The Effects of Covered Electrode Welding Variables on Weld Metal Cooling Rates

The cooling rate of covered electrode weld metal depends only upon energy input and preheat, and not upon electrode diameter or deposition rate during three-dimensional cooling

BY BORIS M. KRANTZ AND VINCENT D. COPPOLECCHIA

ABSTRACT. The yield strength of AX-140 high strength steel weld metal has been shown to vary with the initial weld metal cooling rate which in turn varies as a function of welding energy input parameters and preheat temperature when a three-dimensional mode of heat transfer prevails. In the present study initial cooling rates of covered electrode weld metal have been related to the energy input and other characteristics of this welding process. The investigation revealed: (1) For three-dimensional heat transfer the cooling rate, dT/dt [°F/sec] is controlled only by the average energy input, E [Kj/in], and the preheat temperature, T_o [°F] as:

$$dT/dt_{1300F} = \frac{(2.80 \times 10^{-3})(1300 - T_o)^2}{E} + 18.6$$

$$dT/dt_{1000F} = \frac{(3.16 \times 10^{-3})(1000 - T_o)^2}{E} + 4.7.$$

(2) Electrode diameter and deposition rate had no inherent effect upon initial weld metal cooling rate.

(3) The arc energy transfer efficiency of covered electrode welding was found to be 74%, less than the 84% efficiency of the gas metal-arc process previously observed.

B. M. KRANTZ is Manager, Metallurgical Development, Airco Welding Products, Murray Hill, N. J. V. D. COPPOLECCHIA, formerly with Airco, is presently with Curtiss-Wright, Woodridge, N. J.

Table 1—Materials and Welding Conditions for Determining Cooling Rates

Materials	
Electrode: 1/8, 5/32, 3/16 in. diam E14018	
Base plate: 2-in. thick HY-130 steel	
Surface condition: machined to remove surface scale	
Welding conditions	
Welding position	Flat
Preheat	250F
Arc length	1/4 in.
Current level, 1/8 in. electrode	100, 130, 155 amp
Current level, 5/32 in. electrode	120, 160, 195 amp
Current level, 3/16 in. electrode	200, 240, 260 amp
Arc voltage (dcrp)	22 to 25 v
Travel speed	6 and 10 ipm

