THE OBSERVATION OF PEAK TEMPERATURES AS A METHOD OF EXAMINING HEAT FLOW AND METALLURGICAL TRANSFORMATIONS DUE TO A MOVING HEAT SOURCE IN A METAL PLATE

By

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ABSTRACT

The use of temperature sensitive lacquers to measure peak temperatures in the vicinity of a weld pass is an effective and reliable method for both research and industry. The results presented in this paper were obtained primarily through their use.

At a given distance from the weld center-line a peak temperature will be reached with this distance being directly proportional to such factors as power input, initial plate temperature, and inversely proportional to plate width, thickness, and length. The quantitative values of these proportionalities is shown for a limited welding situation in the plots and data in this report.

It is generally known that metallurgical transformations of the type found in 5056 aluminum alloy are dependent upon both heat treating temperature

and time. However in this investigation this recrystallization is shown to be almost instantaneous and independent of time at temperature such as is the case when these temperatures are experienced transiently as in welding.

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INTRODUCTION

The quantitative effects of many of the variables in a welding process on the completed weld's properties have never been fully examined. The importance of most of these variables is largely due to their influence on the thermal history of the weldment.

Among these factors are plate geometry, power characteristics, initial plate temperature, and the metallurgy of the material being welded.

The use of peak, or maximum, temperatures reached in the plate as a tool by which to gauge these effects has been recently facilitated by the introduction of a relatively simple method of measuring surface temperatures with known-melting-point-lacquers.

The purpose of this investigation is to briefly explore the possibilities made more readily available by these lacquers and in turn to suggest related fields for further study.

The advantages of such a method over the more widely used thermalcouple and potentiometer combination are soon obvious. If research, experimentation, and data were available on the thermal history of a weld as a function of these variables expressed as peak temperatures, the welding engineer would be provided with a non-destructive quality control check on his work.

The results of preliminary investigations using these lacquers to determine temperatures and these temperatures to reconstruct the thermal variations within the weld are given in this report.

THEORETICAL DISCUSSION

The general Fourier equation for heat flow in a solid is

$$\frac{q}{A} = -k\left(\frac{\partial t}{\partial s}\right)_{\theta} \quad \text{where } t = f(s,\theta). \qquad (1)$$

In equation 1, $\frac{q}{A}$ is the heat flow per unit area, k is a characteristic constant of the system, t is the temperature at any given time θ , and s is the distance from the heat source.

In solving for an equation, or equations, which would relate our variables to the desired observable measurement, peak temperatures, two cases lend themselves to theoretical analysis.

In the case for three dimensional heat flow from a point source on the surface of the plate, the equation for a steady temperature T' at a point having the coordinates x,y,z from the source is

$$T' - T_{o} = \frac{Q}{2\pi kR} \quad \exp \frac{-v(R-x)}{2\alpha} \qquad (2)$$[1]

where T_o is the initial plate temperature, k is the thermal conductivity, α is the thermal diffusivity equal to $\frac{k}{\rho C_p}$, ρ is the density, C_p is the specific heat of the plate, Q is the heat input, v is the velocity of the source, and R equals the $\sqrt{x^2+y^2+z^2}$.

[1] Personal communication with Prof. C.M. Adams, Jr., MIT 1958

The assumption has been made that the surface is adiabatic; i.e. that no heat is lost from the surface by radiation.

The corresponding equation for a "thin" plate, with two dimensional heat flow from an edge source cutting the plate perpendicular to its surfaces is

$$T' - T_0 = \frac{Q}{2\pi k t}\left(\exp \frac{vx}{2\alpha}\right) K_0 \sqrt{\left(\frac{vx}{2\alpha}\right)^2 + \left(\frac{vy}{2\alpha}\right)^2}$$

where t is the thickness of the plate, K_0 is a tabulated, modified Bessel function.

In applying these equations to a weld pass, or heat source applied to the surface of a metal plate, a decision as to which case, the "thick" or the "thin" plate, is pertinent must consider the following.

In the instance of finite penetration of the weld pool, the upper portion of the plate may be experiencing predominately the two dimensional situation, with the weld pool acting as an edge heat source of a definitely finite width.

