FUSION ZONE PROPERTIES OF ARC-WELDED MODIFIED 4330 STEEL

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By

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Submitted in Partial Fulfillment of the
Requirements for the Degree of
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Submitted to the Department of Metallurgy
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ABSTRACT

The influence of thermal variables on the fusion zone properties of an arc-welded modified 4330 steel were studied. The only thermal variables considered were preheat temperature, energy input, and post welding tempering temperature. In particular, the thermal variable effects on the microstructure and tensile properties of the fusion zones were investigated. The microconstituents in the fusion zones were also determined.

The structure of the fusion zones were found to be made up mainly of a composite of martensite, bainite, and the temper products of each. The amount of retained austenite in the fusion zone structures was found to be approximately in the range of 0 - 1.0 percent.

It was found that as the preheat temperature was increased, the cooling rates of the fusion zones decreased sufficiently to favor the formation of softer, and therefore more ductile structures as typified by the isothermal transformation diagram of the steel. As the energy input was increased, it was found that cooling rates of the fusion zones decreased sufficiently to allow further formation of softer structures.

Tempering curves of the fusion zones were made. Hardness readings were related to approximate tensile strengths of the fusion zones. The approximate tensile strengths of the fusion zones ranged from 150,000 psi to 245,000 psi, in relation to the thermal variables used. Bend tests made on the fusion zones indicate a minimum of 10 percent elongation in all fusion zones, in relation to the thermal variable used.

THESIS SUPERVISOR:

Clyde M. Adams, Jr.
Assistant Professor of Metallurgy

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ACKNOWLEDGEMENTS

The author wishes to express his sincere appreciation to Professor Clyde M. Adams under whose guidance this project was formulated and developed.

The author further wishes to express his thanks for the effective assistance of Assistant Professor David A. Thomas, William G. Moffatt, Sheldon S. White, Paul E. Brown, and Stephen Oliver.

I. PURPOSE

The purpose of this report is to investigate the influence of thermal variables on fusion zone properties of an arc-welded hardenable steel. The author is concerned only with the thermal variable effects of preheat temperature, energy input, and post welding tempering temperature.

Such an investigation may lead to a better understanding of the microconstituents of the structure, and the mechanical properties of the fusion zone in an arc-welded hardenable steel.

II. TECHNIQUE

A. THE ARC-WELDING OPERATION

The Tungsten-Inert-Gas (T.I.G.) method of welding was used. The T.I.G. process is a permanent-electrode arc-welding process. A 98 percent tungsten - 2 percent thorium electrode was used. The thorium addition to the electrode increases arc stabilization. Argon was used as the inert gas to shield the electrode and the work piece from the atmosphere, and was used as the ionizing gas to carry the current from the electrode to the work piece.

All the welds were made in one pass using no fillerwire. Fillerwire was not used for the purpose of keeping the chemistry of the fusion zone the same as the base plate.

Prior to the actual welding, test welding runs were made on scrap plate to determine workable welding conditions. They are as follows:

1. gas flow rate,
2. arc length,
3. distance from work piece to end of gas shield cylinder,
4. rate of travel of T.I.G. welder,
5. possible energy input variables,
6. diameter of electrode,
7. polarity, and
8. type of welding transformer to be used.

A detailed description of the welding setup used in this investigation appears in Section A of the Appendix.

B. PREPARATION OF STEEL PLATE

The steel plate was sandblasted prior to the welding operation in an attempt to remove much of the oxide and scale. Other than this, the steel plate was used in the as received condition.

C. NUMBER OF WELDS, USE OF PREHEAT AND ENERGY VARIABLES, AND DESIGNATIONS OF EACH WELD

Six welds were made. Three of these welds were made at a particular low energy input at three varying preheat temperatures. The other three welds were made at a particular high energy input at the same three varying preheat temperatures.

Table 1.

Designations of Welds

Weld Number	Energy Input	Preheat Temperature
1	Low	$70^{\circ}F$
5	High	$70^{\circ}F$
4	Low	$300^{\circ}F$
7	High	$300^{\circ}F$
8	Low	$700^{\circ}F$
6	High	$700^{\circ}F$

D. PREHEAT

The preheat temperatures chosen were room temperature ($70^{\circ}F$), $300^{\circ}F$, and $700^{\circ}F$. This variance in preheat temperatures was chosen to make the preheat variable a significant factor in the interpolation of results.

The preheat temperature was established by the use of Tempil Sticks. Tempil Sticks are crayons designed to melt at a particular temperature. Crayon marks were made all along the edges of the surface to be welded. An oxyacetylene torch was used to heat the steel plate up to the various preheat temperatures. After the welds were made, the crayon markings were checked to see if the desired preheat temperature had been maintained.

E. ENERGY INPUT

High and low energy inputs were calculated according to the following equation,

$$(1) \quad \text{Energy} = \frac{KVI}{v} \text{ B.T.U. inches}^{-1}$$

where,

K is a constant equal to 9.480×10^{-4} B.T.U. joule^{-1}

V = volts

I = amperes

v is the velocity in inches per second of the T.I.G. welder.

The velocity of the T.I.G. welder was kept constant in all the welds made.

It was assumed that 80 percent of the energy generated in the arc passed into the plate as heat.[1] Therefore, 80 percent of both the energy values calculated from equation (1) were taken as the actual energy inputs.

The two energy inputs were chosen far enough apart to make the energy input variable significant. The high and low energy inputs used appear in Section B of the Appendix.

F. SECTIONING OF THE FUSION ZONE

Transverse sections of the fusion zone were cut out of the welded plate using a water-cooled cut-off wheel. The welded plate was too hard to be sectioned by any other means. All precautions were taken to keep the fusion zones covered with water during the sectioning operation.

G. POST WELDING TEMPERING TREATMENT

Transverse section from each of the six welded plates were tempered for one hour at the following five tempering temperatures: 70°F, 300°F, 500°F, 700°F, and 1000°F. The temper products in the fusion zone are of course dependent on both the tempering temperature treatment and the time, but the tempering temperature is the more significant variable. The tempering time, therefore, was arbitrarily chosen to be one hour.

H. SPECIMEN INDEX

Fusion zone specimens mentioned in this paper will be referred to by their weld number followed by a dash and then another number designating tempering temperature. For example, fusion zone specimen 1 - 300 indicates, from Table 1, that this fusion zone came from a weld using the low energy input with a 70°F (room temperature) preheat followed by a tempering treatment at 300°F. The words "Room Temperature" will be referred to by the abbreviation "R.T." in the specimen designations occuring in the remainder of this report. Therefore, specimen 7 - R.T. indicates, from Table 1, that this fusion zone came from a weld using the high energy input with a 300°F preheat followed by a tempering treatment at room temperature.

I. HARDNESS MEASUREMENTS RELATED TO TENSILE STRENGTH

Hardness readings taken in the fusion zones were used as an approximate measure of their tensile strengths. This is the generally accepted practice in working with steels.

J. METALLOGRAPHY

A metallographic examination was made on the fusion zones to determine qualitatively the structure and the microconstituents present.

K. TEMPERING CURVES

Tempering curves of Hardness and Approximate Tensile Strength vs. Tempering Temperature were made. From the tempering curves of each of the six welds, the effects of the thermal variables considered in this paper were interpreted.

L. MICROHARDNESS MEASUREMENTS

Microhardness indentations were made in the fusion zone structure in an attempt to further determine qualitatively the microconstituents present and the effects of the tempering treatment.

M. BEND TESTS

Bend tests were made on the specimens to determine the effects of the thermal variables on percentage elongation.

The preparation of the bend specimens and the test conditions appear in Section C of the Appendix.

N. RETAINED AUSTENITE DETERMINATIONS

An attempt was made to determine the amount of retained austenite, if any, in the fusion zones of the welds using metallographic techniques, and X-ray techniques if necessary. The retained austenite determinations were made on the fusion zones prior to the tempering treatment. The effect of retained austenite was related to the microstructures of the fusion zones and the tempering treatments.

III. MATERIALS AND APPARATUS

A. THE STEEL PLATE

A cast 4330 steel was selected as a typical hardenable steel for this investigation. The cast steel plate was generously donated by H. F. Taylor and M. C. Flemings, Jr., Professor of Foundry Metallurgy and Assistant Professor of Metallurgy respectively at the Massachusetts Institute of Technology, Cambridge, Massachusetts, who are currently conducting a research program concerning the casting of such a steel. The steel plates were cast at the M.I.T. foundry.

The cast steel was modified by raising the silicon and manganese levels in order to get better casting and heat-treating characteristics. A typical chemical analysis of the modified 4330 steel appears in Section D of the Appendix.

The cast steel plates, as received, were cut into plates 7 inches long, 2 $\frac{1}{2}$ inches wide, and 1 inch thick.

B. THE T.I.G. WELDER AND ITS SETUP

A water-cooled, T.I.G. Hand-Torch Welder was used. The T.I.G. welder was clamped to a movable, electrically operated trolley which was set upon a trolley track. The T.I.G. welder was passed over the plate by the electrically operated trolley in making the welds.

