PHASE TRANSFORMATION AND WELDING CHARACTERISTICS OF STROLOY 2A

by

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Submitted in Partial Fulfillment of the Requirements

for the Degree of

Master of Science in Engineering

in the

Metallurgical Engineering

Program

Adviser ________________ May 30, 1972 Date

Dean of the Graduate School ________________ June 1, 1972 Date

YOUNGSTOWN STATE UNIVERSITY

June, 1972

ABSTRACT

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A low-alloy quenched and tempered steel, such as Stroloy 2A, requires control of welding heat input to maintain adequate impact toughness in the weld heat-affected zone. Gleeble specimens are subjected to peak temperatures and controlled cooling rates which simulate weld heat-affected zone areas. Charpy V-notch impact tests on Gleeble treated specimens defines the critical minimum cooling rate essential to maintain empirically chosen minimum notch toughness values. For Stroloy 2A, a 30°F per second critical cooling rate was required for 6 foot-pounds V-notch impact strength at -50°F. Metallographic and hardness studies suggest that grain coarsening and mixed microstructures at high peak temperatures and slow cooling rates are responsible for degradation of heat-affected zone impact toughness. In actual welding, control of maximum heat input can be employed to give calculated cooling rates faster than the critical minimum cooling

rate. Using controlled heat inputs to weld Stroloy 2A, actual weld heat-affected zone V-notch impact properties were observed to be much greater than those found in Gleeble simulated studies. This is due to the integrated toughness values of different microstructural constituents that are present in a multipass weld heat-affected zone. Thus, this study suggests that multipass welds will have equal or greater Charpy V-notch impact toughness in the heat-affected zone when welded with heat input controls, as compared to the impact values found from Gleeble studies.

ACKNOWLEDGEMENT

The author wishes to acknowledge that The Babcock and Wilcox Company, Tubular Products Division provided the materials and financial support required to perform this study. Various members of the Welding Section of The Babcock and Wilcox Research and Development Division provided technical assistance required to perform this study.

The author wishes to express his sincere thanks to Dr. Shaffig Ahmed, Chairman, Department of Metallurgical Engineering and Material Science, Youngstown State University, for his guidance and assistance in this study.

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CHAPTER I

INTRODUCTION

Low alloy high strength steel has become increasingly more important in the construction industry because of its ability to meet various complex physical and mechanical property requirements. Stroloy 2A is one such grade of steel which was particularly developed for applications in the crane industry because of high strength and very desirable welding characteristics in the quenched and tempered condition. This particular alloy was developed by The Babcock and Wilcox Company, Tubular Products Division.

Stroloy 2A may be water quenched and tempered to obtain a range of mechanical properties including 90,000 psi, 100,000 psi, or 125,000 psi minimum yield strength. The particular strength level obtained is dependent upon the tempering temperature employed after water quenching. Normal tempering temperatures range from 1050 to 1150°F and austenitizing temperatures range from 1700 to 1750°F. Subsequent fabrication of Stroloy 2A tubing could include joining by the method of welding. No previous attempts have been made to systematically study the welding characteristics of this alloy.

The purpose of this study is to investigate Stroloy 2A's response to welding heat input as related to toughness, tensile, hardness, and microstructural properties in a simulated and actual weld heat-affected zone.

A modern tool often employed to join steels is shielded metal-arc welding. This welding process is sometimes referred to as manual "stick" electrode welding. An arc, between the work piece (base metal) to be welded and the consumable flux coated electrode, generates heat which melts the base metal and electrode to form a molten pool of metal. Upon solidification, a joint is produced which is referred to as the weldment. The effective heat input to the base metal is related to the arc voltage, arc amperage, weld travel speed, and an efficiency factor defining the proportion of the total available heat energy supplied by the arc which enters the plate. The heat input due to welding determines the size of the weld puddle, the size of the heat-affected zone, and hence, affects the mechanical and microstructural properties of the weld.

In low carbon quenched and tempered steels, it has been generally observed that mechanical properties depend upon the chemical composition of the weld metal and the effect that heat input has upon the heat-affected zone. Since the strength and toughness of weld metals are limited by a compromise between alloying for strength and decreasing carbon for toughness, weld metals (stick electrodes) are presently limited to yield strengths of 130,000 psi with adequate toughness. However, even when such high strength weld metals are employed, the strength and toughness of the weld may then be dependent upon the effect of welding heat input on the base metal heat-affected zone.

From classical heat flow theory, the cooling rate of the heat-affected zones can be calculated from known welding heat input conditions, or vice versa. In general, for a particular plate thickness as the heat input increases the cooling rate decreases. Details of such calculations appear in the Appendix.

In determining proper welding procedures, it is desirable to know what effect various thermal cycles and cooling rates have on the notch toughness of the heat-affected zone. Charpy V-notch impact testing is a standard method of measuring relative toughness in terms of foot-pounds of energy absorbed when breaking a standard size specimen. However, since an actual weld has a relatively small heat-affected zone which has been subjected to a multitude of thermal cycles, it is difficult to use a standard Charpy impact test to single out any given area which has been subjected to a particular thermal cycle.

The technique of employing a "Gleeble" machine to simulate points in the heat-affected zone has the advantage of allowing one to determine the notch toughness properties of a sufficiently large mass of metal which has been precisely affected by known heating and cooling conditions. In the operation of subjecting a sample of Stroloy 2A to a particular peak temperature followed by a controlled cooling rate, a specimen is resistance heated and control cooled in the Gleeble machine. After such a treatment, a standard size Charpy V-notch specimen is machined from the Gleeble treated specimen and tested under appropriate test conditions. In this study a test temperature of -50°F was chosen. This test temperature, based upon a transition curve study of base metal Stroloy 2A, represents lower transition shelf toughness. It also represents the lowest actual service temperature to which a fabricated crane boom would be exposed under normal environmental conditions in the United States.

By subjecting specimens of Stroloy 2A steel to numerous thermal cycles with the use of the Gleeble machine, our purpose would be to determine a critical thermal cycle wherein the simulated heat-affected zone notch toughness would be greater than some empirically determined toughness value. Upon defining this critical thermal condition, appropriate calculations can be employed to convert the critical cooling rate to critical heat input values which are used during actual welding. Actual shielded metal-arc welds on plate specimens of Stroloy 2A can be made and mechanically tested to verify the accuracy of predicting suitable welding conditions from the knowledge of the Gleeble response notch toughness characteristics and heat treated properties of the alloy.

Metallographic studies of the weld heat-affected zone and of Gleeble treated specimens can give us clues as to what causes toughness degradation in certain areas of the heat-affected zone.

Such studies, after proper analyses of the metallurgical considerations, will allow us to predict and determine the welding characteristics of this steel.

CHAPTER II

MATERIALS

A 6-foot length of 4-inch diameter hot rolled bar representing steel from a 5000 pound induction heat of Stroloy 2A, Babcock and Wilcox heat number A-1667, was hot forged and rolled into various plates. Plate dimensions included 3/8 inch thick x 5 inch wide x 40 inch long, 1/2 inch thick x 5 inch wide x 40 inch long, and 3/4 inch thick x 5 inch wide x 40 inch long. No attempt was made to cross roll the plates, hence, the 40 inch length direction represented the longitudinal rolling direction.

The plates were tank water quenched from an austenitization temperature of 1750°F and, subsequently, tempered at 1150°F for one hour at temperature followed by air cooling to room temperature. Mechanical properties of the heat treated plates are recorded in subsequent chapters of this report.

The Stroloy 2A heat ladle analysis, along with the alloy range, are reported in Table 1. The elements carbon, phosphorous, and sulphur were determined by combustion analysis techniques; and all other elemental analyses were determined by spectrographic techniques.

TABLE 1

CHEMICAL COMPOSITION OF STROLOY 2A

	% C	% Mn	% P	% S	%Si	%Ni	% Cr	%Mo	% B	%Cu	% Al	% Zr[a]
Range	.15/ .21	.70/ 1.00	.025 max	.025 max	.20/ .35	.40/ .70	.80/ 1.10	.20/ .30	.001/ .005	-	-	.06/ .08
A-1667	.18	.73	.006	.015	.17[b]	.62	.86	.21	.002	.05	.062	-

[a] Aim analysis only

[b] Below Chemical Composition Range

CHAPTER III

PROCEDURE

Plate Studies

Longitudinal tensile, transverse tensile, and longitudinal Charpy V-notch specimens were prepared from the quenched and tempered 3/8, 1/2 and 3/4 inch plates of Stroloy 2A. Because of thickness limitations, 3/4 size Charpy V-notch specimens (.295 inch x .394 inch x 2.165 inch) were machined from the 3/8 inch thick plate; whereas, full size Charpy V-notch specimens (.394 inch x .394 inch x 2.165 inch) were machined from the 1/2 inch and 3/4 inch plate. Details of impact test specimens are described in ASTM A-370-68 specification, entitled "Standard Methods and Definitions for Mechanical Testing of Steel Products". Standard small size round tension specimens referred to as .252 inch (nominal diameter) specimens with one inch gage lengths were machined from the 3/8, 1/2, and 3/4 inch plate. Details of this test specimen are also described in ASTM A-370-68.

The standard .252 inch tensile specimens were tested at room temperature. Mechanical properties including ultimate tensile strength, .2 percent yield strength, percent reduction of area, and percent elongation in gage length were recorded. The full size and sub-size Charpy V-notch specimens were impact tested at various temperatures ranging from 212°F to -150°F. In most cases, only one or two impact specimens were tested at a particular test temperature.

The mechanical properties and notch toughness properties so established represented base metal properties when compared to Gleeble or actual weld samples.

Dilatometric Studies

An Ernst Leitz Wetzlar dilatometer instrument was employed to determine the approximate allotropic transformation temperatures, or often referred to as critical transformation temperatures. Allotropic transformations occur within certain temperature ranges, which can be detected by observing changes in the thermal expansion characteristics during heating and cooling.

Two standard size round dilatometer specimens, .1417 inch diameter x 1.968 inch long, were machined from the quenched and tempered 1/2 inch plate. These specimens were separately run in the dilatometer at a controlled heating and cooling rate of 100°F per hour. Photographic light sensitive paper was employed to record the expansion versus temperature characteristics of the specimens.

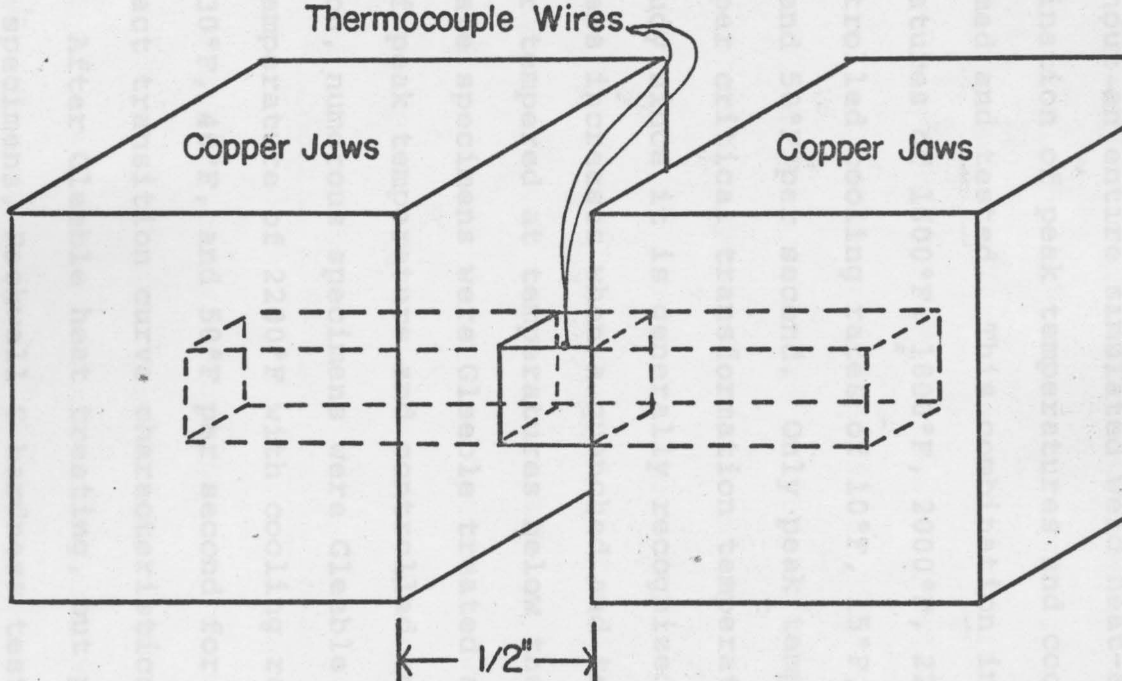
Gleeble Studies

The Gleeble machine is employed to simulate specific thermal points in the heat-affected zone of a weld. Since in an actual weld heat-affected zone, there are a multitude of thermally affected areas within a relatively narrow zone, it is difficult to use standard impact specimens to determine notch toughness properties of any particular microstructure or area. However, with the use of a Gleeble machine, a larger mass of metal can be subjected to a controlled thermal cycle which simulates a point area of an actual weld heat-affected zone. A standard Charpy V-notch specimen can be machined from the Gleeble treated mass of metal and, subsequently, tested to represent the notch toughness of a simulated heat-affected zone point. By subjecting specimens of Stroloy 2A steel to numerous thermal cycles with the use of the Gleeble machine, the fundamental notch toughness characteristics of an actual weld heat-affected zone can be developed.

The Gleeble machine is a programed testing machine which subjects a .400 inch x .400 inch x 4 1/8 inch long longitudinally machined specimen of test material to resistance heating and controlled cooling. The Model 510 Gleeble machine employs copper jaws which grip the test specimen on two ends while leaving a .5 inch separation of specimen exposed to the atmosphere. Figure 1 is a sketch of a specimen in position for Gleeble testing. Also shown in the sketch are .010 mil Chromel-Alumel thermocouple wires, which are percussively welded to the approximate center of the test specimen. The principals of thermometry apply wherein when two dissimilar metal wires, such as Chromel P and Alumel, are joined at one end an electromotive force is generated which results in a difference in electrical potential (voltage) between the two free ends of the wires. This difference in voltage is proportional to the difference in temperature between the cold junction and hot junction. Hence, a potentiometer can be employed to measure the voltage difference in millivolts; and this can be calibrated to hot junction temperature for the particular combination of thermocouple wires employed.

With the Model 510 Gleeble, the specimen temperature is controlled by the program; and the actual temperatures are recorded on a Midwestern Instrument Recording Oscillograph, which employs DuPont Lino-Writ 5 high-speed photorecording paper.

The Gleeble machine is programmed to resistance heat the specimen to a particular peak temperature, to hold at that temperature from 2 to 3 seconds, to air cool just above the Ac_3 critical temperature, then to control cool at a particular cooling rate to room



Schematic of Specimen in Position for Gleeble Heating

Figure I

temperature. Photorecording charts of specimen temperature allowed us to accurately determine if the specimen was properly heated and cooled as programed.

