsten-inert gas process.

Two configurations of plain, i. e. not welded, specimens were used, each being made so that the direction of loading would be parallel to the rolling direction. The initial group was made to the same dimensions as the welded specimens (Fig. 1a). To permit testing at higher stress levels within the load capacity of the testing machine, a second group was made to the dimensions of Figure 1b. In this latter group the width of the critical section of the specimen was reduced from 1 in (25. 4 mm) to 0. 750 in (19. 05 mm).

In all cases the specimen profile was machined using a single point tool swung at the appropriate radius, 5 in (127 mm), in a milling machine. For the initial experiments the surface of the plate was left as rolled and heat treated. In later experiments the specimen surface was ground, in some cases before, and in others after, heat treatment. The objective in grinding the welded specimens was to remove the geometric stress concentration due to the weld bead; the total depth removed was sufficient to eliminate the bead and to show a uniform ground surface on the remainder of the specimen. In the case of the plain specimens the principal interest was in the effect of surface finish, and the depth removed by grinding was simply sufficient to remove all of the original rolling marks and leave a uniform ground surface. This resulted in an average loss in thickness, as measured by a micrometer, of 0. 010 in. In all cases grinding was in a longitudinal direction.

Surface roughness measurements on the plate as supplied gave values of 100μ in. parallel to the rolling direction and 161μ in. across the rolling direction. Corresponding values for the ground plate were about 7μ in. in both directions. Examples of the surface profiles of plate as rolled and after grinding are shown in Figures 2 and 3, respectively.

The mill chemical analyses and tensile strength measurements for each heat of material are given in Tables 1 and 2.

3. 0 NON-DESTRUCTIVE TESTING

Prior to machining the welded plates, each was subjected to non-destructive testing. The plates from heats A and B were inspected by the manufacturer, using the current U. S. Military Specifications, and were certified to have been welded and inspected to the following:

(i) Welding, fusion; Process for. MIL-W-8611.
(ii) Radiographic inspection. MIL-STD-453.
(iii) Inspection, Penetrant, Type II. MIL-I-6866 (ASG).
(iv) Ultrasonic inspection. MIL-STD-271D (SHIPS).

These inspections were reported to have shown no significant defects.

Early in the test program it became apparent that failures were occurring at weld imperfections that had escaped detection by the manufacturer. It was therefore decided to reinspect the untested specimens that remained by using a standard commercial portable ultrasonic test instrument. The presence of surface defects was considered unlikely and, even if present, would have been readily detected by the manufacturer's dye penetrant inspection. Facilities for in-house radiographic inspection were not available; in any event, it was reported in Reference 3 that this material is relatively insensitive to the detection, by radiographic techniques, of many classes of weld defect.

The ultrasonic reinspections were made using a 4 MHz, 60°, miniature angle probe. The use of a miniature probe was dictated by the physical size of the weld area, 1 in × $\frac{1}{4}$ in (25. 4 mm × 6. 35 mm), and by the desire to locate the position of the small defects as precisely as possible.

The probe was traversed at $2\frac{1}{4}$ skip distances from the weld centreline, thus placing it beyond the near field zone. The probe position and alignment were maintained by the use of guide lines lightly scribed on the surface of the plate. These lines were sufficiently remote from the critical minimum width section of the specimen to eliminate the possibility that they might lead to premature failure.

In order to provide a reference standard for the ultrasonic tests, a calibration block containing a "manufactured defect" was prepared. This block consisted of a welded sample in which a No. 58 drill hole (0. 042 in (1. 07 mm) diam.) was made along the weld. This hole was then partially plugged with an interference fit rod so that a cylindrical cavity 0. 042 in. diameter by about 0. 10 in. long (1. 07 mm × 2. 5 mm) was formed in the centre of the weld as shown in Figure 4a. The ultrasonic signal given by this reference standard is shown in Figure 4b.

The interpretation of the results of ultrasonic inspections is a complex subject, highly dependent on operator skill and experience. Thus, at the present state of the art, it is not possible to document quantitatively the results of these inspections. Broadly speaking, two classes of ultrasonic indication were found in the welds studied in this program.

(i) Those that were characterised by a highly directional return signal from defects that were essentially planar, e. g. cracks or lack of fusion.

(ii) Those that produced a multidirectional return. Such signals are obtained from inclusions, pores, and similar defects.

When a defect is detected by traversing a probe, its size can, in principle, be estimated from the length of traverse in which the return signal is detected. The directionality of the signal is determined by traversing in an arc centred on the defect. The intensity of the return signal can also be interpreted qualitatively to give an indication of the nature of the defect.

All welds from heat C (those fabricated in the NRC Workshops) were subjected to ultrasonic inspection in the laboratory. They were not, however, radiographed, nor was dye penetrant used.

4.0 TESTING MACHINE

All fatigue tests were performed in a conventional sub-resonant machine of 10,000 lb (44 kN) capacity equipped with a 5:1 load multiplier to extend the capacity to 50,000 lb (220 kN) at the small deflections required by a tension specimen. This machine operates at a fixed frequency of 30Hz.

Prior to and during the test program the machine was calibrated using a specimen of identical stiffness with that used in the test program, and it is estimated that the loads were within ± 2 percent of the required values.

5.0 TEST PROGRAM AND RESULTS

5.1 Fatigue Tests

5.1.1 Butt Welds as Fabricated

The butt-welded plates from heats A and B yielded a total of 29 specimens and a further 24 specimens were obtained from heat C, welded by NRC Workshops. These specimens were all tested in pulsating tension with the ratio of minimum to maximum stress, R, equal to 0.1. The test stresses were based on the plate thickness and the minimum width; the maximum values ranged from 30 to 140 ksi (207 to 965 MN/m^2).

Specimens that did not fail in less than 15×10^6 cycles at a particular stress level were subsequently retested at a higher level. These retests are marked on the plots with the symbol "R". The results of the tests are given in Table 3, and plotted in Figure 5.

5.1.2 Effects of Weld Bead Removal

In an attempt to improve the fatigue strength of the welded specimens, the weld beads were ground off seven heat-treated specimens from heat C, and a further ten specimens from this heat were ground before heat-treating. The results of the fatigue tests on these specimens are given in Table 4 and plotted in Figures 6 and 7. Of this group of specimens three failed at the grip end because of fretting of the lugs. The results of these tests are identified by the symbol "G" in the plots.

5.1.3 Plain Material Tests

The first group of plain material specimens from heat C were tested with the surfaces as rolled and heat treated. The results of these experiments are given in Table 5 and Figure 8. As with the welded and ground specimens, three of the plain specimens also failed in the grip. In an attempt to minimise this problem and also to permit testing at higher stress levels, the width of the critical section of the next two groups was reduced to 0.75 in (19.05 mm) from the original 1 in (25.4 mm), leaving the dimensions of the grip ends unaltered.

The first group of these narrower specimens was surface ground before aging and the second after aging. The results of the fatigue tests are given in Table 5 and Figures 9 and 10.

5.2 Non-Destructive Tests and Fracture Surfaces

The ultrasonic inspection of the specimens from heat A revealed no significant defects and all specimen failures were normal, occurring at the toe of the weld. The laboratory inspection of welds from heats B and C, however, revealed a significant number of imperfections, and descriptions will be given of the more interesting findings.

5.1.2 Specimen B-5W-AG

This specimen gave two ultrasonic indications; the weaker appeared to be from a planar defect while the stronger gave a multidirectional return signal and might therefore be associated with pores or inclusions. Figures 11a and 11b show the magnitudes of the signals obtained (the relevant signal in these and subsequent illustrations is that part in the gate on the time base of the oscilloscope trace, the latter being used to position the centre of the weld). The specimen was tested at a maximum stress of 70 ksi (483 MN/m^2) with the weld bead removed after heat treatment, and failed after 16×10^6 cycles. The fracture surface, shown in Figure 11c, reveals the origin of the failure as incomplete penetration at the centre of the weld, and the position of the origin was found to correlate with the weaker return signal. This signal was identified as being from a planar defect that obviously generated a more severe stress concentration than did the pores or inclusions associated with the stronger signal.

Examination of the results of the fatigue tests on the group of specimens shown in Figure 6 indicates that these defects had little or no influence on the fatigue strength of this specimen.

5.2.2 Specimen B-1W-AG

This specimen gave an ultrasonic indication of a planar defect; the signal strength is shown in Figure 12a. When tested at 90 ksi (621 MN/m^2) after removal of the weld bend subsequent to heat treatment, it failed after 43×10^3 cycles. The fracture surface, Figure 12b, showed a region of incomplete penetration. In contrast to specimen B-5W-AG, the test result suggests a considerable reduction in fatigue strength.

5.2.3 Specimen B-7W-AG

The ultrasonic indications from specimen B-7W-AG (Fig. 13a) suggested the presence of a cluster of small inclusions close to the edge of the specimen. This interpretation was incorrect as Figure 13b shows that the defect in the fracture surface was, once more, incomplete penetration. This misinterpretation arose, presumably, because of reflections from the edge of the specimen that gave a multidirectional impression of the return signal.

The specimen was ground after heat treatment and tested at 70 ksi (483 MN/m^2). Failure occurred after 32,000 cycles, a relatively low life for this group of specimens.

5.2.4 Specimen B-6W-AG

Specimen B-6W-AG was interesting in that, although no significant defects were located by non-destructive testing, two imperfections are clearly visible in the fracture surface (Fig. 14). The origin of the failure appears to be an inclusion near the centreline of the weld; the crack has also passed through a region of incomplete penetration. In spite of the presence of the two imperfections in this weld, there were no serious consequences to the fatigue strength. The specimen was ground after aging and survived 12×10^6 cycles at a maximum stress of 55 ksi (379 MN/m^2), and failed after a further 1.4×10^6 cycles at 75 ksi (517 MN/m^2).

5.2.5 Specimen C-33W

The ultrasonic inspection of specimen C-33W (Fig. 15a) indicated the presence of an abnormally large defect. Radiography was used to clarify the nature of the defect, and Figure 15b shows a large inclusion. Because of the size and location of the defect, this specimen was tested with the weld bead on at maximum stress of only 30 ksi (207 MN/m^2), well below the fatigue limit.

Failure occurred in the weld after 83×10^6 cycles and the fracture surface is shown in Figure 16a. A microsection taken just below the fracture surface (Fig. 15b) confirmed the presence of a large oxide inclusion.

5.2.6 Specimen C-15W

Specimen C-15W also gave an ultrasonic indication that was identified as an inclusion. The strength of the return signal was particularly high (Fig. 17a). The specimen was tested at a maximum stress of 45 ksi (310 MN/m^2) with the weld bead on, and failed after 145×10^3 cycles. In spite of the size of the inclusion, which was identified in the fracture surface (Fig. 17b) as a piece of tungsten electrode, the effect of its presence on the fatigue life at this stress level was not very great, a reduction by a factor of the order of two on the average life of this group. The smallness of the effect is presumably because the inclusion was well rounded, i.e., that the stress concentration was minimal. In spite of this, failure did occur in the central area of the weld instead of at the toe of the reinforcement, as is more usual.

5.2.7 Specimens C-8W and B-16W

Specimens C-8W and B-16W contained weld imperfections that were considered to be barely detectable by conventional non-destructive testing. Figures 18a and 18b show the ultrasonic signals obtained. In examining these Figures it must be remembered that the relevant signal is only that part at the centre of the gate that indicates the centre of the weld - the major echo is from the geometry of the weld surface away from the centreline. The fracture surface of specimen C-8W, which failed through the weld after 10×10^3 cycles at a maximum stress of 100 ksi (689 MN/m^2), is shown in Figure 19a. Specimen B-16W survived 20×10^6 cycles at 45 ksi (310 MN/m^2) and subsequently failed through the weld after a further 24×10^3 cycles at 80 ksi (552 MN/m^2), giving the fracture surface shown in Figure 20a.

A macrosection through the weld of specimen C-8W (Fig. 20b) shows that there was incomplete penetration of the weld. The fracture surface (Fig. 19) indicates, on the other hand, that some kind of fusion had occurred. A higher magnification examination of the questionable area of the macrosection (Fig. 21a) suggests that, although the temperature was very close to melting, as indicated by the columnar form of the grain growth, no true melting occurred. For comparison with Figure 21a, a typical microstructure of good aged weld is shown in Figure 21b. It can be seen that the dendrites in this condition are interlaced by light areas of alloy-rich material. The disappearance of these light areas, coupled with grain growth, would seem to indicate that the material shown in Figure 21a has been exposed to fairly high temperature.

On the basis of this examination, coupled with the fact that the echo strength in the ultrasonic test was very low, it is postulated that although true melting had not occurred, the joint was mechanically complete.

In neither of these specimens did the fatigue strength depart noticeably from the averages of the group.