C. THE WELDING POWER SOURCE

A Direct-Current, Welding Transformer Rectifying Unit, of 300 ampere capacity, having a drooping Volt-Ampere curve was used.

The setup of the apparatus is shown in Figures 1 and 2.

IV. RESULTS AND DISCUSSION

A. THE HARDNESS READINGS

Rockwell "C" hardness readings were taken in the fusion zones of the transverse section, $\frac{3}{16}$ of an inch thick, cut out of the welded plates after the tempering operations. For a schematic sketch of these sections see Section E of the Appendix. Since the transverse sectioning was made by using a Carborundum cut-off wheel, the transverse, section surfaces were relatively smooth. Any burr that was left on the edges of the sections due to the sectioning operation was ground off. The transverse

Setup of Apparatus

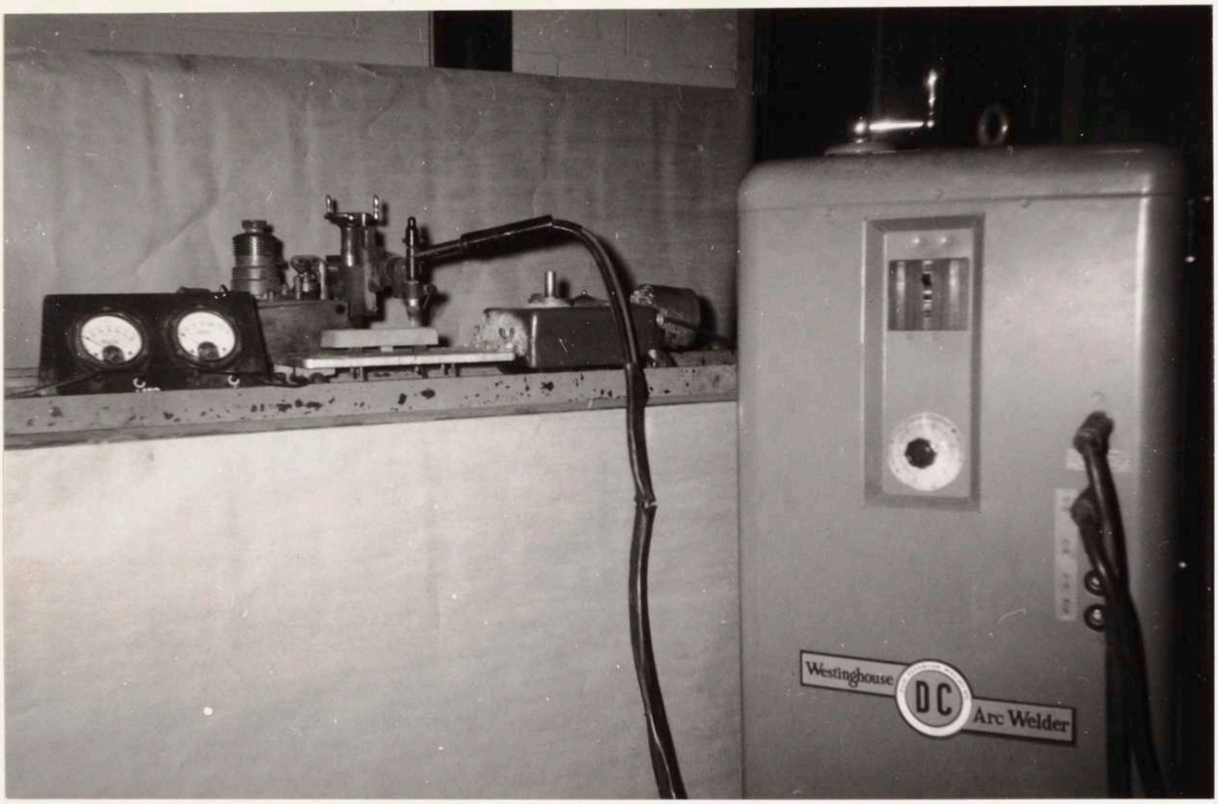


Figure 1

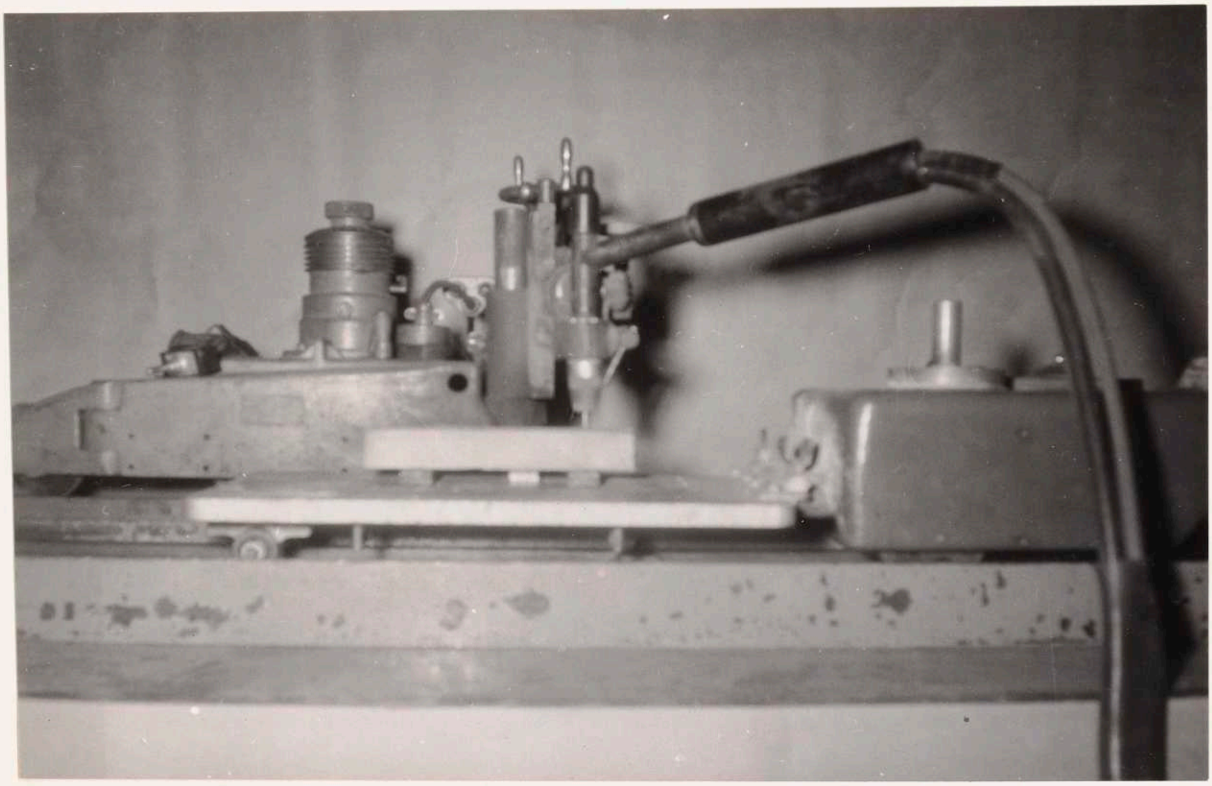


Figure 2

sections were lightly etched with Nital to indicate the location of the fusion zone.

The $\frac{3}{16}$ inch dimension was chosen so that the thickness of the specimen was at least ten times the depth of the indentor impression. This is standard practice as recommended in the "Metals Handbook."[2]

The two energy inputs used yielded fusion zones of approximately 0.9 of a centimeter wide and 0.5 centimeters deep, on the average. Therefore, the areas of the fusion zones on the transverse sections were large enough to take 3 or 4 hardness readings without having any indentations influencing the others appreciably. The hardness readings taken in each of the fusion zones did not vary by more than 1 or 2 Rockwell "C" points. In each fusion zone the hardness reading that predominated was arbitrarily accepted as the correct measure of hardness.

As was expected, the volume of fusion zone metal per unit longitudinal length of fusion zone was greater in the welds made with the high energy input than in the welds using the low energy input.

B. THE RETAINED AUSTENITE DETERMINATIONS

No restrained austenite could be seen in any of the microstructures studied metallographically. An X-ray test pattern was run on the fusion zone of specimen 1 - R.T. to see if an appreciable amount of retained austentie was present. It was found that the austenite peak was indistinguishable from the rest of the background radiation.

A sharp distinguishable peak of ferrite, however, was found. A rough calculation using the ratio of the two approximate areas under the peak intensities of austenite and ferrite indicated that the percent of retained austenite present was about 0.5 percent. This small amount of austenite was considered insignificant in its affect upon the microstructure and the tempering treatment.

C. THE METALLOGRAPHIC INVESTIGATION

Sections of the fusion zones, the same fusion zones in which the hardness readings were taken, were cut out of the transverse sections, mentioned in part A of Discussion and Results; and were mounted cold, in plastic, so that the side opposite the hardness investigation was made available for metallographic investigation. For a schematic sketch of these sections see Section E of the Appendix.

