HAZ Thermocycle and Structure Simulation

Combined computer and Gleeble simulation technique permits quick evaluation of weld process alternatives

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ABSTRACT. During the development of an automatic gas metal-arc welding (GMAW) machine, high speed welds were made in steel at 60 ipm. The attendant low heat input created a heat-affected zone (HAZ) having thin, isolated hard zones. In order to utilize high welding speeds, this study was made on ways to eliminate or prevent the HAZ hard zone formation.

The use of preheat, higher heat input, and a postweld heat treatment all could reduce the HAZ hardness; however, for a variety of reasons these methods were undesirable. In-line heat treating, using an auxiliary heat source following the main welding arc, could prevent hard zone formation by altering the continuous cooling curve to obtain low cooling rates that permit diffusion controlled austenite decomposition to occur before subsequent cooling below the M_s. Another related technique, the use of two welding arcs, was considered also. An empirical approach was deemed too costly; therefore, a computer simulation technique was devised. The simulation technique and its rationale are the subject of this paper.

A two dimensional heat flow equation involving the basic welding parameters and material properties was selected for the simulation. A realistic heat input efficiency factor was used to calibrate the equation to the welding machine. Theoretical time-temperature curves were generated simulating the HAZ temperature cycles. Curves were generated that simulated the weld centerline and five additional positions located in the HAZ.

Auxiliary heating curves were generated and evaluated. Evaluation criteria were based upon a predetermined relationship between the cooling rate at 900 F and the hardness of Gleeble specimens. It was found that:
1. The heat input necessary to achieve the desired hardness reduction was so great that complete remelting of the weld would have occurred.
2. The combined heat input of two arcs would achieve a modest hardness reduction.

Neither of the approaches would have reduced the HAZ hardness to desirable levels; therefore, further "Gleeble" simulations were performed with the result that if an auxiliary heat source arrested the HAZ temperature at 1000 F for 6 sec, the HAZ hardness would be at a desirable level.

The technically significant portion of this work is the simulation technique, since it affords a method for evaluating welding processes and parameters without the need for extensive experimental equipment and costly empirical data.

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Background

A special purpose automatic GMA welding machine was used to butt weld thin carbon manganese steel parts. The weld was made with two passes at a speed of 60 ipm. During the development of the welding techniques problems arose due to the creation of thin high hardness zones (Rc 50-52) in the HAZ of the welds. The hard zones were caused by the attendant high HAZ cooling rates. Due to the end use of the product, the hard zones were undesirable, a hardness limit of Rc25 being the maximum desired. This study was made to determine methods for either eliminating or preventing the HAZ hard zone formation.

For a variety of technical and economic reasons, the use of pre-heat, the use of a higher heat input, and the use of separate postweld heat treatments were undesirable even though these methods could probably achieve the desired hardness reduction. Therefore, the study concentrated on the two following hardness reduction methods:
1. In-line heat treating. If sufficient auxiliary heat were to be added after the weld had solidified, but before the austenite had transformed, the cooling rates, hence hardness, of the HAZ probably could be reduced. The auxiliary heat, however, should not be so high as to cause remelting of the metal.
2. Multiple arc welding. The total heat input of two welding arcs from two weld passes could be sufficient to achieve slow HAZ cooling rates, hence prevent extensive martensite formation.

With the first method, the auxiliary heat might be supplied by an oxyacetylene burner which travels behind the welding electrode at the same speed. The welding head of the automatic welder was so designed that with moderate modifications an auxiliary heat source could be placed 1½ to 2 in. behind the welding electrode. Likewise a second electrode could be mounted 1½ to 2 in. behind the main electrode to weld the second pass simultaneously with the first pass, i.e., multiple arc welding. This latter approach has an added advantage of decreasing the total joint fabrication time.

In order for the first method of auxiliary heating to be successful, i.e., avoid the formation of martensite, the temperature of the bulk of the austenitic portion must not fall below the M_S before the additional heat is applied. If the arc is traveling at 60 ipm and the auxiliary heat source is exactly 2 in. behind the welding electrode, then 2 sec will elapse before the auxiliary heat source passes over any given spot on the weld. Therefore, in those 2 sec, the temperature of a given spot must not fall below the martensite start temperature (M_S) which was known to be about 725 F.