5.2.8 General Comments on Fractures

In almost all of the welded specimens tested with the weld bead on, failure occurred at the toe of the weld bead. With the weld bead removed, failures tended to be on the weld centreline where the incidence of weld defects was highest.

The relatively frequent occurrence of incomplete penetration in the welds would seem to be a consequence of the heavy chill that is customarily used in welding this material. It is fortunate that this form of defect does not appear to have any major consequence in terms of strength.

The plain specimens behaved in a conventional manner, with the fractures occurring at more or less random positions in the minimum area of the specimen. There were no indications of significant inclusions or other defects in the plate.

6.0 DISCUSSION

The results of the fatigue tests on the butt-welded joints from the three heats of material tested with the weld bead on are plotted in Figure 5. An attempt was made to distinguish between the results from the three heats, but it was concluded that the differences were so small that they could not validly be separated in a meaningful statistical sense. A curve has therefore been drawn through the points by eye. It would appear that the fatigue limit obtained from these tests corresponds to a maximum stress of about 34 ksi (234 MN/m^2) i.e., 18.7 ± 15.3 ksi (129 ± 105 MN/m^2).

A fatigue limit of this level seems remarkably low for a material having a basic tensile strength in excess of 250 ksi (1723 MN/m^2), representing a ratio of fatigue limit to tensile strength of only 13.6 percent.

The fatigue limit for the plate as rolled is also relatively low; Figure 8 suggests that its value is about 80 ksi (551 MN/m^2) i.e., 44 ± 36 ksi (303 ± 248 MN/m^2). Thus the fatigue notch factor for the welds at the fatigue limit, (the ratio of the fatigue strength of the plain specimens to that of the welded) is $K_f = 2.35$. Gurney (Ref. 4) has shown from the results of tests on lower strength steels that a very important parameter is the stress concentration due to the weld reinforcement. The magnitude of the stress concentration depends largely on the reinforcement angle, i.e., the angle between the plate surface and a tangent to the weld bead at the point of contact with the plate. Measurement of this angle from a number of macrosections of the maraging steel, such as Figure 20b, shows that for the present welds the angle is of the order 150 to 160°. The data of Reference 4 suggest that, with the lower strength material, the fatigue notch factor for this reinforcement angle is $K_f \simeq 1.4$. Thus the effects of butt welds in the maraging steel are considerably more deleterious than might be anticipated from tests of lower strength material.

Removal of the weld bead by grinding has a number of effects, among which might be listed:

(i) The reduction in geometric stress concentration by removal of the reinforcement.

(ii) Improving the surface finish.

(iii) The introduction of residual stresses.

(iv) The increase in stress level in the weld metal.

(v) The removal of surface material that may have properties differing from the core.

Figure 6 shows that, for five specimens out of seven, there was an appreciable improvement in fatigue strength if the welds were ground after aging, whereas Figure 7 indicates that if the specimens were ground before aging there was a distinct improvement for two out of twelve and a questionable improvement for another three. In no case was an appreciable reduction in fatigue strength apparent.

The increase in stress level at the weld centreline has the effect of increasing the significance of weld imperfections. This was evident from the examination of the fracture surfaces, since the specimens with the weld bead intact almost invariably failed at the toe of the weld and consequently no imperfections were found in the fracture surfaces. Conversely, many of the specimens tested with the weld bead removed failed at the weld centreline and showed evidence of weld imperfections.

The results of the ultrasonic inspections can only be described as inconclusive. While defects were certainly found, most had little effect on the fatigue strength and there was an insufficient number of major defects to draw any meaningful conclusions. It is, perhaps, reassuring to know that ultrasonic tests have the capability of detecting imperfections so small that they do not affect the fatigue strength. This fact, on the other hand, could lead to the unnecessary rejection of welds in quality control inspections. It is clear that much remains to be done to improve the usefulness of the ultrasonic inspection technique.

A study of the effects of weld bead removal on a lower strength grade of maraging steel has been reported in Reference 5. In these experiments the ultimate strength of the steel was about 200 ksi (1380 MN/m^2) compared with 250 ksi (1720 MN/m^2) of the present tests. The conclusion reached was in accord with the findings described above - that weld bead removal increases the average fatigue life at a given stress level, but the minimum lives remain the same.

It is well known that improvements in fatigue strength can be obtained if compressive residual stresses can be induced in the surface of the specimen. Reference 6 describes the results of experiments in which the surfaces of welded maraging steel specimens, again of the slightly lower strength grade, were shot peened. The very high ratio of yield to ultimate strength would lead one to suppose that the potential for absorbing high residual stresses would enable large gains in fatigue strength to be achieved from such treatment. This was found to be the case, and for butt welds the stress for a given life was almost doubled at lives in excess of about 10^4 cycles. For fillet welds, however, virtually no improvement occurred because the failure originated at an inside surface that could not be peened.

Surface grinding of the plain plate specimens can result in only three of the five possible effects that were referred to in connection with welds, viz (i) improvement of surface finish, (ii) introduction of residual stresses, (iii) removal of surface material. Results of the experiments on plain specimens given in Figures 8, 9, and 10 are summarised in Figure 22. The fatigue limit for plate heat treated as rolled corresponds to a maximum stress of 80 ksi (552 MN/m^2). Grinding before aging increases this to about 90 ksi (621 MN/m^2) and grinding after aging to about 108 ksi (745 MN/m^2).

In spite of the considerable improvement in fatigue strength caused by grinding after aging, the results obtained are still substantially lower than those reported in References 1 and 7 for round bar stock of similar material. The consistency between the findings in these two investigations, which are also shown in Figure 22, seems remarkably good and there seems to be no reason to question them. As can be seen, they indicate a fatigue limit of about 132 ksi (910 MN/m^2), some 22 percent higher than the best value found for the plate of the present investigation. The reasons for this discrepancy are not clear; they may lie in the processing of the basic material, i. e. rolling rod versus plate, metallurgical differences, or in the difference in specimen configuration, e. g., the effects of the corners of the plate specimens. It is not considered that the effects of stress ratio, R, would be sufficient to account for it. A sufficient number of checks on machine calibration and specimen alignment were made to preclude the likelihood that the discrepancy was due in any way to errors in testing procedure in the experiments on the plate.

Experiments on the effect of surface preparation on the fatigue strength of maraging steel have also been reported in Reference 8. In this latter investigation the specimens were tested as rotating beams with the load progressively increasing during the test. The stress at failure is taken as the figure of merit in this type of test, the results of which cannot, of course, be directly related to more conventional fatigue tests. The results of interest from these experiments were that specimens aged after turning, or after turning plus peening, gave failure stresses of 81 and 78 ksi (558 and 538 MN/m^2) respectively, whereas if the turning or turning plus peening were done after aging, the failure stresses rose to 112 and 114 ksi (772 and 786 MN/m^2). This improvement agrees remarkably closely with the results of the experiments on the plate, even though both testing and machining methods were quite different. That the effects of shot peening were negligibly small is perhaps surprising.

Reference 6 also includes the results of experiments on the effect of shot peening the lower strength grade of maraging steel. In contrast to the results obtained for the round bar specimens of Reference 8, shot peening the plate increased the fatigue limit from $\pm$ 45 to $\pm$ 67 ksi ($\pm$ 310 to $\pm$ 462 MN/m^2).

7. 0 CONCLUSIONS

(i) The fatigue limit of butt welds in 18(250) maraging steel plate tested in pulsating tension is low, being about 18. 7 $\pm$ 15. 3 ksi (129 $\pm$ 105 MN/m^2).

(ii) The fatigue limit of plate tested as aged and rolled is also low compared with the static strength, being about 44 $\pm$ 36 ksi (303 $\pm$ 248 MN/m^2).

(iii) The fatigue notch factor for these butt welds is considerably higher than would be anticipated from data on lower strength steels.

(iv) Removal of the weld bead, or reinforcement, by grinding either before or after aging, appears to increase the average life without changing the minimum.

(v) Non-destructive testing by the use of ultrasonics is capable of detecting small weld imperfections that have no appreciable effect on fatigue strength. It was not possible, within the scope of the present experiments, to define useable limits to the tolerable ultrasonic indications.

(vi) Surface grinding the plain plate specimens increased the fatigue strength, the greatest increase occurring if grinding was performed after aging.

(vii) The best results obtained from ground plate specimens were considerably inferior to those reported from specimens made from bar stock.

8.0 SUGGESTIONS FOR FURTHER WORK

The high ratio of yield to ultimate strength of maraging steel strongly suggests that the poor fatigue strength might be very considerably improved by subjecting it to processes that give high residual stresses at the surface. The reported effects of shot peening are inconsistent and require further investigation. The merits of surface grinding have been demonstrated, but no attempt has so far been reported to determine the optimum conditions for the generation of surface residual stress, e.g., wheel type, speed and feed rate.

This high yield/ultimate ratio may also lead to abnormal situations in cumulative damage of notched specimens subjected to non-constant amplitude loading because of the effects of residual stresses at the notch root. Experiments with programed and random loading are therefore desireable.

A noteworthy feature of the experiments was the relatively large number of specimens that failed in the grips of the testing machine. These failures lead to the suspicion that maraging steel may be particularly susceptible to fretting fatigue. This should be investigated, using simple lug-type specimens.

There is clearly much scope for further development in non-destructive testing of welds. The fact that weld bead removal promotes failure at the centreline of the weld provides a useful tool to correlate ultrasonic indications with the defects that most frequently occur in this area, since these can be seen readily in the fracture surface.

9.0 ACKNOWLEDGEMENT

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TABLE 1

MILL CHEMICAL ANALYSES OF MATERIALS

Form	Plate			Filler Wire	
Used in Specimen Groups	A	B	C	A	C
Heat No.	09759	09784	25966	09522	25433
C	0.02	0.02	0.02	0.01	0.009
Si	0.03	0.06	0.02	0.03	0.012
Mn	0.05	0.03	0.06	0.06	0.027
S	0.006	0.004	0.008	0.007	0.008
P	0.004	0.004	0.003	0.002	0.006
Al	0.14	0.14	0.08	0.08	0.054
Ti	0.42	0.49	-	0.48	0.40
B	0.003	0.004	-	0.003	-
Mo	4.71	4.85	4.78	4.53	4.60
Co	7.38	7.98	7.89	7.80	7.40
Ni	18.20	19.00	18.42	18.02	18.69
Zr	0.016	0.013	-	0.017	-
Ca	0.05	0.05	-	0.05	-

TABLE 2

TENSILE PROPERTIES OF PLATE

Heat No.	09759	09784	25996
Used in Specimen Groups	A	B	C
Aging	925°F, 3 hr	900°F, 3 hr	900°F, 3 hr
Ultimate tensile strength	256.7 ksi	264.4 ksi	257.8 ksi
Yield strength	250.0 ksi	262.8 ksi	253.0 ksi
Elongation	13.0%	11.5%	8.0%

TABLE 3

FATIGUE TEST RESULTS FROM BUTT WELDS - AS WELDED

Minimum Stress/Maximum Stress = 0.1

(i) Heat A

Maximum Stress		Specimen	Life
ksi	MN/m^2		Cycles $\times 10^{-3}$
140	965	A-12W	7
90	621	A-4W	36
90	621	A-8W	36
90 (R)	621	A-9W	34
80	552	A-3W	16
80 (R)	552	A-2W	77
70 (R)	483	A-13W	87
70	483	A-7W	78
55	379	A-5W	138
50	345	A-1W	97
50	345	A-6W	383
50	345	A-10W	330
45	310	A-9W	23,409 (NF)
40	276	A-2W	23,168 (NF)
35	241	A-13W	25,739 (NF)

(ii) Heat B

100 (R)	690	B-8W	34
100 (R)	690	B-13W	91
90	621	B-2W	48
80 (R)	552	B-16W	24
70	483	B-9W	63
70	483	B-12W	14
55	379	B-11W	91
50	345	B-4W	282
45	310	B-16W	20,399 (NF)
45	310	B-15W	380
45	310	B-10W	52,284 (NF)
40	276	B-8W	52,900 (NF)
40	276	B-13W	61,537 (NF)
40	276	B-3W	439

(iii) Heat C

100	689	C-14W	21
100	689	C-8W	10
100	689	C-19W	11
100 (R)	689	C-18W	57
80	552	C-28W	24
80	552	C-9W	38
55	379	C-16W	230
55	379	C-13W	126
55	379	C-3W	192
55	379	C-5W	251
55	379	C-1W	239
45	310	C-27W	278
45	310	C-15W	145
40	276	C-4W	784
40	276	C-32W	681
40	276	C-26W	1,062
40	276	C-22W	176
40	276	C-25W	337
40	276	C-29W	880
40	276	C-17W	741
35	241	C-18W	54,111 (NF)
30	207	C-33W	83,120

Note: (NF) Indicates no failure at life tabulated.
(R) Denotes a retest of a specimen that did not fail at a lower stress.