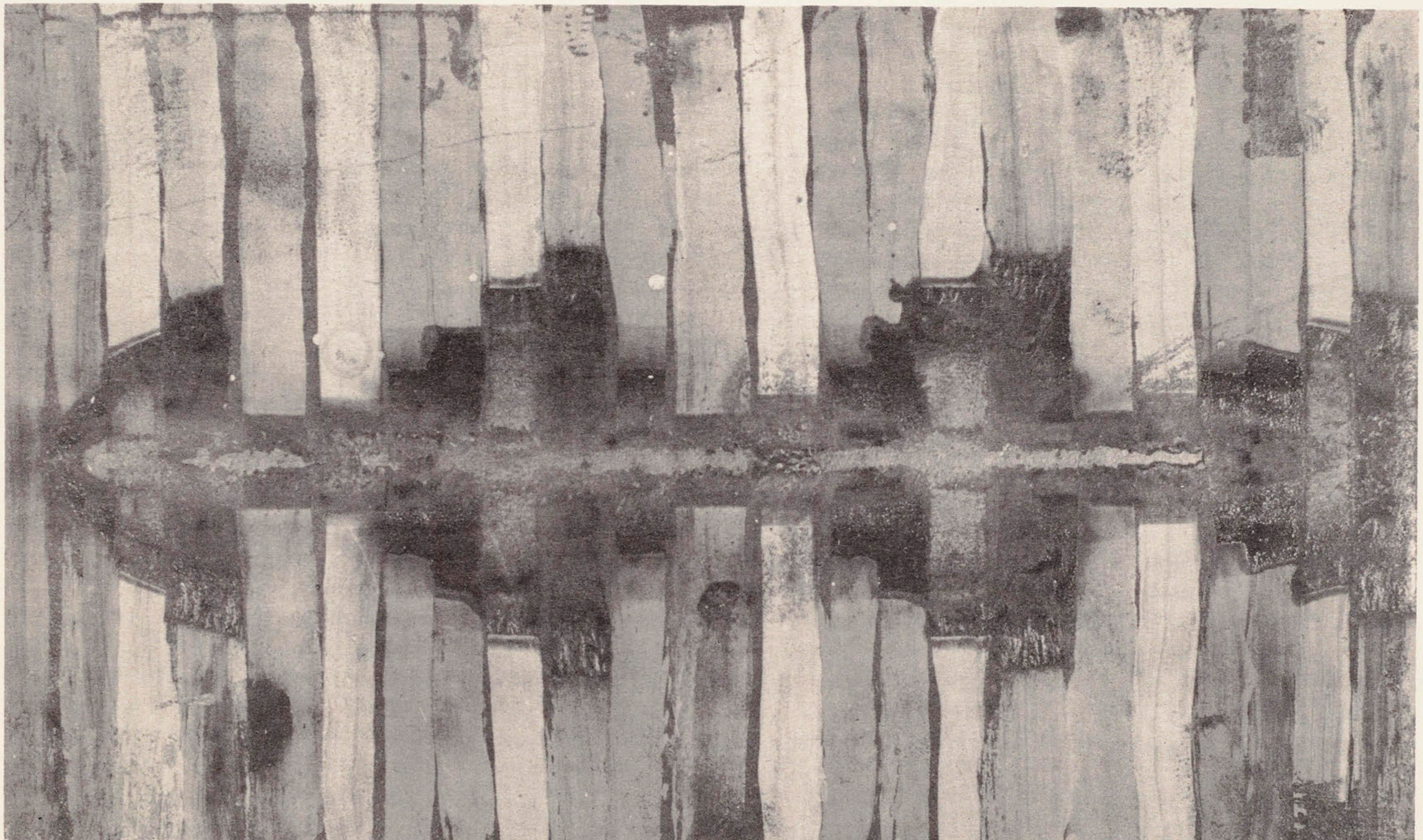
The lower portion just below the penetration level sees only a point heat source, namely the bottom of the weld pool. Thus the isotherms on our hypothetical top portion will be concentric around the "point source", as the actual bottom of the plate will not heat up from the same initial temperature as will the lower portion's top surface.

Thus any given weld will be defined by a combination of these two equations. If the engineer is concerned only with limiting temperature specifications, he may simply apply the one equation giving him the highest temperature, thereby incorporating a built-in safety factor.

However if the actual temperature is desired, more serious consideration will have to be given to the physical governing conditions present. This will probably include the depth of penetration relative to plate thickness, and most important the temperature limits with which he is working. For obviously a relatively low temperature at a high power input will indeed have its isotherms observably vertical with a negligible curvature, while in the same weld pass a temperature two hundred degrees higher may not even appear on the underside of the plate. Thus the extent to which the third dimension of the plate may be ignored is a function of the inverse temperature.

FIGURE 6

PHOTOGRAPH SHOWING RESPONSE TO WELDING HEAT OF LACQUERS, SENSITIVE TO VARIOUS TEMPERATURES. TEMPERATURE-SENSITIVE LACQUER IS OF GREAT VALUE IN EVALUATING PEAK TEMPERATURE DISTRIBUTION IN A HIGH CONDUCTIVITY MATERIAL (SUCH AS ALUMINUM), SINCE THIS SENSING DEVICE HAS NEITHER THE CONTACT NOR CAPACITY LAG CHARACTERISTIC OF THERMOCOUPLES.



RESULTS

The symbol $\hat{T}$ shall be used to designate peak temperatures.

RELATIONSHIPS BETWEEN $\hat{T}$, D, AND Q.

Graph #(2) shows clearly the relationship between the width of the zone at any given temperature and the heat input holding all other variables essentially constant.

Graph #(5) attempts to combine all the variables commonly encountered in automatic welding. In this case the voltage, amperage, carriage speed, plate thickness, and zone width have been combined and plotted against the temperature differential above room temperature.

