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MEASUREMENT OF THERMAL CYCLES IN THE WELD HEAT AFFECTED ZONE OF MILD STEEL

by

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M.D. Coward and R.L. Apps

SUMMARY

The thermal cycles in the mild steel parent plate adjacent to a bead on plate weld have been measured for heat inputs of 108, 54 and 42 kJ/inch, by means of embedded thermocouples connected to high response automatic recorders. The results show that decreasing the heat input increases the cooling rate and decreases the width of the heat affected zone.

For thermal cycles in which the peak temperatures reached 900°C or above, two points of inflection have been noted in the temperature ranges 400° - 600°C and 950° - 1200°C. The inflection in the lower temperature range, which has been observed by other workers, has been attributed to latent heat from the exothermic transformation of austenite to ferrite. The higher inflection point, not previously reported, has been tentatively related to the solidification in the weld pool and the release of the latent heat of fusion.

Contents

1. Introduction

In the process of fusion welding an intense localised heat source melts some of the parent material to form a pool of molten metal to which additional filler metal may be added. The parent material immediately adjacent to the molten zone is subjected to extremely rapid changes in temperature over a relatively small distance. In this heat affected zone the combination of a wide range of thermal cycles produces a whole series of different metallurgical structures with accompanying variation in mechanical properties.

The temperature/time relationships for points in the parent plate at various distances from the fusion boundary are of particular significance in the determination of the mechanical properties of the heat affected zone. The important parameters are the maximum temperature reached and the cooling rate through any particular temperature range. These allow us to predict and control metallurgical microstructure and hence mechanical properties, and also to predict and control distortion caused by the rapid heating and cooling cycle.

The influence of microstructure on mechanical properties is well known. Hardened and tempered steels develop the best combination of tensile strength, ductility and notched-bar impact properties when their structures consist wholly of tempered martensite. The presence of ferrite, pearlite or bainite usually lowers the values for proof stress, impact and fatigue strength. In welding, the limited time cycle during which the heat affected zone is raised to the maximum temperature and then cooled again permits in many cases only a partial degree of austenitisation, and does not allow enough time for complete diffusion of carbon and other alloying elements. Although the heat affected zone in mild steel plate generally consists of ferrite and carbide, other structures may be produced by changes in the rate of heating and cooling or by the use of plate of greater hardenability. Thus it is possible that the heat affected zone may consist of a range of mixed structures including martensite, bainite, pearlite and ferrite, giving very different mechanical properties to those of the unwelded parent material.

The use of continuous cooling transformation data has been applied for many years to the control and understanding of the heat treatment of alloy steels and, in a more qualitative manner, to the welding of such steels. The weldability of a steel may be partially attributed to the hardenability and the crack-sensitivity of the heat affected zone and consequently the use of the C.C.T. diagram for inferring the structural and the mechanical properties of that zone offers a reliable method of predicting the weldability of a steel and for determining the welding conditions for a given steel. However, the transformation of austenite is considerably influenced by the thermal condition of austenitisation; therefore it is essential that the C.C.T. diagram used for welding research be determined under the exact conditions of heating and cooling of regions in the heat affected zone. This has been achieved by the use of specially designed high speed dilatometers (1)(2). In this way INAGAKI and his colleagues (2) have drawn up a table for a series of high tensile steels showing, together with their chemical composition, the limits of martensite, bainite and pearlite corresponding to the various cooling rates found in the regions of the heat affected zones.

The determination of weld heat affected zone thermal cycles is therefore of paramount importance in determining the mechanical properties of the welded joint. The determination of these cycles was the first step in a programme of research carried out at Cranfield into the investigation of the properties of the weld heat affected zone. Previous techniques used to measure the temperature distribution in materials have ranged from the use of temperature sensitive lacquers (3)(4) which change colour when heated above a critical temperature, through crayons and wax pellets which have fixed melting points to thermocouples welded to the plate and connected to automatic recording instruments (5) (6) (7). The accuracy of the latter method is considerably better than the others which measure temperatures to only ± 10% and are very sensitive to change in heating rate. For these reasons automatic recorders were used for this work.

In the second stage of the work a rig was constructed to simulate exactly the measured thermal cycles in specimens of the parent plate which were then tested to determine the mechanical properties of the various regions of the heat affected zone. These results will be published later.

2. <u>Experimental Work</u>

Heating and cooling thermal cycles in the parent plate adjacent to the weld were measured by means of thermocouples connected to high response, direct, continuous recording millivoltmeters. For the measurement of temperatures above 1,200°C the thermocouples were constructed from 0.005″ diameter wire of pure platinum and an alloy of platinum - 10% rhodium. For the measurement of temperatures below 1,200°C the thermocouples were constructed from 0.005″ diameter wire of chromel (an alloy of 90% nickel and 10% chromium) and alumel (an alloy of 95% nickel plus aluminium, silicon and manganese additions). The thermocouple was constructed by feeding the separate wires through a two inch long twin bore alumina insulator, of outside diameter 0.063″, twisting the ends of the bare wires together and welding in a carbon arc to form a very small globule. Several of these thermocouples, of both types, together with their cold junctions and compensating leads were calibrated against the melting points of standard pure salts and metals using the thermal arrest technique.