In order to develop the notch toughness properties throughout an entire simulated weld heat-affected zone, a combination of peak temperatures and cooling rates were programed and tested. This combination included peak temperatures of 1600°F, 1800°F, 2000°F, 2200°F, and 2400°F at controlled cooling rates of 10°F, 15°F, 20°F, 30°F, 40°F, and 50°F per second. Only peak temperatures above the upper critical transformation temperature were chosen for study since it is generally recognized that notch toughness increases when a quenched and tempered steel is further tempered at temperatures below the critical range. Duplicate specimens were Gleeble treated at each combination of peak temperature and controlled cooling rate. In addition, numerous specimens were Gleeble treated at a peak temperature of 2200°F with cooling rates of 10°F, 20°F, 30°F, 40°F, and 50°F per second for determination of impact transition curve characteristics.

After Gleeble heat treating, but prior to machining Charpy specimens, Rockwell C hardness tests were taken at the center of the heat-affected zone as indicated by the small weld bead left by the thermocouple wires. Care was employed to assure that the hardness impressions were on a side which would represent through thickness direction (perpendicular to plate surface) when compared to the original plate from which the Gleeble specimens were machined.

Charpy V-notch full size specimens (.394 inch x .394 inch x 2.165 inch) were machined from the Gleeble treated specimens. Care was exercised in placing the V-notch in the center of the heat-affected zone which was marked by the hardness impressions. The Charpy V-notch specimens machined from the various Gleeble treated specimens were impact tested at -50°F. Additional Gleeble treated specimens representing a peak temperature of 2200°F with cooling rates of 10°F, 20°F, 30°F, 40°F, and 50°F per second were impact tested at -100°F, -50°F, 0°F, 78°F, and +212°F. These specimens were used to establish impact transition curve behavior.

<u>Cooling Rate Conversion to Heat Input</u>

Since in actual welding it is normal to control the cooling rate of the weld and heat-affected zone by control of heat input in kilojoules per inch of weld, it was desirable to convert Gleeble controlled cooling rates into heat input terms. This conversion using classical heat flow theory takes into consideration factors such as thermal conductivity, density, specific heat, efficiency of arc heat transferred to base metal, and plate thickness. Details of such actual calculations are described in Appendix A; but for convenience, Table 2 lists typical calculated heat inputs for various cooling rates in 3/8, 1/2, and 3/4 inch plates.

TABLE 2

HEAT INPUT VS. COOLING RATE FOR VARIOUS PLATE THICKNESSES

Cooling Rate (°F/second)	Heat Input (Kilojoules per inch)		
	3/8" Plate	1/2" Plate	3/4" Plate
10	55.4	74.8	110.7
20	39.3	52.2	78.3
30	33.0	42.6	63.9
40	27.7	36.9	55.4
50	24.8	33.0	49.5

Actual Weld Studies

Using various heat inputs to weld 3/8 inch plates together, 1/2 inch plates together, and 3/4 inch plates together to form butt welded joints, it was our purpose to verify the accuracy of predicting suitable welding parameters from the knowledge of the Gleeble impact characteristics and heat treated properties of the alloy.

All the welds were performed by a regular welder under optimum conditions. The plates to be welded were beveled 30 degrees and abutted with a 1/16 inch root opening. Neither preheat nor post heat treatments were employed.

Three types of flux coated welding electrodes were employed. These included Atom-Arc 12018, Atom-Arc T (11018), and P&H 107 (11018). The manufacturers reported typical weld metal analyses and mechanical properties are recorded in Table 3. All electrodes were low-hydrogen types to prevent the occurrence of under-bead cracking when welding high strength steels.

During actual welding, which in all cases consisted of numerous weld passes, an Esterline Angus AC-DC Wattmeter Recording Instrument charted the kilowatts of power versus time produced by welding. From these charts, average heat input in kilojoules per inch of weld could easily be calculated for each weld pass. The average heat input of each weld pass was used to establish the actual total average heat input to make the weld. In addition, an Esterline Angus Model A602C Two Channel Voltage and Amperage Recorder charted the voltage and amperage versus time for each weld pass. These recordings served as a second check of heat input using appropriate calculations.

TABLE 3

MANUFACTURERS STICK ELECTRODE DATA

Brand Name	AWS Number	Typical As-Welded Tensile (Ksi)	Yield (Ksi)	%Elong (2")	Charpy V-Notch at-60°F(Ft-Lbs)	Typical Chemical Analysis% C	Mn	Si	Cr	Ni	Mo
Atom-Arc "T"	11018-M	115	103	22	41	.06	1.53	.27	.31	1.88	.42
Atom-Arc 12018	12018-M	132	120	22	32	.05	1.90	.25	.85	2.00	.50
P&H 107	11018	114	97	24	35	.07	1.60	.45	.15	1.75	.40

Atom-Arc manufactured by ARC Products Manufacturing, Division of Chemetron Corporation

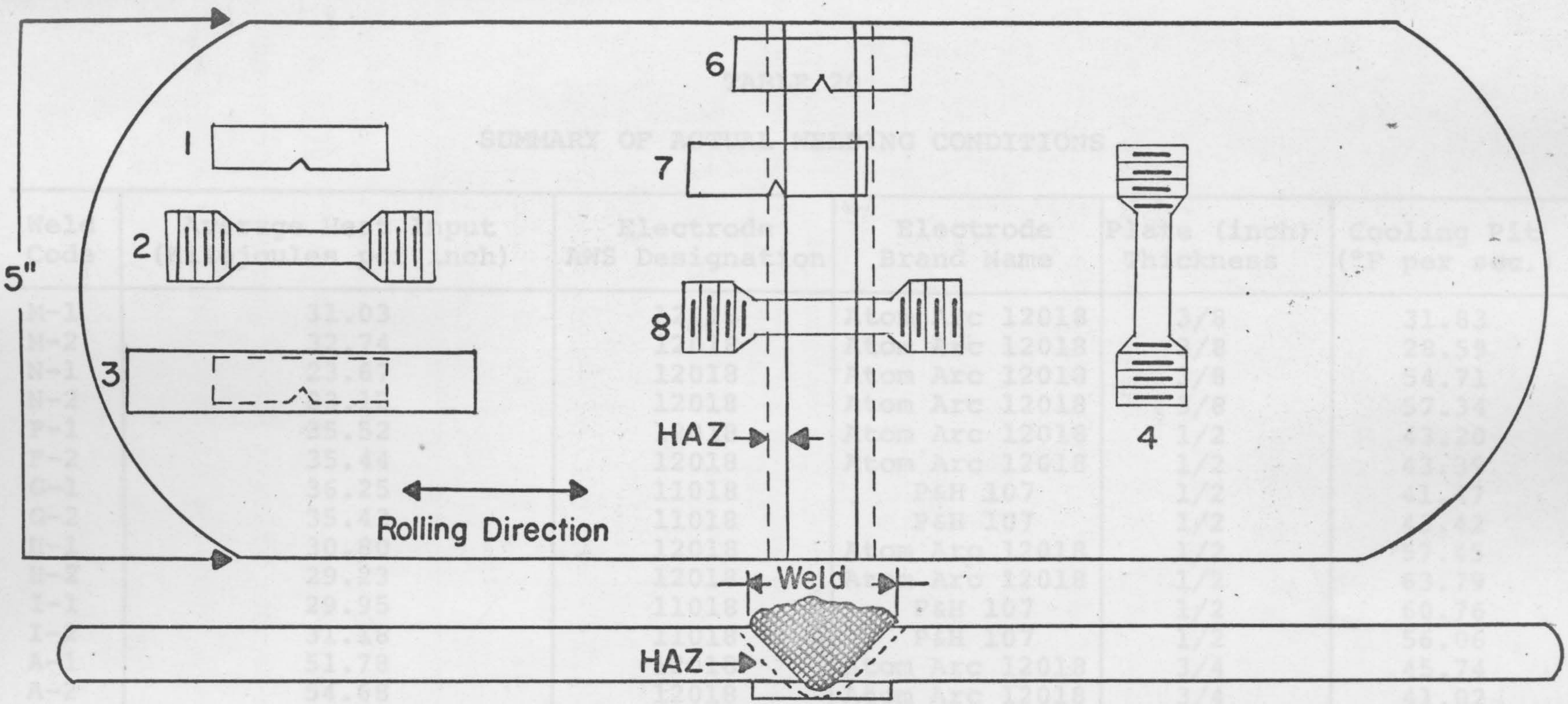
P&H manufactured by P&H Welding Products Division of Harnischfeger

Table 4 through 19 placed in Appendix B, record the actual welding procedure and individual weld pass conditions for each of sixteen welds made for this study. For convenience, Table 20 shown here records a summary of the average heat inputs per weld, the stick electrodes employed for each weld, the plate thickness, and the calculated cooling rate of the weld.

All welds were approximately 5 inches long in a direction perpendicular to the longitudinal rolling direction of the base metal plate. All welds were radiographed for quality checks. The welds were cut into 1/2 inch longitudinal sections, which were subsequently macro etched to show the weld and heat-affected zone. Transverse-weld substandard round tensile specimens and transverse-weld sub-size and full size Charpy V-notch impact specimens were machined from the various weldments. Figure 2 schematically represents the location of the weld, heat-affected zone, and base metal specimens.

Extreme care was exercised to assure that the Charpy V-notch of the impact specimens were positioned either in the heat-affected zone or weld metal as appropriate. The gage lengths of the transverse-weld tensiles were carefully positioned to cover the weld metal, heat-affected zone, and a portion of the base metal.

Using a section cut from the 3/8 inch Code M weld, metallographic studies were made of the weld metal and heat-affected zone.



No.1 Longitudinal base metal Charpy V-notch impact specimen.

No.2 Longitudinal base metal tensile specimen.

No.3 Longitudinal base metal Gleeble specimen.

No.4 Transverse base metal tensile specimen.

No.6 Transverse-weld Charpy V-notch impact specimen, notched in weld metal.

No.7 Transverse-weld Charpy V-notch impact specimen, notched in heat-affected zone.

No.8 Transverse-weld tensile specimen.

Schematic of Specimens Cut from Weld and Base Metal

Figure 2

TABLE 20

SUMMARY OF ACTUAL WELDING CONDITIONS

Weld Code	Average Heat Input (Kilojoules per inch)	Electrode AWS Designation	Electrode Brand Name	Plate (inch) Thickness	Cooling Pit (°F per sec.)
M-1	31.03	12018	Atom Arc 12018	3/8	31.83
M-2	32.74	12018	Atom Arc 12018	3/8	28.59
N-1	23.67	12018	Atom Arc 12018	3/8	54.71
N-2	23.12	12018	Atom Arc 12018	3/8	57.34
F-1	35.52	12018	Atom Arc 12018	1/2	43.20
F-2	35.44	12018	Atom Arc 12018	1/2	43.39
G-1	36.25	11018	P&H 107	1/2	41.47
G-2	35.43	11018	P&H 107	1/2	43.42
H-1	30.80	12018	Atom Arc 12018	1/2	57.45
H-2	29.23	12018	Atom Arc 12018	1/2	63.79
I-1	29.95	11018	P&H 107	1/2	60.76
I-2	31.18	11018	P&H 107	1/2	56.06
A-1	51.78	12018	Atom Arc 12018	3/4	45.74
A-2	54.68	12018	Atom Arc 12018	3/4	41.02
B-1	52.47	11018	Atom Arc "T"	3/4	44.54
B-2	52.58	11018	Atom Arc "T"	3/4	44.35

CHAPTER IV

RESULTS AND DISCUSSION

Plate Results

Longitudinal tensile and transverse tensile results from quenched and tempered 3/8, 1/2, and 3/4 inch plates of Stroloy 2A are recorded in Table 21.

TABLE 21

PLATE TENSILE RESULTS

Plate Thickness (inch)	Specimen Orientation	Tensile Strength (Ksi)	Yield Strength (Ksi)	%Elong in 1 inch	% Reduc. Area
3/8	Longitudinal	133	126	22	67.4
	Transverse	135	127	18	56.2
1/2	Longitudinal	139	132	20	64.0
	Transverse	139	132	19	55.1
3/4	Longitudinal	136	128	19	63.6
	Transverse	134	128	18	51.8

These results represent Stroloy 2A tank water quenched from 1750°F and subsequently tempered at 1150°F. In this fundamental study, these results represent the base metal properties when compared to weldment results.

Charpy V-notch impact results over a range of test temperatures are recorded in Table 22, for 3/8, 1/2, and 3/4 inch quenched and tempered plates. These results represent base metal impact properties when compared to weldment results.

Dilatometric Results

The approximate critical transformation temperatures for Stroloy 2A were determined using heating and cooling rates of 100°F per hour. The results were recorded as follows:

Upper critical on heating, Ac_3 1530°F

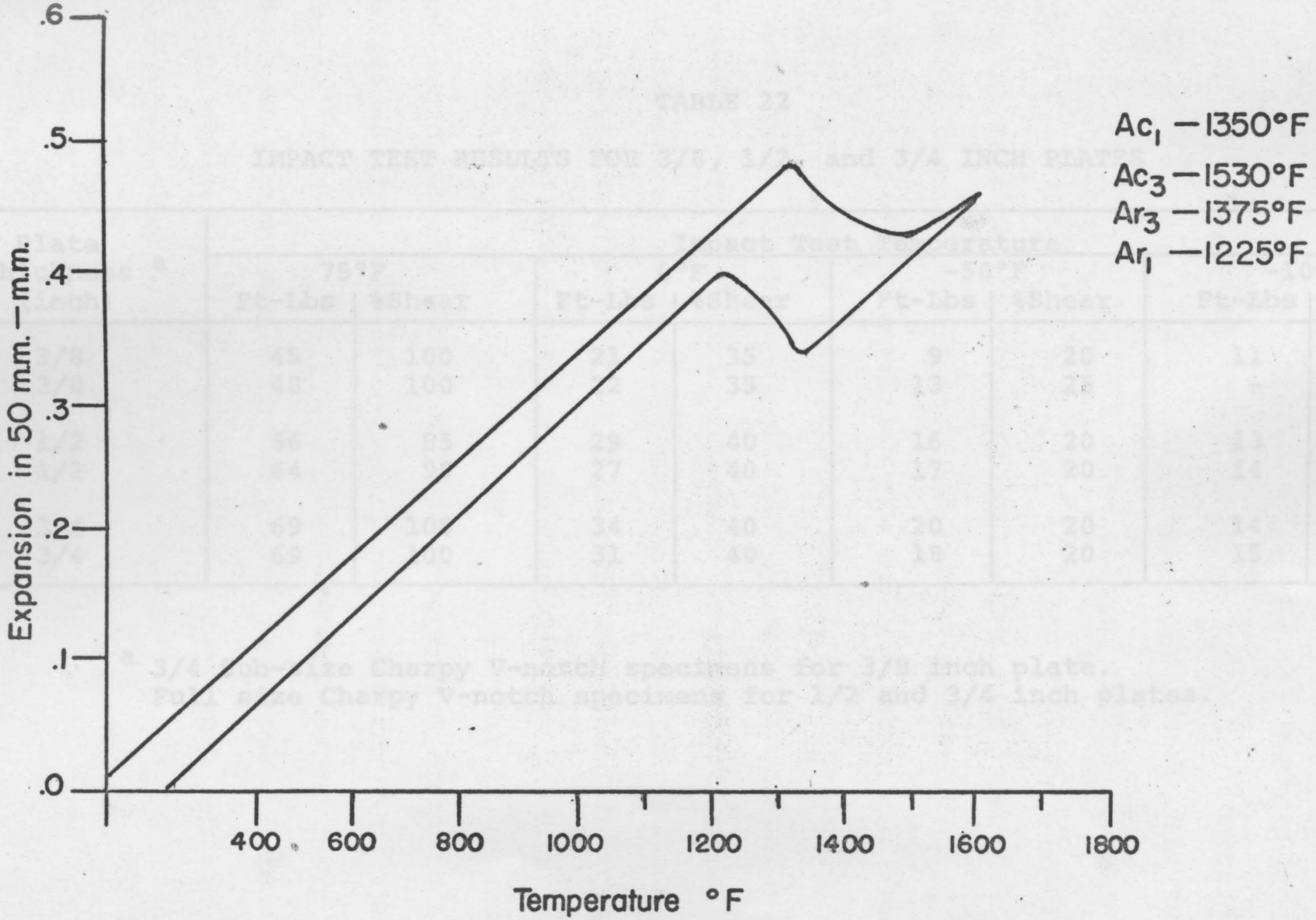
Lower critical on heating, Ac_1 1350°F

Upper critical on cooling, Ar_3 1375°F

Lower critical on cooling, Ar_1 1225°F

Figure 3 illustrates the expansion versus temperature characteristic curves which were used to find the critical temperatures.