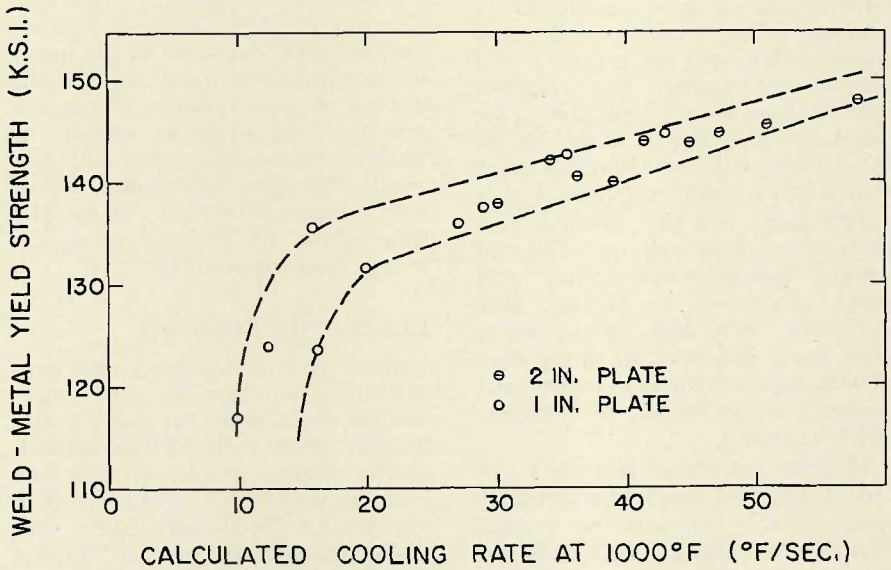

Fig. 1—Influence of cooling rate on AX-140 weld metal yield strength

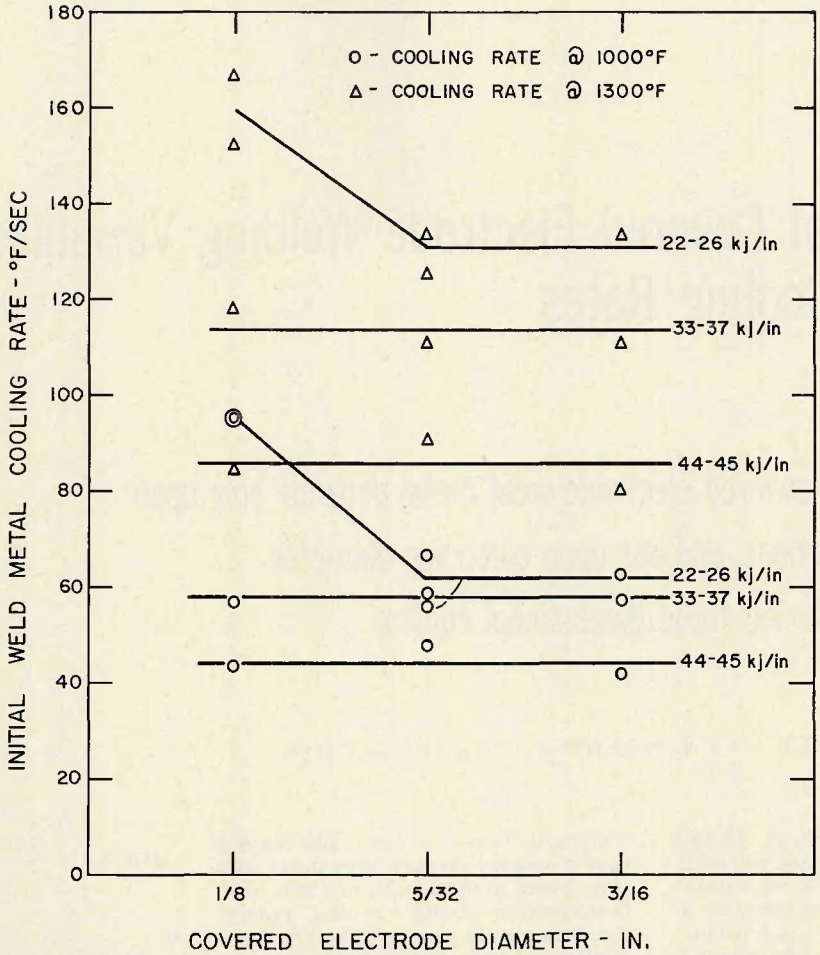

Fig. 2—Influence of covered electrode diameter on initial weld metal cooling rate

Introduction

Arc welding with covered electrodes is the most widely used electric arc welding process. It is capable of depositing in any position weld metal meeting many strength, toughness and porosity specifications. These capabilities make the process applicable to the welding of high strength steels, such as HY-130 where the positioning of heavy section joints often is not possible.

This study was part of an overall program to determine the effects of welding process variables on weld metal properties by studying their interaction with weld metal cooling rates. Fig. 1 illustrates the strong effect of weld metal cooling rates on the yield strengths of gas metal-arc, multipass, AX-140 deposits.

Dorschu[1] has shown that the initial weld metal cooling rates at a particular temperature, T, are inversely proportional to the welding energy input and directly proportional to $(T - T_o)^2$, where T_o is the preheat temperature. By changing the welding conditions, the cooling rates will vary and the weld properties are changed accordingly. The objective of the present investigation was to determine at a constant preheat temperature whether the energy input controls weld metal cooling in the covered electrode process, as was the case with gas metal-arc welding, or whether electrode diameter and deposition rate have independent effects. If so it would be necessary to consider their effects on weld properties in selecting welding conditions.

Experimental Procedure

Initial weld metal cooling rates were measured from bead-on-plate stringer deposits made in the flat position with 0.020-in. diam W3Re-W25Re thermocouples plunged into the trailing edge of the weld puddles. Cooling rates were measured at 1000 and 1300F since these temperatures are of greatest metallurgical interest for low-alloy steel systems.