Initial trials were made with the thermocouples spot welded, by means of a capacitor discharge unit, to the surface of the plate at regular intervals away from the region to be welded. This technique proved unsuccessful since the thermocouples that were closest to the weld were detached from the plate surface during welding by the turbulent molten flux. By drilling holes about 1/16″ deep and spot welding thermocouples to the bases of the holes with subsequent peening of the edges of the hole around the insulator, this problem was overcome. However, the method was not acceptable for the following reasons: (1) The molten flux produced during the welding process caused additional heating of the thermocouple wires away from the hot junction and thus introduced errors in the measurement of the plate temperature; (2) Positioning the finite-sized hot-junction just below the top surface of the plate caused the hot junction to straddle several isotherms, thus producing a large temperature gradient across the hot junction. To avoid these errors it was necessary to position the hot junction along an isotherm and this was achieved by welding the thermocouple to the base of a hole drilled upwards from the underside of the plate, immediately underneath the weld bead where the temperature isotherms were parallel to the plate surfaces.

For the actual measurement of the heat affected zone thermal cycles a bead on plate weld was produced by an automatic submerged arc welding unit, using 3/16" mild steel filler wire, on a 1½" thick mild steel (B.S.15), plate approximately 26" long and 12" wide. The composition of the mild steel is given in Table I, whilst welding conditions for each heat input are listed in Table II. The weld was then sectioned in numerous places, etched in 10% Nital, and measurements made of the bead width, depth of penetration and width of the heat affected zone at the point of maximum penetration.

From this information holes of 0.067 in. diameter were drilled into another mild steel plate of identical dimensions along the longitudinal centre line to depths which on subsequent welding, under the same conditions, on the reverse side of the plate, would take them into various regions of the heat affected zone. The thermocouples were then spot welded to the bottom of the drilled holes. This was achieved by connecting the plate to one terminal of the capacitor discharge unit and the thermocouple wires to the other. By gently lowering the twin bore aluminium insulator down the drilled hole electrical welding of the thermocouple to the base of the hole took place immediately it touched the bottom. In order to produce a satisfactory weld it was essential to ensure that the drilled hole did not contain any dirt or grease. Also it was necessary to ensure that the small length of thermocouple wires emerging from the insulator to the hot junction globule did not touch the sides of the drilled hole during the lowering of the thermocouple or else welding of the wire took place above the base of the hole. Finally the twin bore alumina insulators were fixed in position by cementing to the place surface with alumina paste. The thermocouple cold junction was maintained at 0°C by means of an ice/water mixture.

In order to avoid disturbance of the thermal state of the plate the holes were drilled to as small a diameter as possible (this was limited by the diameter of the smallest twin bore alumina insulators manufactured) and the holes were spaced at not less than one inch intervals.

Very fine thermocouple wires were used for three reasons; firstly, to produce a hot junction as small as possible in order to minimise the temperature gradient across the globule, i.e. to minimise the region of the heat affected zone whose thermal cycle was to be measured, secondly, to minimise conduction of heat from the solid and the error due to a temperature gradient along the wires, and thirdly, to keep the response time of the thermocouple to a minimum.

The thermocouples were connected via a multiple switch system to four Sefram Graphispot high response, single channel, direct continuous recording millivoltmeters, especially designed for the measurement of low voltages. The Graphispot recorded low potentials by means of an immersed coil galvanometer which was insensitive to vibration and consumed essentially zero current. A response time of $\frac{1}{2}$ sec. was given for full scale deflection, i.e. it took $^1/_4$ sec. to reach a temperature of 1,500°C. A trolley carried a pen giving inscription in rectilinear co-ordinates, as well as the photo electric receiver serving as a detector for the light spot. The current from this detector was amplified and fed to a servo motor which corrected any error in position between the light spot from the galvanometer and the detector. By correctly spacing the thermocouple holes in the plate and by using a multiple switching system three thermal cycles from three different couples could be recorded on a single Graphispot during the welding of the length of the plate.

The technique for the actual temperature measurements consisted of first lining up the welding unit and adjusting to the correct conditions for welding on a run-on plate adjacent to the plate containing the thermocouples. When these conditions were obtained all the four Graphispot recorders were switched on and the bead on plate weld was produced, using the multiple switching system at the appropriate times to record all the thermal cycles. The experimental arrangement is shown in Fig. 1.

After welding, the plate was sectioned next to each thermocouple and small portions containing the thermocouples carefully ground until the hole containing the thermocouple was visible. This surface was then macro-etched in 10% Nital solution for several minutes to show the heat affected zone and fusion boundary. The distance between the welded thermocouple and the fusion boundary was measured with a finely graduated steel rule and a magnifying glass to within 0.25 mm. This region is shown in Fig. 2.