TABLE 4

EFFECT OF WELD BEAD REMOVAL

(i) Aged Before Grinding Specimens from Heat B

Maximum Stress		Specimen	Life
ksi	MN/m^2		Cycles × 10^{-3}
90	621	B-1W-AG	43
80	552	B-17W-AG	1,044 (G)
75 (R)	517	B-6W-AG	1,388
70	483	B-5W-AG	15,729
70	483	B-7W-AG	32
70	483	B-14W-AG	3,047 (G)
55	379	B-6W-AG	12,270 (NF)

(ii) Ground Before Aging - Specimens from Heat C

165	1138	C-6W-GA	51
165 (R)	1138	C-23W-GA	47
125	862	C-7W-GA	9
125	862	C-11W-GA	252
125	862	C-12W-GA	10
125 (R)	862	C-10W-GA	10
125 (R)	862	C-30W-GA	13
100	689	C-31W-GA	176
80	552	C-20W-GA	13,367 (G)
80	552	C-21W-GA	28
80	552	C-24W-GA	44
80	552	C-23W-GA	14,776 (NF)
30	207	C-30W-GA	17,285 (NF)
30	207	C-10W-GA	15,117 (NF)

Note: (NF) Indicates no failure at life tabulated.
(R) Denotes a retest of a specimen that did not fail at a lower stress.
(G) Specimen failed at grip end.

TABLE 5

TEST RESULTS FROM PLAIN PLATE
All Specimens from Heat C

(i) Surface as Rolled

Maximum Stress		Specimen	Life
ksi	MN/m^2		Cycles × 10^{-3}
165	1138	C-4P	19
150	1034	C-7P	37
100	689	C-1P	74
100	689	C-6P	90
100	689	C-11P	82
100 (R)	689	C-2P	133
85	586	C-8P	591
85	586	C-9P	2,478 (G)
85	586	C-12P	180
85	586	C-13P	166
85	586	C-17P	196
80	552	C-15P	175
80	552	C-16P	8,847 (G)
75	510	C-3P	569
75	510	C-5P	16,662 (G)
75	510	C-14P	10,010 (NF)
55	379	C-2P	15,317 (NF)

(ii) Aged before Grinding

240	1655	C-29P-AG	17
180	1241	C-21P-AG	34
180	1241	C-24P-AG	51
160	1793	C-25P-AG	65
140	965	C-22P-AG	184
140	965	C-23P-AG	78
120	827	C-27P-AG	2,708
120	827	C-28P-AG	5,612
100	689	C-18P-AG	2,649 (G)
100	689	C-19P-AG	715
100	689	C-20P-AG	12,623 (NF)
100	689	C-26P-AG	24,488 (NF)

(iii) Ground before Aging

220	1517	C-40P-GA	20
220 (R)	1517	C-40P-GA	18
180	1241	C-32P-GA	39
180	1241	C-33P-GA	28
180 (R)	1241	C-31P-GA	23
160	1103	C-34P-GA	46
140	965	C-35P-GA	69
140	965	C-37P-GA	52
100	689	C-30P-GA	357
100	689	C-31P-GA	15,813 (NF)
100	689	C-36P-GA	139
85	586	C-38P-GA	19,263 (G)
85	586	C-39P-GA	11,476 (G)
85	586	C-40P-GA	10,140 (NF)

Note: (NF) Indicates no failure at life tabulated.
(R) Denotes a retest of a specimen that did not fail at a lower stress.
(G) Specimen failed at grip end.

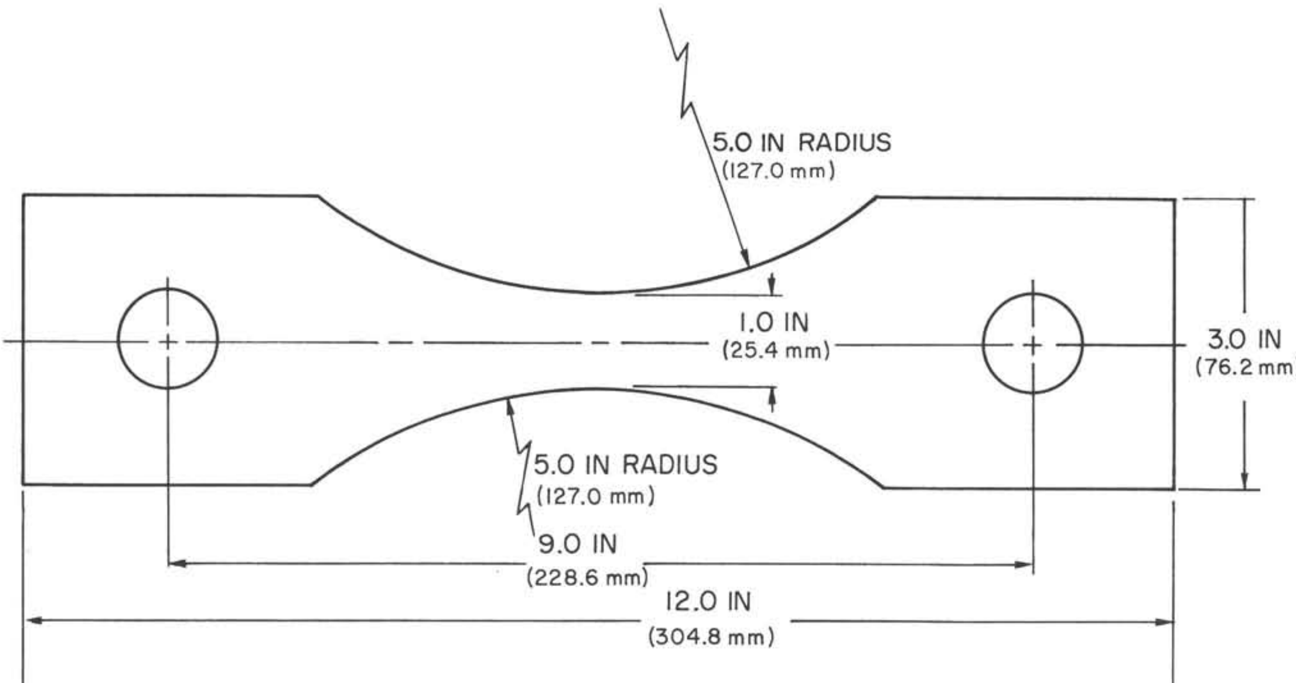


FIG. 1a: 1-INCH WIDE SPECIMEN

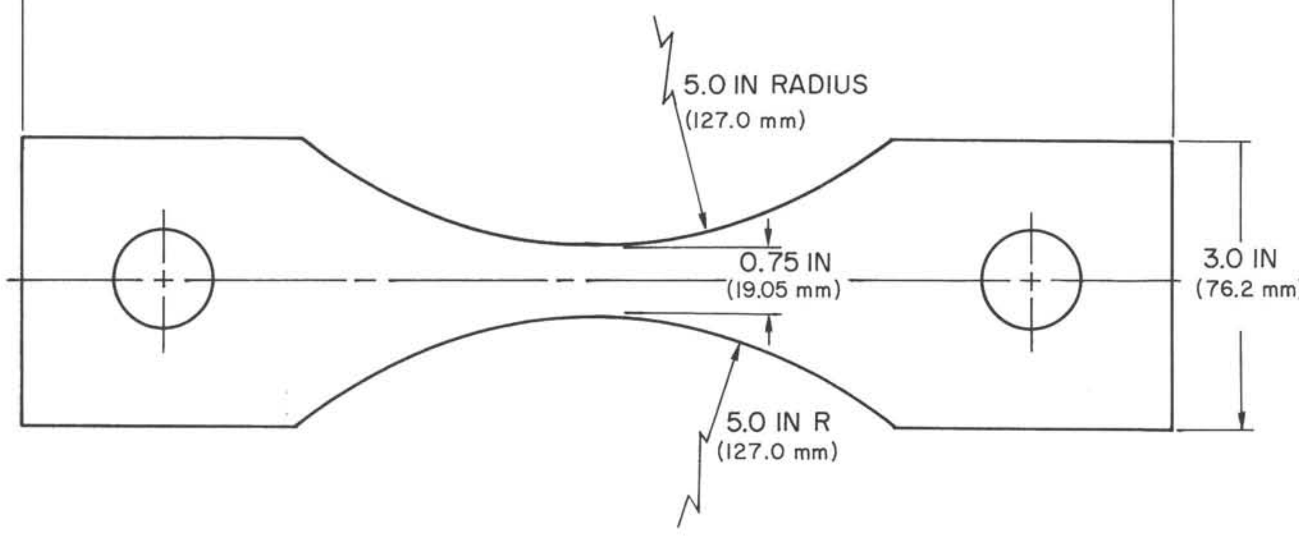
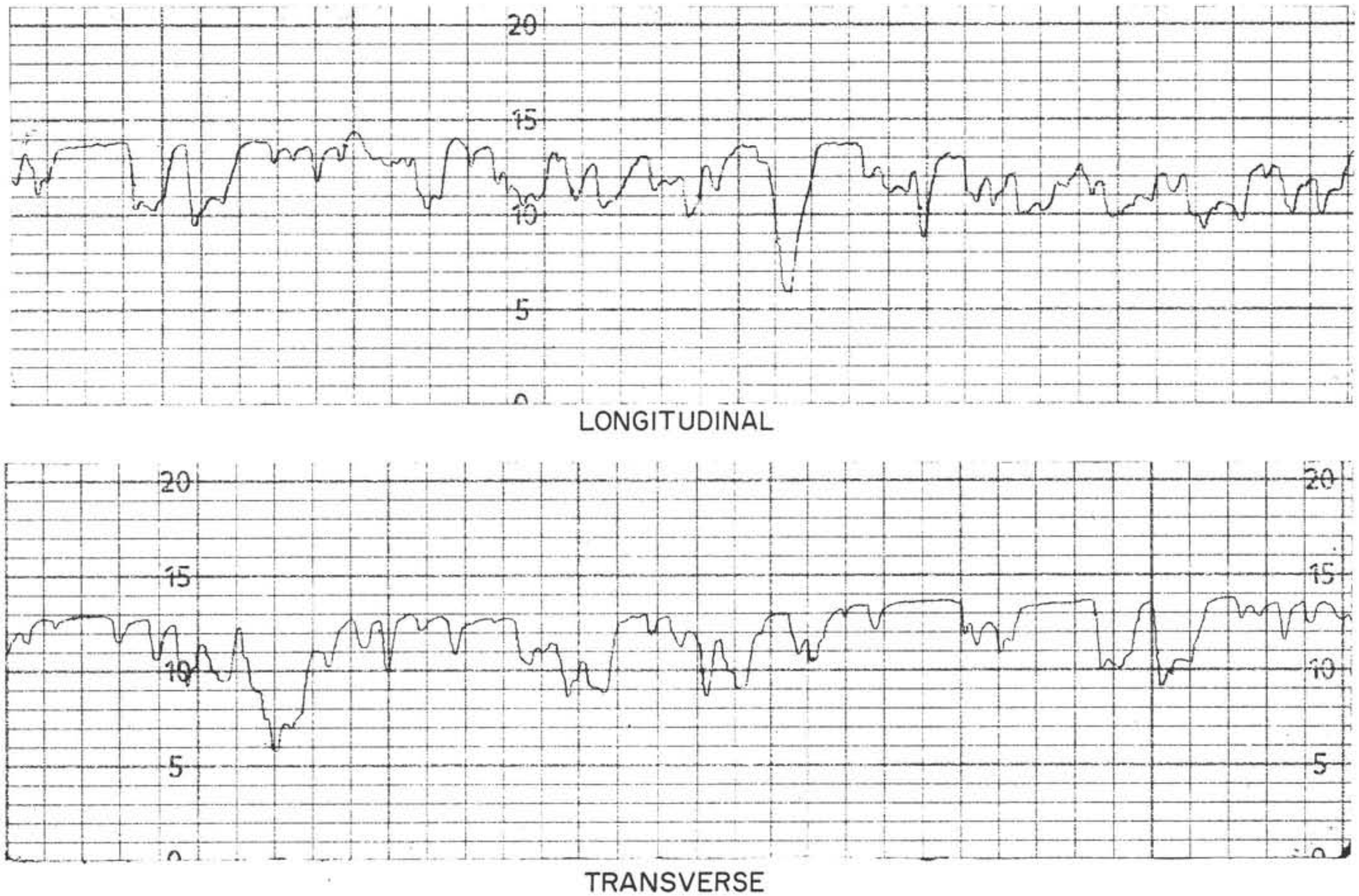
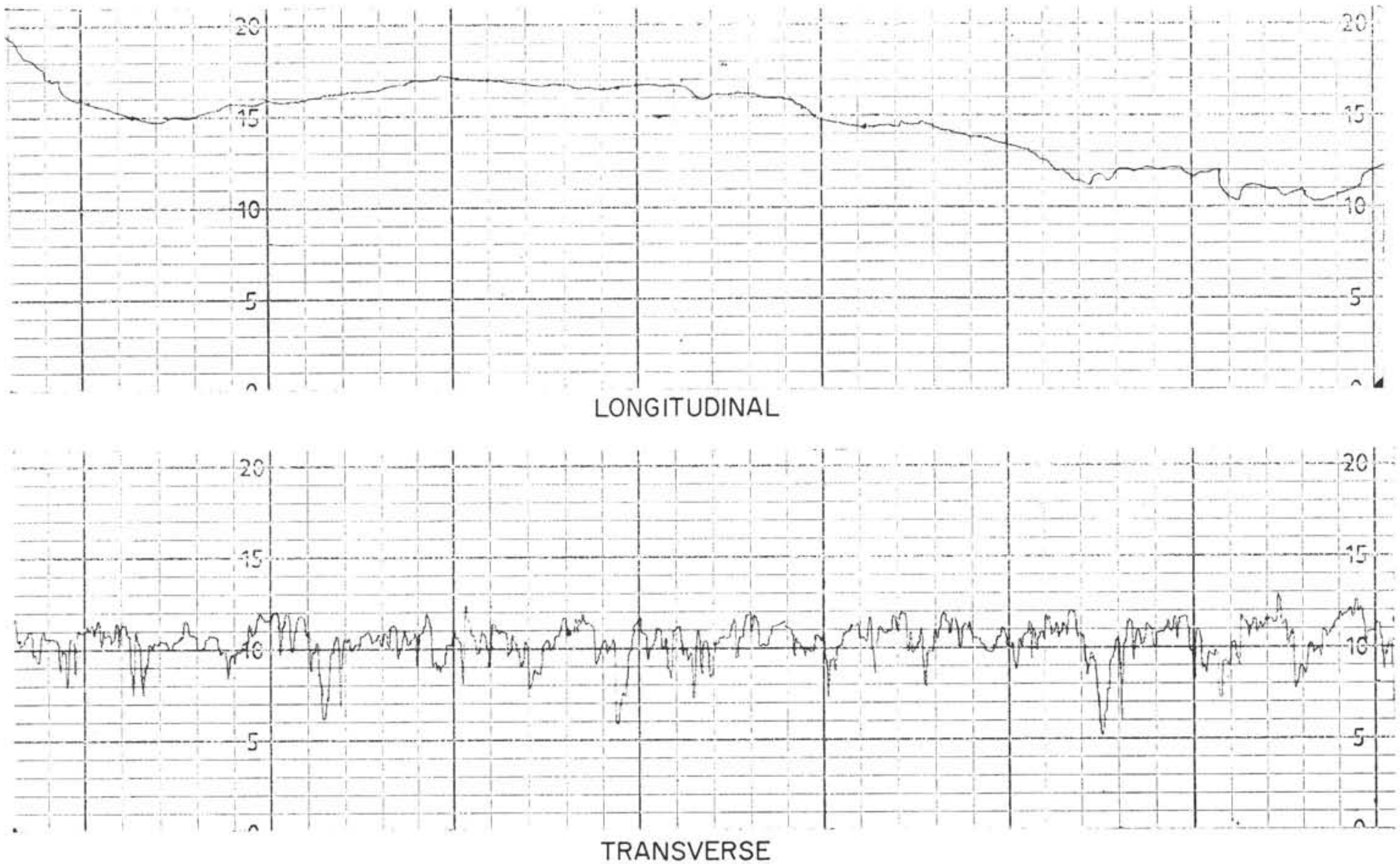