One technique for determining if the temperature of the HAZ has fallen below the M_S in the 1½ to 2-in. distance, or 2 sec time interval for the example previously cited, involves placing thermocouples in the HAZ of a test weld and generating the true cooling curves. These curves could then be examined for the desired information. This would have been time consuming and expensive in that a rather elaborate experimental setup would have been required. Also, any subsequent process alterations would have to be studied in the same manner. Therefore a second technique was selected. It involved the use of a calibrated mathematical simulation to provide the desired information. This technique and its results are presented in the following sections.

Technical Approach

The general approach for simulating the in-line heat treating was as follows.

A heat flow equation was selected to generate theoretical HAZ heating and cooling curves. The curves, which were calculated and plotted using a digital computer, were then calibrated to the actual heating and cooling curves of a test weld. The calibrated equation was then used to simulate various weld process alterations designed to reduce the HAZ hardness. The more attractive process alterations were then tested using Gleeble specimens to verify that they would indeed produce a low hardness HAZ zone.

There are several equations which can be used to calculate weld metal and/or HAZ cooling curves. The equation selected for this work was developed by Tall (Ref. 1). It is a two dimensional heat flow equation which best fits the heat flow of the weld.

$$T = \frac{Qp}{2Kh}[ko(\lambda vr)] \exp(-\lambda v \xi) \qquad (1)$$

Where T = temperature of any point in the weld area at any time (t). Note also that T = T-To where the pre-heat (To) is zero.