Table 1 lists the materials and welding conditions used for the cooling rate study. The current levels selected are within the recommended range for each electrode diameter, the travel speeds are typical of manual welding and all experiments were conducted at the same 250F preheat/interpass temperature.

An automated welding apparatus was used to deposit the stringer beads. It consisted of a covered electrode feeder which was mounted on a post whose horizontal and vertical motion could be precisely controlled. After selecting the horizontal travel speed the covered electrode was moved toward the work until an arc was produced.

The covered electrode was spring-loaded, which prevented stubbing of the arc at the initial point of contact with the plate. After an arc was produced, the vertical speed of the electrode was adjusted to maintain a nominal ¼-in. arc length. In this manner the selected travel speed and arc length could be maintained and the electrode

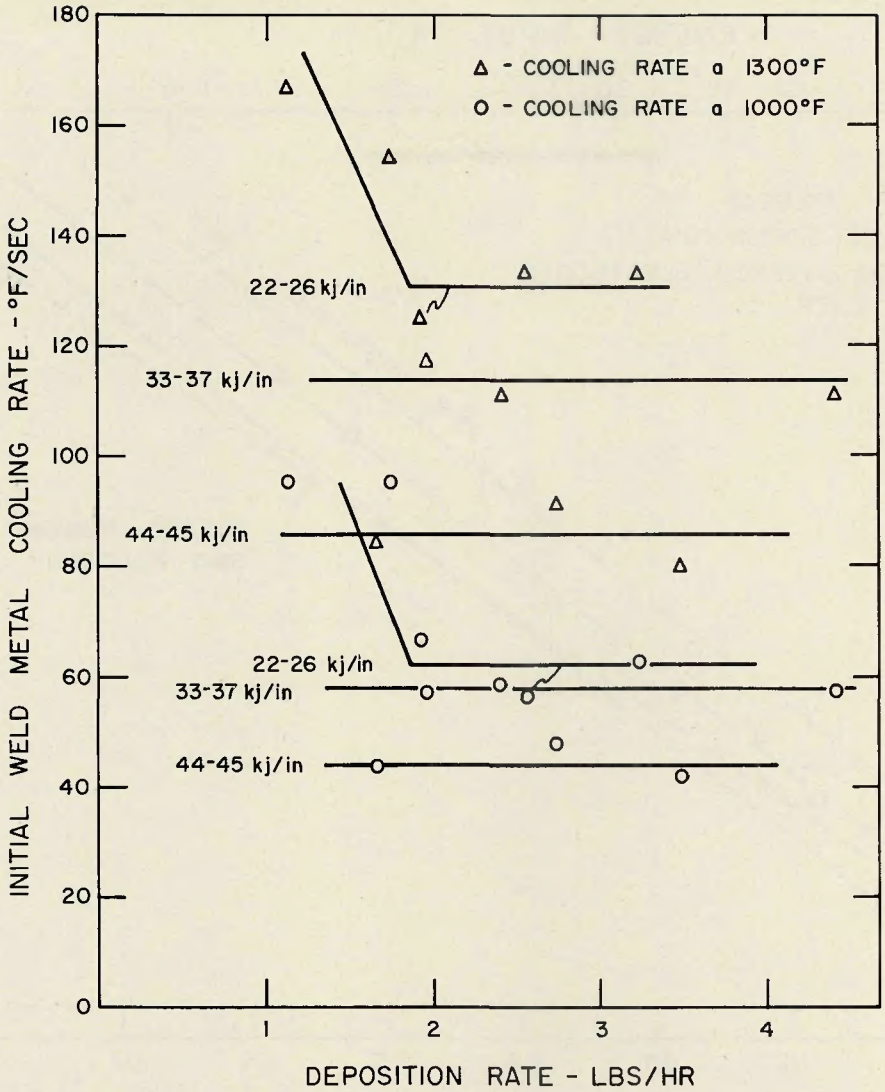

Fig. 3—Influence of deposition rate on initial weld metal cooling rate

deposition rate could be measured accurately and precisely.