FIG. 1b: 3/4-INCH WIDE SPECIMEN



HORIZONTAL MAGNIFICATION x 100
VERTICAL MAGNIFICATION x 1000

FIG. 2: SURFACE PROFILE OF PLATE AS ROLLED



HORIZONTAL MAGNIFICATION x 100
VERTICAL MAGNIFICATION x 10,000

FIG. 3: SURFACE PROFILE OF PLATE AFTER AGING AND GRINDING

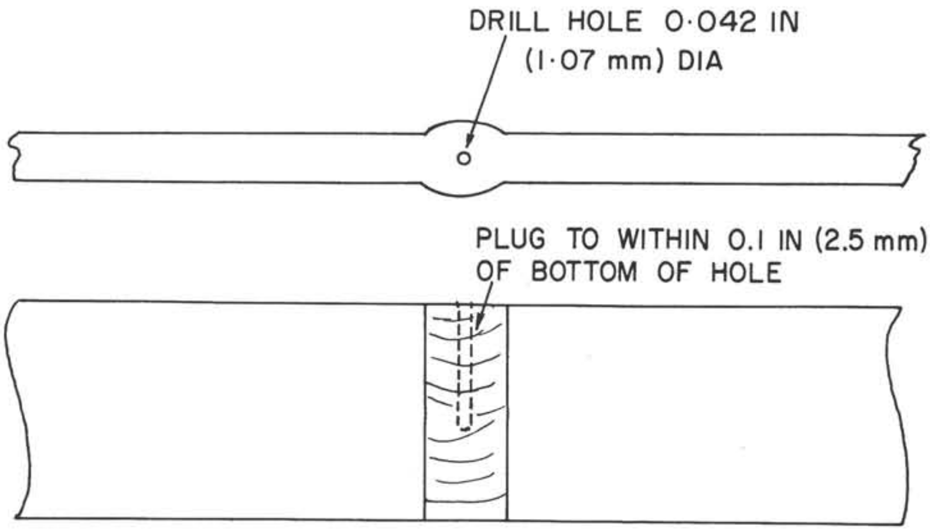


FIG. 4a: REFERENCE STANDARD FOR ULTRASONIC INSPECTIONS

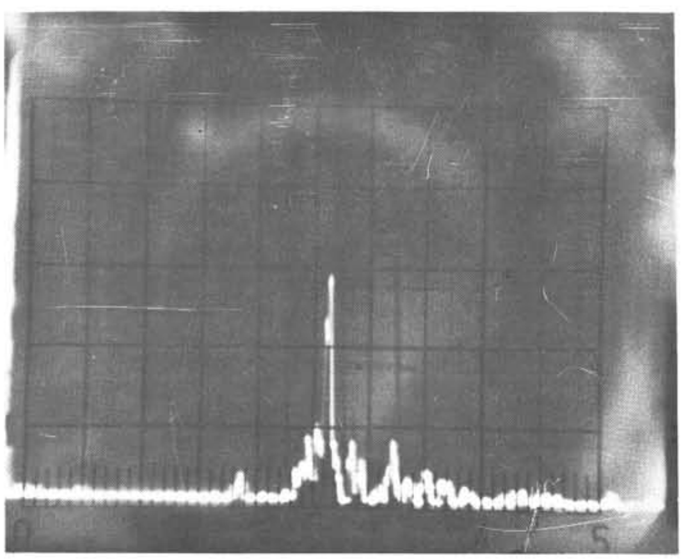


FIG. 4b: ULTRASONIC INDICATION FROM REFERENCE STANDARD

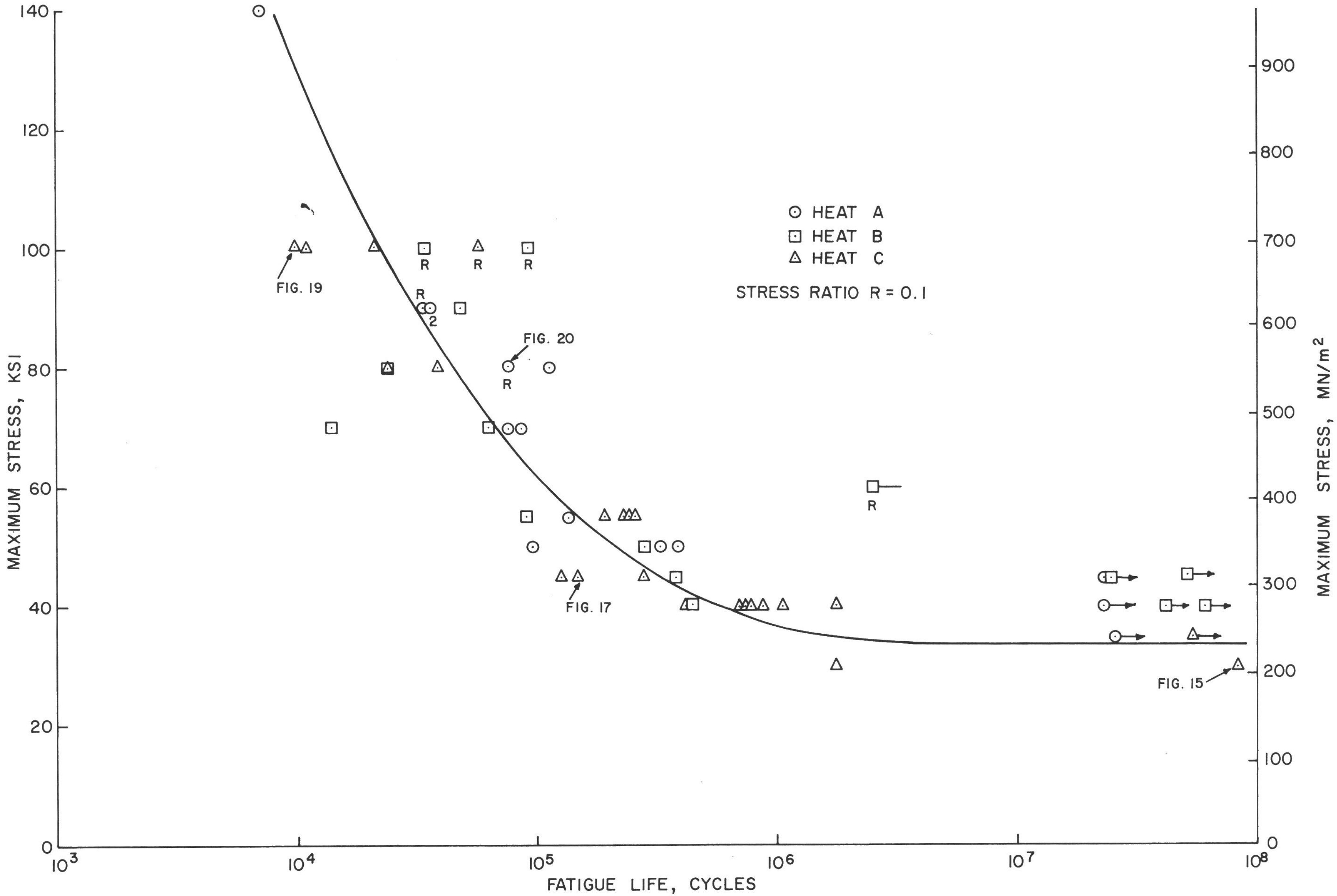


FIG. 5: BUTT WELDS — AS WELDED AND AGED