K = thermal conductivity
λ = SP/2K where S = specific heat and P = density

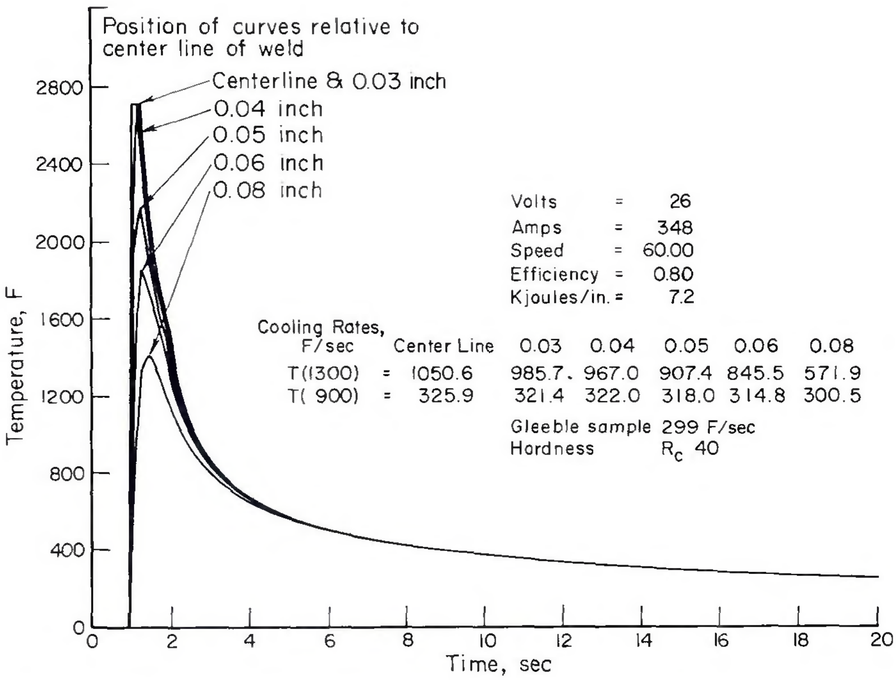

Fig. 1 — Typical thermal cycles based on a 0.80 thermal efficiency factor

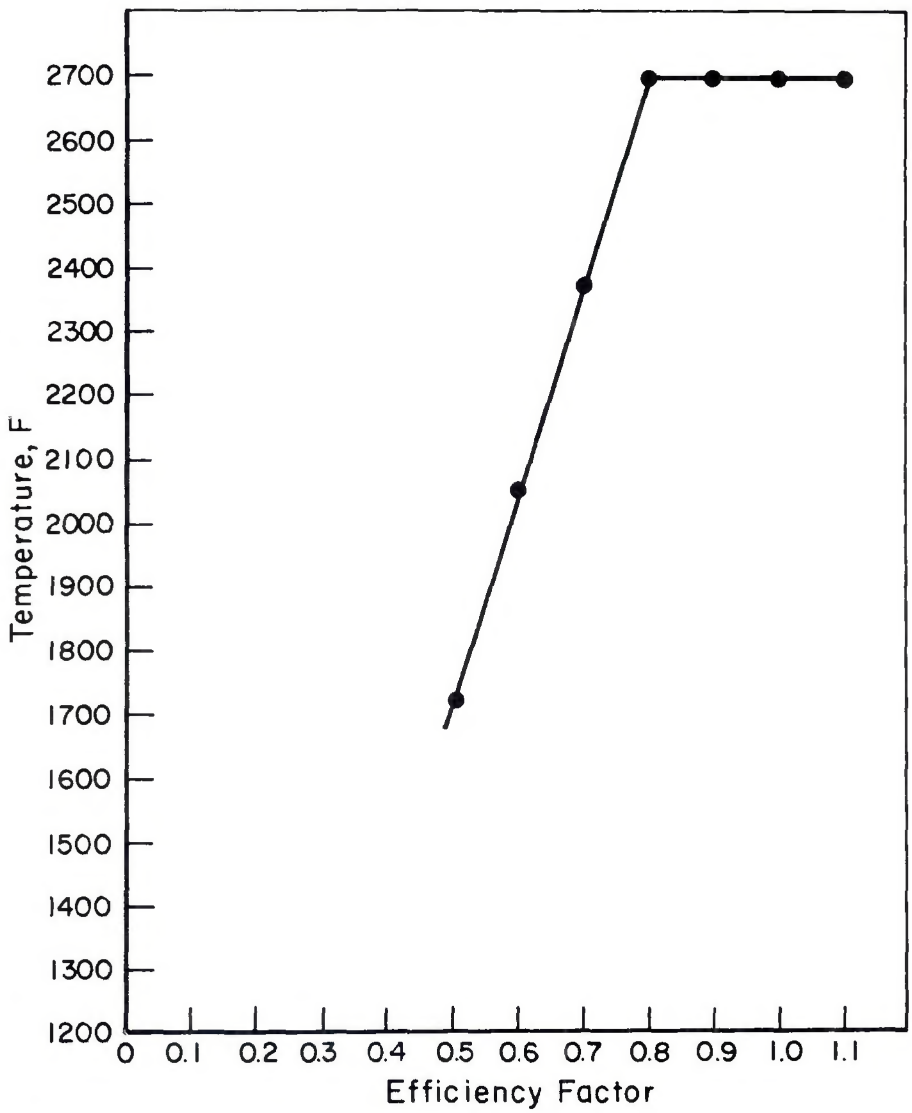

Fig. 2 — Peak temperature of 0.04 in. cycle as a function of efficiency

ξ = x-vt where x = distance behind heat source, v = travel speed and t = time

ko = Modified Bessel function of second kind, zero order

$r = \sqrt{\xi^2 + y^2}$ where Y = distance from weld centerline

h = Plate Thickness

Qp = Total heat input including an efficiency factor.

The terms, ξ and r, represent the mathematical terms necessary to calculate the temperature at any point in the HAZ, i.e., some point other than the weld centerline. These latter terms have the effect of translating the X-Y coordinate system from the plate to the torch which permits one to calculate the temperature distribution about the arc in an X-Y plane.

The term, Ko, is a modified Bessel function of the second kind, zero order, which is used to provide the desired solution to the differential equation from which Eq. 1 was derived.

Masabuchi, Simmons, and Monroe (Ref. 2) have produced a digital computer program which in part utilizes Talls' equation, (Eq. 1). The applicable portion of the above computer program was extracted and slightly modified for use in this investigation.

The computer program utilizing appropriate library subroutines will simultaneously graph the heating and cooling curves for up to six points in the total weld area and will calculate the cooling rate at any two temperatures for each cooling curve. In addition, a complete table of temperature versus time data is computed and tabulated along with the heat input in kilojoules/inch.