Results and Discussion

Initial Weld Metal Cooling Rates

The effects of covered electrode welding variables such as electrode diameter and deposition rate on weld metal cooling rates were measured at three ranges of energy input, 22–26, 33–37, and 44–45 kj/in. As shown in Figs. 2 and 3, electrode diameter and deposition rate had no effect on weld metal cooling rate at the higher energy inputs. The maximum deviation from constant cooling rate conditions at a selected energy input was 8%, the same level as the experimental errors.

However, at the lowest energy input range the smallest electrode diameter and deposition rate caused faster cooling rates than the larger electrode diameters and deposition rates. At the larger electrode diameters and higher deposition rates, the initial weld metal cooling rates were essentially independent of these variables. The deposits that exhibited the exceptionally high cooling rates were very narrow because both the deposition rate and energy input were low. It was difficult to plunge the thermocouples in these small weld puddles and it is suspected that the exceptionally high cooling rates observed were associated with this difficulty.

Since electrode diameter and deposition rate had no inherent effect on initial weld metal cooling rates, the effects of energy input were examined. These variables were investigated for the gas metal-arc process[1] and the generalized expression for cooling rate (dT/dt) at a particular temperature (T) can be expressed as:

$$dT/dt_T = \frac{M(T - T_o)^2}{E} + D \qquad (1)$$

where E is the energy input, T_o is the preheat and M and D are constants.

The initial cooling rates of weld metal deposited over a wide range of welding variables are plotted as a function of reciprocal energy input at constant preheat in Figs. 4 and 5. Analysis of these figures revealed the linear relationship predicted by Eq. (1), with correlation coefficients of 0.97 and 0.96, respectively. The following least squares relationships were obtained:

$$dT/dt_{1300F} = \frac{(2.80 \times 10^{-3})(1300 - T_o)^2}{E} + 18.6 \qquad (2)$$

$$dT/dt_{1000F} = \frac{(3.16 \times 10^{-3})(1000 - T_o)^2}{E} + 4.7 \qquad (3)$$

The cooling rate equation may be expanded to include factors describing the efficiency of energy transfer, n, and thermal conductivity of the plate, k, as:

$$dT/dt = \frac{2k}{nE}(T - T_o)^2 \qquad (4)$$

To compare the relative efficiency of welding process, it is necessary to have an intercept or "D" value in Eq. (1) of zero. Theoretically, a linear expression