In order to determine possible errors in the measurement of the thermocouple millivoltages a number of tests were carried out. For instance, Beevers(8) has shown that one of the major difficulties in the measurement of temperatures in welding by means of thermocouples is the reduction of voltage pick-up from extraneous sources. To investigate the magnitude of this problem, the welding power supply was switched off at a particular point in the thermal cycle of a trial run and the immediate change in millivoltage noted. The results of the test showed that this effect was negligible. The calibration of both types of thermocouples was carried out to investigate errors due to the circuit, (i.e. connection wires to the cold junction and to the recorder), and due to the Graphispot recorders and the appropriate corrections made. The results were used directly in the correlation of the measured temperature values.

3. Results and Discussion

The results of the temperature - time measurements for the various positions in the mild steel parent plate adjacent to the bead on plate weld for welding conditions giving three different heat inputs are shown in Fig. 3, 4 and 5. The results show that the heat input has a considerable effect on the cooling rate, as shown in Fig. 6. As would be expected decreasing the heat input increases the cooling rate and markedly reduces the width of the visible heat affected zone. The variations in peak temperatures with distance from the fusion boundary for the different heat inputs are shown in Fig. 7.

Of special interest is the fact that during cooling there are two regions which show a definite inflection in cooling rate over a certain temperature range. These temperature ranges are 400° - 600°C and 1200° - 950°C. The lower temperature inflection depends on the heat input and peak temperature of the thermal cycle. This region has been reported by Calvo et al.(9) and is thought to represent the temperature at which the exothermic transformation of the austenite began during cooling. The temperature at which austenite transforms depends upon its homogeneity and grain size and upon the cooling rate from the austenite range. To check this the C.C.T. diagram for this steel was determined by means of high speed dilatometry at B.W.R.A.(10). In this test the material was rapidly heated to 1325°C at a heating rate similar to those found in the weld heat affected zones, held at this austenitising temperature for several seconds and then cooled at various cooling rates.

The results are shown in Figure 8, with the cooling rate for a weld heat affected zone thermal cycle, with a peak temperature of 1347°C superimposed on the graph. From this it can be seen that transformation to ferrite and pearlite starts at about 650°C for cooling rates similar to those used in the present work. However, in the actual weld heat affected zone thermal cycle the material is not held at its peak temperature for any length of time but immediately cooled and this may not produce such complete homogenisation of the austenite, which may explain why there is a difference of 50°C in the transformation starting temperatures.

The second inflection has not been reported previously in any of the papers on temperature measurement in plates during welding. This inflection occurs in the temperature range of about 1200-950°C again depending on the thermal cycle and heat input, and it is tentatively suggested that it is caused by the solidification progression in welding.

Rabkin(11) has studied the temperatures in the weld pool of automatically submerged arc welded aluminium. He showed that in the welding pool there is a powerful flow of molten superheated metal forced from under the arc, which flows to the rear part of the weld pool and produces a slower cooling rate in the rear part of the weld pool than in the forward part. This explains why the molten pool shape is not elliptical, as predicated by heat flow theory,(12) but includes an elongated tail.

The shape of the molten weld pool for a bead on plate weld is shown in Fig. 9, from which it may be noted that the melting point isotherm is very nearly parallel to the weld surface at the front of the pool, with lower temperature isotherms following a similar pattern. Thus a thermocouple located in the heat affected zone immediately below the arc would remain at a high temperature for a longer time than would be predicted by heat flow theory or by temperature measurements in a static system (compare, for example, the results of Apps and Milner 13). Most of the latent heat of fusion is released at the end of the pool and transfer of this heat could result in an inflection in the cooling curve.

No attempt has been made to correlate the experimental results with heat flow theory since the size of the plates used for the work was insufficient to eliminate edge effects. Additionally, the thickness of the plates together with the heat inputs used were such as to produce a heat flow pattern that was neither pure two-dimensional nor three-dimensional heat flow (14).

It may be noted that the width of the heat affected zone increases markedly with increase in heat input, although cooling rates within the zone decrease. The significance of high cooling rates in mild and low alloy steels is readily appreciated but the width of the heat affected zone could also be important in determining the properties of welded structures. Future work may well show the importance of selecting welding variables such that a correct balance is maintained between heat affected zone structure and dimensions.

4. References

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6. Acknowledgements

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TABLE I: Composition of Parent Plate

Element	Composition %
C	0.21
Mn	0.89
Si	0.065
S	0.050
P	0.040

TABLE II: Welding Conditions

Heat Input kJ/inch	Welding Current amps.	Welding Voltage	Welding Speed in/min.	Wire Diameter inches
108	390 ± 10	30 ± 2	$6\frac{1}{2} \pm \frac{1}{2}$	$^3/_{16}$
54	390 ± 10	30 ± 2	$12\frac{1}{2} \pm \frac{1}{2}$	$^3/_{16}$
42	300 ± 10	30 ± 2	$12\frac{1}{2} \pm \frac{1}{2}$	$^3/_{16}$