Figure 1 shows a typical output plot. The welding conditions used to generate the thermal cycle shown in Fig. 1 are identical to the welding conditions used to make the test weld. Note that the six curves represent the weld centerline and five other positions, 0.03, 0.04, 0.05, 0.06, and 0.08 in. from the weld centerline. The three last locations are in the HAZ. The cooling rate has been calculated at 1300 F and 900 F for each of the curves.* Also note that the thermal efficiency factor was considered to be 0.80 in this case.

Calibration Technique

The equation used to produce the typical HAZ curves shown in Fig. 1 must be calibrated to the true thermal cycle produced by the automatic machine if the equation is to be useful. The proper efficiency factor was

The 900 F cooling rate was considered to be representative of the transformation behavior of the steel during continuous cooling (Refs. 3-6).

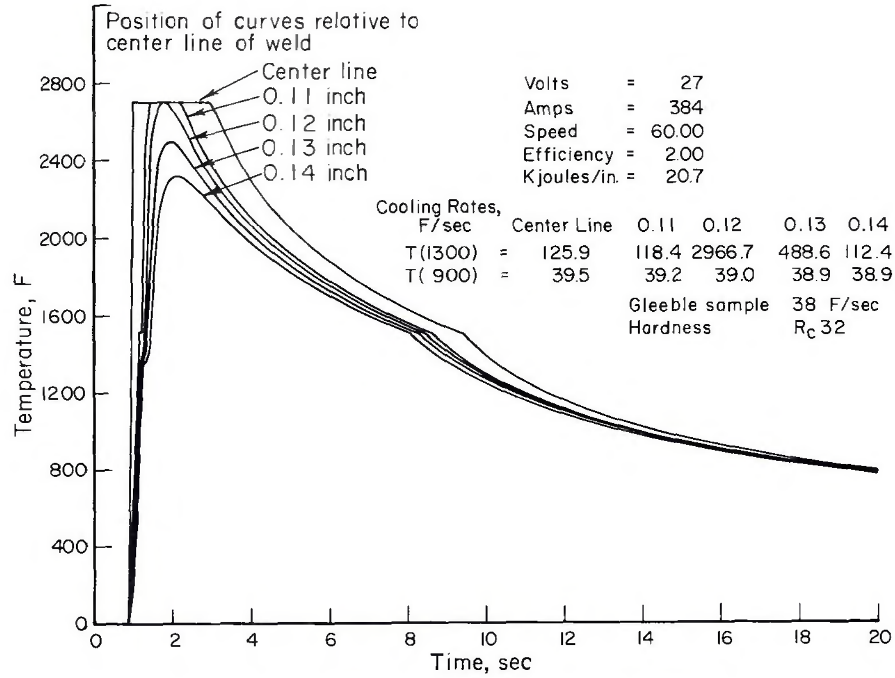

Fig. 3 — Typical thermal cycle exhibiting slow cooling rate at 900F

determined in the following manner.

A test weld was made using the welding parameters shown in Fig. 1. The test weld was cross sectioned transversely at various locations. The fusion-HAZ interface was located about 0.04 in. from the weld centerline and the maximum hardness zone of Rc41 occurred at the 0.05 in. location.

A series of thermocycle curves that correspond to the test welding conditions were computer generated by varying only the efficiency factor, namely at efficiencies of 0.70, 0.80, 0.90, 1.00, and 1.10. The peak temperature of each curve that was located at 0.04 in. from the centerline was compared with 2750 F, the approximate melting point of steel; i.e., the temperature of the HAZ-fused metal interface. The efficiency factor that produced a curve that just reached the melting point at the 0.04 in. location was 0.80, therefore this efficiency factor was selected for use. A plot of the peak temperature of the 0.04 in. cycle as a function of arc efficiency is shown in Fig. 2.