Having found the critical transformation temperatures, and from a general knowledge that impact properties are normally increased when a quenched and tempered structure is further tempered at a temperature below its lower critical, this program consisted of studying the expected degradation of notch impact properties when Gleeble simulated heat-affected zone specimens are peaked at temperatures above the upper critical.



Dilatometer Curve of Stroloy 2A, Heat A-1667 Figure 3

TABLE 22

IMPACT TEST RESULTS FOR 3/8, 1/2, and 3/4 INCH PLATES

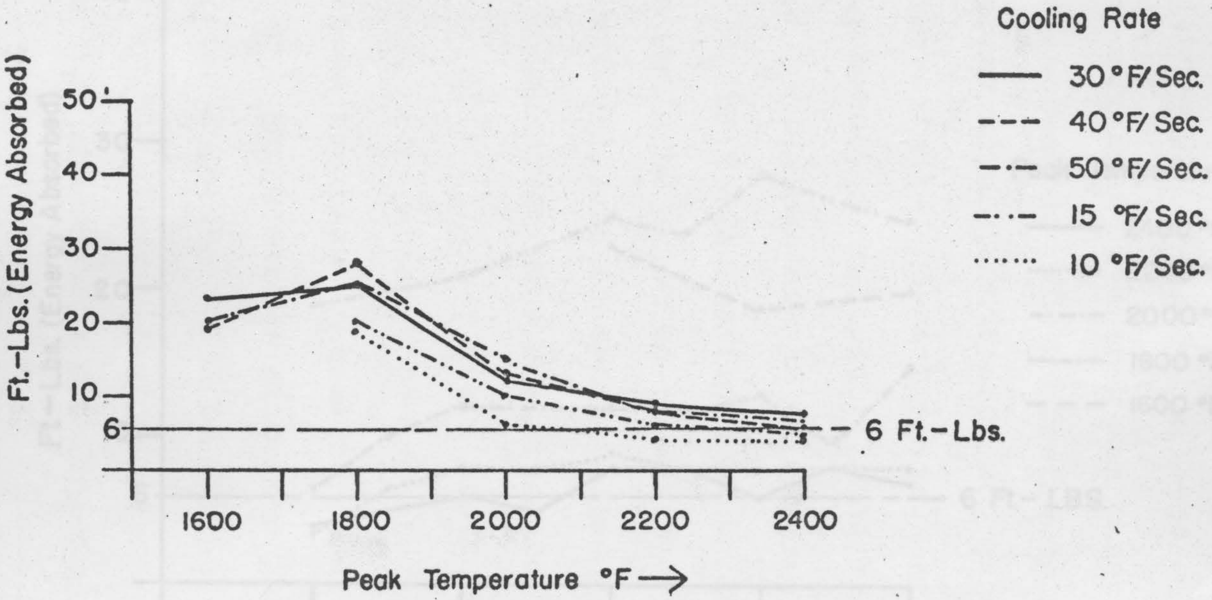
Plate Thickness[a] (inch)	Impact Test Temperature							
	75°F		0°F		-50°F		-100°F	
	Ft-Lbs	%Shear	Ft-Lbs	%Shear	Ft-Lbs	%Shear	Ft-Lbs	%Shear
3/8	45	100	21	35	9	20	11	10
3/8	48	100	22	35	13	25	-	-
1/2	56	85	29	40	16	20	13	15
1/2	64	90	27	40	17	20	14	15
3/4	69	100	34	40	20	20	14	15
3/4	69	100	31	40	18	20	15	15

[a] 3/4 Sub-size Charpy V-notch specimens for 3/8 inch plate.
Full size Charpy V-notch specimens for 1/2 and 3/4 inch plates.

Gleeble Results

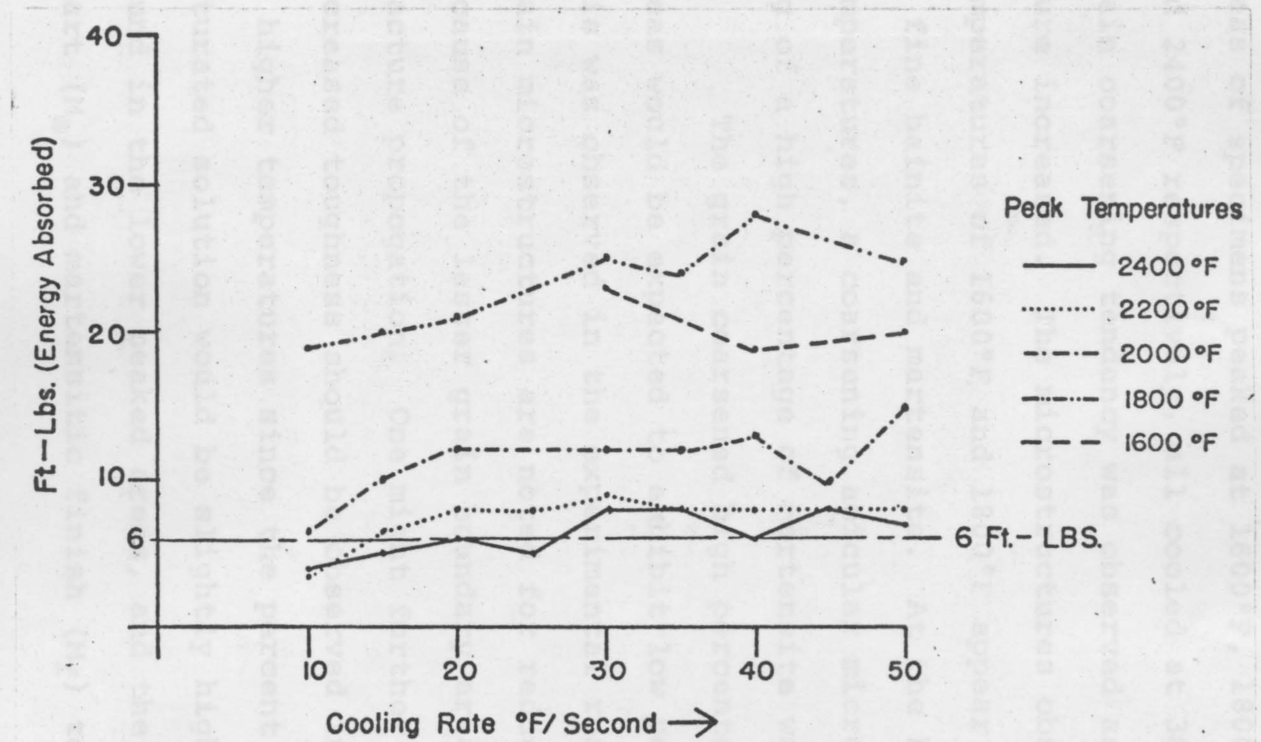
In an attempt to determine the toughness characteristics of simulated heat-affected zone points, numerous specimens were peaked at temperatures of 1600°F, 1800°F, 2000°F, 2200°F, and 2400°F then control cooled at rates of 10°F, 20°F, 30°F, 40°F, and 50°F per second. Charpy V-notch specimens were subsequently machined from the Gleeble treated specimens. The Charpy specimens were broken at -50°F to establish the lower transition curve shelf impact characteristics of Stroloy 2A. Table 23, appearing in Appendix B, records the specific impact properties for the various Gleeble treated specimens. For convenient interpretation, the minimum foot-pounds energy absorbed at -50°F are plotted using two presentation methods in Figures 4 and 5 presented here.

It was observed (Figure 4 and 5) that in general the impact energy absorbed (notch toughness) significantly decreases with increasing peak temperature for a constant cooling rate. It was also observed that impact energy absorbed (notch toughness) decreases to a lesser degree as the cooling rate decreases when observing a constant peak temperature curve.



Peak Temperature VS. Ft.-Lbs. At Various Cooling Rates
Test Temperature Was -50°F

Figure 4

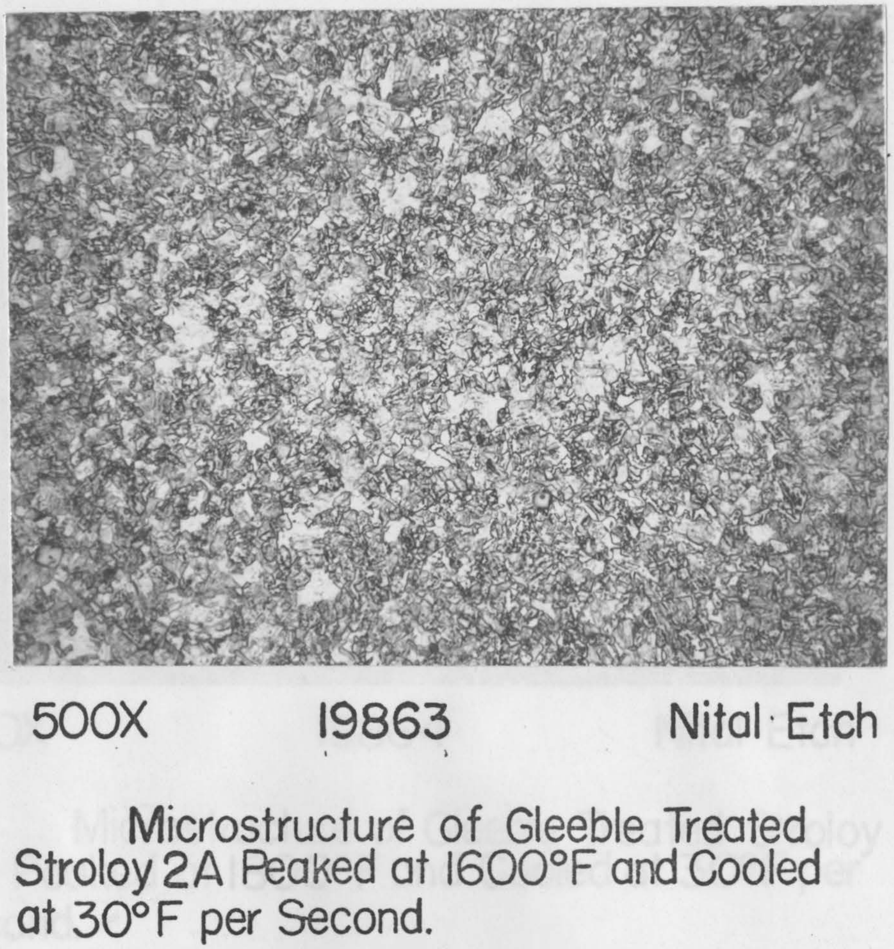


Cooling Rate VS Ft.-Lbs. At -50°F At Various Peak Temperatures

Figure 5

To explain this phenomenon, metallographic studies of a select number of Gleeble treated specimens were conducted. Figures 6 through 10 illustrate nital etched areas of specimens peaked at 1600°F, 1800°F, 2000°F, 2200°F, and 2400°F respectively, all cooled at 30°F per second. A grain coarsening tendency was observed as the peak temperature increased. The microstructures observed at peaked temperatures of 1600°F and 1800°F appear as a combination of fine bainite and martensite. At the higher peak temperatures, a coarsening acicular microstructure consisting of a high percentage of martensite was observed.

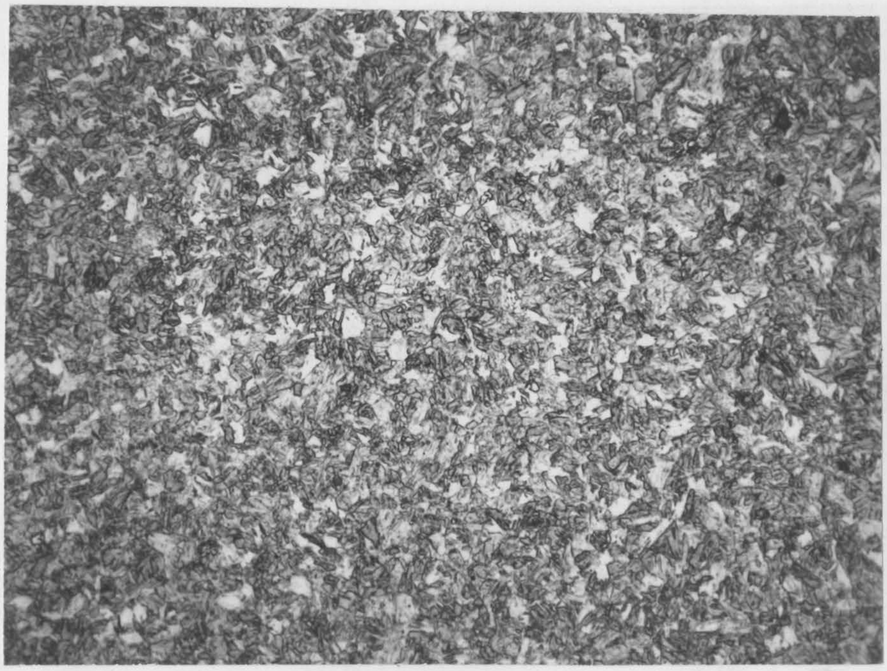
The grain coarsened high percentage martensitic areas would be expected to exhibit low notch toughness. This was observed in the experimental results. Coarse grain microstructures are noted for reduced toughness because of the lesser grain boundary areas to resist fracture propogation. One might further hypothesize that decreased toughness should be observed in specimens peaked at higher temperatures since the percent carbon in saturated solution would be slightly higher than that found in the lower peaked areas, and the martensitic start (M_s) and martensitic finish (M_f) temperatures are



500X 19863 Nital · Etch

Microstructure of Gleeble Treated Stroloy 2A Peaked at 1600°F and Cooled at 30°F per Second.