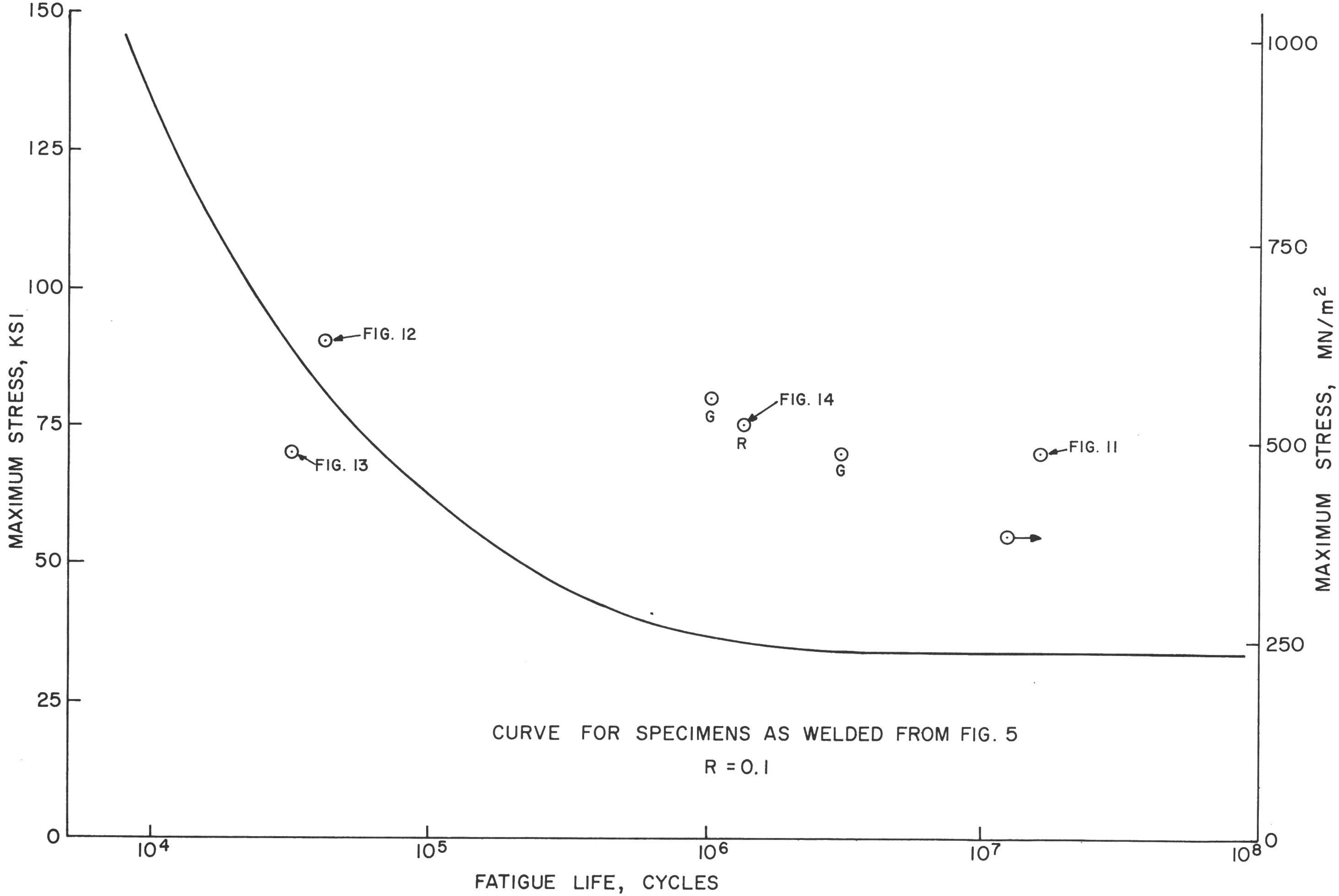


FIG. 6: EFFECT OF GRINDING WELD BEAD AND SURFACE AFTER AGING

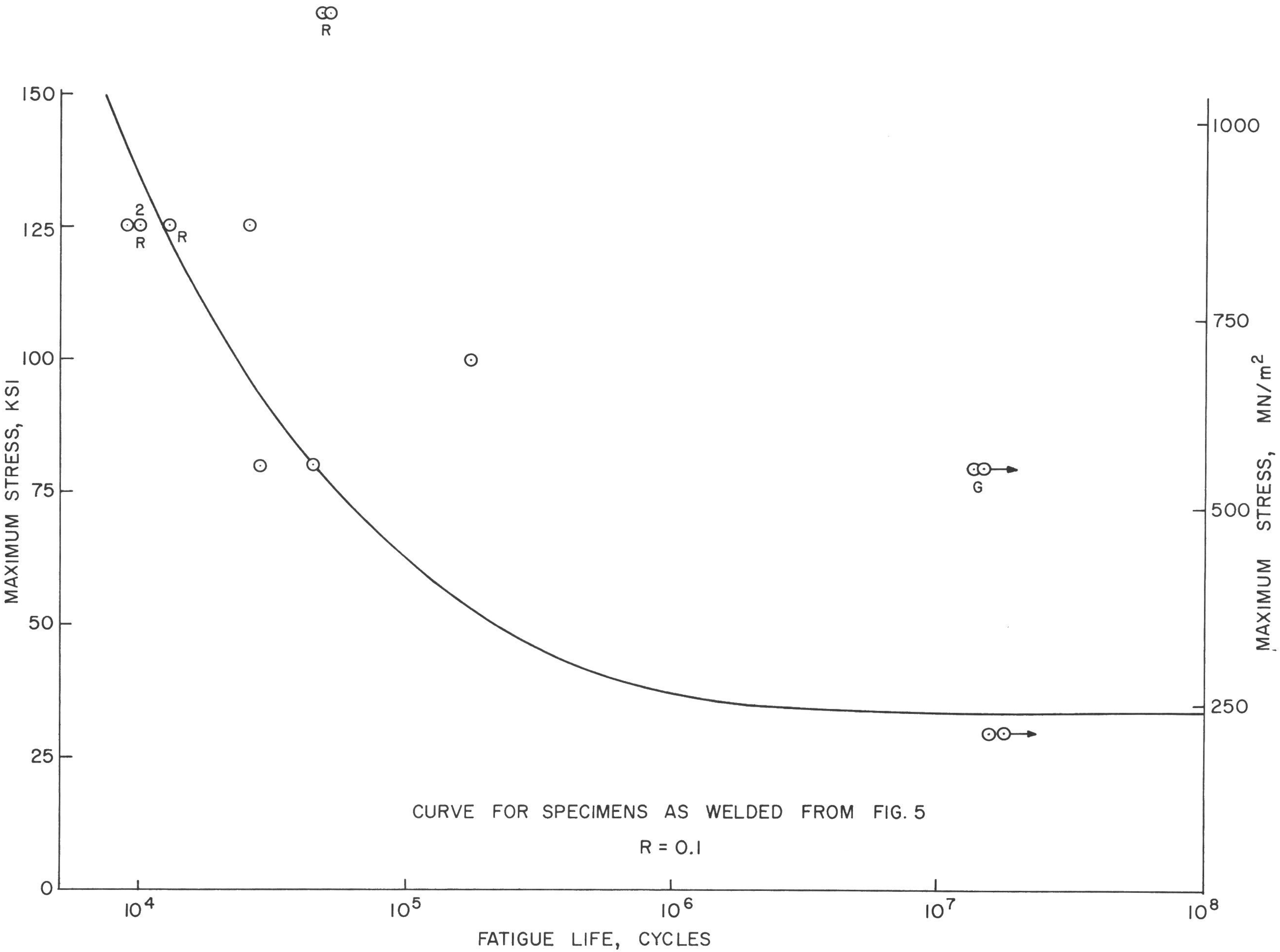


FIG. 7: EFFECT OF GRINDING WELD BEAD AND SURFACE BEFORE AGING

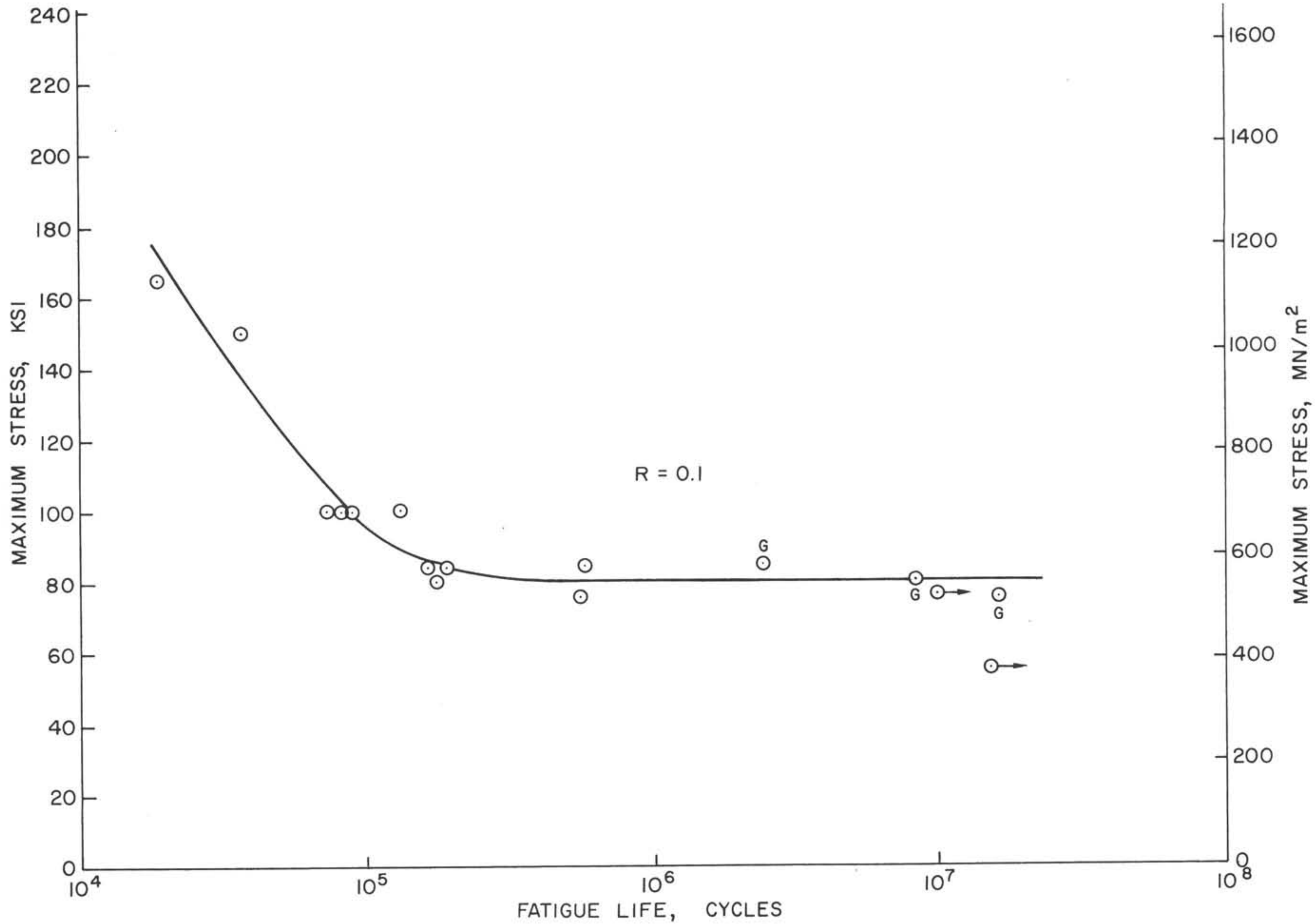


FIG. 8: PLAIN PLATE — AGED AND TESTED AS ROLLED

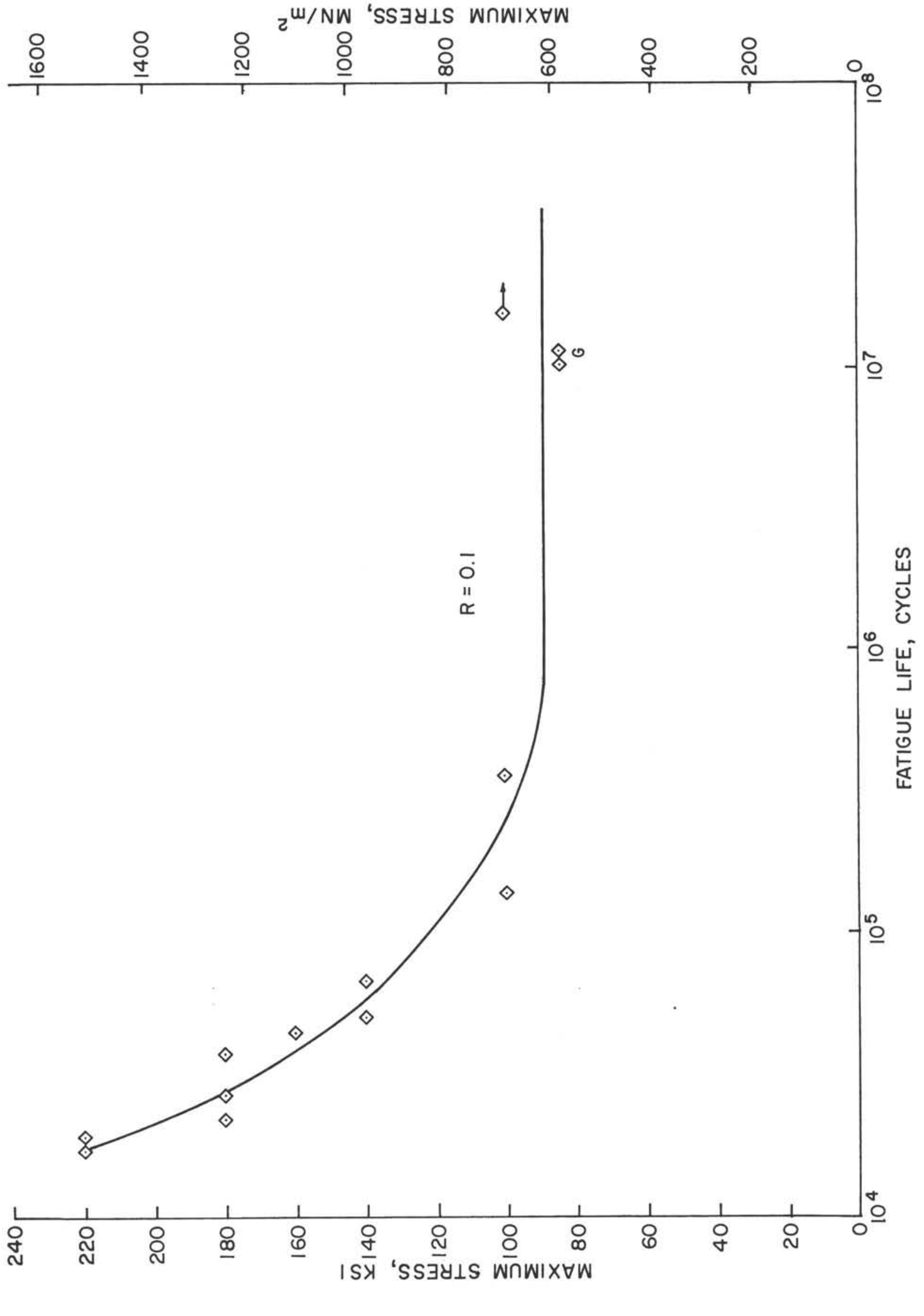


FIG. 9: PLAIN PLATE — GROUND BEFORE AGING

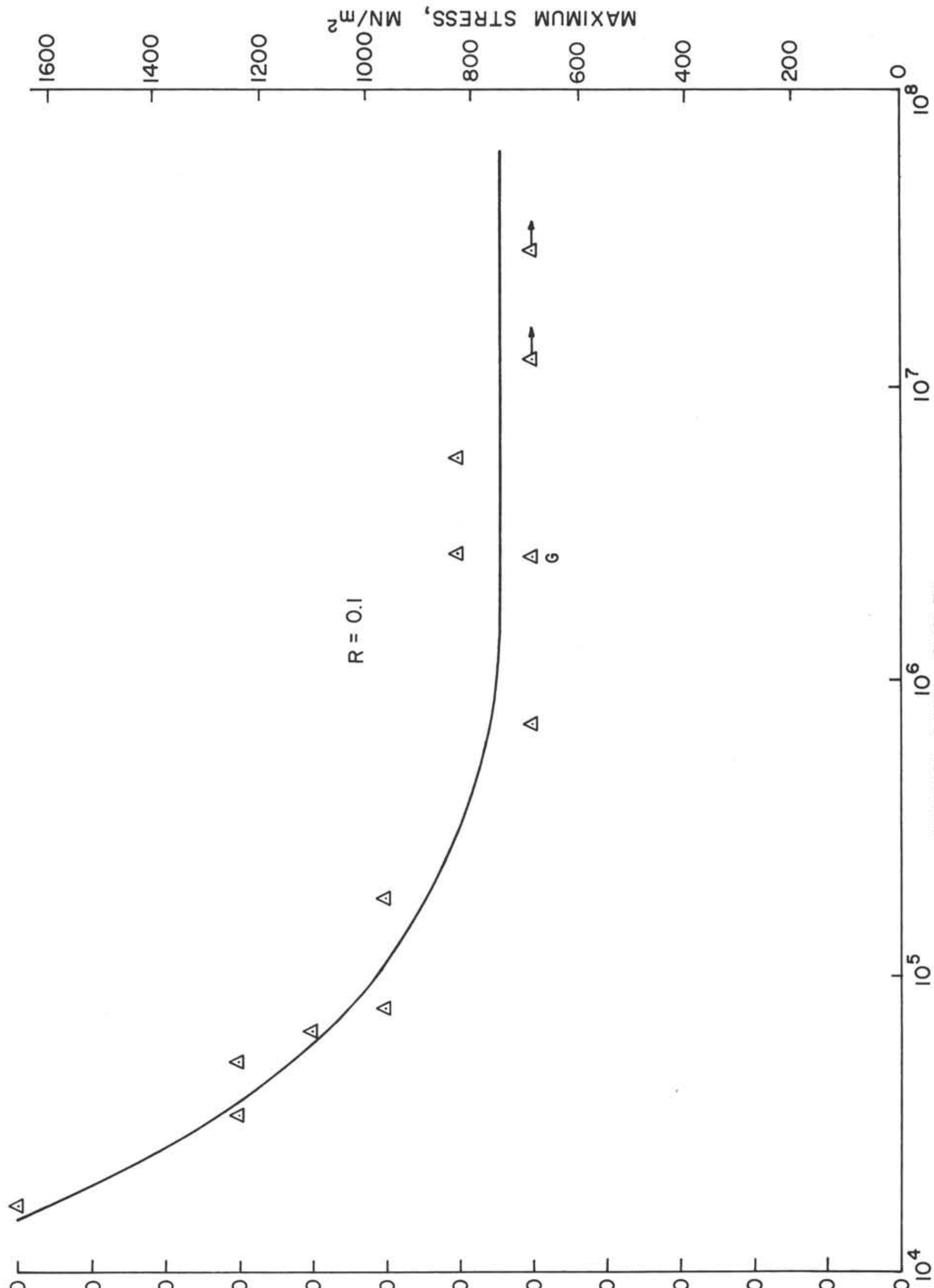


FIG. 10: PLAIN PLATE — GROUND AFTER AGING

SPECIMEN B-5W-AG

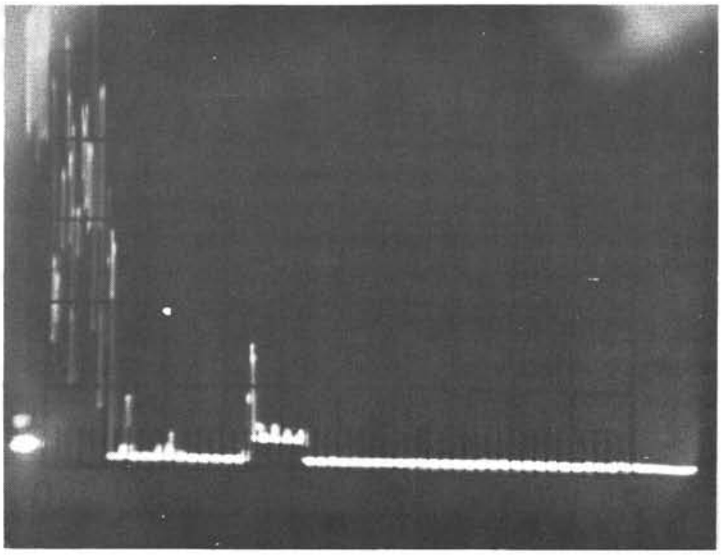


FIG. 11a: ULTRASONIC INDICATION FROM PLANAR DEFECT