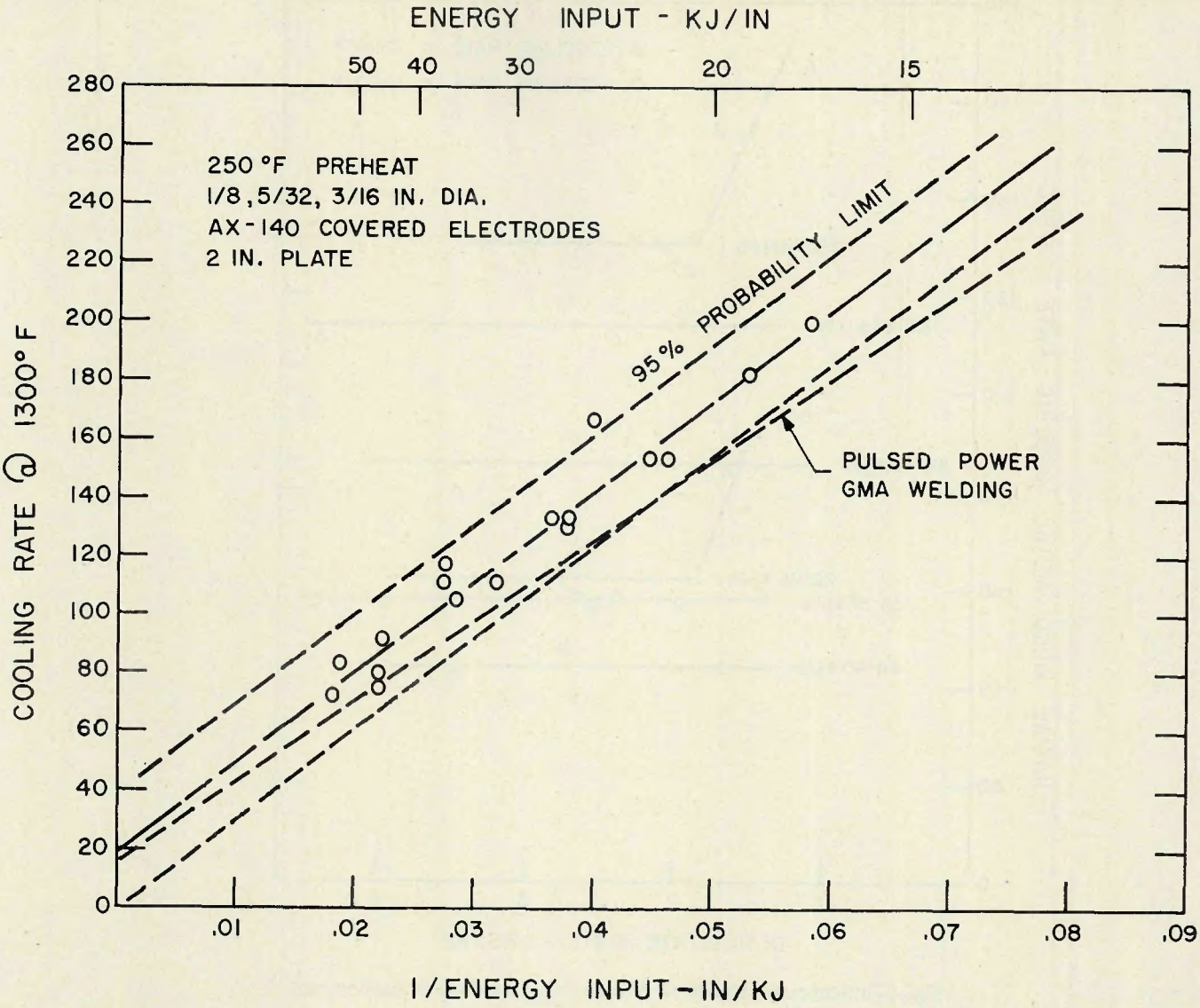

Fig. 4—Comparison of reciprocal energy input cooling rate at 1300F relationships of covered electrode welding and pulsed-power gas metal-arc welding

relating cooling rate and reciprocal energy input should have a zero intercept. For covered electrode welding, a least squares line with a D of zero yields M_{1300F} from Eq. (1) equal to 3.42 $\times 10^{-3}$. Combining Eq. (1) and (4) and using an average value of the thermal conductivity of steel to be 0.068 cal/cm°C-sec with appropriate conversion factors, the efficiency factor for covered electrode welding was calculated to be 74%. For gas metal arc welding (1) and pulsed power welding (2) these values were 84 and 86%, respectively.

The covered electrode process is less efficient because of the energy expended in melting and vaporizing the electrode coating. This is further illustrated in Fig. 4 where the cooling rate at 1300F-energy input relationship of pulsed power welding[2] are compared to the covered electrode process. This comparison is logical since these are common welding processes employed for the out-of-position use of high strength, low-alloy steel weld metals such as AX-140. The initial weld metal cooling rates during covered electrode welding are somewhat greater than those of the pulsed power process. This is expected since some of the arc energy is absorbed by the electrode coating. Thus less energy at a selected energy input is transferred to the base metal in the covered electrode process than in the gas metal-arc processes and predictably the cooling rates are greater.

Continuous Cooling Transformation Behavior

Ferrite or bainite can form after a weld bead of AX-140 has been deposited at relatively high energy input levels[2] since the ferrite-start (F_s) or bainite-start (B_s) curves are intersected during continuous cooling. The presence of these transformation products of austenite in the as-deposited microstructure will lower the resultant strength of the weldment[3]. The continuous cooling curves of covered electrode weld metal deposited at 13.5 and 55 kj/in. is shown superimposed upon the continuous cooling transformation diagram of AX-140 in Fig. 6. In both cases the cooling rates were rapid enough to produce only the desired self-tempered martensite in the as-deposited microstructures at room temperature and would attain the desired weld metal yield strength.

References

1. Dorschu, K. E., "Control of Cooling Rates in Steel Weld Metal," *Welding Journal*, Vol. 47, No. 2, 1968, pp. 49-s to 62-s.