Data Analysis

Based upon data from the 0.05 in. location, thermocycle tabular print out data, the HAZ metal at a point in time 2 sec (or 2 in., since the speed is 60 ipm) behind the main arc was 831 F.‡ This temperature is above the probable M_S temperature of 725 F. It should be recognized that the above statement strictly applies to the 0.05-in. location; however, it is considered to be valid for all locations in the HAZ where the peak temperature was above A_1 (about 1300 F). This consideration was deduced by noting that the 0.08 in. location thermocycle with a peak temperature of 1407 F, or about 100 F above A_1, had a temperature of 790 F after 2 sec. Therefore, the curve with a peak temperature of about 1300 F should be above 750 F after 2 sec and certainly above 750 F at 1.5 sec elapsed time. Therefore, the simulation indicates that it would be possible to use an auxiliary heat source placed 1.5 to 2 in. behind the main welding arc to reheat the HAZ before it reached the M_S.

‡ Note that the time scale on Figure 1 begins before the arc has passed a given spot; therefore, 2 seconds elapsed time occurs at about 3.5 sec on the graph's time scale.

Auxiliary Heating Simulation Cycles

As deduced from the calibration work previously described, the use of an auxiliary heat source to decrease the cooling rate appears feasible. However, more simulation was needed to define the heat input of the auxiliary heat source so that the desired cooling rate reduction could be achieved. Although a wide variety of auxiliary heating thermocycles could be generated and a Gleeble test performed to evaluate each cycle, this approach would have been too time consuming. Therefore, a series of thermocycles representing auxiliary heat inputs in the range of 5 to 20 kJ/in. were generated. This was done