The microstructures of all the fusion zones showed a fine columnar structure originating at the interface of the heat-affected zone and the fusion zone. At the ends of these long dendrites, the columnar zone of crystals was replaced by an equiaxed, randomly oriented structure. The columnar structure is the result of the chill effect imposed on the fusion zone by the base plate.

Most of the welds made were sound, i.e., they were free of macroporosity, pipes, and center-line shrinkage. In weld number 1, however, a crack running from the bottom of the fusion zone to just below the top surface of the zone was observed. Metallographic investigation indicated that center-line shrinkage had caused the crack.

A typical photomicrograph of the fusion zones is shown in figure 3. This figure happens to be the fusion zone structure of specimen 6 - R.T.

The structure shown in figure 3 consists of segregated columnar and equiaxed grains. The dark regions, the first areas to solidify, are most likely composed of bainite, in a messy carbide and ferrite pattern, and martensite. The light regions, the last areas to solidify, are most likely composed of all martensite.

The author has based this qualitative interpretation of the microstructure upon the following considerations, (1) the isothermal transformation diagram for the steel, (2) end-quench hardenability data on the steel, (3) Rockwell "C" hardness measurements, and (4) microhardness measurements. The isothermal transformation diagram[3] indicates that the cooling rate, of the type most likely to be found in the fusion zones, would miss the pearlite nose completely, and would cross the bainite nose somewhere near its origin. Therefore, the possibility that the dark regions, the first areas to solidify, contain bainite as well as martensite is quite high. The light regions are therefore thought to be almost all martensite, since this region solidifies at a lower temperature, probably at or below the M_s. End-quench hardenability data[4] shows that even at a distance of 2.5 inches from the quenched end, the percentage of martensite in the entire structure is approximately between 75 and 85 volume percent, the remaining percentage being that of the banite.

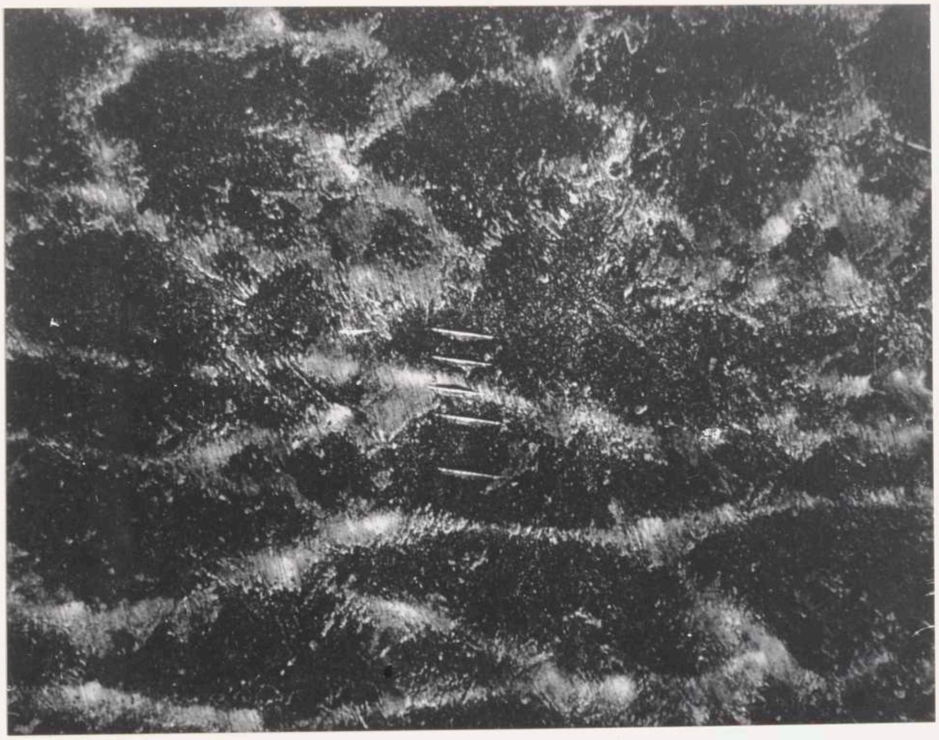


Figure 3

500 x

Nital Etch

Photomicrograph of the fusion zone in specimen 6 - R.T. Columnar and equiaxed grains are present. The dark regions, the first areas to solidify, contain bainite and martensite. The white regions, the last areas to solidify, contain approximately 100% martensite.

Microhardness indentations are shown in both dark and light regions, indicating qualitaively the amounts and types of the microconstituents present.

Rockwell "C" hardness readings taken in the fusion zones of the untempered welds, see figure 5, were of the order of 48 and 49 R_c. These hardness measurements indicate the presence of large amounts of martensitic-bainitic structure in the as welded fusion zone.

Microhardness traverses made across the dark and light regions of the fusion zone microstructure further indicate qualitatively where the majority of the microconstituents present are located. All of the microhardness indentations were made using the same indentor and load (10 grams). The indentations in the dark areas are longer and deeper than the indentations made in the white areas. This fact conclusively proves the existence of a great deal of a single, hard microconstituent, martensite, in the white regions. The dark regions, although they contain mostly martensite, do have enough bainite present to make these regions softer than the white areas. The microhardness traverse shown in figure 3 is typical of all such traverses made in this investigation.

The amount, distribution, and types of alloying-element carbides present in the fusion zone structure could not be determined by the techniques employed in this investigation. The carbide forming elements present, the low carbon content of the steel (0.27 percent C), and the amount of martensite present indicate that the amount of alloying element carbides present is probably small.

The affect of the tempering treatments on the fusion zone structures is shown by relating the structures of figures 3 and 4. Figures 3 and 4 are the fusion zone structures of specimens 6 - R.T. and 6 - 1000, respectively.

Figure 4

500 x

Nital Etch

Photomicrograph of the fusion zone in specimen 6 -- 1000. Columnar grains are present. Structure is similar to figure 3, except that in some places the white boundary separating the dark areas has disappeared, and the white regions are narrower.

Figure 3 shows that the dark areas are completley surrounded by the white regions. The white regions in figure 4 are narrower than in figure 3, and in some parts of figure 4 the white boundary separating the dark areas has disappeared. This effect is attributed to the tempering effects on the martensite present in the white areas. As the martensite is tempered it becomes darker, therefore, reducing the area fraction of white region initialy present. This tempering effect has been explained only in the case of weld number 6. These same tempering effects were observed in all of the other welds.

D. THE TEMPERING CURVES

The tempering curves relating the thermal effects of the variables are shown in figures 5, 6, and 7. The approximate tensile strengths of the fusion zones as well as their hardness have been plotted versus tempering temperature.

All of the tempering curves show a general shape, characteristic of tempering treatment. As the tempering temperature is increased the curves drop off in hardness. This is the case in the welds numbered 1, 5, and 4. In the case of welds numbered 7, 8, and 6, there is a noticeable increase in hardness up to 500°F, followed by a decrease in hardness at higher tempering temperatures.

The afore mentioned characteristics mentioned in the last paragraph can be explained by the mechanisms of tempering, i.e., the first and third stages of tempering. The second stage of tempering, concerning the transformations of retained austenite, was not considered in this investigation due to the small amounts of retained austenite present, and the small