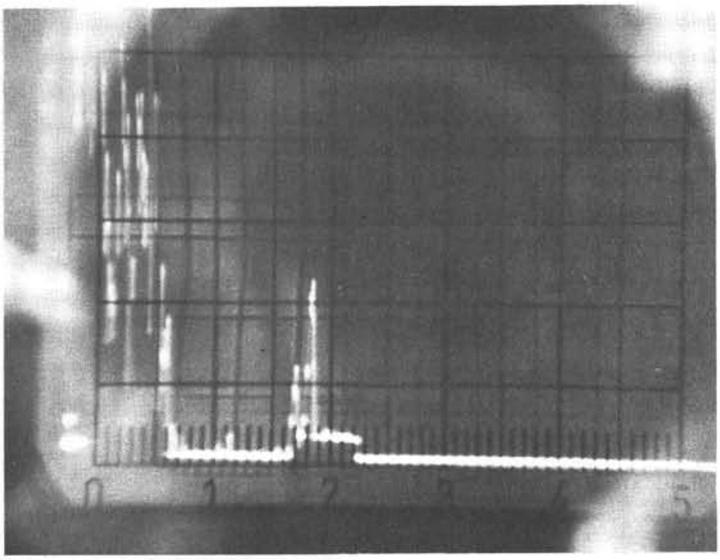


FIG. 11b: MULTIDIRECTIONAL ULTRASONIC INDICATION

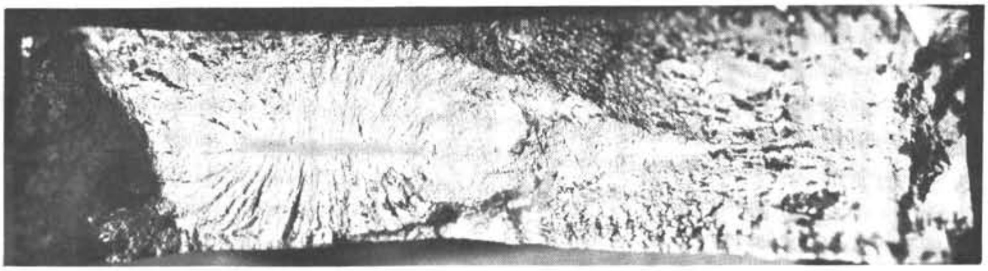


FIG. 11c: FRACTURE SURFACE — INCOMPLETE PENETRATION

SPECIMEN B-IW-AG

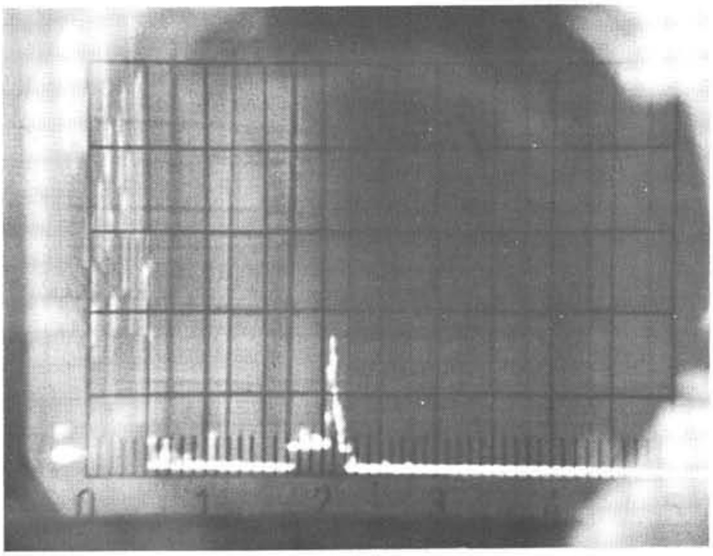


FIG. 12a: ULTRASONIC INDICATION FROM PLANAR DEFECT

FIG. 12b: FRACTURE SURFACE — INCOMPLETE PENETRATION

SPECIMEN B-7W-AG

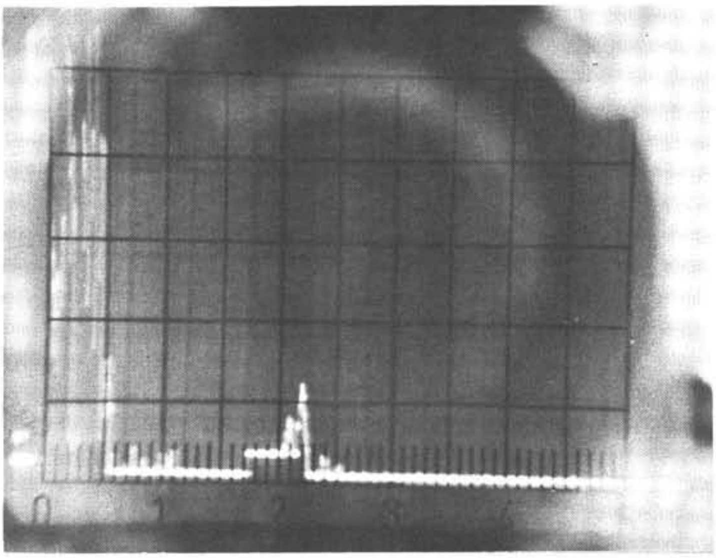


FIG. 13a: MULTIDIRECTIONAL ULTRASONIC INDICATION

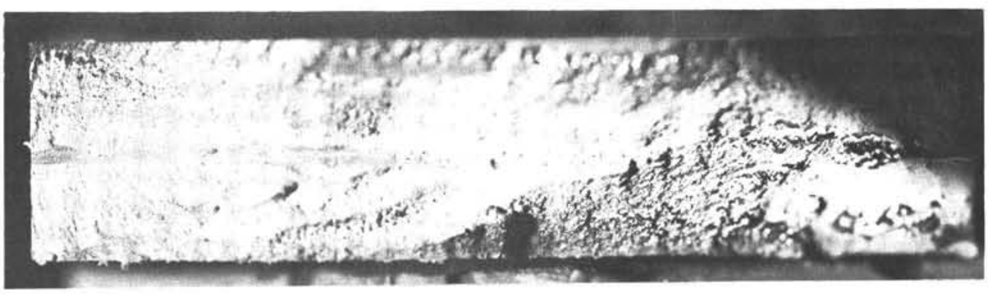
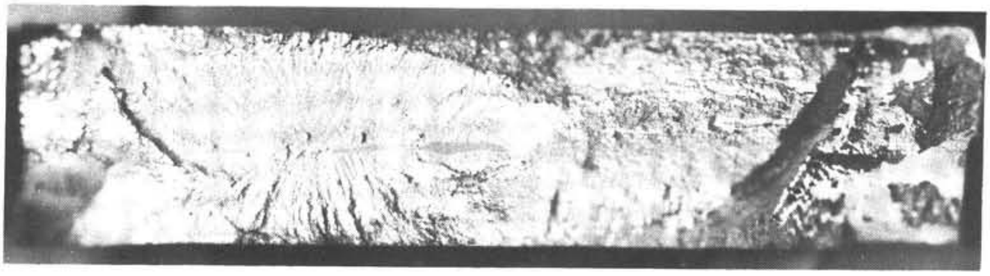