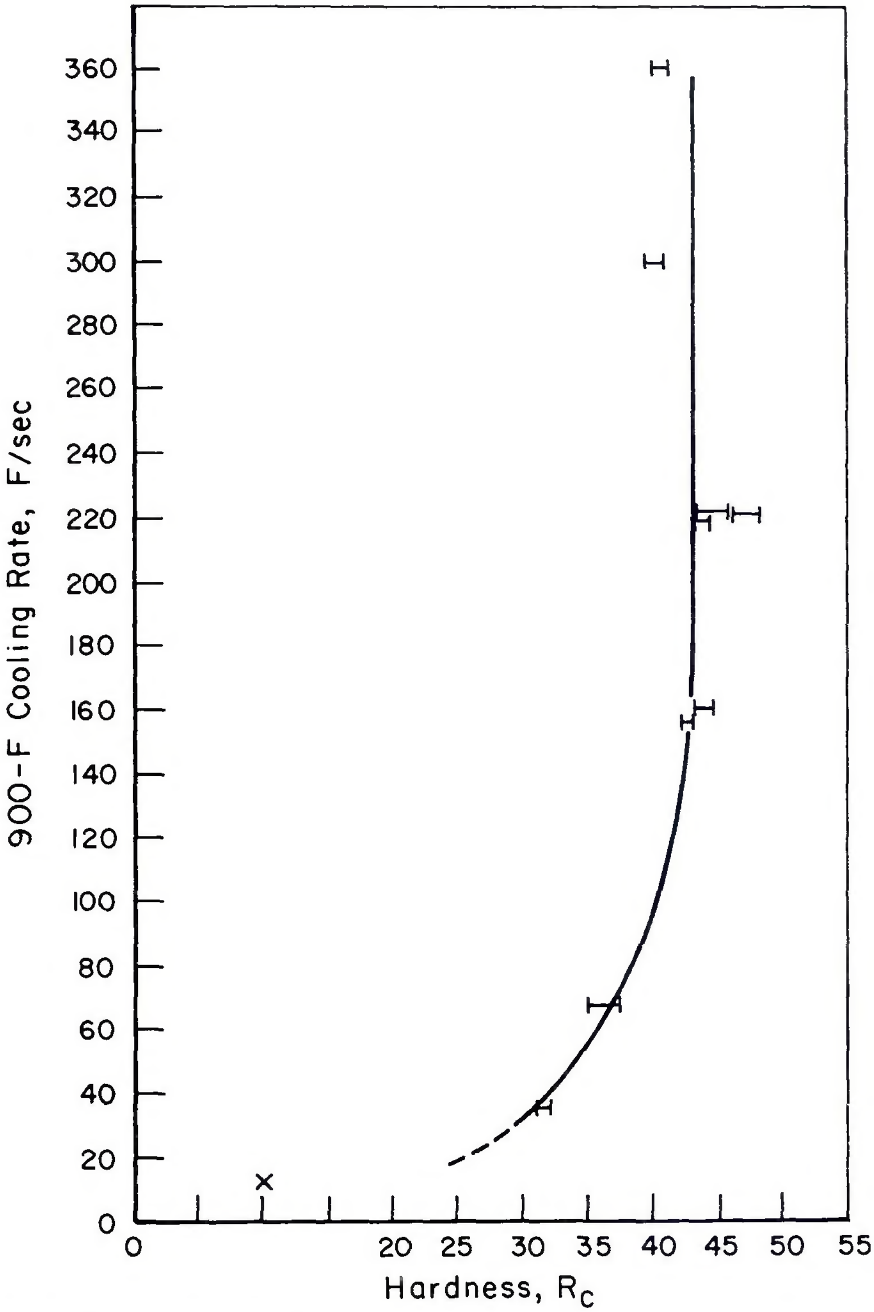

Fig. 4 — 900F cooling rate versus hardness of Gleeble samples

by using typical weld parameters and changing the efficiency factor to 0.50-1.00-1.50-2.00, respectively. Here, the use of very high efficiency factors was merely a convenient method for altering the total heat input with a minimum of key punching.

Figure 3 shows the 2.00 efficiency factor (high heat input) thermocycles. In Fig. 3 the cooling curve at the 0.05 in. location would have been so close to the weld centerline that it would have been indistinguishable from the centerline curve, even though this location corresponded to the zone of maximum hardness on the actual test weld. This occurred because the theoretical equation using a high efficiency factor depicted a much wider weld than had been previously simulated. This is analogous to the physical situation; i.e., an increased heat input would create a larger weld pool. Therefore, larger HAZ distances from the centerline were chosen to represent the desired HAZ thermocycles; namely, thermocycles located 0.11, 0.12, 0.13, and 0.14 in. from the centerline.

The thermocycle of each plot, which had a maximum temperature closest to the 2400 F range, hence analogous to the peak temperature of the 0.05 thermocycle of that test weld, was selected for Gleeble and subsequent hardness tests. This curve would represent the heating and cooling cycle of metal located near the HAZ-fusion interface when made at high heat input conditions.

Gleeble samples were forced to undergo the various HAZ thermocycles and their hardness levels were plotted against the respective (900 F) cooling rates developed in the actual Gleeble samples. The resulting plot is shown in Fig. 4. The lowest hardness level produced in this series was Rc32. It was achieved with a cooling rate of about 38 F/sec at 900 F and with a heat input of 20.7 kJ/in. The results of these runs indicate that the desired auxiliary heating source must be such that the cooling rate at 900 F is below 38 F/sec. The heat input in this case would be above 21 kJ/in.

In fact, an extrapolation of the data of Fig. 4 (dashed lines) indicated that a cooling rate of about 16F/sec would be required to achieve the target hardness level of about Rc25 or less. Therefore, this value will be used as first test criterion for any simulated auxiliary heating thermocycle. This test applies only if the auxiliary heating cycle produced continuous cooling; i.e., isothermal decomposition was not considered at this time.

A new set of runs was made to simulate the use of an auxiliary heat source located behind the main welding arc. Figure 5 shows a simulated auxiliary heat thermocycle superimposed upon the first pass thermocycle. The first peak was generated using the first pass weld parameters with the calibrated efficiency factor of 0.80. The auxiliary heat source thermocycle was generated by using a second heat input of 10 kJ/in. The auxiliary heat source was considered to have been applied when the cooling curve at the 0.05 in. location reached 800 F, which was about 2.3 sec behind the first pass electrode. Upon cooling after the auxiliary heat source had passed, the cooling rate at 900 F was 57.6 F/sec.

From Fig. 4, this cooling rate would be expected to produce a hardness of about Rc35 which is above the Rc25 target value. The thermocycle shown in Fig. 5 represented a total heat input of about 17 kJ/in., which was approximately equal to the heat input that would be developed if the first and second passes were to be combined.

Therefore, based on this cycle, and assuming that the auxiliary heat was representative of a second pass, it was deduced that the hardness would not be reduced to Rc25 or lower; i.e., the use of a multiple arc technique while offering a substantial hardness reduction would still not be enough.