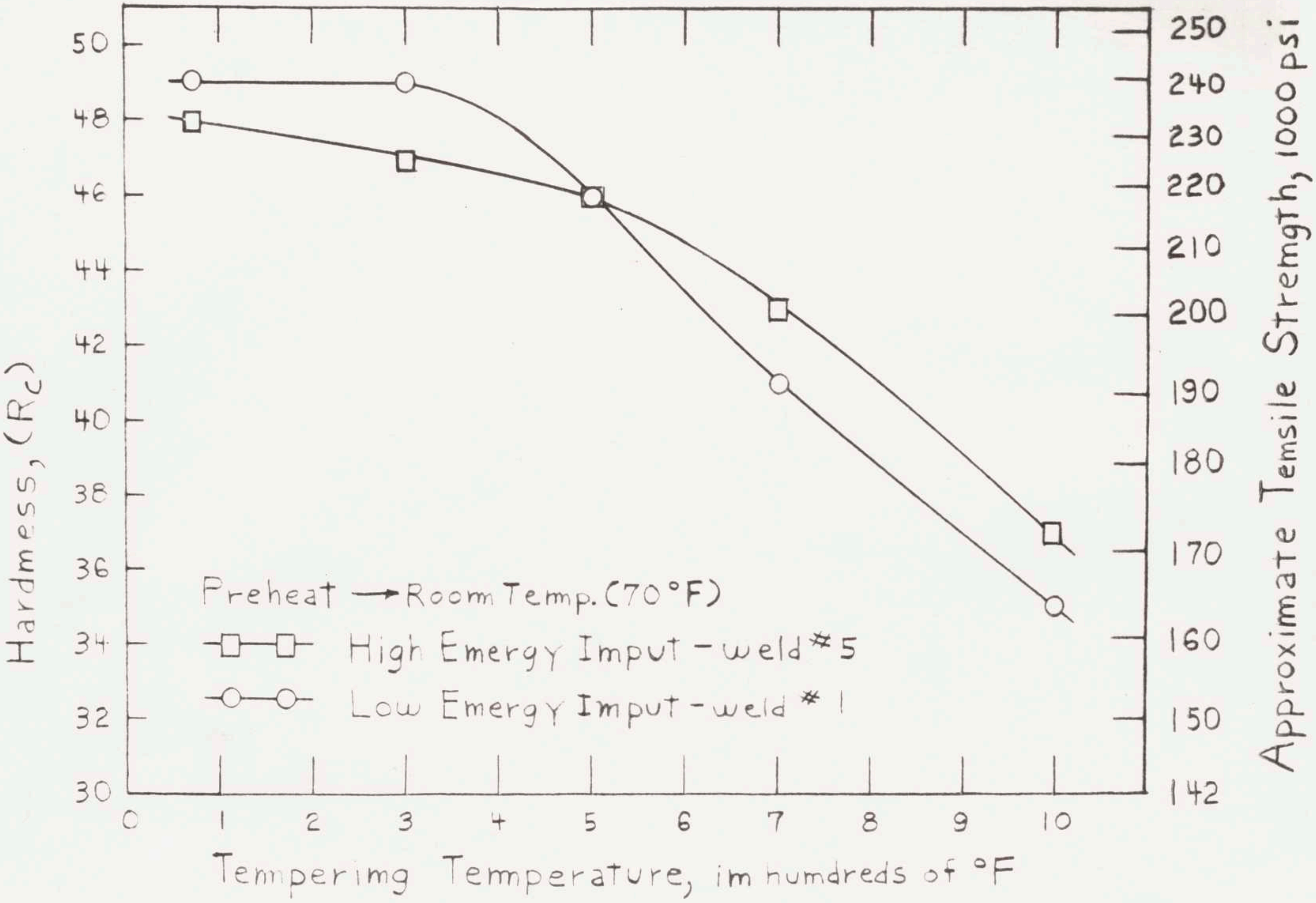


Figure **5.** Temperimg Curves for welds with 70°F Preheat

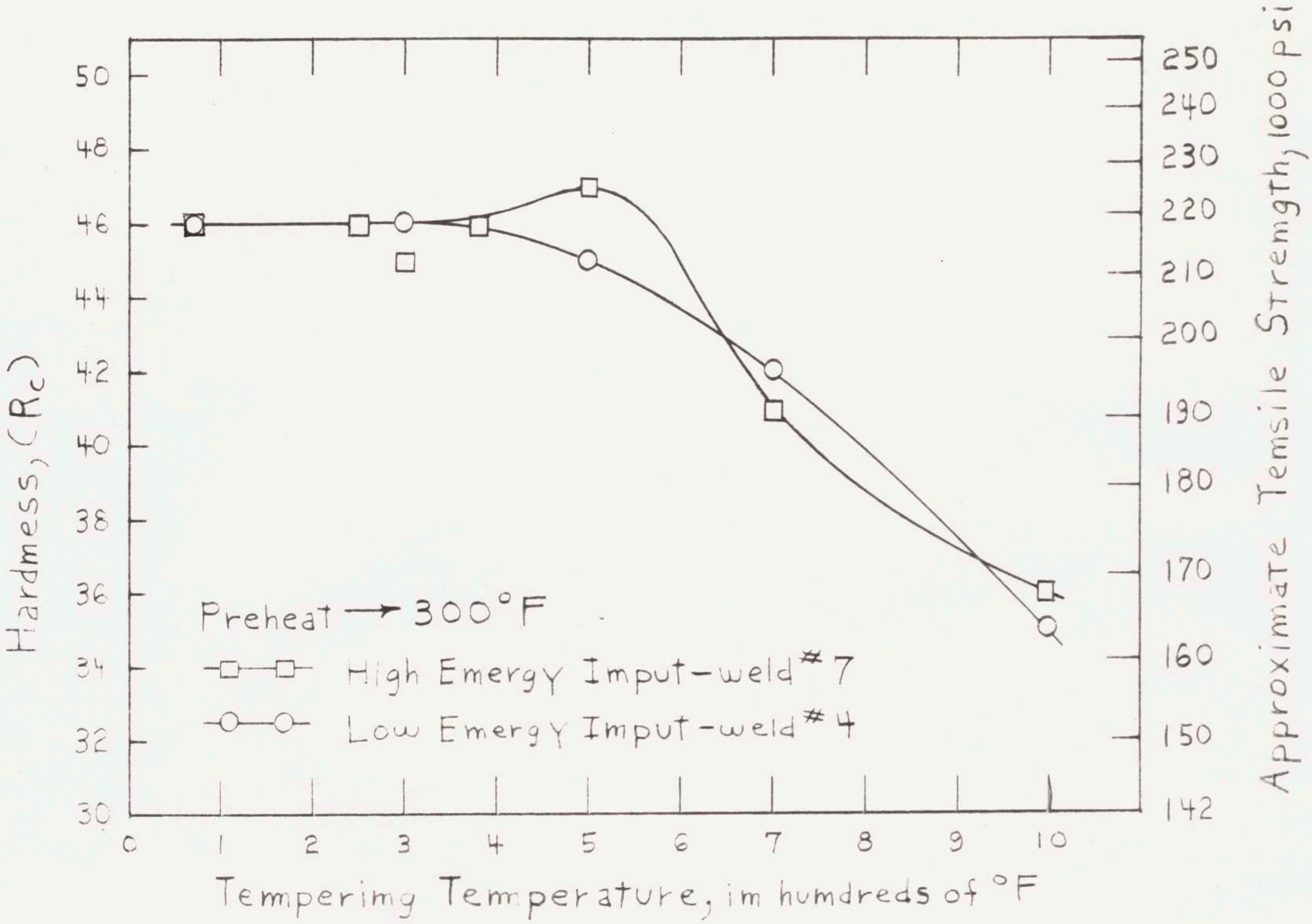


Figure 6. Tempering Curves for welds with 300°F Preheat

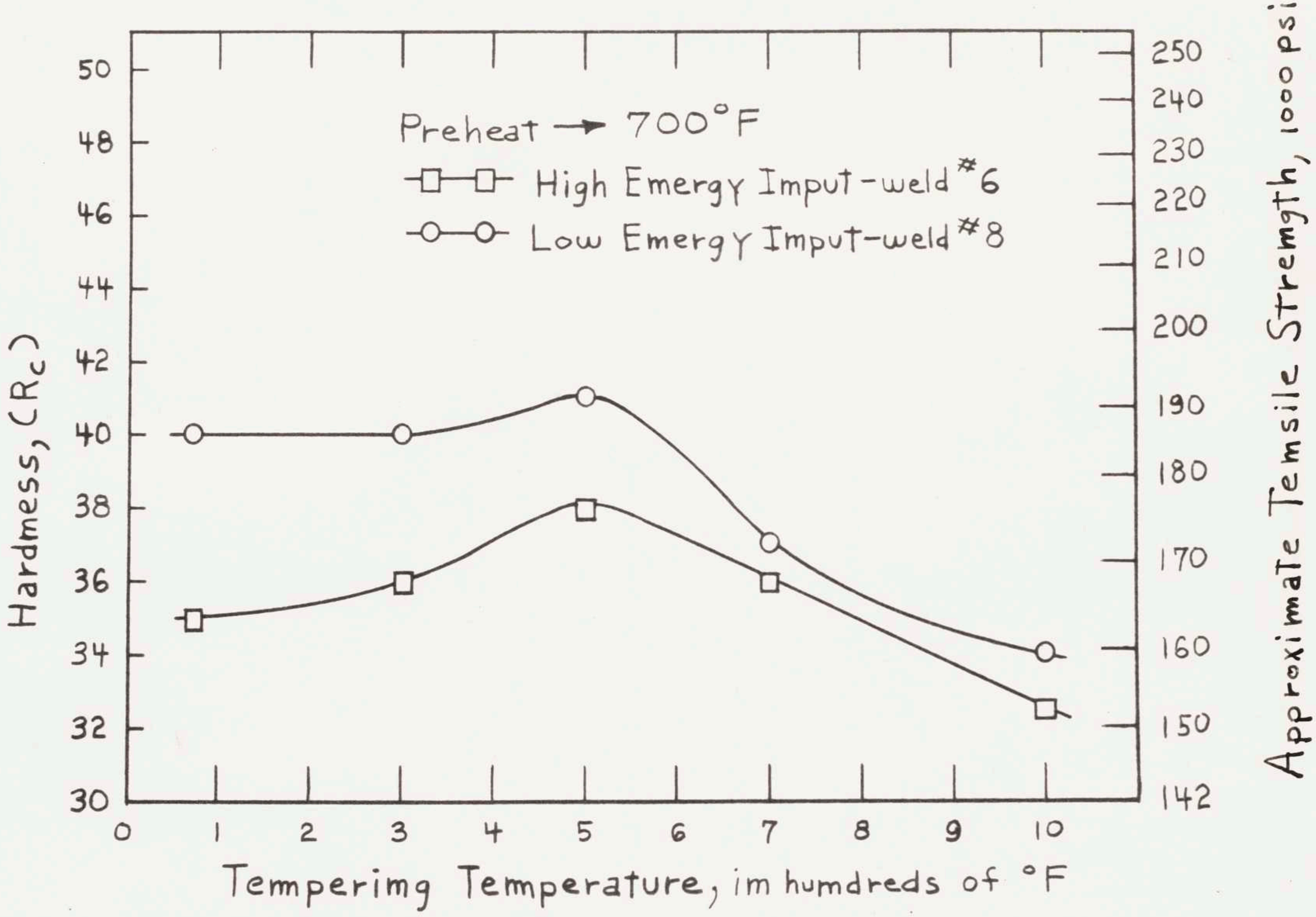


Figure 7. Tempering Curves for welds with 700°F Preheat

geometric shape of the fusion zone. Dimensional stability effects encountered in the transformations of austenite are, of course, important, especially in large geometric shapes; but these effects were not studied in this investigation.