Using this plot, or similar ones prepared for other materials, the critical $\hat{T}$ in any given weld may be met in terms of an expression specifying only the total of the factors involved.

In this way should one variable such as the amperage of the generating unit be a limiting one, it would be a relatively simple matter to adjust the others to reach this desired total.

It is interesting to note that in terms of dimensions, the plot is one of temperature rise versus watt-seconds per unit volume of material.

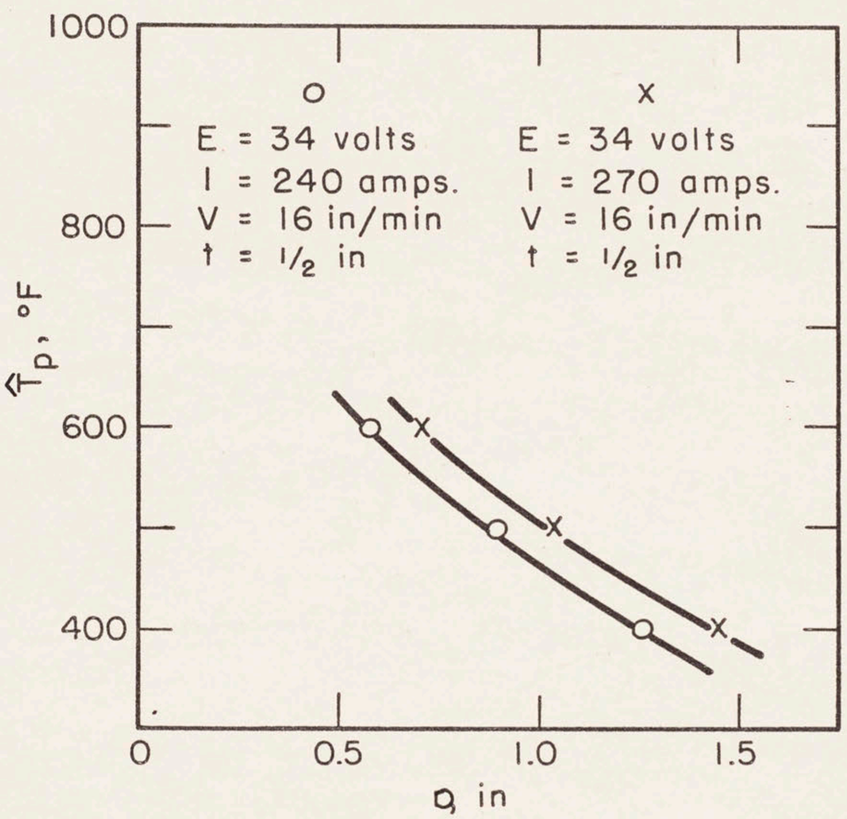


FIGURE 2

MEASURED PEAK TEMPERATURE DISTRIBUTIONS

SHOWING EFFECT OF AMPERAGE

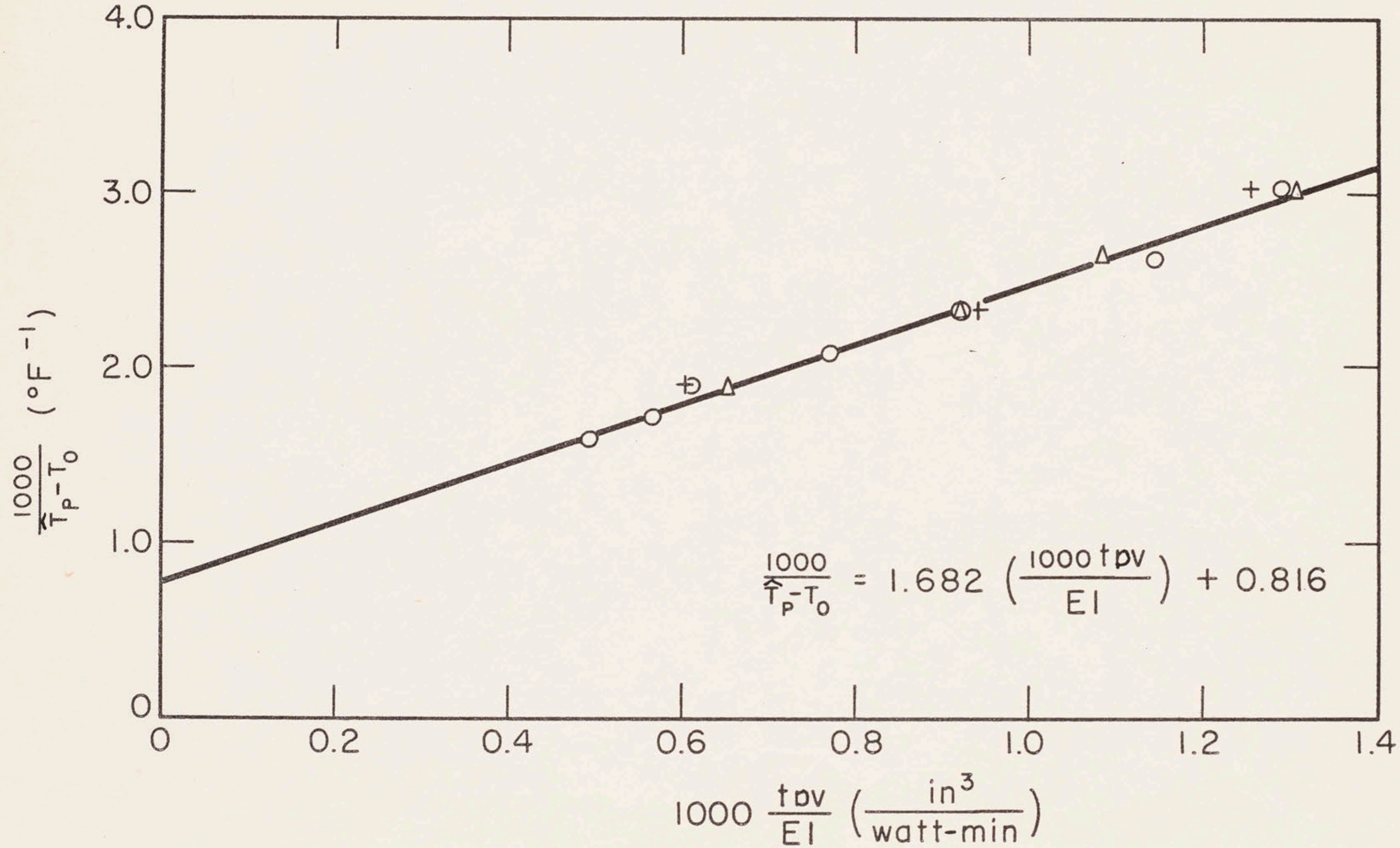


FIGURE 5

RECIPROCAL OF PEAK TEMPERATURE RISE IN ALUMINUM AS A FUNCTION OF: DISTANCE, D, FROM THE WELD CENTERLINE, PLATE THICKNESS, t, VELOCITY, V, VOLTAGE, E, AND AMPERAGE, I, UNDER CONDITIONS OF TWO-DIMENSIONAL HEAT FLOW.

EDGE EFFECTS AND PLATE GEOMETRY

This series of plots shows the change in heat flow due to varying temperature gradients and thus the variation in zone width with changing plate dimensions.

It is seen in graph #(1) that decreasing the width of the plate results in an increase in the width of the zone for any given temperature. In the same way, experimentation showed that a corresponding decrease in plate thickness increased the zone width as would be expected from the concept of ΔT versus watt-second per unit volume.

A similar effect was noted and is shown in graph #(1-A). It was observed that at high power inputs or low carriage speed, a plate less than one foot in length experienced heat reflection from the end of the plate ahead of the moving arc. This gave rise to a gradual increasing of the zone width. This same reflection effect caused zone widening when overly narrow plates were used and this widening overshadowed changes normally due to the increased temperature gradient.

When the power input was decreased 30%, the zone widths were unchanging within the first nine inches of the weld. However, upon approaching the end of the plate, widening was once again experienced.