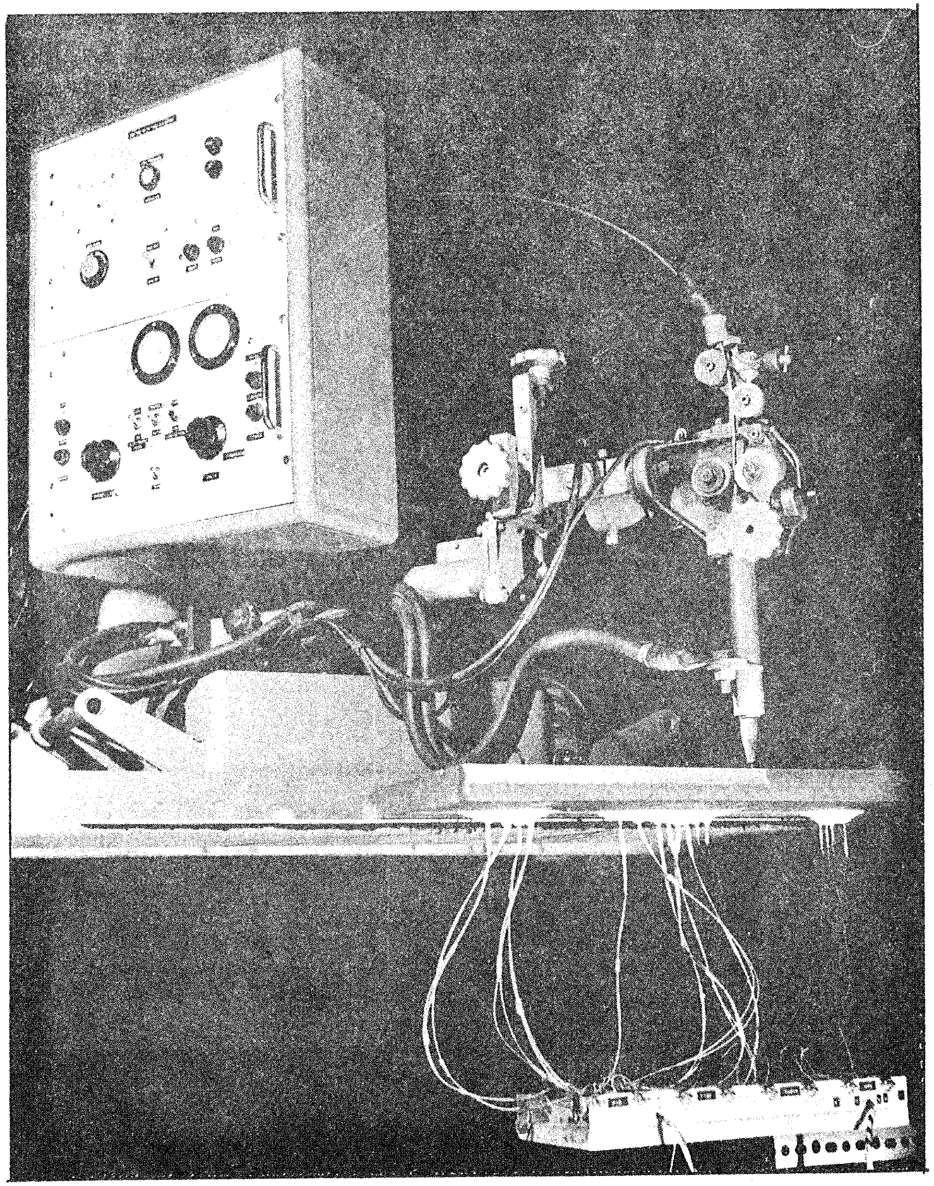


FIG. I THE MEASUREMENT OF THE HEAT AFFECTED ZONE THERMAL CYCLES

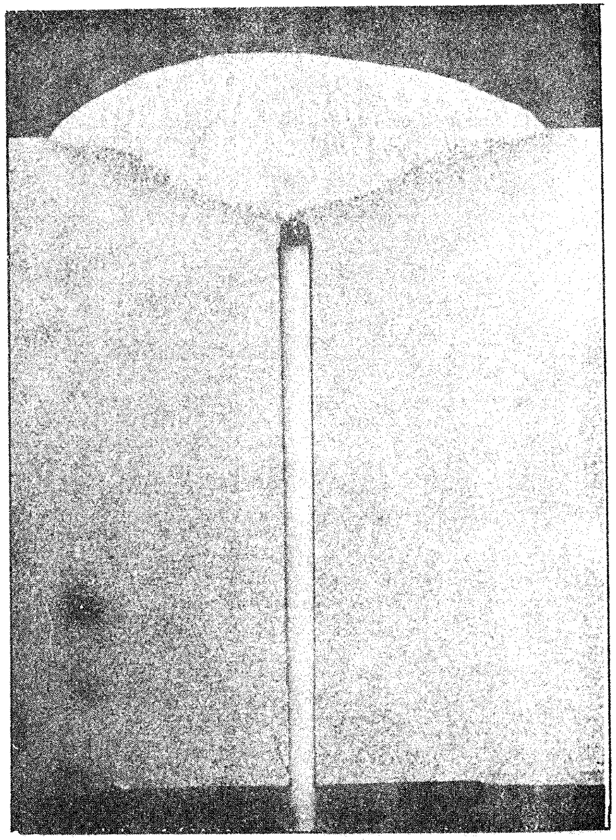


FIG. 2. THERMOCOUPLE HOT JUNCTION IN THE HEAT AFFECTED ZONE.