Roberts, Averbach, and Cohen[5] have stated the mechanisms of martensite decomposition, and the approximate tempering temperatures at which the transformation effects of the first and third stages become distinctly noticeable in a steel, similar in carbon content to the 4330 steel used in this investigation. These temperatures are 300°F and 400°F, respectively.

Figures 5, 6, and 7 show that the first stage of tempering is well underway on tempering for 1 hour at 300°F. In figures 6 and 7 the third stage of tempering is shown to be well underway on tempering for 1 hour above 400°F. This early formation of cementite at the expense of the ε-carbide may well account for the noticeable increase in hardness shown in welds 6, 7, and 8.

The effect of the preheat variable is shown in figures 5, 6, and 7. As the preheat temperature is increased the tempering curves are shifted down, relative to hardness. As the preheat temperature is increased the cooling rates of the fusion zones are decreased. These decreasing cooling rates imposed on the fusion zones favor the formation of a softer structure, according to the isothermal transformation diagram.

The effect of the energy input variable is shown in figures 5, 6, and 7. The choice of energy input variables used in this investigation show only the general trends of varying energy input, since each of the 3 sets of curves in figures 5, 6, and 7 are relatively close to each other.

The significant factor concerning energy input is that as the energy input is increased, the cooling rate of the fusion zone is decreased allowing the formation of a softer structure.

E. THE BEND TESTS

Bend test were made only on the following specimens: 1 - R.T., 7 - 300, 7 - 500, 8 - 300, 8 - 500, and 6 - 500. The bend tests were made only on these welds simply because of the lack of material on hand. The preparation of the bend specimens and the test conditions appear in Section C of the Appendix.

Table 2 lists the percentage elongations obtained from the bend tests.

Table 2

Percent Elongations for the Bend Specimens

Specimen Number	°/₀ Elongation
1 - R.T.	10 °/₀
7 - 300	6 °/₀
7 - 500	5 °/₀
8 - 300	10 °/₀
8 - 500	12 °/₀
6 - 500	11 °/₀

Bend specimen 1 - R.T. was the only specimen that was bent with the fusion zone running longitudinally across the bend specimen. All the other bend specimens had their fusion zones running transversally across the bend specimen. The results of the bend tests made on these latter specimens were not very informative, since yielding occured in the parent plate next to the heat-affected zone.

The results of bend test 1 - R.T. was quite informative, however, because of the longitudinal positioning of the fusion zone. Ten percent elongation was found in this specimen indicating that the fusion zone is, at least, not brittle. If this specimen had been tempered below 400°F or above 600°F, more ductility probably would have been found.

In the other bend tests, varying degrees of yielding were found in the parent plate next to the heat-affected zone. Specimen 7 - 300, for example, showed only 6 percent elongation; but the parent plate had yielded considerably, therefore decreasing the bend stress in the fusion zone. Specimen 7 - 500 showed only 5 percent elongation, but the specimen broke at the parent metal-heat affect zone interface. Pictures of the bend test specimens are shown in figures 8 through 13,

The only general conclusions that can be drawn from the bend test results are; (1) the fusion zones are, at least, not brittle, (2) tempering treatments below 400°F and above 600°F would probably increase the ductility of the fusion zones, (3) preheats of 300°F and 700°F respectively, will increase the ductility of the fusion zones.