FIG. 13b: FRACTURE SURFACE SHOWING INCOMPLETE PENETRATION AT EDGE OF SPECIMEN

SPECIMEN B-6W-AG



NOTE: ORIGIN AWAY FROM REGION OF INCOMPLETE PENETRATION

FIG. 14: FRACTURE SURFACE

SPECIMEN C-33W

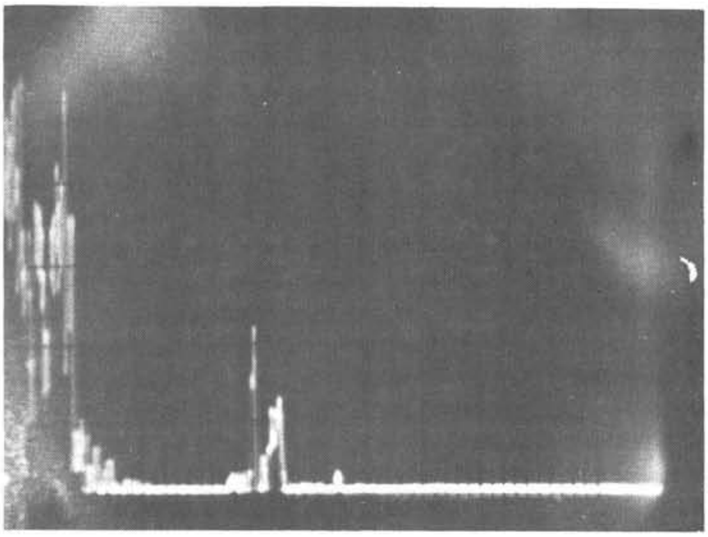


FIG. 15a: ULTRASONIC INDICATION FROM LARGE DEFECT

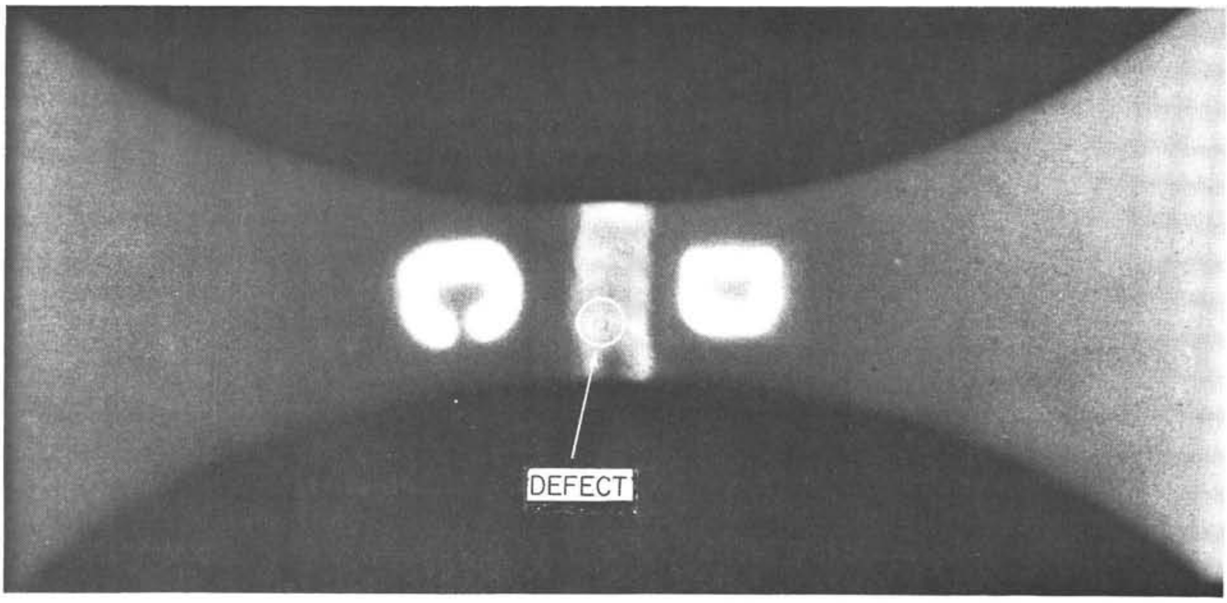


FIG. 15b: RADIOGRAPH OF DEFECT

SPECIMEN C-33W

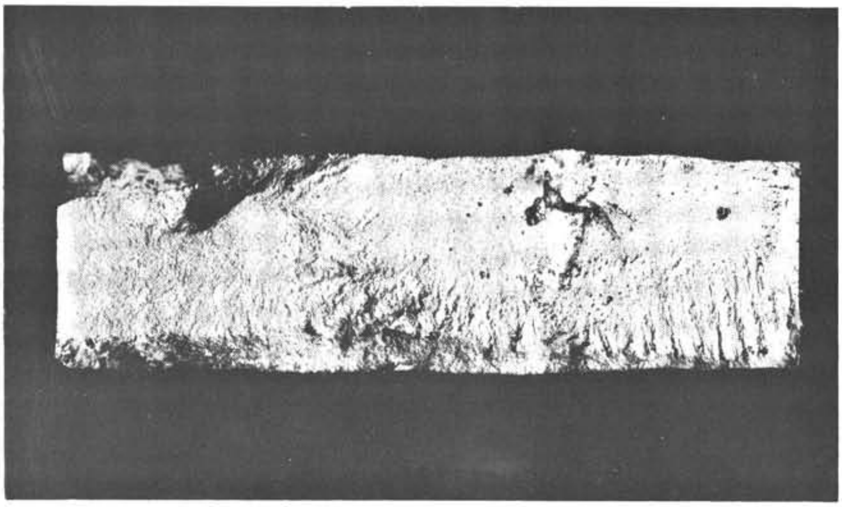


FIG. 16a: FRACTURE SURFACE SHOWING LARGE INCLUSION

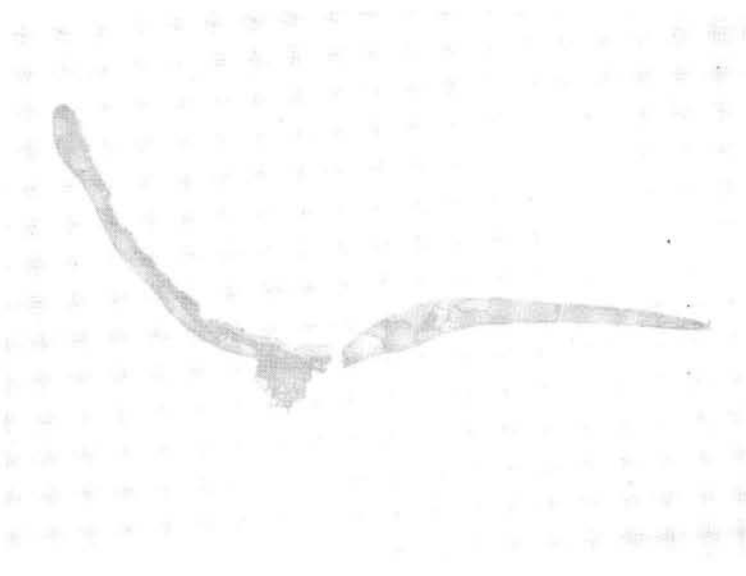


FIG. 16b: MACROPHOTOGRAPH OF INCLUSION

SPECIMEN C-15W

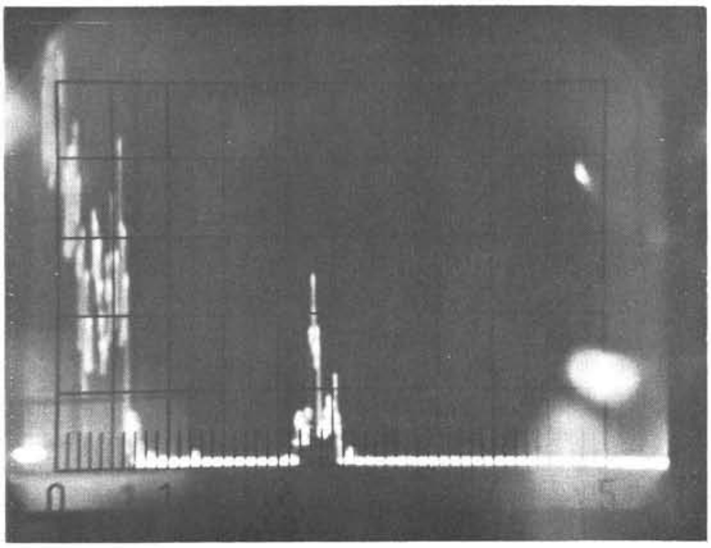


FIG. 17a: ULTRASONIC INDICATION

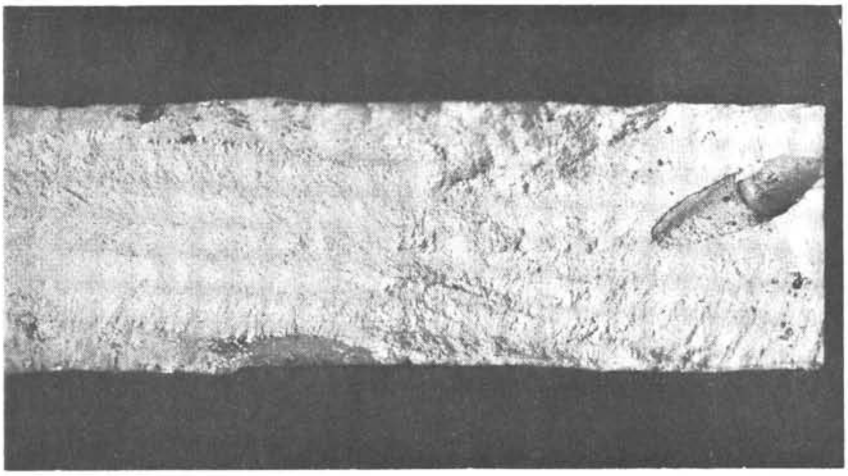


FIG. 17b: FRACTURE SURFACE SHOWING INCLUSION FROM TUNGSTEN ELECTRODE

SPECIMENS C-8W AND B-16W

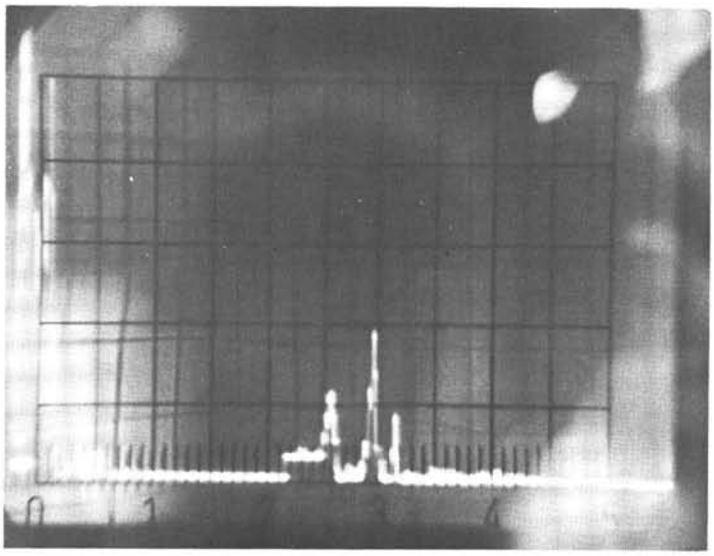