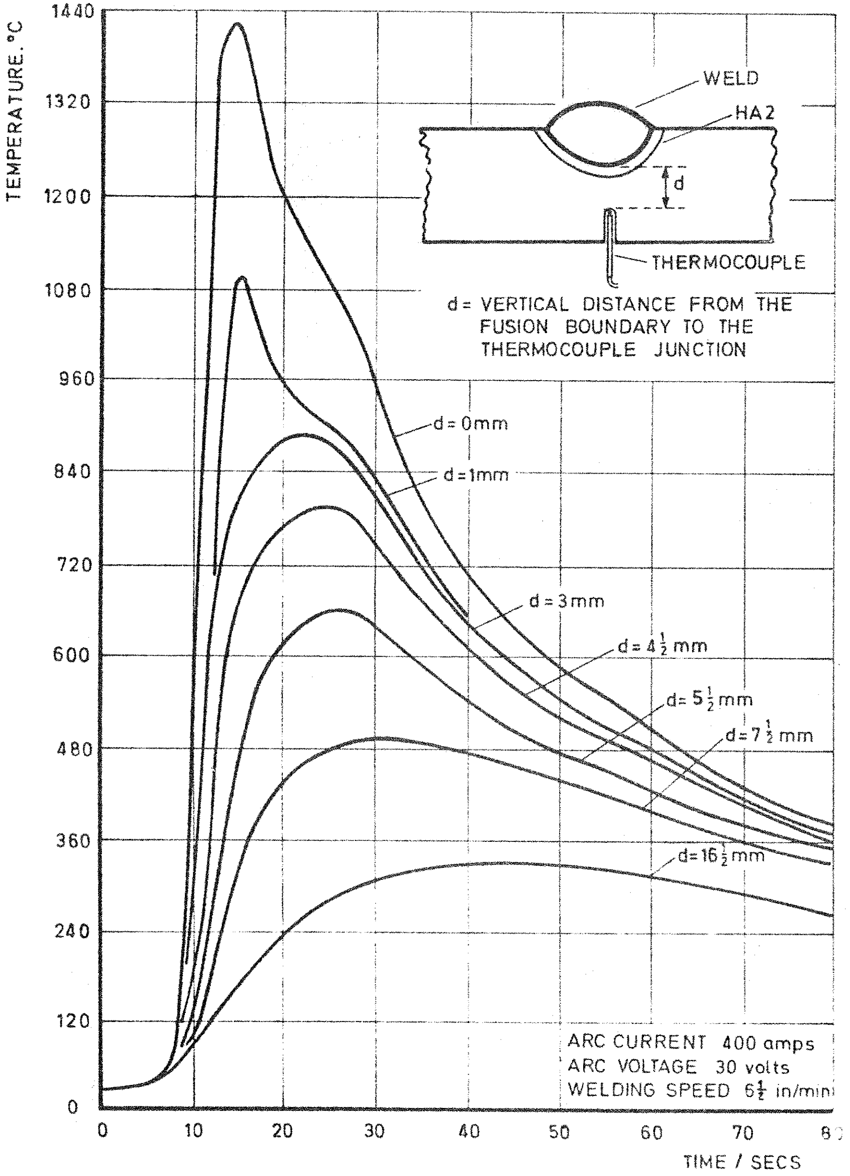


FIG. 3. THERMAL CYCLES PRODUCED IN THE PARENT PLATE ADJACENT TO THE WELD FOR A HEAT INPUT OF 108 kJ / IN

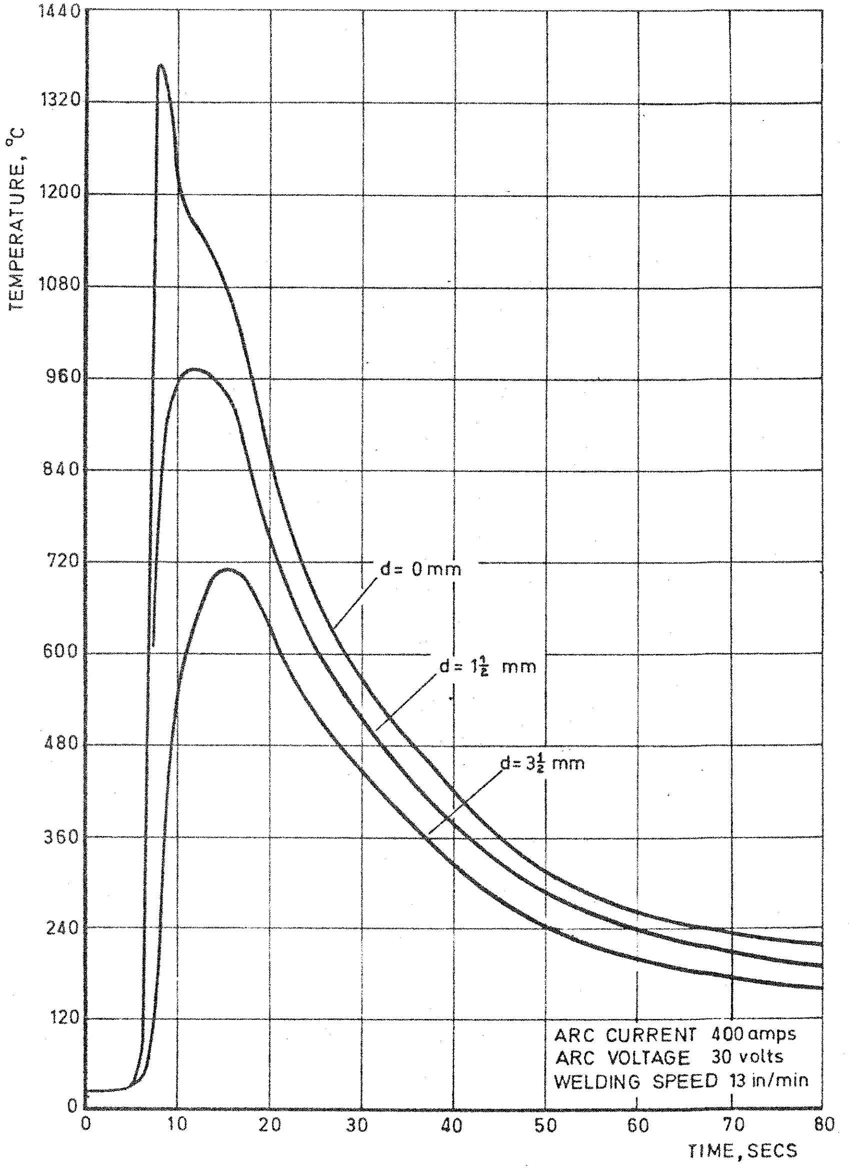