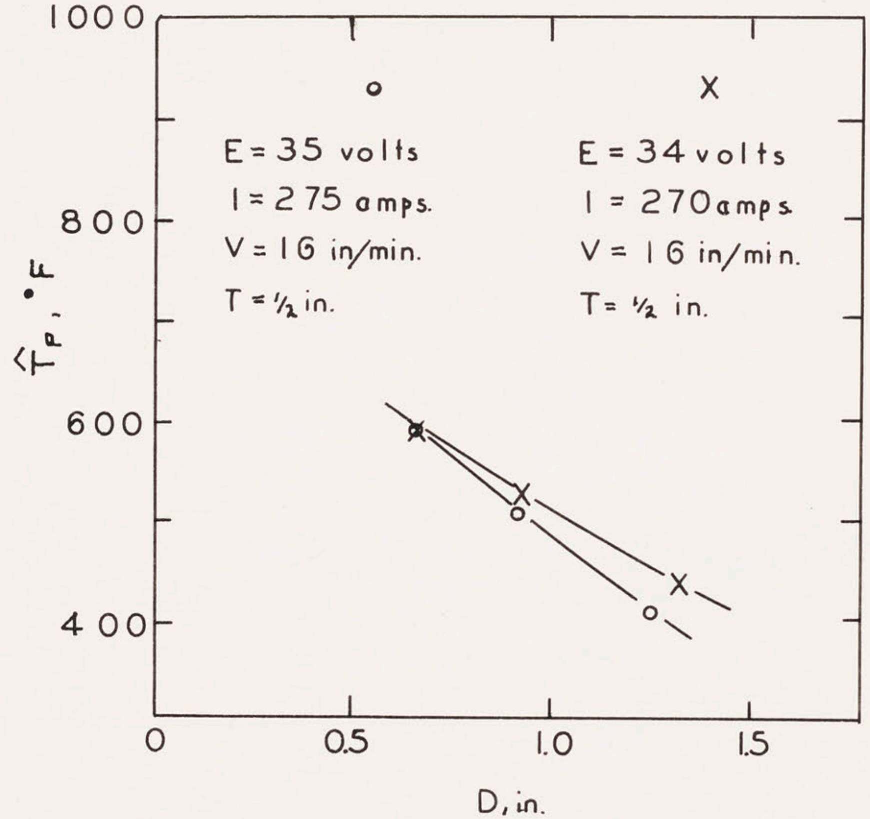


FIGURE 1

EFFECT OF PLATE GEOMETRY

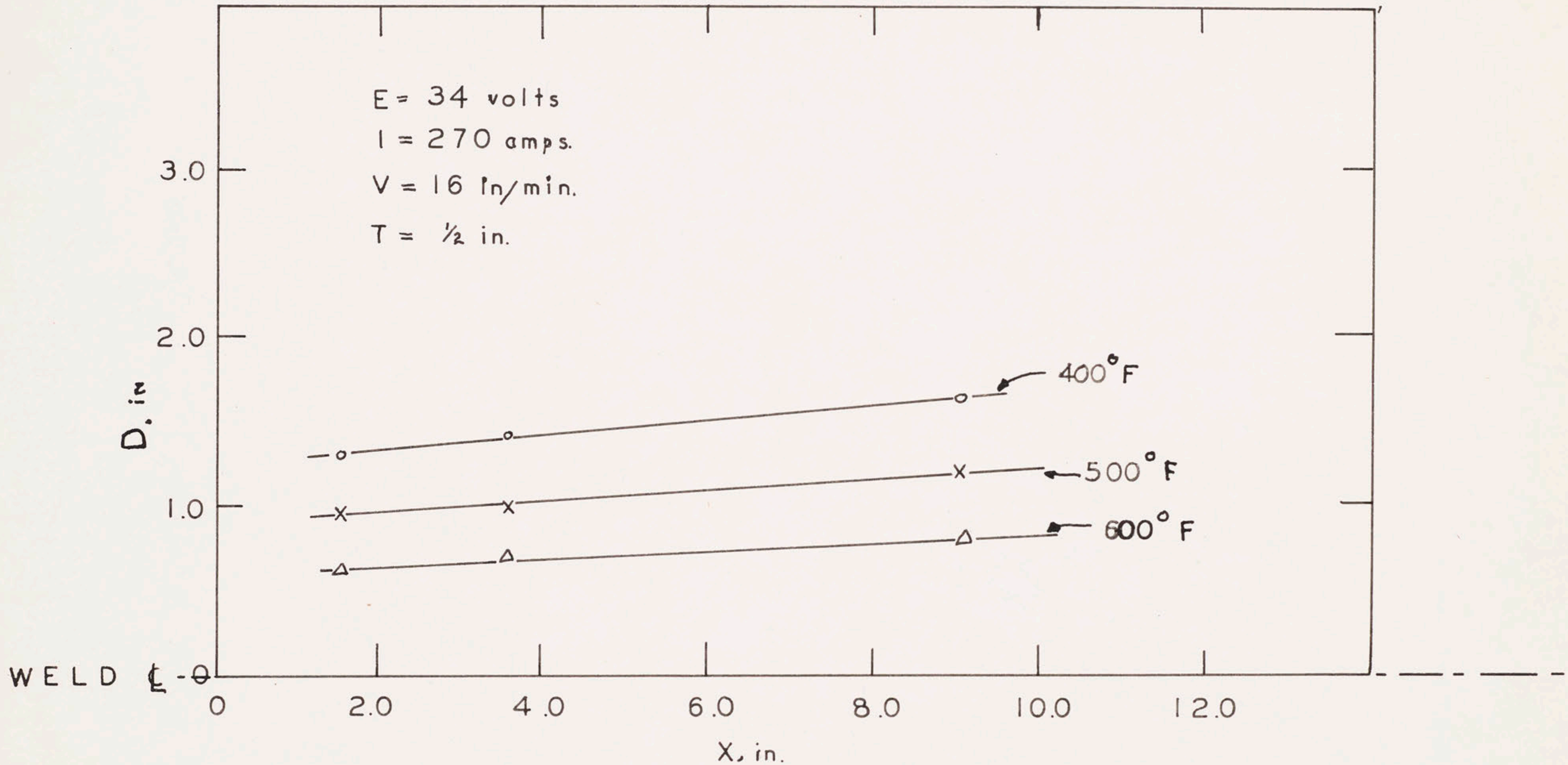


FIGURE I-A

EFFECT OF HEAT REFLECTION, END OF PLATE

INTENTIONAL PREHEAT

The top of the plate was preheated by torch to 225°F above room temperature. The plate was then allowed to cool to a 200°F differential and the weld pass was made. Due to this high degree of preheat, it would be expected that considerable reflection from the hot plate edges had occured, thereby, accentuating the zone width increase. **1-B