FIG. 18a: ULTRASONIC INDICATION FROM C-8W

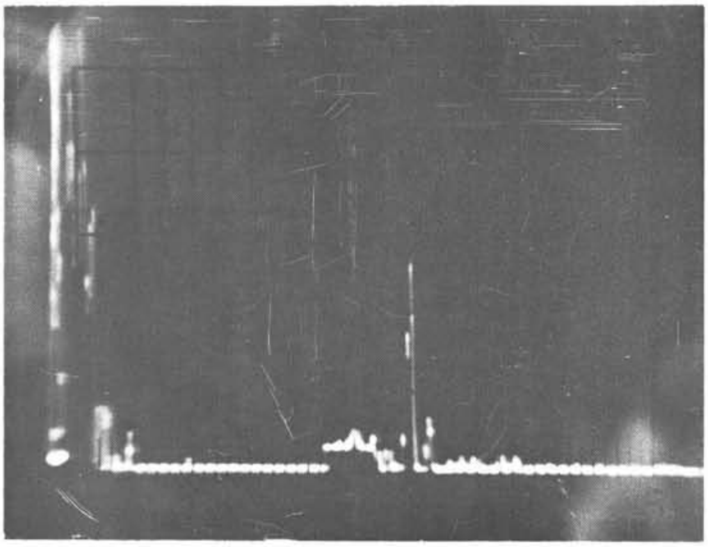


FIG. 18b: ULTRASONIC INDICATION FROM B-16W

SPECIMEN C-8W

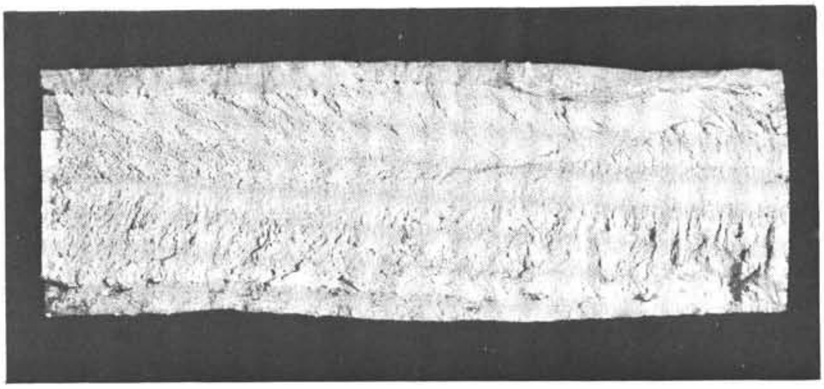


FIG. 19a: FRACTURE SURFACE (x 4)

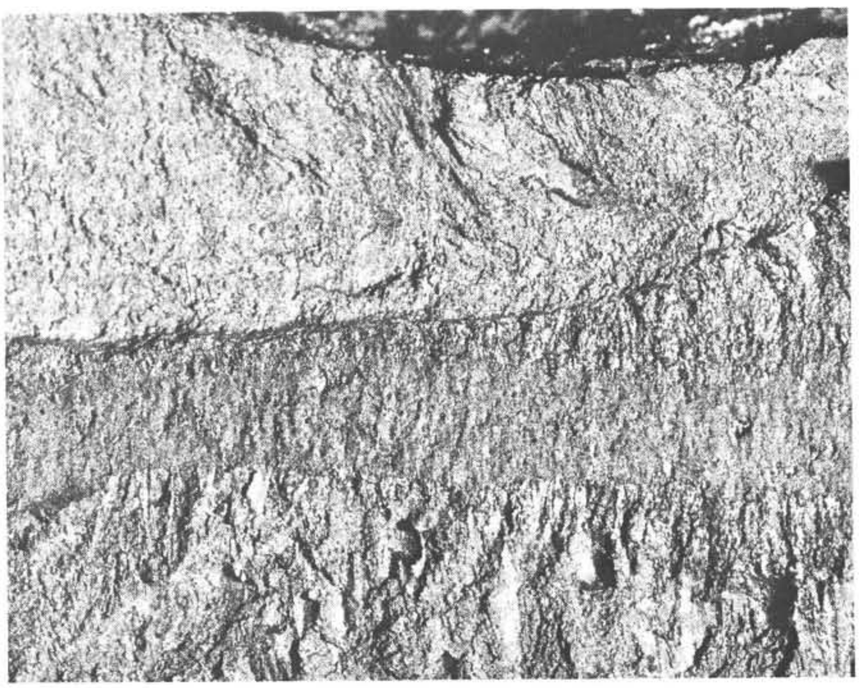


FIG. 19b: DEFECTIVE AREA (x 15)

SPECIMENS C–8W AND B–16 W

FIG. 20a: FRACTURE SURFACE OF B–16W

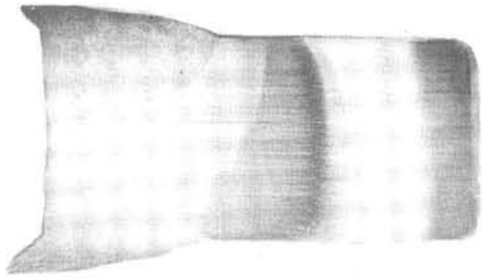


FIG. 20b: MACROSECTION THROUGH FAILURE OF C–8W
(ETCHED 50% FeC_l, x 4)

SPECIMEN C-8W

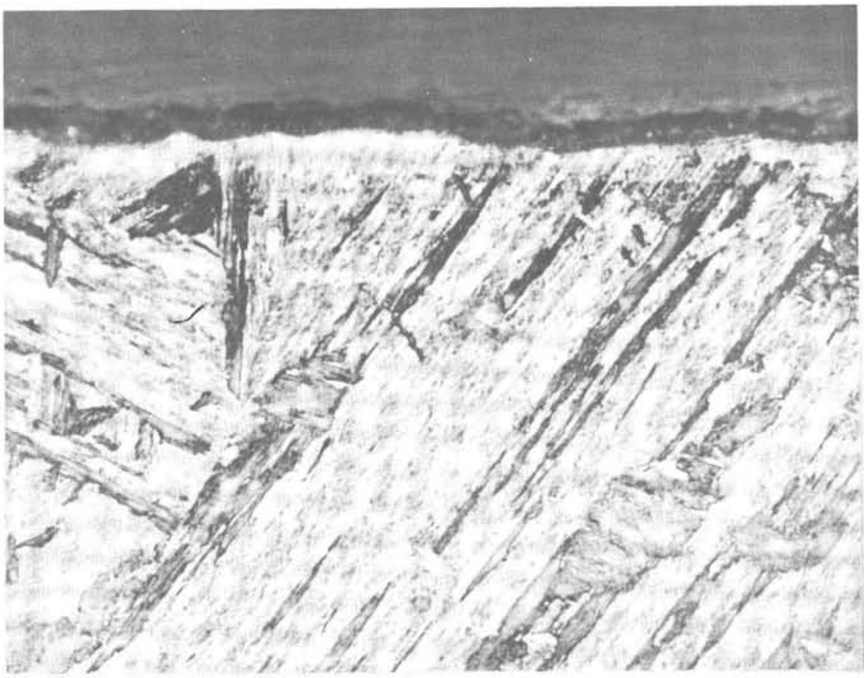


FIG. 21a: MICROSECTION THROUGH DEFECTIVE WELD
(ETCHED 2% NITAL x 750)

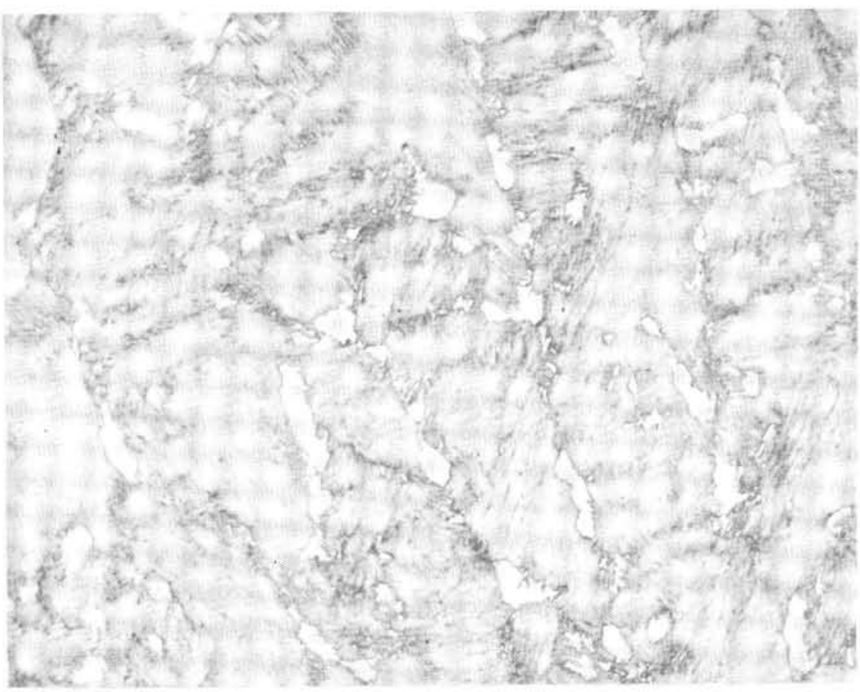


FIG. 21b: MICROSECTION THROUGH TYPICAL GOOD WELD
(ETCHED 2% NITAL x 750)

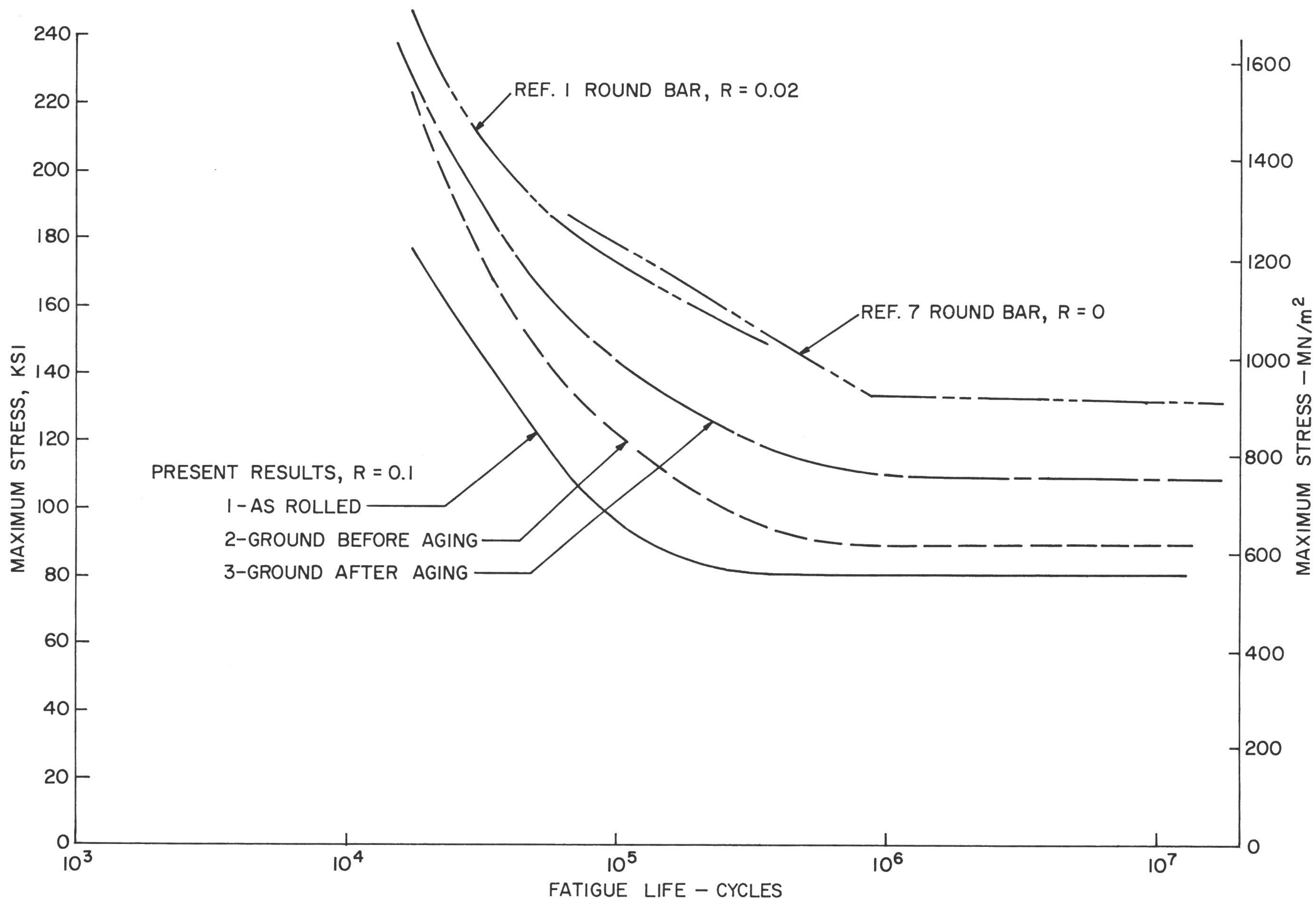


FIG. 22: SUMMARY OF DATA ON PLAIN SPECIMENS