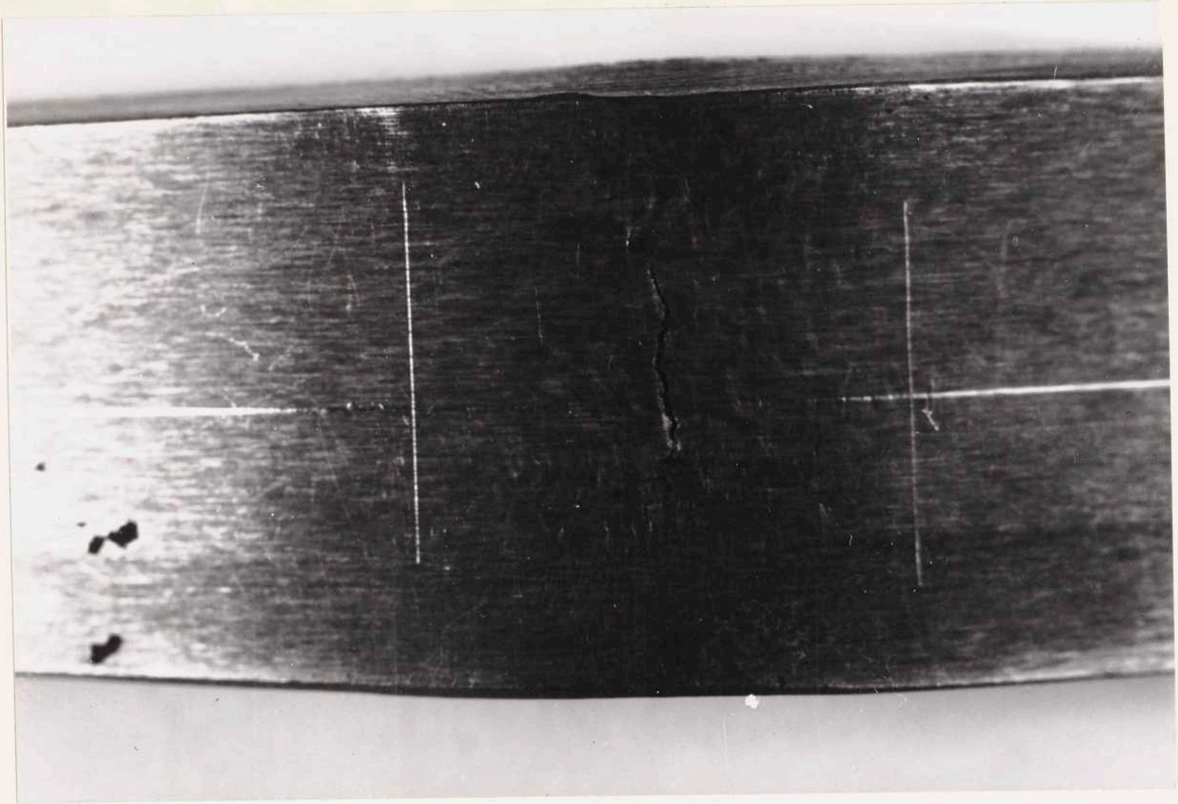


Figure 8. 6x
Specimen 1 - R.T. 10 % Elongation

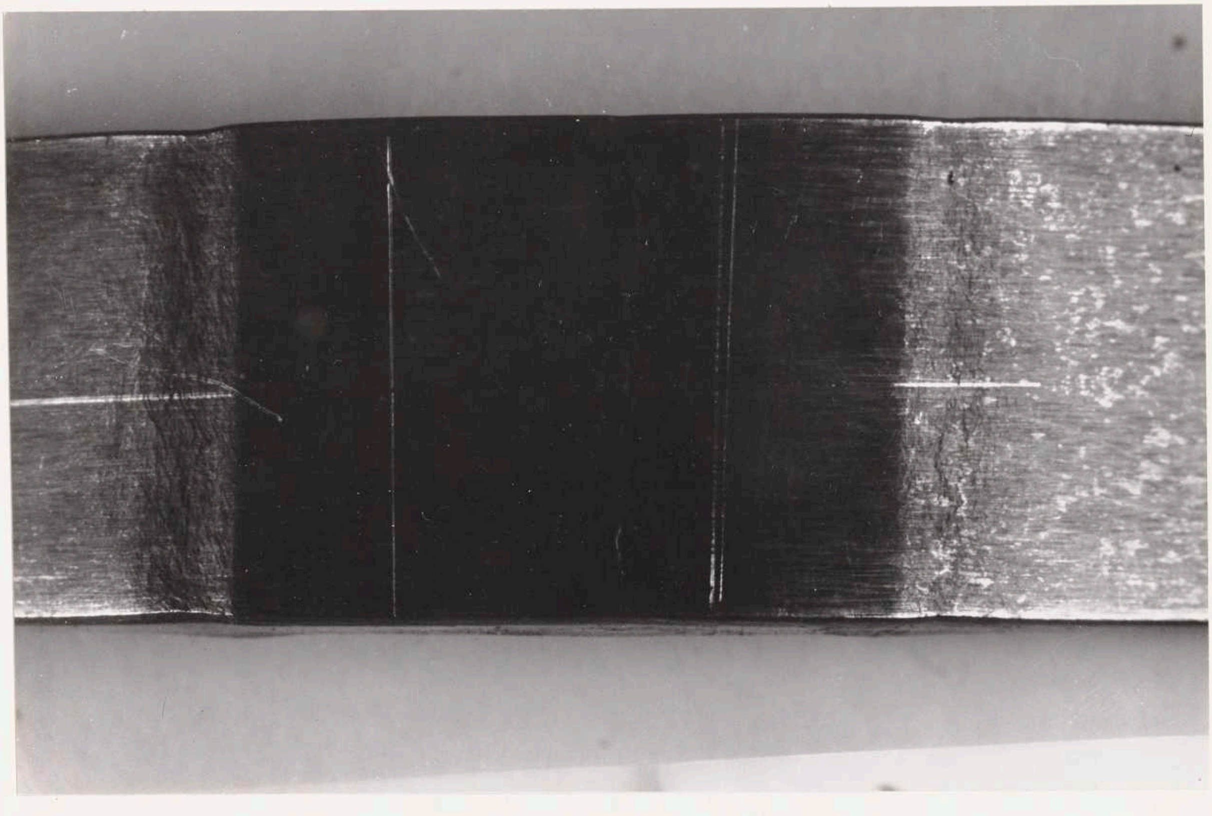


Figure 9. 6x
Specimen 7-300 6 % Elongation

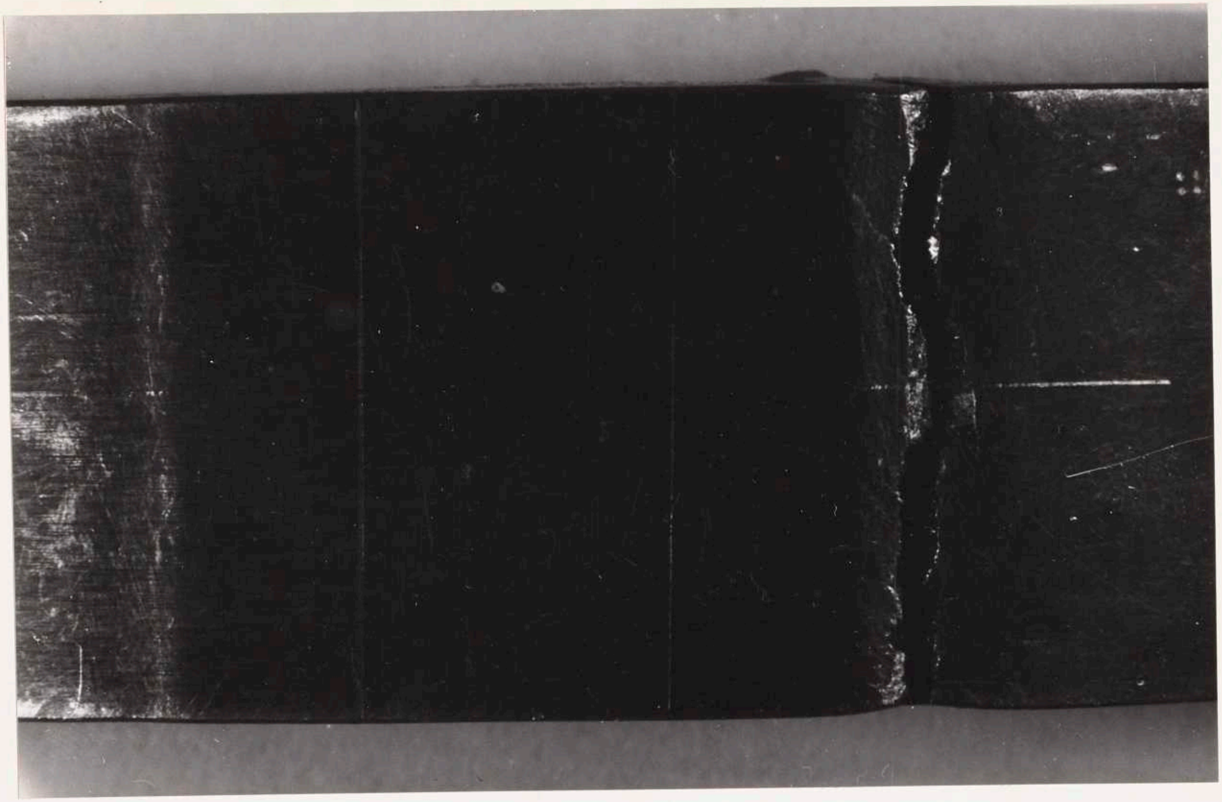


Figure 10. 6x
Specimen 7 - 500 5 % Elongation

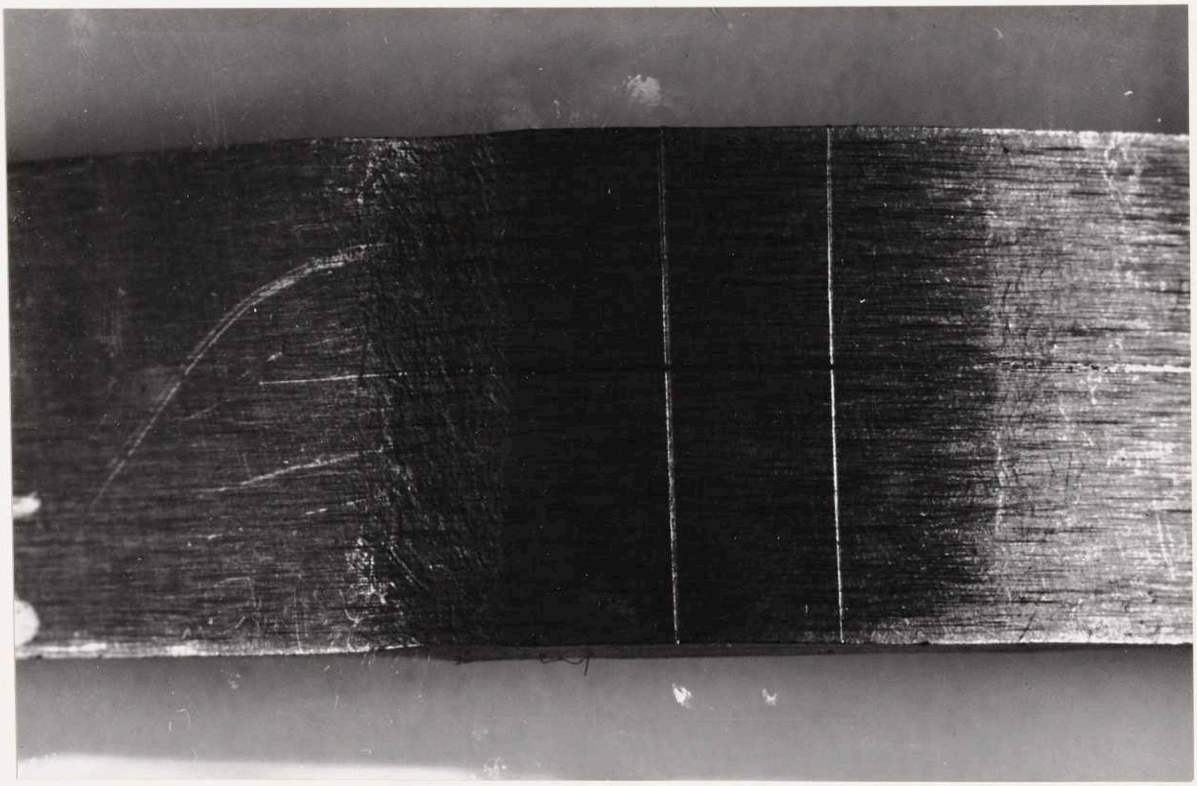


Figure 11. 6x
Specimen 8-300 10% Elongation

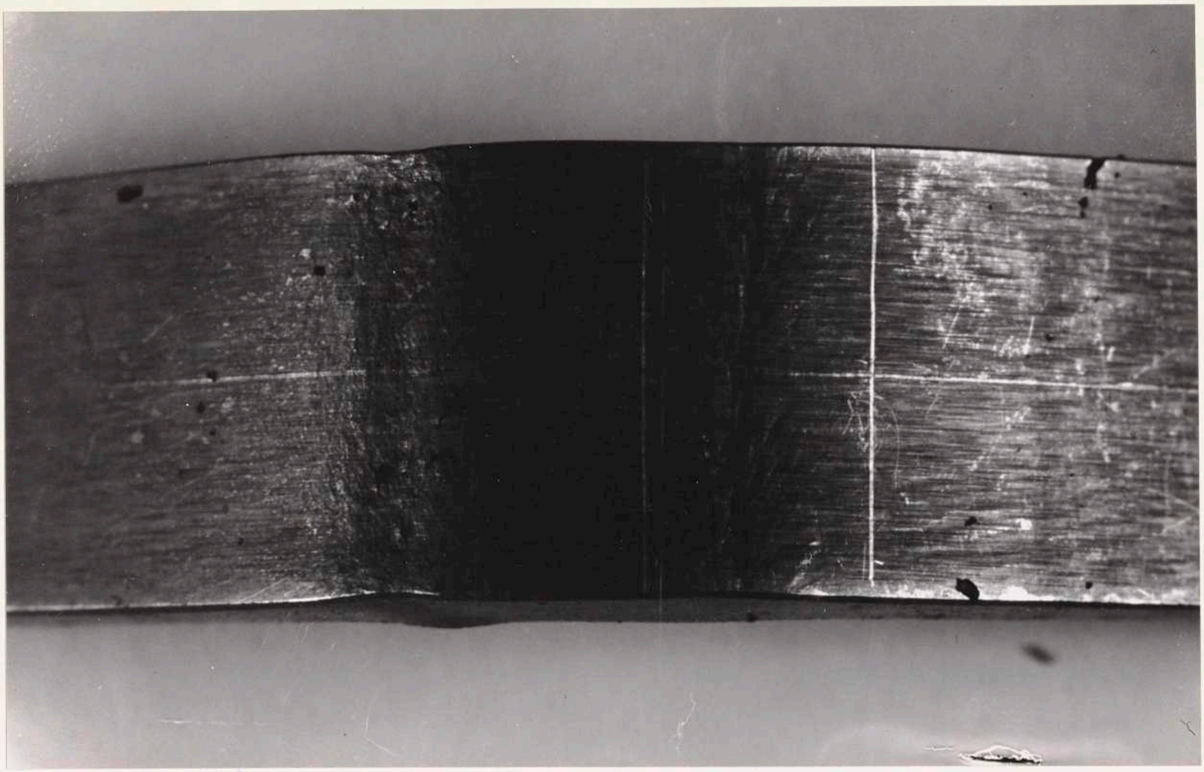


Figure 12. 6x
Specimen 8 - 500 12 % Elongation

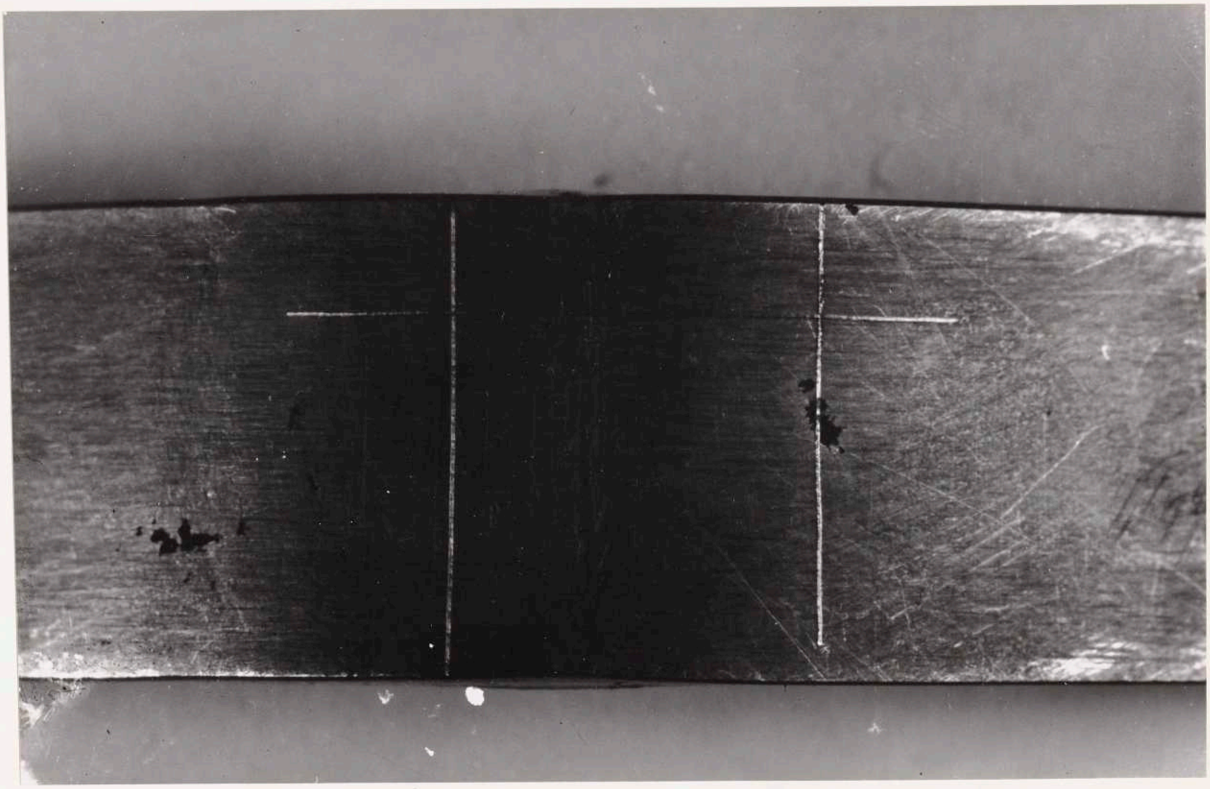


Figure 13. 6x
Specimen 6-500 11 % Elongation

V. CONCLUSIONS

The following conclusions may be drawn from this investigation:

1. The microstructures of the fusion zones consist of segregated columnar and equiaxed grains. The areas first to solidify contain mostly martensite and some bainite. The areas last to solidify contain virtually all martensite. The amount of alloying-element carbides present is probably very small.

2. As the preheat temperature is increased the cooling rates of the fusion zones are decreased, favoring the formation of softer, and therefore more ductile, structures as typified by the isothermal transformation diagram.

3. As the energy input is increased, more heat per unit length of weld, is put into the steel plate. Therefore, the cooling rates of the fusion zones are decreased, favoring the formation of softer, and therefore more ductile, structures as typified by the isothermal transformation diagram.

4. Tempering curves determined by this investigation are of the general type, showing the effects of the first and third stages of tempering.

5. The amount of retained austenite present in the fusion zones was found to be approximately 0.5 ± 0.5 percent.

6. The fusion zone of an arc-welded steel plate in the as welded condition with no preheat, was found to have 10 percent elongation. This indicates that the fusion zones are, at least, not brittle. The ductility of the fusion zones can be increased by selective tempering treatments. Hardness readings were related to approximate tensile strengths of the fusion zones.