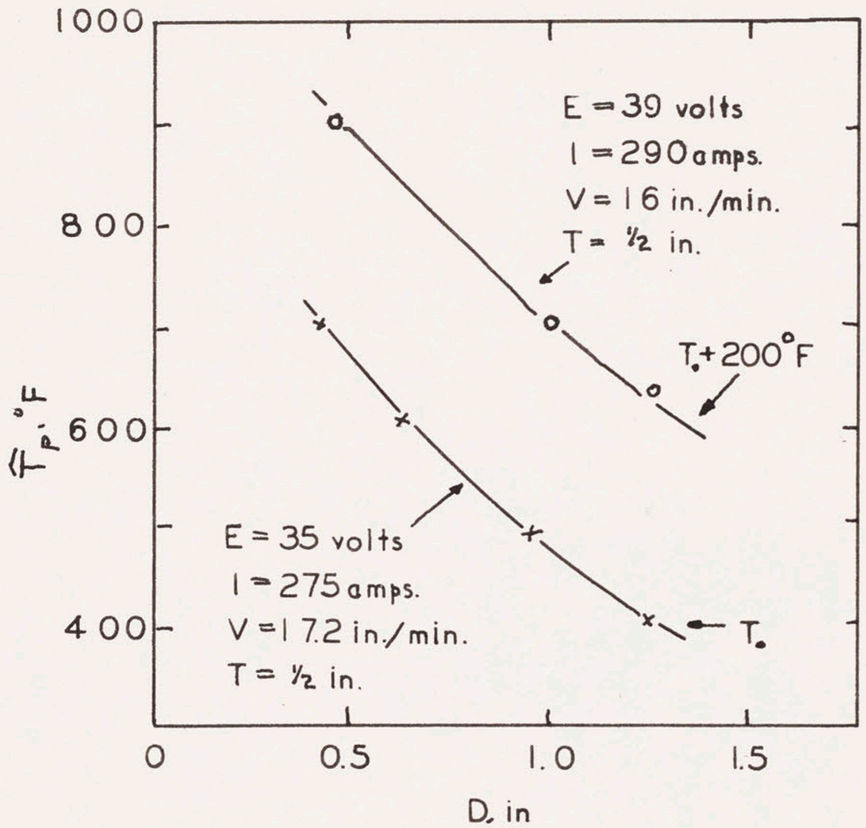


FIGURE 1-B

EFFECT OF PLATE PREHEAT

PEAK TEMPERATURES

As is seen on the accompanying graphs #(3) and #(4) no sharp lines exist in practice between two and three dimensional flow. Obviously in dealing with an aluminum plate one-half inch thick or greater, the extent to which the isotherms diviate from vertical is proportional to temperature.

For reasons of argument, if one assumes an error of 15% in temperature measurement, he may then state that all temperatures whose isotherms differ by less than 15% in width at a given temperature are vertical. Certainly it could be assumed that in our case to attempt to detect this difference below 500°F would be unreasonable.