Therefore, a series of simulated auxiliary heat thermocycle curves (0.05 in. position) were generated with increasing heat input until the cooling rate at 900 F decreased to a value below 20 F/sec. Figure 6 shows the curve generated using a heat input of 25 kJ/in. for the auxiliary heat source. The 900 F cooling rate was 16 F/sec and from the extrapolation in Fig. 4 this cooling rate should be slow enough to reduce the heat-affected zone hardness below Rc25.

A Gleeble sample, arbitrarily designated A, was used to verify the hardness reduction. The Gleeble cycle was slightly different from the actual curve in that the sample was heated directly to about 2000 F and held until reaching Point A in Fig. 6. The Gleeble sample was then forced to follow the computer generated cooling curve. The altered cycle was much easier to achieve in the Gleeble, and the sample should have transformed in a manner equivalent to a sample which had followed exactly the computer curve. The cooling rate (at 900 F) of the Gleeble sample was found to be about 13 F/sec and the hardness was well below the Rc25 target value. This value is denoted by an X on Fig. 4 and shows that the original extrapolation was not quite correct. Note that the X value is based upon conversion from microhardness data and the Rc hardness scale ends at Rc20.

The thermocycle shown in Fig. 6 appears to have solved the problem, but it has not; the simulated auxiliary heat input is so great that, in practice, considerable melting would be expected to occur. The heat input of this auxiliary heat source would be nearly 3½ times as great as the heat input used to make the weld's first pass. An auxiliary heat source having a heat input that high appears impractical, even if one were to consider that the extra energy could be spread over a finite area rather than an infinitesimal area as used in the 2D heat flow equation.

Diffusion-Controlled Decomposition

Fortunately, the austenite in the heat-affected zone can be made to transform to relatively soft products by transformation at essentially a constant temperature. Therefore, to study this possibility two Gleeble samples were run. The first Gleeble sample was made to follow the original thermocycle shown in Fig. 6 except that after reaching a temperature of about 1200 F on the second heating cycle the Gleeble sample was held for 6 sec and then cooled rapidly to room temperature.

The second Gleeble sample likewise was made to follow the thermocycle except that it was held at 1000 F for 6 sec and rapidly cooled to room