The approximate tensile strengths of the fusion zones studied ranged from 150,000 psi to 245,000 psi, in relation to the thermal variable used.

VI. SUGGESTIONS FOR FURTHER WORK

1. In order to obtain a more quantitative and qualitative analysis of the microconstituents present in the fusion zone structure, an intense investigation should be made employing an electron microscope and a sensitive X-ray technique.

2. The mechanical properties of the various fusion zones should be further investigated by the use of tensile tests, impact tests, and longitudinal bend tests.

APPENDIX

A. A DETAILED DESCRIPTION OF THE WELDING OPERATION

Many practice runs were made on scrap plate to determine the constant welding conditions to be used in order to obtain satisfactory welds. Finally, the following welding conditions were decided upon.

1. argon flow rage 6 c.f. hr^{-1}
2. arc length $=$ 0.14 inches
3. distance from work piece to end of gas shield cylinder $=$ 0.55 inches
4. rate of travel of T.I.G. welder $=$ 0.1 inches sec^{-1}
5. maximum workable energy input $=$ 52.1 B.T.U. inches^{-1}
6. diameter of electrode $\frac{1}{16}$ inches
7. water flow rate in T.I.G. welder $=$ 521 milliliter min^{-1}
8. straight polarity was used
9. a D.C. welding rectifying unit, of 300 ampere capacity, with a drooping volt-ampere curve was used

B. HIGH AND LOW ENERGY INPUTS USED

$$\boxed{\text{Energy} = \frac{KVI}{v} \ \text{B.T.U. inch}^{-1}}$$

(1) Low energy input calculation:

V = 16 volts, (constant for all low energy input welds)

I = 174 amperes, (constant for all low energy input welds)

$K = 9.480 \times 10^{-4}$ B.T.U. joules^{-1}

v = 0.1 inches sec^{-1}

$$\text{Energy} = \frac{9.480 \times 10^{-4} \times 16 \times 174}{0.1} = 26.4 \ \text{B.T.U. inch}^{-1}$$

$\therefore$ actual energy input $\approx 0.80 \times 26.4 = \underline{21.1}$ B.T.U. inch^{-1}

(2) High energy input calculation:

V = 21 volts, (constant for all high energy input welds)

I = 262 amperes, (constant for all high energy input welds)