2. Coppolecchia, V. D. and Krantz, B. M., "Pulsed Power Welding, the Effects of Welding and Travel Parameters on Weld Metal Cooling Rates," *Welding Journal*, Vol. 50, No. 11, 1971, pp. 475-s to 479-s.

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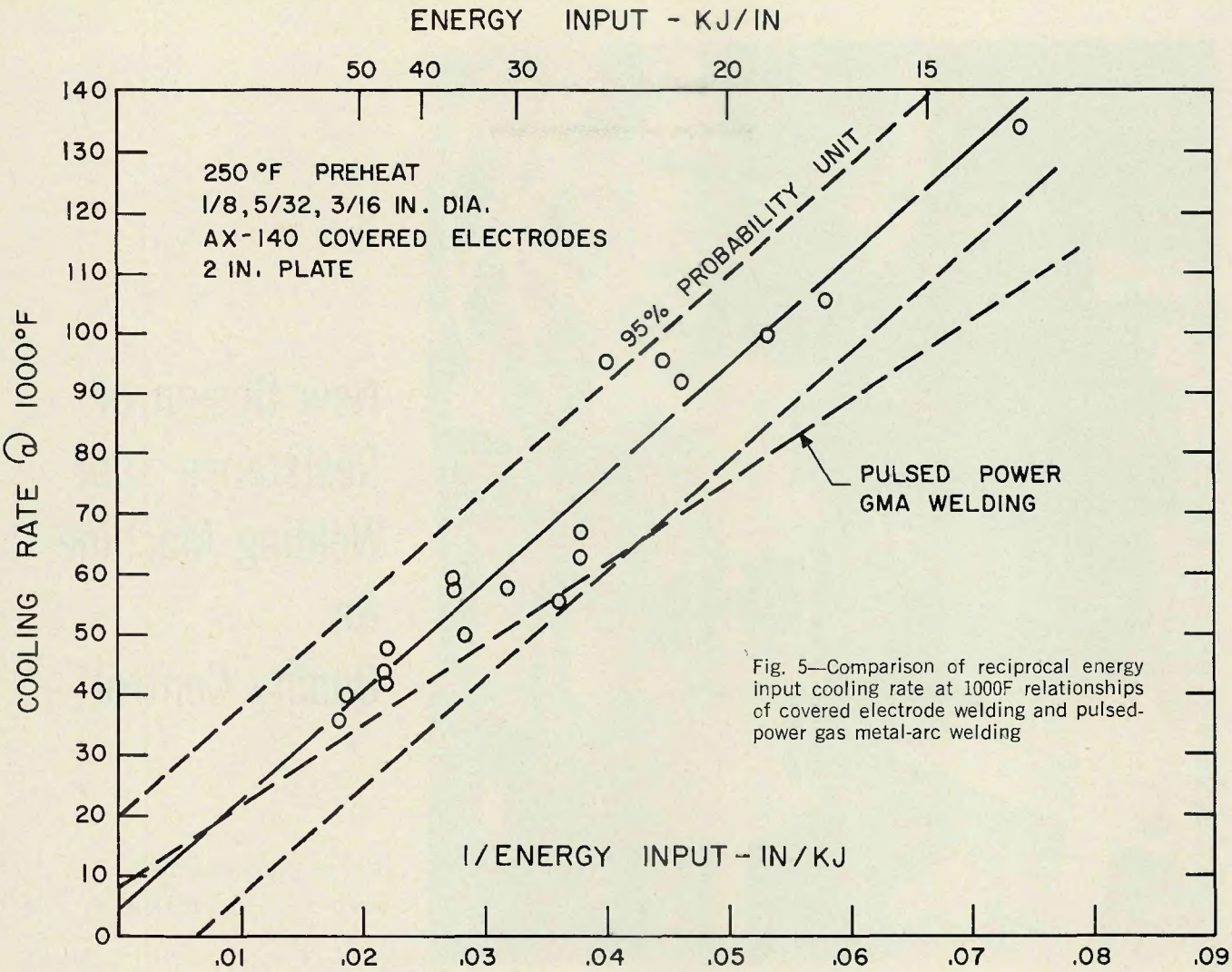