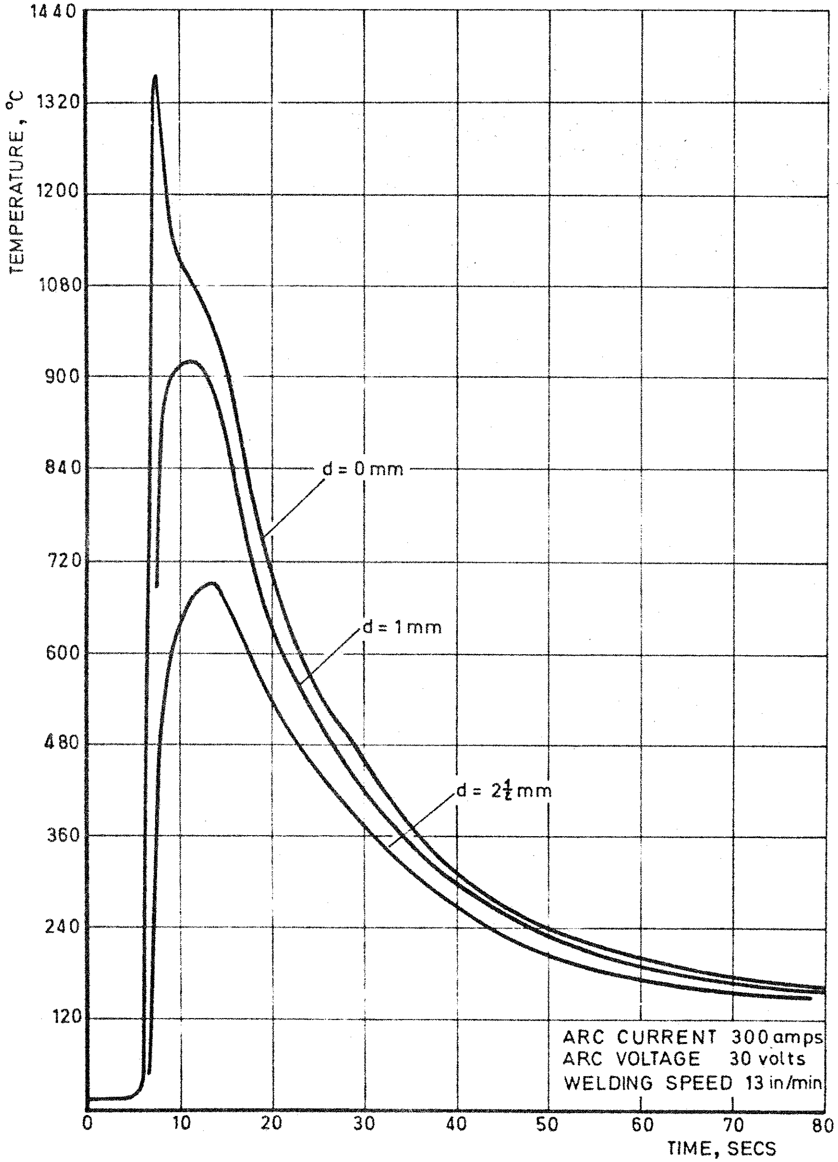


FIG. 4. THERMAL CYCLES PRODUCED IN THE PARENT PLATE ADJACENT TO THE WELD FOR A HEAT INPUT OF 54 kJ / IN.