Figure 6



500X 19864 Nital Etch

Microstructure of Gleeble Treated Stroloy 2A Peaked at 1800°F and Cooled at 30°F per Second.

Figure 7

500X 19865 Nital Etch

Microstructure of Gleeble Treated Stroloy 2A Peaked at 2000°F and Cooled at 30°F per Second.

Figure 8

500X 19866 Nital Etch

Microstructure of Gleeble Treated Stroloy 2A Peaked at 2200°F and Cooled at 30°F per Second.

Figure 9

500X 19867 Nital Etch

Microstructure of Gleeble Treated Stroloy 2A Peaked at 2400°F and Cooled at 30°F per Second.

Figure 10

lower for steels with higher carbon in solution.[1] Thus, the lower peaked specimens with theoretically higher M_s and M_f temperatures would receive extensive autotempering. The higher peaked specimens with lower M_s and M_f temperatures would receive less autotempering during cooling to room temperature. Autotempering or self tempering during cooling to room temperature, of course, relates to the removal of carbon from solid solution by a carbide precipitation reaction within the martensitic plates. Autotempered low carbon martensites would be expected to exhibit greater impact toughness because of reductions in the strain fields surrounding the carbon atoms which are in interstitial site in the untempered martensite lattice.

A general trend of lower notch toughness with decreased cooling rates was also observed for the fine grain low-peaked microstructures as well as the coarse grain high-peaked microstructures. This can be explained on the basis of a mixed microstructure martensite and some bainite existing in the slower cooled specimens. This nonhomogeneous structure could be expected to exhibit slightly lower impact toughness as compared to a homogeneous

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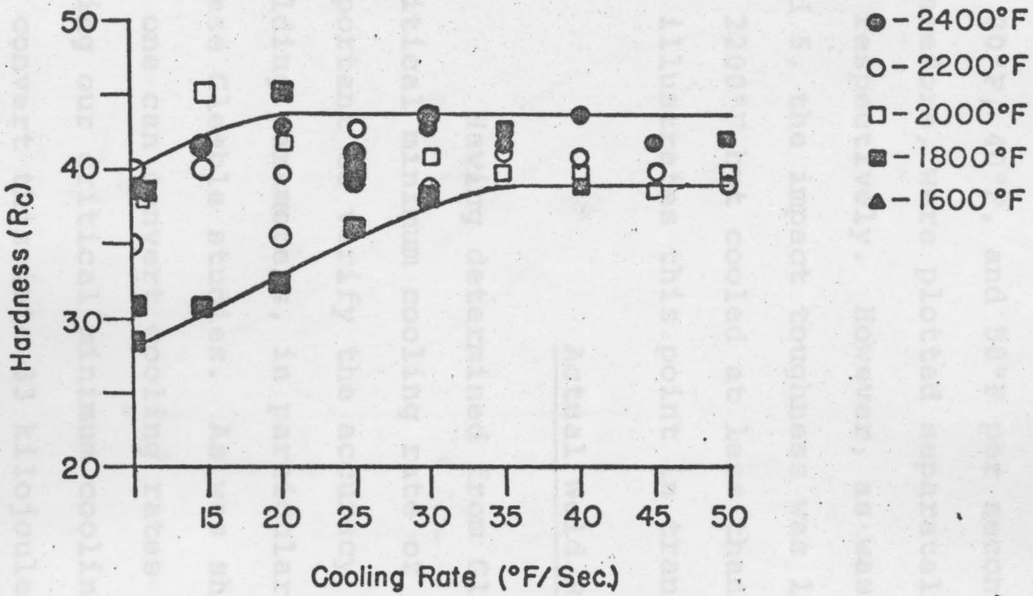
[1]K. J. Iwine, F. B. Pickering, and J. Garstone, "The Effect of Composition On The Structure and Properties of Martensite," Journal of the Iron and Steel Institute, Vol. 196 (September 1960).

martensitic structure present in the rapidly cooled specimens.

Hardness tests on Gleeble treated specimens suggest a lowering of hardness in specimens cooled at slower cooling rates. Figure 11 illustrates this occurrence as a general hardness band. This would be consistent with our analysis that a mixed microstructure exists in slower cooled specimens.

Referring again to Figures 4 and 5, we observe that the specimens peaked at 2200°F and 2400°F had the lowest notch impact toughness. The degree of low impact toughness was further related to the cooling rate. An empirically chosen minimum impact value of 6 foot-pounds energy absorbed, requires a minimum cooling of 30°F per second in our simulated weld heat-affected zone. This will be referred to as our critical cooling rate. As previously observed, the attainment of this minimum impact toughness is dependent upon appropriately rapid cooling to permit the formation of a microstructure essential to achieving the desired toughness.

Having chosen a minimum cooling rate of 30°F per second based upon impact toughness at -50°F, a further limited study of transition curve behavior was conducted. Table 24, appearing in Appendix B, records the specific notch impact properties of the various Gleeble treated specimens which were peaked at 2200°F and control cooled



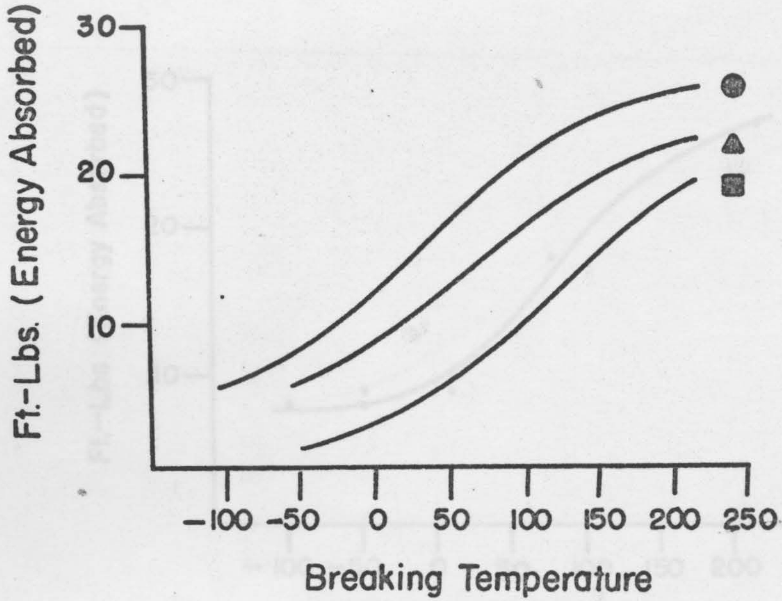
Hardness at Center of Heat Affected Zone of Gleeble Treated Specimens Peaked at Various Temperatures and Cooled at Various Cooling Rates.

Figure 11

at 10°F, 20°F, 30°F, 40°F, and 50°F per second respectively. For convenient interpretation, the minimum foot-pounds energies absorbed at each test temperature are plotted in transition curve form in Figures 12, 13, and 14. The transition curves for specimens peaked at 2200°F and cooled at 30°F, 40°F, and 50°F per second were similar and, therefore, were plotted separately in Figures 12, 13, and 14 respectively. However, as was observed in Figures 4 and 5, the impact toughness was lower for specimens peaked at 2200°F but cooled at less than 30°F per second. Figure 12 illustrates this point in transition curve form.

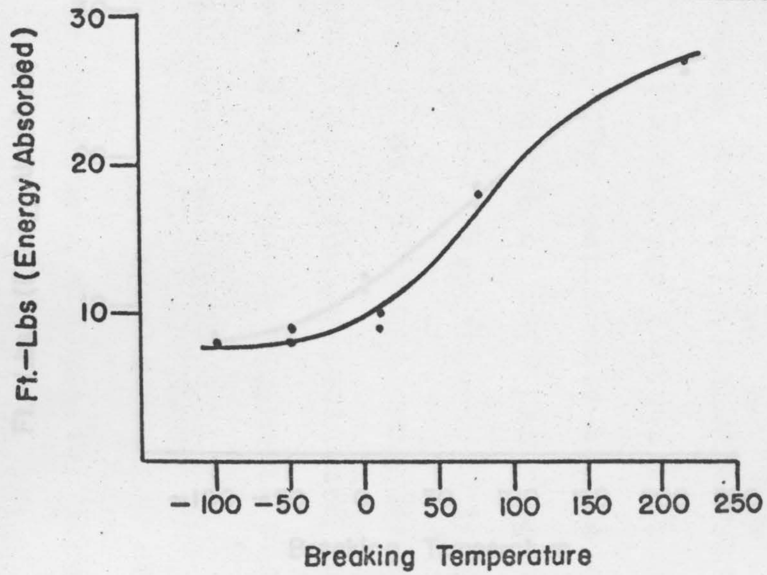
Actual Weld Results

Having determined from Gleeble studies the critical minimum cooling rate of 30°F per second, it was important to verify the accuracy of predicting suitable welding parameters, in particular heat input values, from these Gleeble studies. As was shown in Chapter III, Table 2, one can convert cooling rates into heat input terms. Using our critical minimum cooling rate of 30°F per second, we convert this into 33 kilojoules per inch in 3/8 inch plate, 42.6 kilojoules per inch in 1/2 inch plate, and 63.9 kilojoules per inch in 3/4 inch plate. These values then represent the maximum heat input allowable to maintain a minimum cooling rate of 30°F per second.



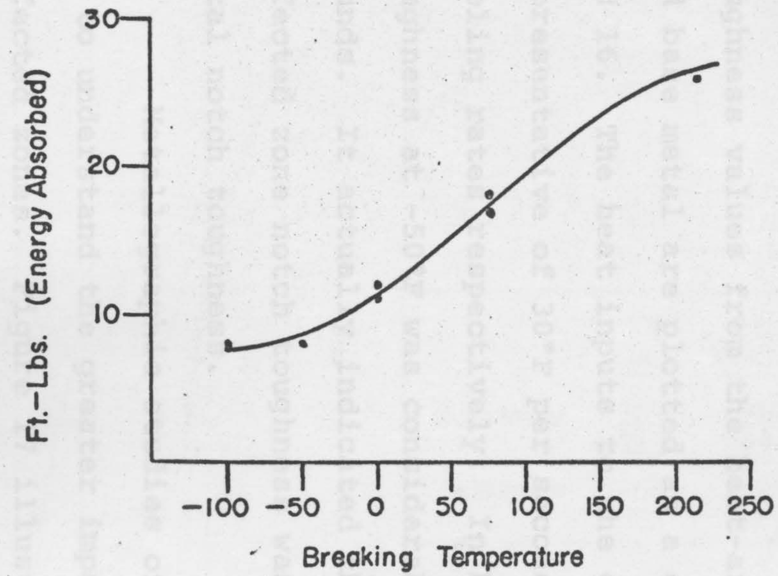
Impact Transition Curves for Stroloy 2A Simulated Weld (Gleeble) Tested at 2200°F Peak Temperature with 30°F/Sec.(●),20°F/Sec. (▲) and 10°F/Sec.(■) Cooling Rate

Figure 12



Impact Transition Curve for Stroloy 2A Simulated Weld (Gleeble) Tested at 2200°F Peak Temperature and 40°F/Second Coolinç Rate

Figure 13



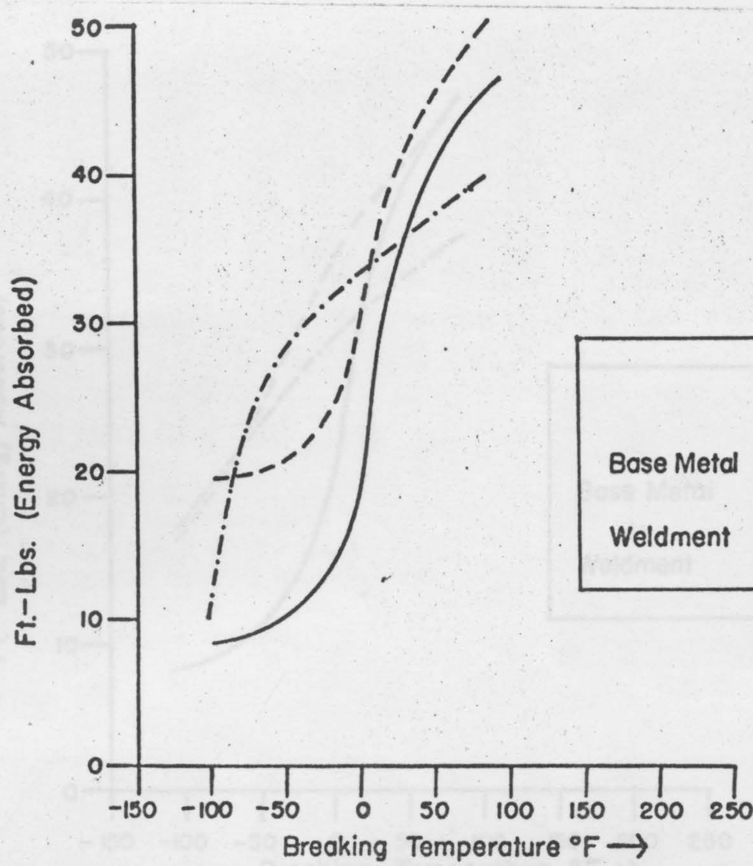
Impact Transition Curve for Stroloy 2A Simulated Weld (Gleeble) Tested at 2200°F Peak Temperature and 50°F/ Second Cooling Rate

Figure 14

Actual welds, as summarized in Chapter III Table 20, were prepared and tested. If our Gleeble studies are valid, the notch impact toughness in the heat-affected zone of each weld should be greater than 6 foot-pounds at -50°F.

Considering the welds made on 3/8 inch plates, weld codes M and N, the actual impact and tensile results are recorded in Tables 25 and 26 appearing in Appendix B. For easy interpretation, the impact transition curve toughness values from the heat-affected zone, weld center, and base metal are plotted as a composite in Figures 15 and 16. The heat inputs to the code M and N welds were representative of 30°F per second and 50°F per second cooling rates respectively. In both cases, the impact toughness at -50°F was considerably greater than 6 foot-pounds. It actually indicated that the measured heat-affected zone notch toughness was greater than the base metal notch toughness.