$K = 9.480 \times 10^{-4}$ B.T.U. joules^{-1}

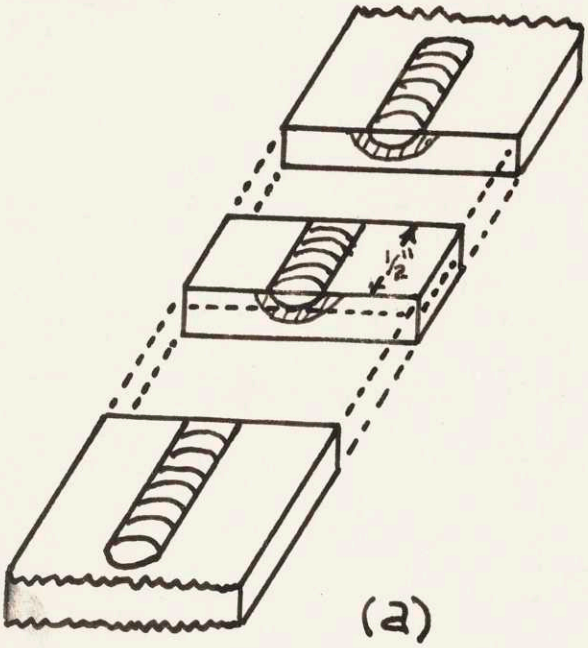
v = 0.1 inches sec^{-1}

$$\text{Energy} = \frac{9.48 \times 10^{-4} \times 21 \times 262}{0.1} = 52.1 \ \text{B.T.U. inch}^{-1}$$

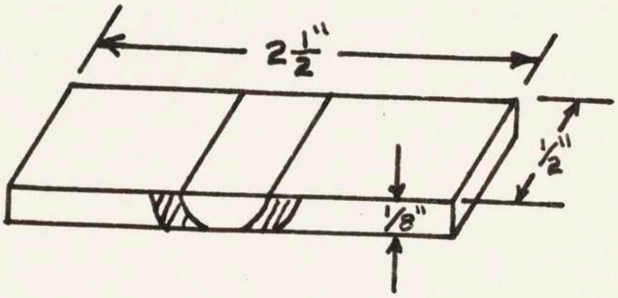
$\therefore$ actual energy input $\approx 0.80 \times 52.1 = \underline{41.7}$ B.T.U. inch^{-1}

C. PREPARATION OF BEND SPECIMEN AND TEST CONDITIONS

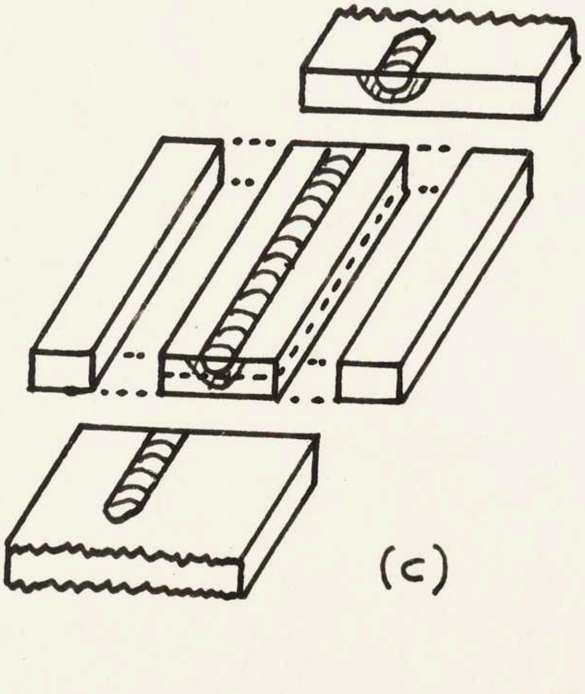
Transverse sections of the welded plate were cut out $\frac{1}{2}$ inch thick, see sketch (a) below. The bend specimens were then cut out of these sections as shown in (b). The one longitudinal bend specimen was cut out as shown in (c) and (d). The specimens were bent in a vice as shown in (e).



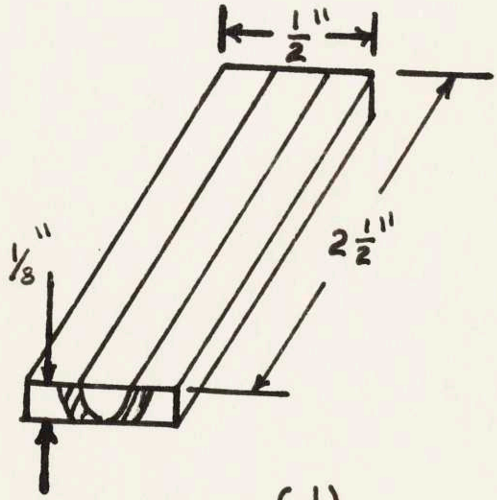
(a)



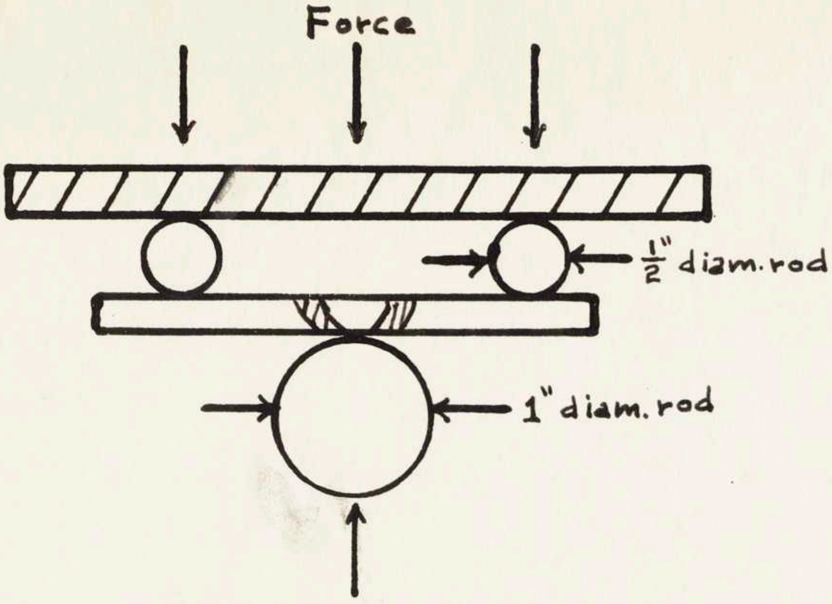
(b)



(c)



(d)

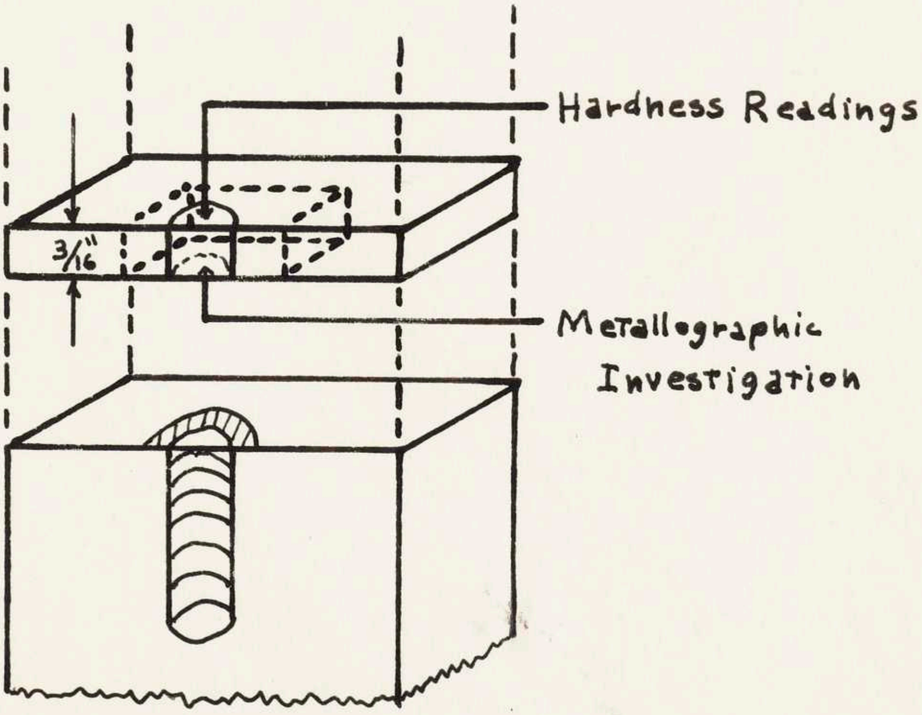


(e) Top View

D. TYPICAL CHEMICAL ANALYSIS OF THE MODIFIED 4330 STEEL (%)

C	Mn	Si	Ni	Cr	Mo	S	Fe
.27	1.10	.55	1.85	.90	.40	<.01	balance

E. SCHEMATIC SKETCH OF THE TRANSVERSE SECTIONS CUT OUT OF THE WELDED PLATE



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