ARC CURRENT 300 amps
ARC VOLTAGE 30 volts
WELDING SPEED 13 in/min

FIG. 5. THERMAL CYCLES PRODUCED IN THE PARENT PLATE ADJACENT TO THE WELD FOR A HEAT INPUT OF 42 kJ/IN.

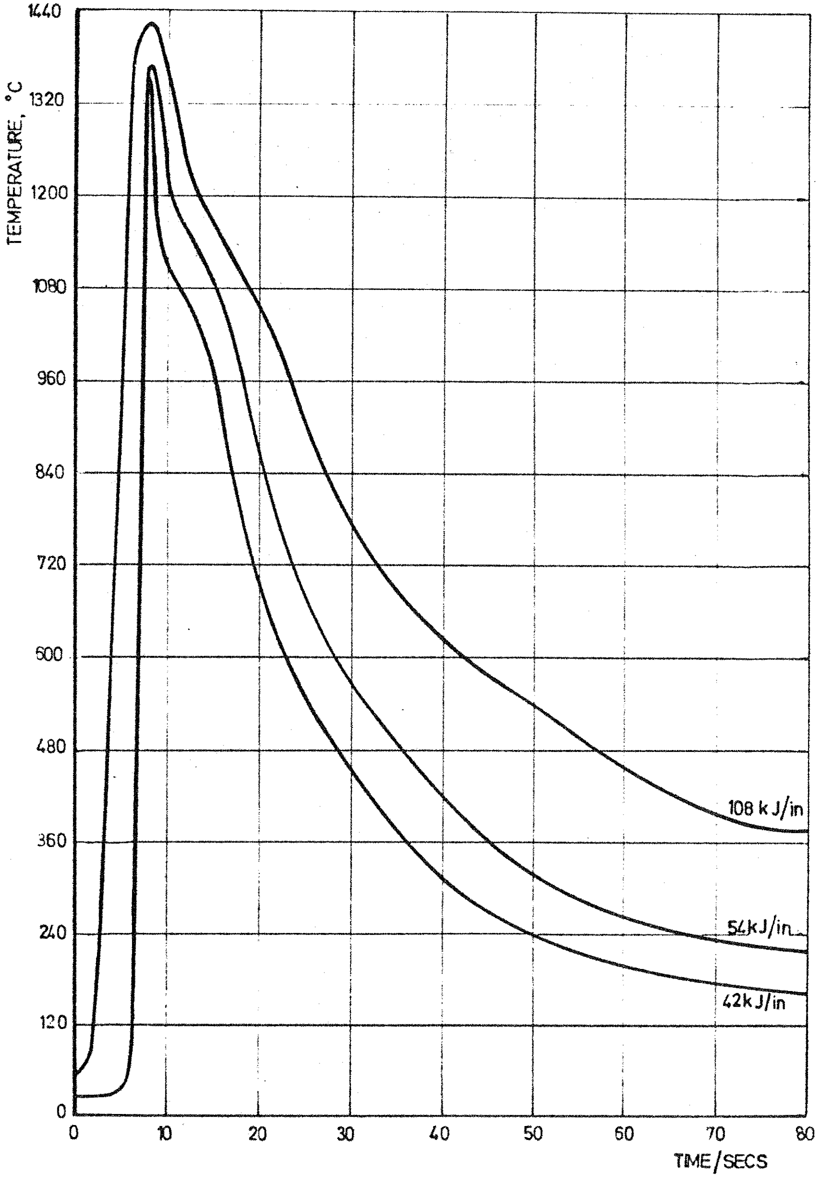


FIG. 6. EFFECT OF HEAT INPUT ON COOLING RATE.

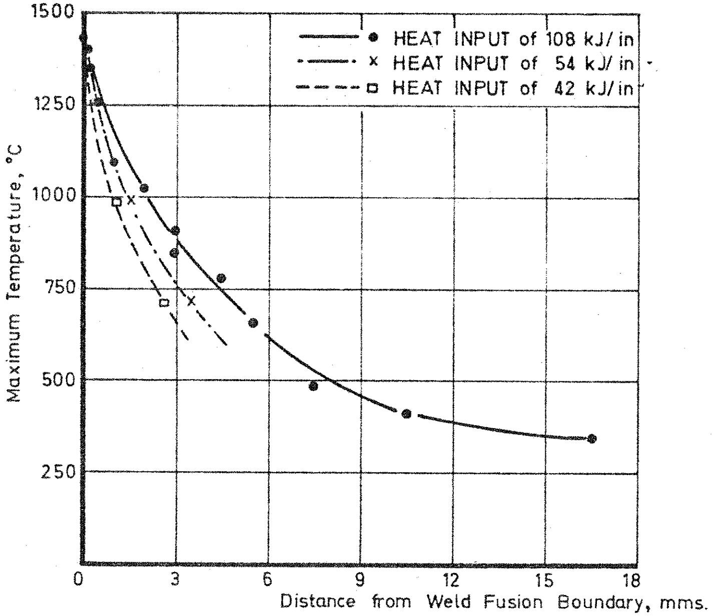


FIG. 7 VARIATION OF THERMAL CYCLE PEAK TEMPERATURE WITH DISTANCE FROM THE FUSION BOUNDARY FOR WELDS WITH HEAT INPUTS OF 108 kJ/in, 54 kJ/in and 42 kJ/in.