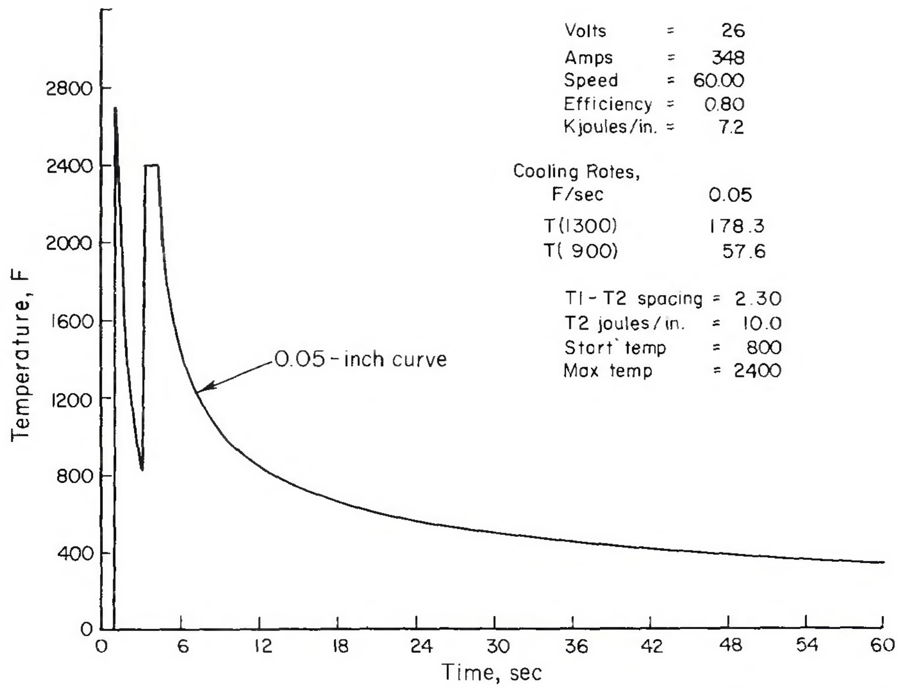

Fig. 5 — Auxiliary heating thermal cycle using a 10 kJ/in. heat input

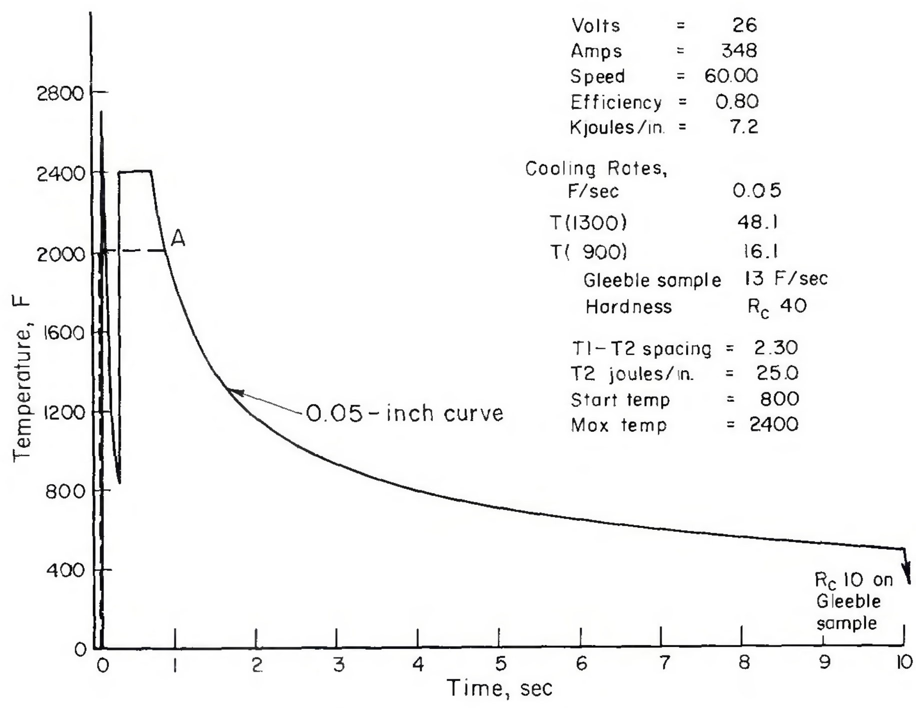

Fig. 6 — Auxiliary heating thermal cycle using a 25 kJ/in. heat input

temperature. A cooling rate of about 500 F/sec at 900 F was achieved.

The hardness of the sample held at 1200 F was Rc35 and the hardness of the sample held at 1000 F was about Rc20. The hardness value of Rc20 thus indicated that a diffusion-controlled transformation for 6 sec at 1000 F would be sufficient to reduce the heat-affected zone hardness to below Rc25.

Summary of Predictions of Simulation Studies

The analytical and Gleeble work predicted that:

1. It would be possible to apply heat 1½ to 2 in. behind the arc to arrest the cooling of the heat-affected zone before this zone reached the Ms temperature.
2. Multiple arc welding probably

would produce a hardness reduction to about the Rc35 level.

3. By maintaining a temperature of 1000 F for 6 sec the hardness of the heat-affected zone could be reduced to below Rc25.
4. A hold period of 6 sec at 1200 F probably would not reduce the heat-affected zone hardness unless controlled slow cooling followed. Based upon these predictions, the welding equipment was modified so that two welding arcs could be used simultaneously. Preliminary results from a few test welds made with the modified machine indicated that the hardness of the HAZ ranged from Rc30 to 38, thus agreeing with the prediction.

Conclusions

A combined computer and Gleeble simulation technique for welding applications has been developed. The technique features (a) a Fortran IV program to generate welding thermocycles and (b) a means of selecting the proper arc efficiency factor, and (c) a means for verifying the metallurgical effects upon the welded material by utilizing the Gleeble.

This technique permits the simulation of welding processes to accurately predict the effects of process changes upon metallurgical properties of the weldment due to the thermocycles imposed by the welding process.

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