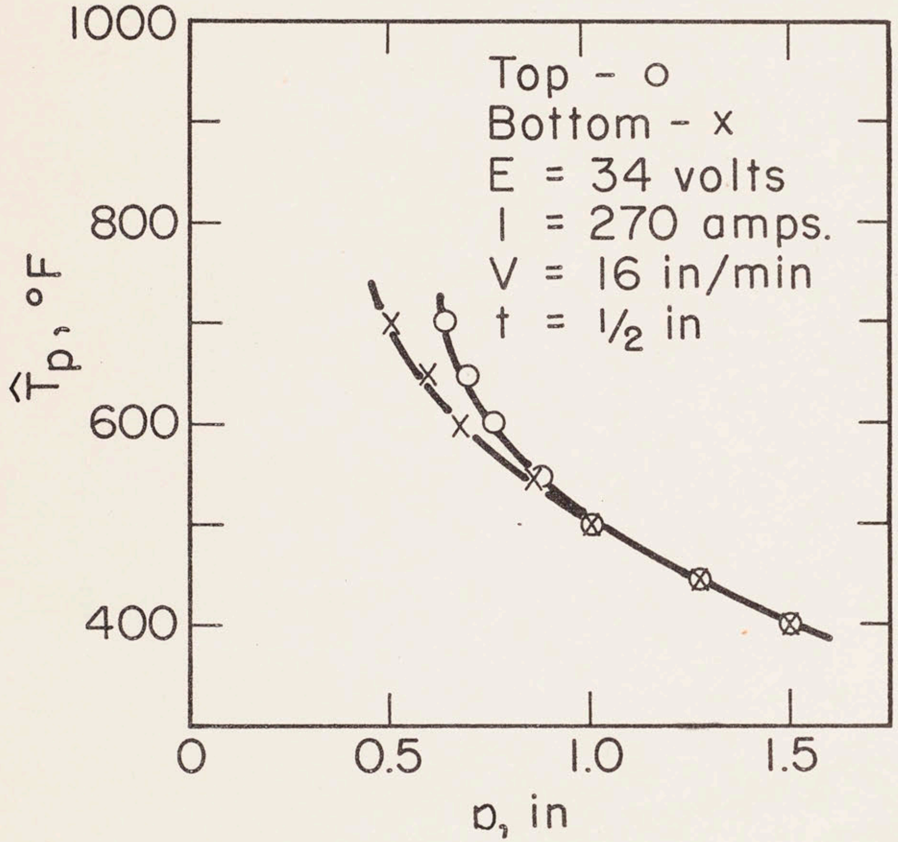


FIGURE 3

MEASURED PEAK TEMPERATURE DISTRIBUTIONS SHOWING SLIGHTLY HIGHER VALUES ON THE TOP (ARC) SIDE OF THE PLATE

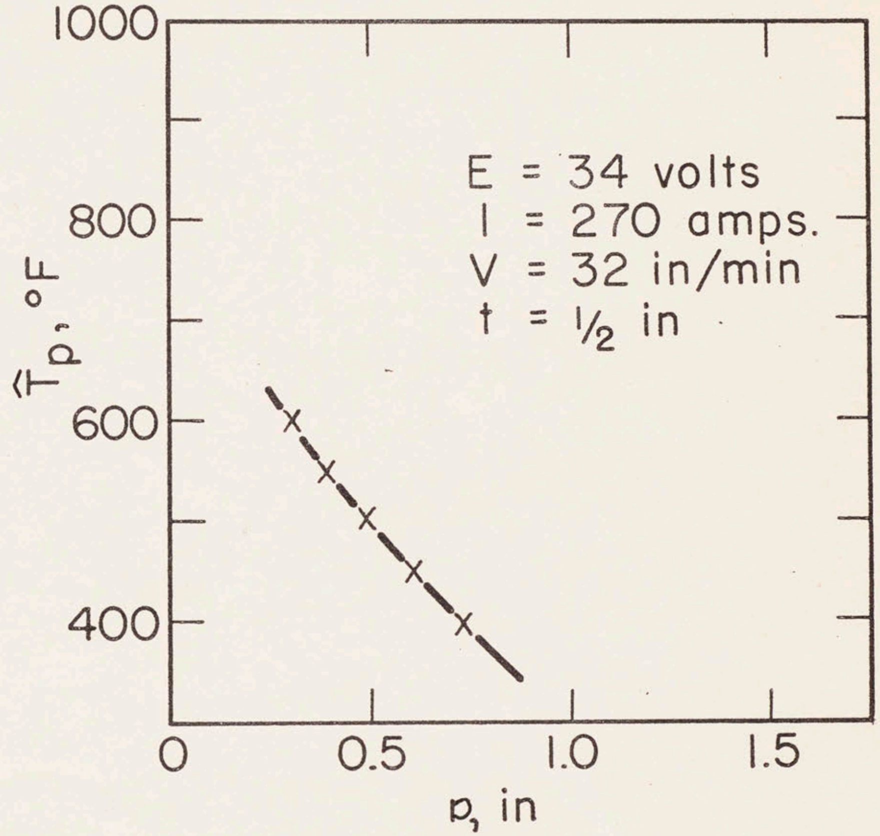


FIGURE 4

MEASURED PEAK TEMPERATURE DISTRIBUTION FOR HIGH VELOCITY WELD

INSTANTANEOUS RECRYSTALLIZATION

To obtain the data for graph #(7), weld #10 was cut perpendicular to the centerline and hardness data was taken as a function of distance from the centerline. The $\hat{T}$ values for the same locations were plotted along with the hardnesses and in this was the smooth curve for $\hat{T}$ as a function of hardness at any value was obtained.

Points from this curve were then superimposed on the corresponding furnace treatment curves. Here the predominant dependance of the transformation upon temperature and not time is seen clearly.