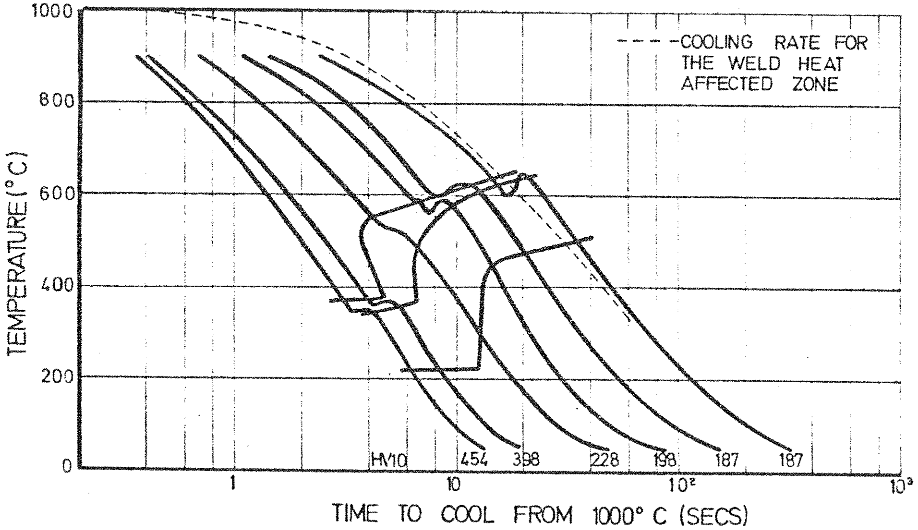


FIG. 8 C.C.T. DIAGRAM FOR MILD STEEL AUSTENITISED AT 1325° C

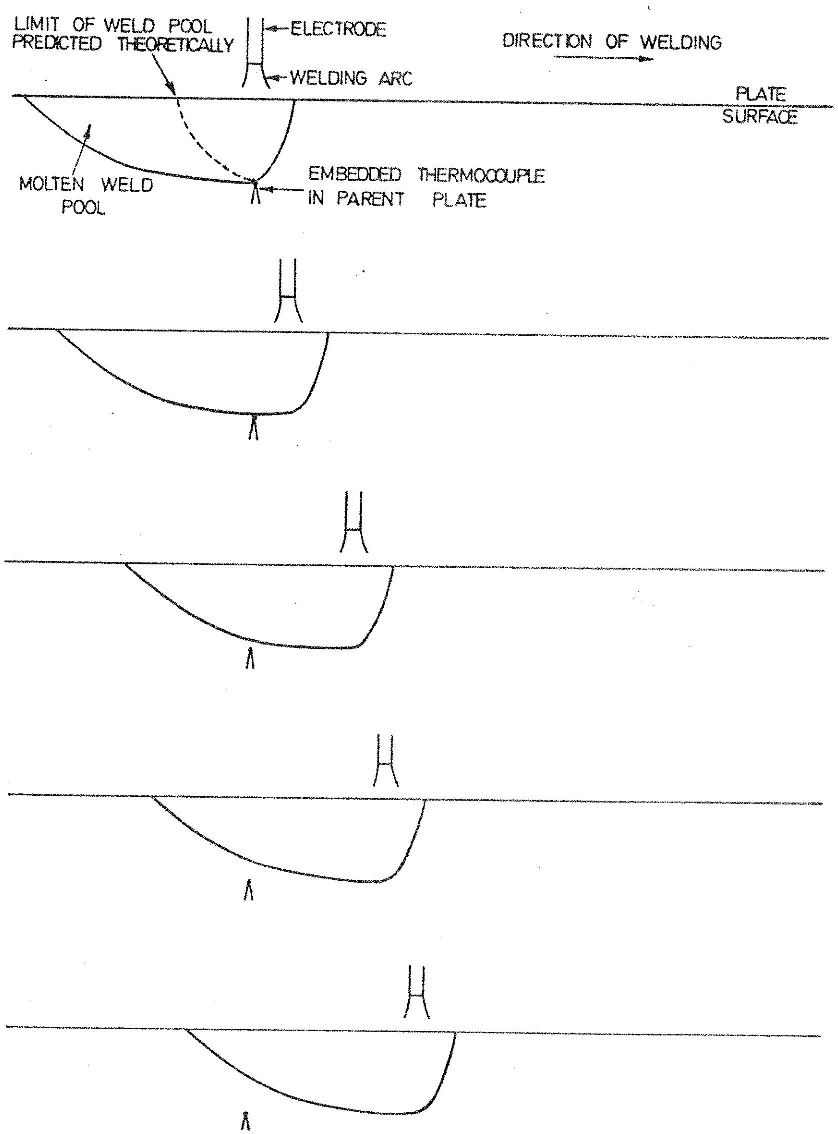


FIG. 9 MOVEMENT OF MOLTEN WELDPOOL OVER EMBEDDED THERMOCOUPLE.