Fig. 5—Comparison of reciprocal energy input cooling rate at 1000F relationships of covered electrode welding and pulsed-power gas metal-arc welding

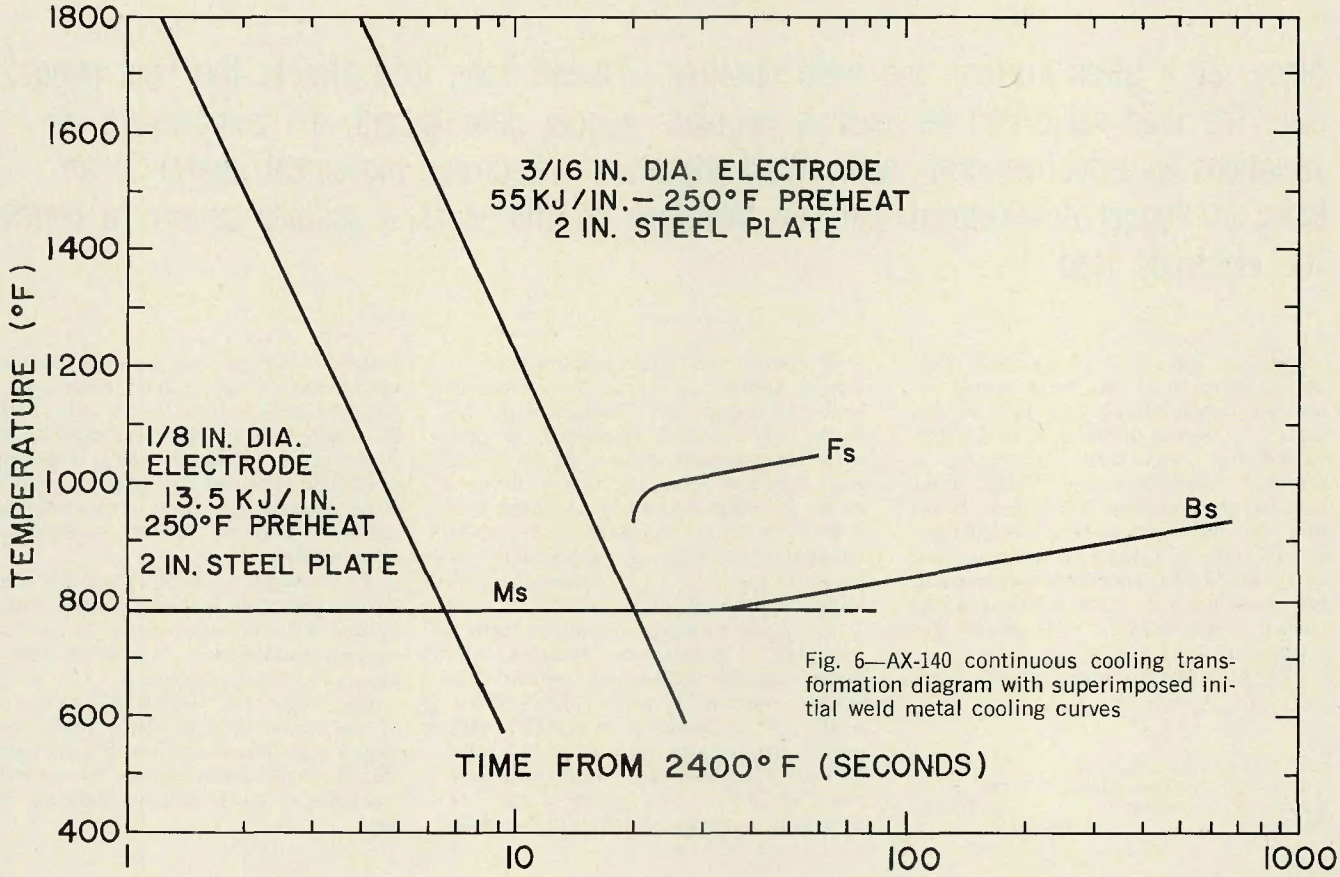

Fig. 6—AX-140 continuous cooling transformation diagram with superimposed initial weld metal cooling curves