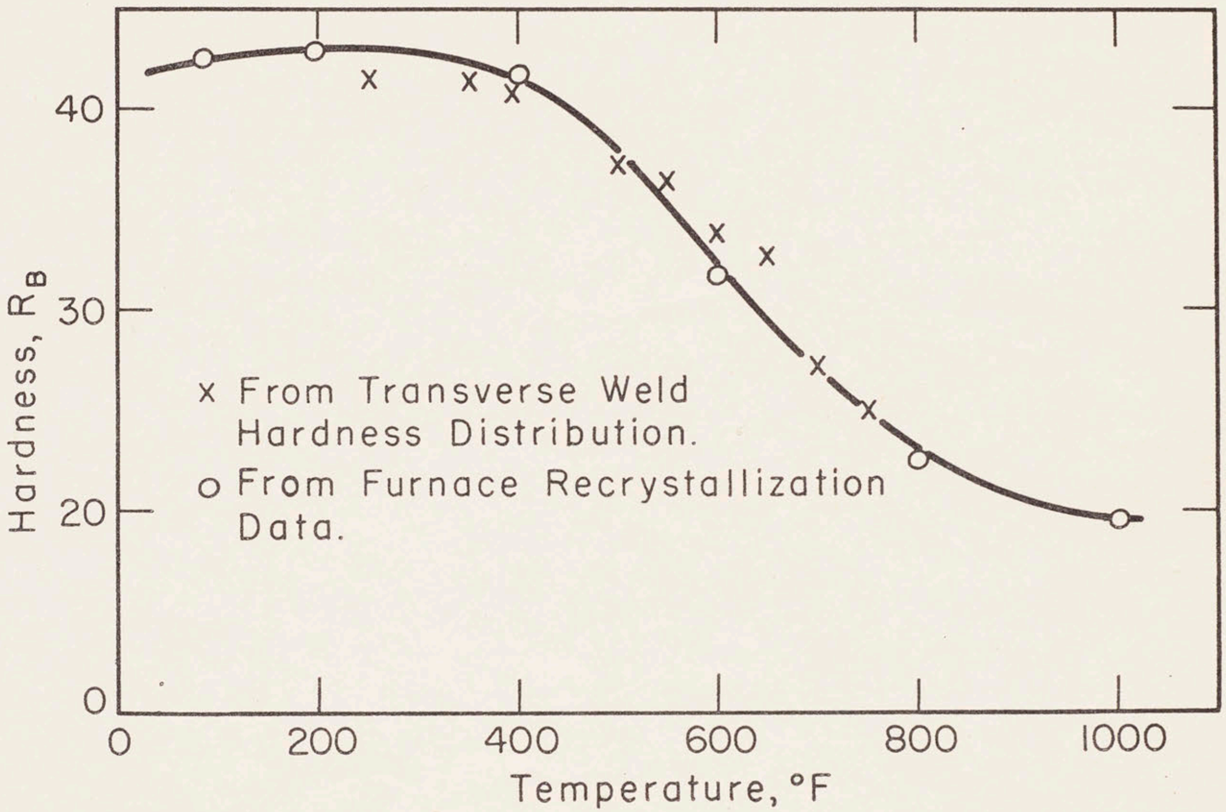


FIGURE 7

HARDNESS AS A FUNCTION OF (a) PEAK TEMPERATURE IN WELDING OR (b) FURNACE ANNEALING TEMPERATURE, ALLOY 5356-H321.

In addition, welds were made with the following general results being obtained.

For this welding situation, heat losses due to convection and radiation were not large enough to be measured by this method.

An increase or decrease of 50% in the gas flow rate caused no noticeable $\hat{T}$ changes.

CONCLUDING REMARKS

This investigation has not attempted to cover completely any one of the phases entered. Rather, it has been the object to explore several related effects and problems encountered in a general way, and in so doing to open the door to further use of the lacquers and the avenues of investigation which they present.

Suggested fields for further work would have to include all of this report with particular emphasis upon the problem of equating instantaneous recrystallization times to their furnace counterparts.

DATA:

WELD	TxWxL	V	I	s	Gas Flow	Material	Remarks
1	½x6x10	35	290	25	130	6061	
2	⅛x10x12	23	215	25	*60	6061	
3	⅛x7x4	23	215	25	*60	6061	
4	½x11x8	39	290	16	130	6061	200° F Pre-heat
5	½x8x11	34	270	16	130	6061	
6	½x8x20	34	270	16	130	6061	
7	½x12x12	35	275	16	130	5056	
8	½x11.5x 12	35	275	17.2	130	5056	
9	½x8x12	34	240	16.5	130	5056	
10	½x8x50	34	270	16	130	5056	
32	½x8x12	34	270	32	130	5056	
	"	volts	amps	"/min	ft³/min		

*denotes Argon rather then Helium

WELD	Location	350°	400°	450°	500°	600°	650°	700°	900°
1	Bottom	1.25						0.5	
2	Top	2.0						0.88	0.75
	Bottom	2.0						0.81	0.50
3	Top							0.7	0.5
4	Reverse	3.0						1.0	0.46
5	Top		1.50	1.31	1.06	0.75	0.70	0.63	
	Bottom		1.50	1.31	1.06	0.70	0.6	0.50	
6	Top		1.50		1.06	0.75			
	Bottom		1.50		1.06	0.62			
7	Top		1.25		0.94				
	Bottom		1.25		0.94	0.63			
8	Top		1.25		0.94				
	Bottom		1.25		0.94	0.63	0.44		
9	Top		1.25		0.88	0.63			
	Bottom		1.25		0.88	0.56			
10	Top		1.44		1.06	0.72			
	Bottom		1.44	1.22	1.03	0.66	0.59		
32	Top		0.75	0.62	0.56	0.44			
	Reverse		0.75	0.62	0.50	0.31	0.16		

Distance from weld ℄	0	.25	.50	.75	1.0	1.25	1.5
Hardness, R_B	24	25	32	36	38	40	42

From weld number 10