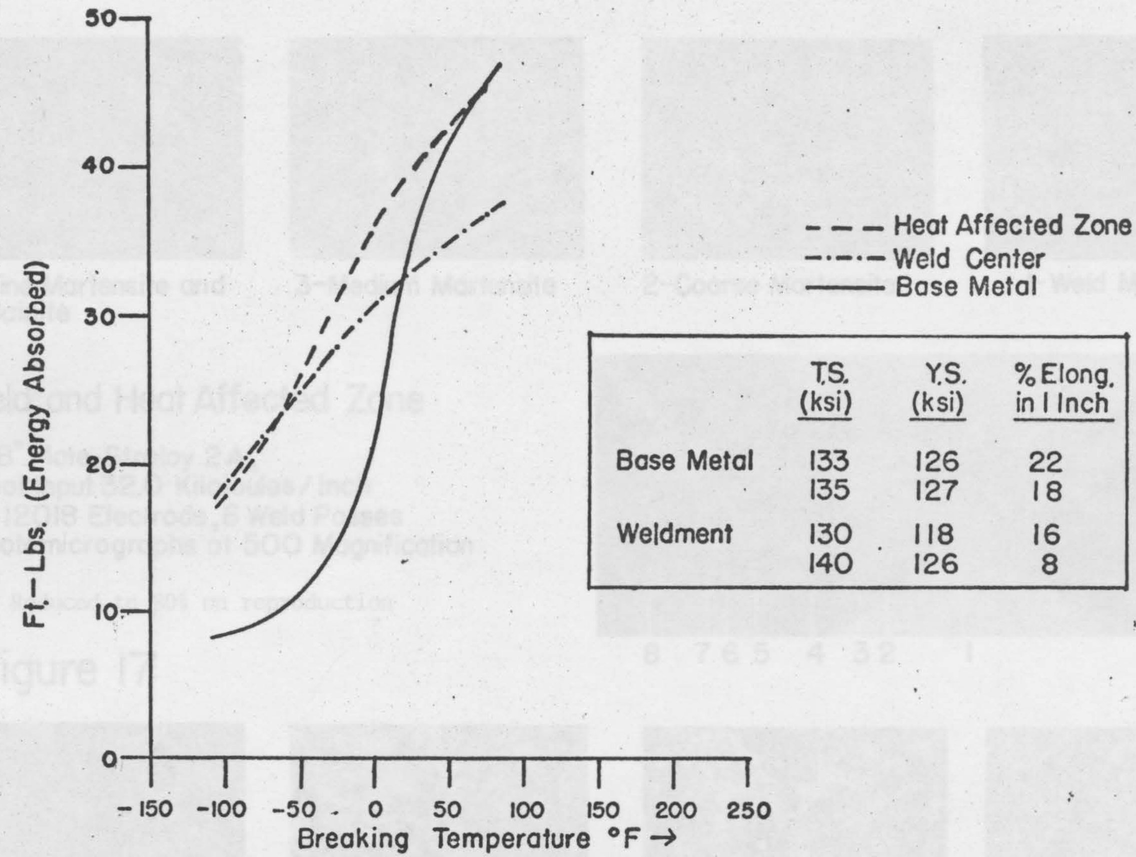
Metallographic studies of weld code M were conducted to understand the greater impact toughness of the heat-affected zones. Figure 17 illustrates in photomicrograph form the results of this study. The enlarged macrograph of the weld cross section illustrates the multiple heat-affected zone effects of six weld passes. High magnification photomicrographs of areas through the weld and heat-affected zone are illustrated separately. A multiplicity of microstructurally different areas was observed. A



	T.S. (ksi)	Y.S. (ksi)	% Elong. in 1 Inch
Base Metal	133	126	22
	135	127	18
Weldment	135	122	15
	133	117	14

Impact Transition Curves from Base Metal, Weld Center, Heat Affected Zone of 3/8" Welded Stroloy 2A Plate (Code M)
Heat Input 32 Kilojoules Per Inch (30° F Per Second Cooling Rate)
1/8" Diameter E-12018 Electrode

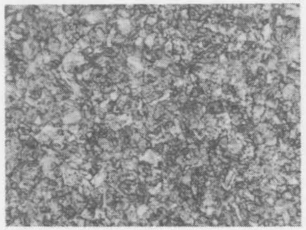
Figure 15



	T.S. (ksi)	Y.S. (ksi)	% Elong. in 1 Inch
Base Metal	133	126	22
	135	127	18
Weldment	130	118	16
	140	126	8

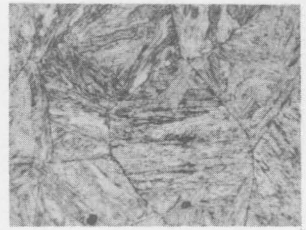
Impact Transition Curves from Base Metal, Weld Center, Heat Affected Zone of 3/8" Welded Stroloy 2A Plate (Code N)
Heat Input 24.8 Kilojoules Per Inch (50° F Per Second Cooling Rate)
1/8" Diameter E-12018 Electrode

Figure 16

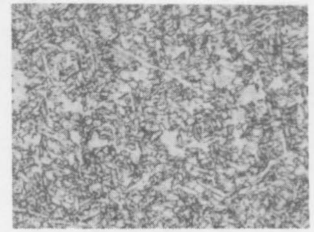


4-Fine Martensite and Bainite

3-Medium Martensite



2-Coarse Martensite



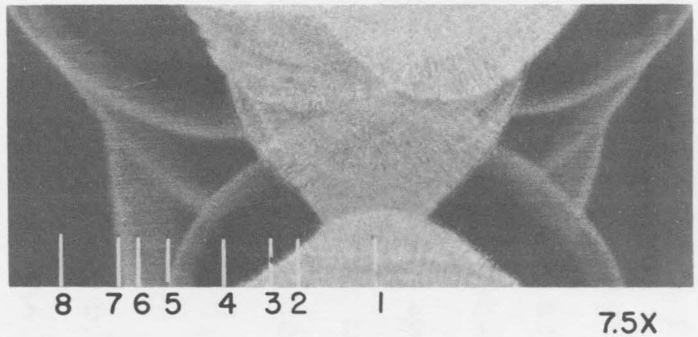
1-Weld Metal

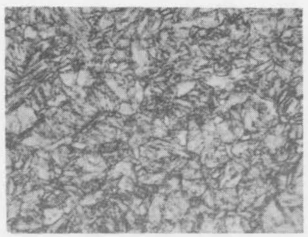
Weld and Heat Affected Zone

3/8" Plate, Stroloy 2A,
Heat Input 32.0 Kilojoules/Inch
E-12018 Electrode, 6 Weld Passes
Photomicrographs at 500 Magnification

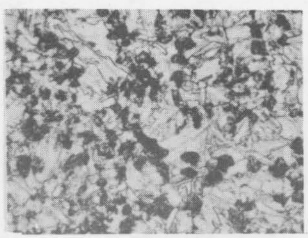
Reduced to 80% on reproduction

Figure 17

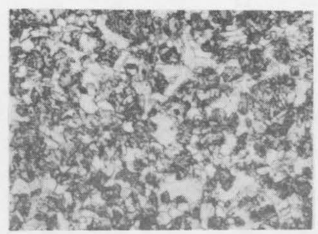




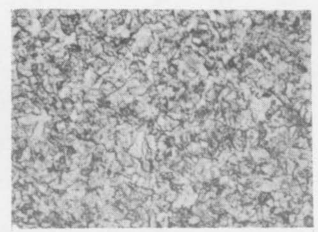
8-Base Metal Tempered Martensite



7-Incipient Bainite in Tempered Martensite



6-Bainite and Tempered Martensite

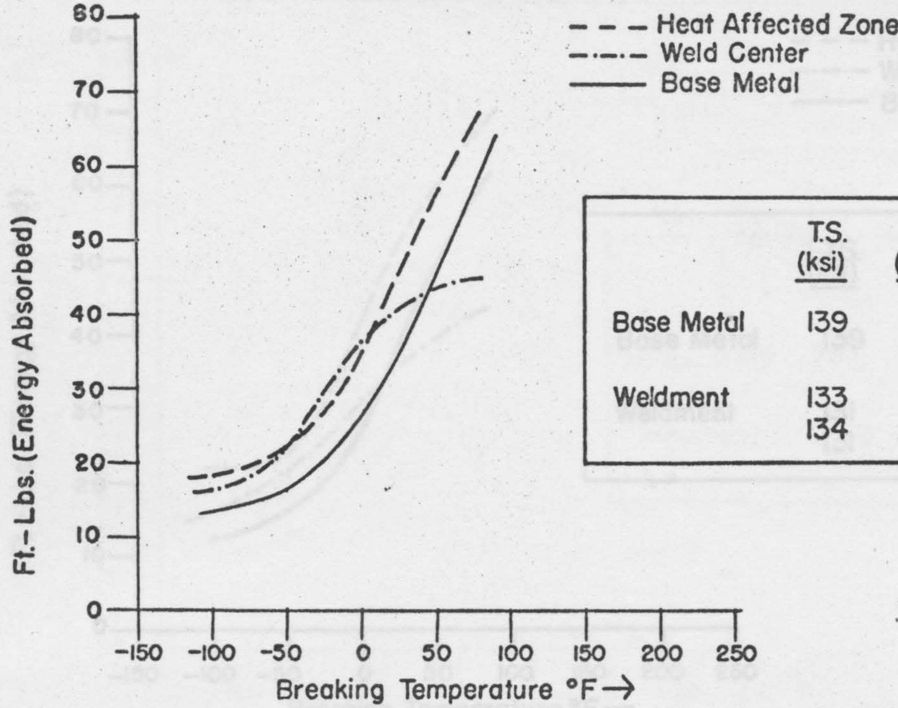


5-Fine Martensite and Bainite

comparison of area labeled 2 in Figure 17 with that of Figure 10 representing a Gleeble specimen peaked at 2400°F, suggest similar microstructural characteristics. A similar comparison can be made of area 3 in Figure 17 with that of Figure 8 representing a Gleeble specimen peaked at 2000°F. The same holds true when comparing area 4 with Figure 6 representing a Gleeble specimen peaked at 1800°F. Therefore, this study does confirm that appropriately treated Gleeble specimens do subject larger masses of metal to thermal conditions which simulate microstructurally an actual point in a weld heat-affected zone.

The heat-affected zone notch impact toughness was measured as greater than the worst condition in the simulated Gleeble heat-affected zone. This is easily understood considering that the energy value obtained in the Charpy V-notch test of the heat-affected zone constitutes an integration of the toughness of various structures across the heat-affected zone.

Mechanical tests on 1/2 inch plates, weld codes F, G, H and I, also confirmed that heat-affected zone notch impact toughness at -50°F was greater than 6 foot-pounds. In all such welds the heat input was such as to have a cooling rate greater than 30°F per second. Figures 18 through 21 illustrate graphically the mechanical properties of the weld, heat-affected zone and base metal. Tables 27

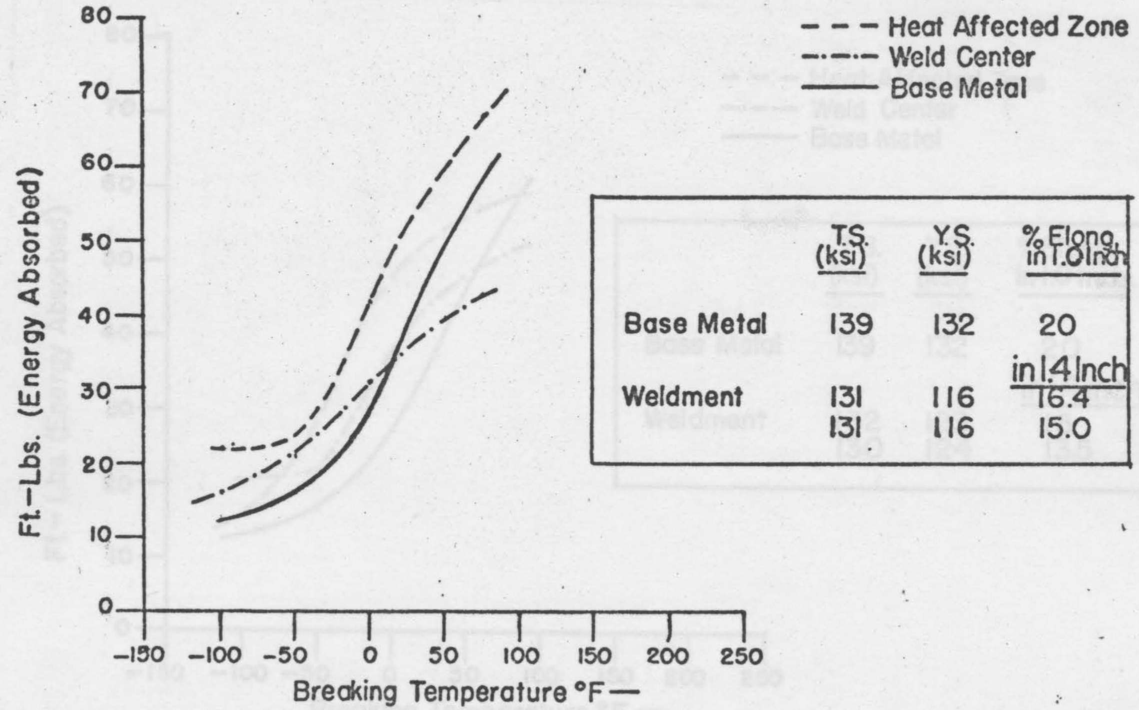


	T.S. (ksi)	Y.S. (ksi)	%Elong in 1.0 Inch
Base Metal	139	132	20
			in 1.4 Inch
Weldment	133	120	15.7
	134	118	17.1

Impact Transition Curves from Base Metal, Weld Center, Heat Affected Zone of 1/2" Welded Stroloy 2A Plate (Code F)

Heat Input 35.5 Kilojoules Per Inch (43.2 °F Per Second Cooling Rate)
1/8" Diameter E-12018 Electrode

Figure 18

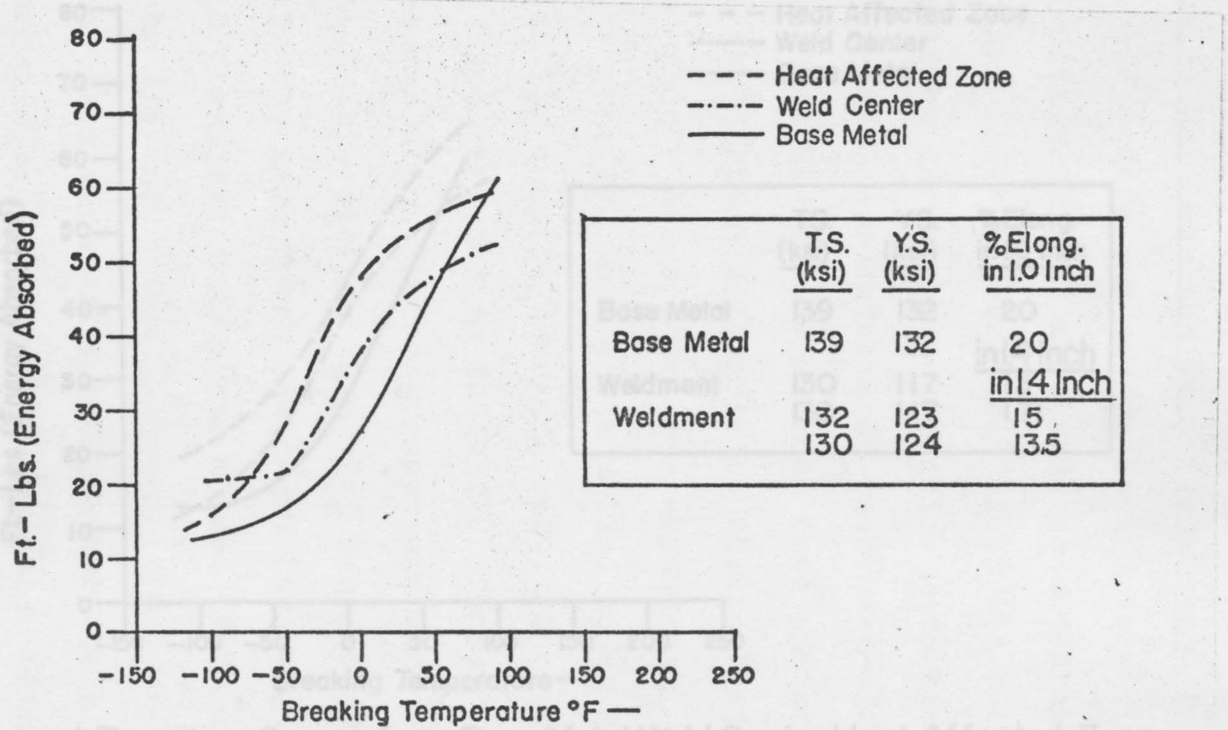


	T.S. (ksi)	Y.S. (ksi)	% Elong, in 1.0 Inch
Base Metal	139	132	20
			in 1.4 Inch
Weldment	131	116	16.4
	131	116	15.0

Impact Transition Curves from Base Metal, Weld Center, Heat Affected Zone of 1/2" Welded Straloy 2A Plate (Code G)

Heat Input 36.2 Kilojoules Per Inch (41.6°F Per Second Cooling Rate)
1/8" Diameter E-11018 Electrode

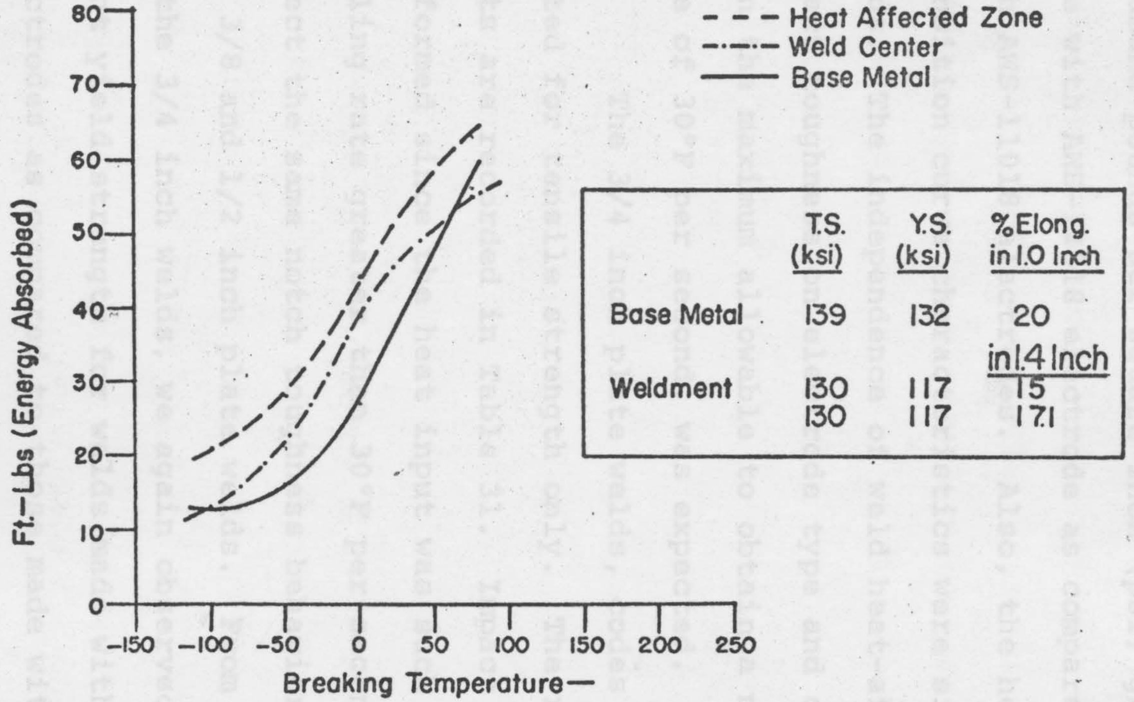
Figure 19



	T.S. (ksi)	Y.S. (ksi)	%Elong. in 1.0 Inch
Base Metal	139	132	20
			in 1.4 Inch
Weldment	132	123	15
	130	124	13.5

Impact Transition Curves from Base Metal, Weld Center, Heat Affected Zone of 1/2" Welded Stroloy Plate (Code H)
Heat Input 30.8 Kilojoules Per Inch (57.4°F Per Second Cooling Rate)
1/8" Diameter E-12018 Electrode

Figure 20



	T.S. (ksi)	Y.S. (ksi)	%Elong. in 1.0 Inch
Base Metal	139	132	20
			in 1.4 Inch
Weldment	130	117	15
	130	117	17.1

Impact Transition Curves from Base Metal, Weld Center, Heat Affected Zone of 1/2" Welded Stroloy 2A Plate (Code 1)
Heat Input 31.2 Kilojoules Per Inch (55.3°F Per Second Cooling Rate)
1/8" Diameter E-11018 Electrode

Figure 21

through 30, appearing in Appendix B, record the actual impact and tensile results.

One interesting fact in the 1/2 inch plate series of welds was that the weld joint yield strength was several thousand pounds per square inch (psi) greater for the welds made with AWS-12018 electrode as compared to those made with AWS-11018 electrodes. Also, the heat-affected zone transition curve characteristics were similar for all welds. The independence of weld heat-affected zone impact toughness on electrode type and on heat input, less than the maximum allowable to obtain a minimum cooling rate of 30°F per second, was expected.

The 3/4 inch plate welds, codes A and B, were tested for tensile strength only. The results of these tests are recorded in Table 31. Impact tests were not performed since the heat input was such as to have a cooling rate greater than 30°F per second, and we would expect the same notch toughness behavior as observed in the 3/8 and 1/2 inch plate welds. From the tensile results of the 3/4 inch welds, we again observed a slightly higher joint yield strength for welds made with AWS-12018 electrodes as compared to those made with AWS-11018 electrodes.

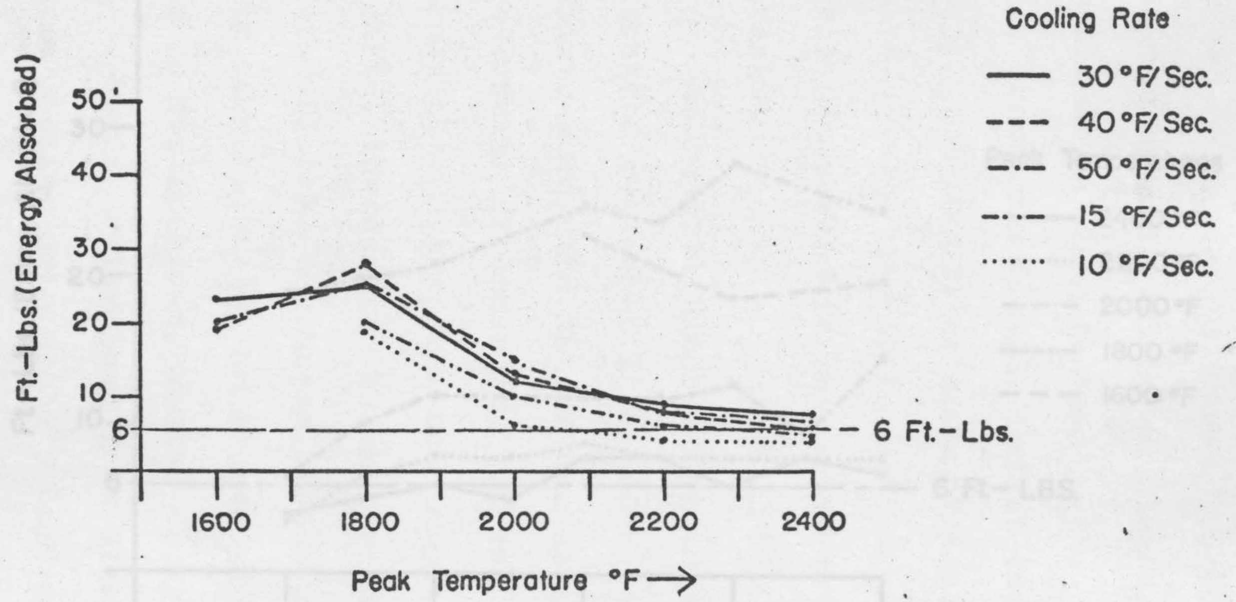
Therefore, this study directly results in a correlation between the ideal Gleeble conditions with those of actual industrial welding practice with concurrent evaluation and understanding of physical and mechanical properties under various experimental conditions. The results indicate significant trends in physical and mechanical properties in the various areas of a weld heat-affected zone. These have been explained on the basis of metallurgical changes under welding conditions.

CHAPTER V

SUMMARY

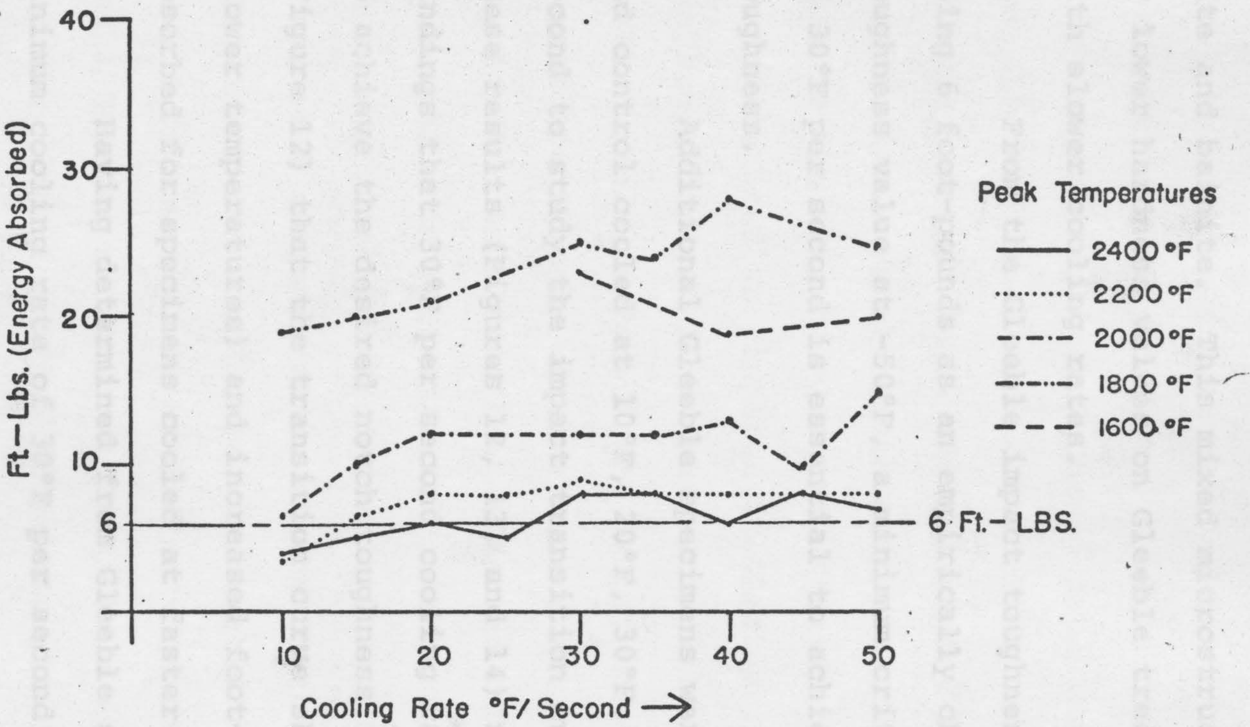
Gleeble heat-treated specimens of quenched and tempered Stroloy 2A, a low-alloy steel, were Charpy V-notch impact tested to determine the fundamental notch toughness characteristics of a simulated weld heat-affected zone. The Gleeble heat-treatments consisted of resistance heating specimens to peak temperatures including 1600°F, 1800°F, 2000°F, 2200°F, and 2400°F followed by control cooling at rates of 10°F, 20°F, 30°F, 40°F, and 50°F per second.

Figures 4 and 5, represented here, illustrate the notch impact toughness characteristics observed in the simulated weld heat-affected zones of Stroloy 2A. A degradation of impact toughness as peak temperature increases was characteristic of this grade. The grain coarsening at higher peak temperatures and less autotempering after martensitic transformation on cooling the higher peaked specimens explains the lower notch impact toughness. Metallographic studies of specimens peaked at various temperature indicate grain coarsening of various degrees.



Peak Temperature VS Ft.-Lbs. At Various Cooling Rates
Test Temperature Was -50 °F

FIGURE 4



Cooling Rate VS Ft.-Lbs. At -50°F At Various Peak Temperatures

FIGURE 5

A less drastic decrease in notch impact toughness observed in slower cooled specimens at a constant peak temperature is due to a mixed microstructure of martensite and bainite. This mixed microstructure is suggested by lower hardness values on Gleeble treated specimens with slower cooling rates.

From the Gleeble impact toughness studies and using 6 foot-pounds as an empirically chosen minimum notch toughness value at -50°F, a minimum critical cooling rate of 30°F per second is essential to achieve the desired toughness.

Additional Gleeble specimens were peaked at 2200°F and control cooled at 10°F, 20°F, 30°F, 40°F, and 50°F per second to study the impact transition curve characteristics. These results (Figures 12, 13, and 14) support our initial findings that 30°F per second cooling rate is essential to achieve the desired notch toughness. It was observed (Figure 12) that the transition curve shifted to the left (lower temperatures) and increased foot-pounds were absorbed for specimens cooled at faster cooling rates.

Having determined from Gleeble studies a critical minimum cooling rate of 30°F per second, it was important to determine the accuracy of predicting suitable welding parameters, in particular heat input values, from these Gleeble studies. Actual welds in 3/8 inch, 1/2 inch, and 3/4 inch plates were made and mechanically tested. These welds were made using welding conditions from heat input considerations which would give calculated cooling rates greater than 30°F per second. Wattmeter recordings were used to determine the actual average heat inputs to each weld. These heat inputs were converted to cooling rates as discussed in Appendix B.

Notch impact toughness values in actual weld heat-affected zones were considerably higher than the minimums observed in Gleeble simulated heat-affected zone studies. Metallographic studies illustrated that areas of the actual weld heat-affected zone had similar microstructures as compared to Gleeble specimens. Thus this study does confirm that appropriately treated Gleeble specimens do subject larger masses of metal to thermal conditions, which simulate microstructurally an actual point in a weld heat-affected zone. However, in the actual weld heat-affected zone notch toughness test, the energy value obtained from a Charpy V-notch specimen constituted an integration of the toughness of various microstructures across the weld heat-affected zone.

In summary, it is indicated from these results that a Gleeble machine can simulate a weld heat-affected zone. By impact testing these Gleeble treated specimens, the minimum notch impact toughness characteristics can be determined. Using an empirically chosen minimum foot-pounds energy absorbed, one can determine a critical minimum cooling rate essential to achieve the desired notch toughness. From the critical cooling rate, appropriate calculations can be preformed to determine a maximum heat input to an actual weld to achieve the desired toughness. With Stroloy 2A, a critical cooling rate of 30°F per second was required to attain 6 foot-pounds at -50°F. When welded with heat input conditions which allow for a cooling rate of 30°F per second or faster, actual weld heat-affected zones in Stroloy 2A had notch toughness much greater than 6 foot-pounds at -50°F because of the integration of toughness of various structures across the weld heat-affected zone.

APPENDIX A

Heat Input Calculations From Cooling Rates

Dimensional heat flow theory can be used to predict cooling rates of welds from a knowledge of arc heat input, plate thickness, thermal conductivity, density, and specific heat. The subject of cooling rates in fusion welding thin plates was discussed by Adams.[2] The following two dimensional heat flow equation applies to a source of heat moving in a straight line (example stringer bead welding) at a constant speed:

$$\frac{dT}{d\theta} = 2\pi K \rho Cp \left(\frac{Vt}{q}\right)^2 (T - To)^3 \qquad (1)$$

where

$dT/d\theta$ = cooling rate on the center line of the weld behind the moving heat source, °F/hr,

K = thermal conductivity of metal, Btu/ft, hr, °F,

V = arc travel speed, ft/hr,

q = arc power, Btu/hr,

T_o = initial temperature of plate, °F,

T = temperature at which cooling rate is to be determined, °F,

ρ = density of the metal, lb/ft^3,

Cp = specific heat of the metal, Btu/lb, °F,

t = plate thickness, ft.

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[2] Clyde M. Adams Jr., "Cooling Rates and Peak Temperatures in Fusion Welding," The Welding Journal, 37(5), Research Supplement, 213-s (1958).

APPENDIX A

Classical heat flow theory can be used to predict cooling rates of welds from a knowledge of arc heat input, plate thickness, thermal conductivity, density, and specific heat. The subject of cooling rates in fusion welding thin plates was discussed by Adams.[2] The following two dimensional heat flow equation applies to a source of heat moving in a straight line (example stringer bead welding) at a constant speed:

$$\frac{dT}{d\Theta} = 2\pi K \rho Cp \left(\frac{Vt^2}{q}\right)^2 (T - To)^3 \qquad (1)$$

where

$dT/d\Theta$ = cooling rate on the center line of the weld behind the moving heat source, °F/hr,

K = thermal conductivity of metal, Btu/ft, hr, °F,

V = arc travel speed, ft/hr,

q = arc power, Btu/hr,

T_o = initial temperature of plate, °F,

T = temperature at which cooling rate is to be determined, °F,

ρ = density of the metal, lb/ft^3,

Cp = specific heat of the metal, Btu/lb, °F,

t = plate thickness, ft.

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[2]Clyde M. Adams Jr., "Cooling Rates and Peak Temperatures in Fusion Welding," The Welding Journal, 37(5), Research Supplement, 213-s (1958).

APPENDIX A (CONT.)

In our study, we have known cooling rates in °F per second from which we want to calculate heat input in kilojoules per inch of weld. Thus by putting equation 1 into a modified form, we have equation 2 which is easier to use:

$$\frac{dT}{d\theta} = \frac{Ct^2}{H^2} \qquad (2)$$

where H = kilojoules per inch heat input

t = plate thickness, inches,

$$C = \frac{2\pi K \rho Cp (T-T_o)^3}{Z^2}$$

In calculating a constant value for C, the following reference values were used:

K = 20 Btu/hr, ft, °F

ρ = 480 lb/ft^3

Cp = .15 Btu/lb, OF

T_o = 75°F

T = 1000°F

Z = 70 percent

The efficiency factor of 70 percent referring to the available arc heat, which actually enters the plate, was chosen to be typical of shielded metal-arc welding. Krantz and Coppolecchia recently calculated an efficiency

APPENDIX A (CONT.)

factor of 74 percent.[3] Cooling rates were determined at 1000°F since this temperature is of metallurgical interest for the Stroloy 2A alloy system. Since no preheat was applied, the initial plate temperature was 75°F.

Using appropriate conversion factors, C was calculated as equal to 218000 kilojoules ^{2}/second/inch^4/°F. Thus equation 2 becomes:

$$\frac{dT}{d\theta} = \frac{218000\ t^2}{H^2} \quad (3)$$

where T = plate thickness, inches

H = heat input, kilojoules per inch, and

$\frac{dt}{d\theta}$ = cooling rate, °F per second.

See Table 2 in Chapter III for various cooling rates versus heat input for various plate thicknesses calculated from equation 3.

In actual welding, the heat or energy input to the weld is controlled by variations in welding voltage, welding current, and weld travel speed as given by the following formula:

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[3]Boris M. Krantz and Vincent D. Coppolecchia, "The Effect of Covered Electrode Welding Variables On Weld Metal Cooling Rates," The Welding Journal, 37(3), Research Supplement, 120-s (1972).

APPENDIX A (CONT.)

$$E = \frac{60\ VI}{S} \qquad (4)$$

where V = welding voltage, volts,

I = welding current, amperes

S = travel speed of arc, inches per minute,

60 = constant of proportionality, and,

E = total energy input to weld, joules per inch of weld.

When one has a known heat input limitation (H), one must manipulate the factors in equation 4 such that energy input (E) equals heat input (H). If done properly, the weld cooling rate can be controlled.

APPENDIX B

Data Tables

TABLE 4

WELDING CONDITIONS PER WELD PASS FOR WELD M-1

3/8 inch plate, 30° bevel, 1/16 inch root opening, 1/8 inch Atom Arc 12018 electrode, stringer bead

Weld Pass No.	Wattmeter Average Kilojoules per Inch	Average Voltage	Average Amperage	Time (sec)	Length (inch)
1	35.60	21	105	81	5
2	-	-	-	-	-
3	30.77	21	105	71	5
4	30.06	21	105	69	5
5	29.40	21	105	67.5	5
6	29.32	21	105	68	5
Average	31.03	21	105	71.3	5

TABLE 5

WELDING CONDITIONS PER WELD PASS FOR WELD M-2

3/8 inch plate, 30° bevel, 1/16 inch root opening, 1/8 inch Atom Arc 12018 electrode, stringer bead

Weld Pass No.	Wattmeter Average Kilojoules per Inch	Average Voltage	Average Amperage	Time (sec)	Length (inch)
1	31.46	23	105	65	5
2	30.98	22	110	64	5
3	33.88	23	108	70	5
4	34.85	22	108	72	5
5	34.53	22	107	73	5
6	30.74	23	106	65	5
Average	32.74	22.5	107	68.2	5

TABLE 6

WELDING CONDITIONS PER WELD PASS FOR WELD N-1

3/8 inch plate, 30° bevel, 1/16 inch root opening, 1/8 inch Atom Arc 12018 electrode, stringer bead

Weld Pass No.	Wattmeter Average Kilojoules per Inch	Average Voltage	Average Amperage	Time (sec)	Length (inch)
1	25.08	22	108	53	5
2	24.02	22	110	52	5
3	25.41	23	105	55	5
4	22.00	21	110	50	5
5	22.88	22	105	52	5
6	23.76	22	108	54	5
7	22.88	22	108	52	5
8	22.55	22	108	50	5
9	24.80	22	108	55	5
10	23.32	22	106	53	5
Average	23.67	19.8	107.6	52.6	5

TABLE 7

WELDING CONDITIONS PER WELD PASS FOR WELD N-2

3/8 inch plate, 30° bevel, 1/16 inch root opening, 1/8 inch Atom Arc 12018 electrode, stringer bead

Weld Pass No.	Wattmeter Average Kilojoules per Inch	Average Voltage	Average Amperage	Time (sec)	Length (inch)
1	24.02	23	105	52	5
2	23.90	22	110	53	5
3	22.17	22	110	48	5
4	23.76	22	110	54	5
5	22.44	21	110	51	5
6	23.45	21	111	52	5
7	24.48	22	110	53	5
8	20.29	22	110	45	5
9	23.56	22	112	51	5
10	23.17	22	112	49	5
Average	23.12	21.9	110	50.8	5

TABLE 8

WELDING CONDITIONS PER WELD PASS FOR WELD F-1

1/2 inch plate, 30° bevel, 1/16 inch root opening, 1/8 inch Atom Arc 12018 electrode, stringer bead

Weld Pass No.	Wattmeter Average Kilojoules per Inch	Average Voltage	Average Amperage	Time (sec)	Length (inch)
1	37.90	22	103	84	4.875
2	33.84	23	105	75	4.875
3	36.1	22	107	80	4.875
4	35.65	22	106	79	4.875
5	36.43	22	106	83	4.875
6	35.54	22	106	81	4.875
7	32.04	21	106	73	4.875
8	35.20	21	108	78	4.875
9	37.00	21	105	82	4.875
Average	35.52	21.8	105.8	79.4	4.875

TABLE 9

WELDING CONDITIONS PER WELD PASS FOR WELD F-2

1/2 inch plate, 30° bevel, 1/16 inch root opening, 1/8 inch Atom Arc 12018 electrode, stringer bead

Weld Pass No.	Wattmeter Average Kilojoules per Inch	Average Voltage	Average Amperage	Time (sec)	Length (inch)
1	38.81	21	105	86	4.875
2	33.85	22	105	75	4.875
3	38.36	22	105	85	4.875
4	36.10	21	107	80	4.875
5	37.46	21	105	83	4.875
6	33.85	21	106	75	4.875
7	34.24	22	106	78	4.875
8	33.39	22	107	74	4.875
9	32.94	22	106	73	4.875
Average	35.44	21.6	105.8	78.8	4.875

TABLE 10

WELDING CONDITIONS PER WELD PASS FOR WELD G-1

1/2 inch plate, 30° bevel, 1/16 inch root opening,
1/8 inch P&H 107 electrode, stringer bead

Weld Pass No.	Wattmeter Average Kilojoules per Inch	Average Voltage	Average Amperage	Time (sec)	Length (inch)
1	40.71	23	105	82	4.875
2	35.54	22	108	75	4.875
3	38.22	22	105	77	4.875
4	38.31	21	107	83	4.875
5	36.00	22	108	78	4.875
6	35.54	21	110	77	4.875
7	36.01	21	110	76	4.875
8	33.85	21	109	75	4.875
9	32.04	21	109	71	4.875
Average	36.25	21.6	107.9	77.11	4.875

TABLE 11

WELDING CONDITIONS PER WELD PASS FOR WELD G-2

1/2 inch plate, 30° bevel, 1/16 inch root opening, 1/8 inch P&H 107 electrode, stringer bead

Weld Pass No.	Wattmeter Average Kilojoules per Inch	Average Voltage	Average Amperage	Time (sec)	Length (inch)
1	39.22	22	105	79	4.875
2	34.75	21	108	77	4.875
3	36.96	22	106	78	4.875
4	35.54	21	112	75	4.875
5	36.10	21	110	80	4.875
6	34.75	21	109	77	4.875
7	34.30	21	108	76	4.875
8	33.17	22	110	70	4.875
9	34.12	21	108	72	4.875
Average	35.43	21.3	108.4	76	4.875

TABLE 12

WELDING CONDITIONS PER WELD PASS FOR WELD H-1

1/2 inch plate, 30° bevel, 1/16 inch root opening,
1/8 inch Atom Arc 12018 electrode, stringer bead

Weld Pass No.	Wattmeter Average Kilojoules per Inch	Average Voltage	Average Amperage	Time (sec)	Length (inch)
1	31.42	22	105	68	5
2	30.36	21	107	69	5
3	33.44	21	107	76	5
4	30.80	21	105	70	5
5	30.80	21	107	70	5
6	33.00	21	107	75	5
7	28.00	21	107	67	5
8	30.36	21	108	69	5
9	29.48	21	108	67	5
10	30.36	21	107	69	5
Average	30.80	21	106.8	70	5

TABLE 13

WELDING CONDITIONS PER WELD PASS FOR WELD H-2

1/2 inch plate, 30° bevel, 1/16 inch root opening,
1/8 inch Atom Arc 12018 electrode, stringer bead

Weld Pass No.	Wattmeter Average Kilojoules per Inch	Average Voltage	Average Amperage	Time (sec)	Length (inch)
1	30.80	22	107	70	5
2	28.16	21	104	69	5
3	30.80	21	107	78	5
4	29.26	21	105	70	5
5	29.68	21	105	71	5
6	32.18	21	105	77	5
7	28.84	21	105	69	5
8	29.26	21	107	70	5
9	28.42	21	107	68	5
10	28.42	21	105	68	5
11	25.74	21	105	65	5
Average	29.23	21	105.6	70.5	5

TABLE 14

WELDING CONDITIONS PER WELD PASS FOR WELD I-1

1/2 inch plate, 30° bevel, 1/16 inch root opening,
1/8 inch P&H 107 electrode, stringer bead

Weld Pass No.	Wattmeter Average Kilojoules per Inch	Average Voltage	Average Amperage	Time (sec)	Length (inch)
1	31.42	23	103	68	5
2	29.68	21	105	71	5
3	32.12	22	104	73	5
4	30.52	21	105	73	5
5	28.84	22	100	69	5
6	31.68	23	103	72	5
7	29.68	21	105	71	5
8	25.50	21	105	61	5
9	30.80	22	106	70	5
10	29.48	21	107	67	5
11	30.16	21	105	72	5
12	29.48	21	108	67	5
Average	29.95	21.6	104.7	69.5	5

TABLE 15

WELDING CONDITIONS PER WELD PASS FOR WELD I-2

1/2 inch plate, 30° bevel, 1/16 inch root opening, 1/8 inch P&H 107 electrode, stringer bead

Weld Pass No.	Wattmeter Average Kilojoules per Inch	Average Voltage	Average Amperage	Time (sec)	Length (inch)
1	32.34	25	100	70	5
2	26.76	22	107	64	5
3	33.72	22	105	73	5
4	31.24	21	108	71	5
5	34.66	22	108	75	5
6	31.24	21	107	71	5
7	29.92	21	106	68	5
8	31.42	22	107	68	5
9	31.36	21	110	75	5
10	31.24	21	110	71	5
11	28.60	21	105	65	5
12	31.68	22	105	72	5
Average	31.18	21.8	106.5	70.2	5

TABLE 16

WELDING CONDITIONS PER WELD PASS FOR WELD A-1

3/4 inch plate, 30° bevel, 1/16 inch root opening, 3/16 inch Atom Arc 12018 electrode, stringer bead

Weld Pass No.	Wattmeter Average Kilojoules per Inch	Average Voltage	Average Amperage	Time (sec)	Length (inch)
1	58.00	23	215	59	5
2	46.90	21	220	52	5
3	46.90	21	218	52	5
4	46.90	21	218	52	5
5	50.5	21	220	56	5
6	50.5	21	222	56	5
7	55.1	22	220	56	5
8	56.0	23	220	57	5
9	56.0	22	220	57	5
10	48.7	21	220	54	5
11	54.1	22	220	55	5
Average	51.78	21.6	219.4	55.1	5

TABLE 17

WELDING CONDITIONS PER WELD PASS FOR WELD A-2

3/4 inch plate, 30° bevel, 1/16 inch root opening,
3/16 inch Atom Arc 12018 electrode, stringer bead

Weld Pass No.	Wattmeter Average Kilojoules per Inch	Average Voltage	Average Amperage	Time (sec)	Length (inch)
1	53.10	22	220	54	5
2	54.10	22	220	55	5
3	61.00	22	220	62	5
4	54.10	22	224	55	5
5	58.00	22	224	29	5
6	56.00	21	222	57	5
7	58.00	22	224	59	5
8	49.60	22	220	55	5
9	48.20	22	222	49	5
Average	54.68	22	221.8	56.1	5

TABLE 18

WELDING CONDITIONS PER WELD PASS FOR WELD B-1

3/4 inch plate, 30° bevel, 1/16 inch root opening, 3/16 inch Atom Arc T electrode, stringer bead

Weld Pass No.	Wattmeter Average Kilojoules per Inch	Average Voltage	Average Amperage	Time (sec)	Length (inch)
1	-	-	-	-	5
2	51.40	21	220	57	5
3	61.00	22	220	62	5
4	53.20	22	218	59	5
5	56.00	23	218	57	5
6	52.30	21	220	58	5
7	50.00	21	220	61	5
8	47.80	21	220	53	5
9	50.50	21	220	56	5
10	50.00	23	220	51	5
Average	52.47	21.7	219.5	57.1	5

TABLE 19

WELDING CONDITIONS PER WELD PASS FOR WELD B-2

3/4 inch plate, 30° bevel, 1/16 inch root opening, 3/16 inch Atom Arc T electrode, stringer bead

Weld Pass No.	Wattmeter Average Kilojoules per Inch	Average Voltage	Average Amperage	Time (sec)	Length (inch)
1	54.10	22	215	55	5
2	52.30	21	220	58	5
3	54.10	22	210	60	5
4	55.00	21	210	61	5
5	58.60	21	207	65	5
6	50.00	21	207	61	5
7	53.30	21	205	65	5
8	51.60	22	205	63	5
9	44.20	21	210	54	5
Average	52.58	21.3	209.9	60.2	5

TABLE 23

IMPACT TEST RESULTS AT -50°F OF GLEEBLE TREATED STROLOY 2A

Peak Temperature (°F) Aim	Actual	Cooling Rate (°F/sec)	Ft-Lbs at -50°F	Percent Shear	Laterial Expansion (inch)
1600	1624	30	23	20	.009
1600	1610	30	24	20	.009
1600	1587	40	21	22	.007
1600	1592	40	19	18	.007
1600	1597	50	20	18	.008
1600	1597	50	22	22	.009
1800	1795	10	19	-	.007
1800	1791	10	41	-	.013
1800	1791	15	24	-	.009
1800	1795	15	20	-	.005
1800	1795	20	21	-	.006
1800	1795	20*	21*	-	.010
1800	1791	25*	12*	-	.010
1800	1791	25*	25*	-	.010
1800	1786	30*	19*	-	.005
1800	1782	30*	21*	-	.008
1800	1800	30	37	23	.019
1800	1819	30	25	22	.007
1800	1795	35	26	30	.007
1800	1800	35	24	25	.006
1800	1800	40	28	25	.007
1800	1805	40	46	25	.019
1800	1810	50	54	25	.021

(TABLE 23 CONTINUED)

Peak Temperature (°F) Aim	Peak Temperature (°F) Actual	Cooling Rate (°F/sec)	Ft-Lbs at -50°F	Percent Shear	Laterial Expansion (inch)
1800	1800	50	25	35	.007
2000	2006	10	6.5	-	.002
2000	1997	10	7.5	-	.002
2000	2001	15	10	-	.003
2000	2001	15	10	-	.003
2000	2006	20*	6*	-	.001
2000	2016	20*	10*	-	.002
2000	1987	20	12	10	.003
2000	1992	20	15	15	.004
2000	2006	25	8	-	.003
2000	1997	25	10.5	-	.003
2000	1992	30*	10*	-	.002
2000	1992	30*	12*	-	.003
2000	1987	30	13	10	.002
2000	1987	30	12	10	.002
2000	1992	35	12	10	.003
2000	1997	35	12	10	.002
2000	1987	40	13	10	.003
2000	1992	40	13	10	.002
2000	2011	45	10	5	.001
2000	2006	45	10	5	.001
2000	2001	50	16	15	.004
2000	1987	50	15	15	.003
2200	2174	10	4	0	.001
2200	2186	10	3.5	0	.001
2200	2171	15	6.5	0	.002
2200	2201	15	7	0	.002
2200	2201	20*	6*	0	.001
2200	2176	20*	6*	0	.001

(TABLE 23 CONTINUED)

Peak Temperature (°F) Aim	Actual	Cooling Rate (°F/sec)	Ft-Lbs at -50°F	Percent Shear	Laterial Expansion (inch)
2200	2186	20	8	5	.001
2200	2196	20	10	5	.001
2200	2221	25*	6*	0	.001
2200	2206	25	10	0	.003
2200	2196	25	8	0	.001
2200	2225	25	8	0	.001
2200	2191	30*	6*	-	.001
2200	2191	30*	6*	-	.003
2200	2191	30	9	0	.001
2200	2186	30	9	0	.002
2200	2196	35	8	0	.001
2200	2006	35	11	5	.002
2200	2191	40	8	0	0
2200	2191	40	9	0	.002
2200	2211	45	11	5	.001
2200	2201	45	8	0	.001
2200	2216	50	8	0	.001
2200	2216	50	8	0	.001
2400	2383	10	5	0	.001
2400	2394	10	5	0	.001
2400	2383	10	5	0	.001
2400	2404	10	4	0	.001
2400	2394	15	5	0	.001
2400	2394	15	5	0	.001
2400	2394	20	6	0	.002
2400	2383	20	6	0	.002
2400	2404	20	7	0	.000
2400	2404	20	7	0	.000
2400	2404	25	6	0	.000

(TABLE 23 CONTINUED)

Peak Temperature (°F) Aim	Actual	Cooling Rate (°F/sec)	Ft-Lbs at -50°F	Percent Shear	Laterial Expansion (inch)
2400	2404	25	8	0	.000
2400	2404	25	8	0	.001
2400	2388	25	5	0	.001
2400	2368	25*	6*	0	.002
2400	2378	30*	6*	0	.001
2400	2394	30*	6*	0	.001
2400	2399	30	8	0	.001
2400	2378	30	8	0	.001
2400	2404	35	9	0	.001
2400	2394	35	7	0	.001
2400	2430	40	6	0	.001
2400	2404	40	6	0	.000
2400	2383	45	8	0	.001
2400	2399	45	9	0	.001
2400	2394	50	7	0	.001
2400	2388	50	9	0	.001

* Actual temperature recording graph indicated that a constant cooling rate was not obtained, therefore, the impact results are void.

TABLE 24

IMPACT TRANSITION CURVE RESULTS OF GLEEBLE TREATED STROLOY 2A
PEAKED AT 2200°F AND COOLED AT 10°F, 20°F, 30°F, 40°F, AND 50°F PER SECOND

Peak Temperature Actual	Cooling Rate (°F/second)	Test Temperature (°F)	Ft-Lbs Absorbed	Percent Shear	Laterial Expansion (inch)
2181	10	+212	19	36	.012
2181	10	+ 75	7	21	.004
2181	10	0	4	10	.003
2181	10	- 50	1	5	.000
2191	20	+212	23	58	.012
2185	20	+ 75	15	30	.006
2186	20	0	10	14	.005
2186	20	- 50	7	5	.003
2186	30	212	26	43	.009
2206	30	75	20	22	.007
2196	30	75	48	22	.006
2191	30	0	9	15	.002
2206	30	0	9	15	.005
2186	30	- 50	9	0	.002
2191	30	- 50	9	0	.001
2206	30	-100	6	0	.001

(TABLE 24 CONTINUED)

Peak Temperature Actual	Cooling Rate (°F/second)	Test Temperature (°F)	Ft-Lbs Absorbed	Percent Shear	Laterial Expansion (inch)
2191	40	212	27	43	.011
2206	40	75	18	20	.005
2181	40	75	18	20	.006
2196	40	0	10	5	.002
2211	40	0	9	5	.002
2191	40	- 50	9	0	.002
2191	40	- 50	8	0	.000
2191	40	-100	8	0	.002
2201	50	212	26	43	.010
2196	50	75	17	25	.005
2216	50	75	18	25	.005
2216	50	0	12	10	.002
2201	50	0	11	10	.002
2216	50	- 50	8	0	.001
2216	50	- 50	8	0	.001
2201	50	-100	8	0	.001

TABLE 25

MECHANICAL TEST RESULTS ON 3/8 INCH WELDED PLATE
CODE M

Test Location	Test Temperature (°F)	Ft-Lbs 3/4 Size Specimen	Percent Shear	Lateral Expansion (inch)
HAZ	75	51	100	.034
HAZ	75	50	100	.035
HAZ	0	40	85	.036
HAZ	0	31	55	.029
HAZ	- 50	20	30	.018
HAZ	- 50	22	30	.022
HAZ	-100	20	25	.016
Weld	75	39	100	.014
Weld	0	33	75	.032
Weld	- 50	29	50	.019
Weld	-100	10	35	.009

Tensile Specimen	TS (psi)	YS (psi)	%Elong. in 1"	% Red. Area	Failure Location
M-1	135470	122404	15	59.2	HAZ
M-2	133066	117835	14	63.6	HAZ

TABLE 26

MECHANICAL TEST RESULTS ON 3/8 INCH WELDED PLATE
CODE N

Test Location	Test Temperature (°F)	Ft-Lbs 3/4 Size Specimen	Percent Shear	Lateral Expansion (inch)
HAZ	75	55	100	.056
HAZ	75	45	100	.044
HAZ	0	35	80	.033
HAZ	0	42	80	.047
HAZ	- 50	25	40	.029
HAZ	- 50	27	35	.026
HAZ	-100	18	30	.016
Weld	75	37	100	.038
Weld	0	31	80	.032
Weld	- 50	25	70	.024
Weld	-100	18	50	.017

Tensile Specimen	TS (psi)	YS (psi)	%Elong. in 1"	% Red. Area	Failure Location
N-1	130260	118316	16	66.9	HAZ
N-2	140681	126733	8	28.6	HAZ

TABLE 27

MECHANICAL TEST RESULTS ON 1/2 INCH WELDED PLATE
CODE F

Test Location	Test Temperature (°F)	Ft-Lbs	Percent Shear	Lateral Expansion (inch)
HAZ	75	65	100	.048
HAZ	0	32	43	.021
HAZ	0	42	46	.029
HAZ	- 50	21	25	.013
HAZ	- 50	21	30	.014
HAZ	-100	18	18	.009
HAZ	-150	4	10	.001
Weld	75	45	100	.037
Weld	0	39	65	.027
Weld	- 50	20	22	.013
Weld	-100	16	14	.011

Tensile Specimen	TS (psi)	YS (psi)	%Elong. in 1.4"	% Red. Area	Failure Location
F-1	133366	120479	15.7	55.5	HAZ
F-2	133866	118081	17.1	55.9	Weld

TABLE 28

MECHANICAL TEST RESULTS ON 1/2 INCH WELDED PLATE
CODE G

Test Location	Test Temperature (°F)	Ft-Lbs	Percent Shear	Lateral Expansion (inch)
HAZ	75	69	100	.052
HAZ	75	67	100	.047
HAZ	0	43	54	.033
HAZ	0	42	54	.032
HAZ	- 50	22	30	.017
HAZ	- 50	25	25	.017
HAZ	-100	22	26	.013
HAZ	-150	5	5	.001
Weld	75	43	100	.042
Weld	0	31	60	.026
Weld	- 50	21	25	.016
Weld	-100	16	15	.013

Tensile Specimen	TS (psi)	YS (psi)	%Elong. in 1.4"	% Red. Area	Failure Location
G-1	131368	116283	16.4	58.1	HAZ
G-2	131368	116883	15.0	54.4	Weld

TABLE 29

MECHANICAL TEST RESULTS ON 1/2 INCH WELDED PLATE
CODE H

Test Location	Test Temperature (°F)	Ft-Lbs	Percent Shear	Lateral Expansion (inch)
HAZ	75	60	100	.050
HAZ	75	46	100	.041
HAZ	0	51	76	.035
HAZ	0	48	71	.035
HAZ	- 50	27	40	.018
HAZ	- 50	26	36	.016
HAZ	-100	16	30	.013
HAZ	-150	9	15	.004
Weld	75	51	100	.042
Weld	0	38	59	.028
Weld	- 50	22	36	.017
Weld	-100	21	36	.016

Tensile Specimen	TS (psi)	YS (psi)	%Elong. in 1.4"	% Red. Area	Failure Location
H-1	131868	122877	15.0	58.1	HAZ
H-2	130369	123776	13.5	57.7	HAZ

TABLE 30

MECHANICAL TEST RESULTS ON 1/2 INCH WELDED PLATE
CODE I

Test Location	Test Temperature (°F)	Ft-Lbs	Percent Shear	Lateral Expansion (inch)
HAZ	75	67	100	.055
HAZ	75	63	100	.044
HAZ	0	44	58	.034
HAZ	0	44	56	.037
HAZ	- 50	32	40	.028
HAZ	- 50	28	30	.021
HAZ	-100	21	18	.012
HAZ	-150	9	15	.003
Weld	75	55	100	.043
Weld	0	39	67	.032
Weld	- 50	21	36	.014
Weld	-100	13	15	.007

Tensile Specimen	TS (psi)	YS (psi)	%Elong. in 1.4"	% Red. Area	Failure Location
I-1	130369	116883	15.0	47.4	Weld
I-2	130369	116883	17.1	45.7	HAZ

TABLE 31

TENSILE RESULTS OF 3/4 INCH WELDED PLATE
CODES A AND B

Tensile Specimen	Tensile Strength (psi)	Yield Strength (psi)	Percent Elong. in 1.4"	Percent Red. Area	Failure Location
A-1	122377	104895	16.4	62.0	Weld
A-2	124375	106993	16.4	61.6	Weld
B-1	118881	103396	16.4	63.4	Weld
B-2	119380	105194	13.5	48.9	Weld

BIBLIOGRAPHY

Adams, D. M. Jr. "The Effect of Plate Thickness and Radiation on Heat Flow in Welding and Cutting." The Welding Journal, 37(3), Research Supplement, 215-s (1958).

Irvine, K. J., Pickering, F. B. and Garstone, J. "The Effect of Composition on the Structure and Properties of Martensite." Journal of the Iron and Steel Institute, Vol. 196 (September, 1960), 66 to 81.

Krantz, B. M. and Coppolecchia, V. D. "The Effect of Covered Electrode Welding Variables on Weld Metal Cooling Rates." The Welding Journal, 37(3), Research Supplement, 117-s to 121-3 (1972).