

PARAMETRIC STUDY OF HEAT FLOW DURING RESISTANCE SPOT WELDING

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Abstract

A linearized lumped parameter heat balance model was developed and is discussed for the general case of resistance welding to see the effects of each parameter on the lobe shape. The parameters include material properties, geometry of electrodes and work piece, weld time and current, and electrical and thermal contact characteristics. These are then related to heat dissipation in the electrodes and the work piece.

The results indicate that the ratio of thermal conductivity and heat capacity to electrical resistivity is a characteristic number which is representative of the ease of spot weldability of a given material. The increases in thermal conductivity and heat capacity of the sheet metal increase the lobe width while increases in electrical resistivity decrease the lobe width.

Inconsistencies in the weldability of thin sheets and the wider lobe width at long welding times can both be explained by the heat dissipation characteristics. These are mainly a function of the ratio of electrode diameter to the square of the work piece thickness.

Introduction

The weldability of a material in resistance spot welding is determined by two main factors. Firstly, the width of the lobe curve, which shows the permissible weld current range at a constant weld time and secondly the wear of the electrodes. These two factors are controlled by the interplay between the many parameters which govern the temperature distribution in the parts during the welding thermal cycle.

A number of analytical and numerical models have been developed to understand the mechanism of nugget formation (1-9). Although the models have attempted to incorporate the complexities of the weld parameters, these models offer very limited explanations about the effect of each parameter on the weld lobe curve. In order to understand the basics of weld lobe shape, a linearized lumped parameter heat balance model was developed for the general case of resistance spot welding. It is hoped that this model will show the effect of each parameter on the lobe curve shape. The variables include the welding current and time, the geometry of electrodes and the work pieces, electrical contact resistance, material properties, phase changes and heat dissipation into the cooling water and the surrounding sheet metal.

Model Development

The model described in figure 1 was developed to determine the heat balance in the system as a function of nugget growth. A temperature discontinuity at the electrode-work piece interface is assumed. The overall thermal equilibrium is established by considering a adiabatic boundary at the electrode and the work piece surfaces except the contact surfaces and water cooling surfaces. A fixed temperature θ_c , equal to the cooling water temperature is assumed at the internal water cooling surface of the electrode. The size of the work pieces is assumed to be infinite in the radial direction. The nugget shape is assumed to be a disk growing radially and axially in the same proportions as found in a post mortem examination of the maximum nugget size. This assumption is supported by the computer simulation results found in reference 9. The expulsion nugget size is assumed to have 80% penetration and to be equal to the electrode contact diameter. The equations are established with linearized lumped parameters.

The total heat generation rate, $\dot{Q}_g$, can be described as

$$\dot{Q}_g = I^2 R \quad (1)$$

where, $R = R_w + R_c + R_e$
 R_w : work piece bulk resistance
 R_c : total contact resistance
 R_e : electrode resistance
 Δt : welding time
 I : welding current

The heat of fusion required for nugget formation, h_f , is

$$H_f = H \Delta V_n \quad (2)$$

where, H : heat of fusion per unit volume
 ΔV_n : nugget volume ($=\pi a^2 p$)

If the temperature rise in the model is described in the three different regions with lumped quantities, the total heat required is,

$$\begin{aligned} Q_T &= \rho_n C_{pn} \Delta\theta_n \Delta V_n + \rho_s C_{ps} \Delta\theta_s \Delta V_s + \rho_e C_{pe} \Delta\theta_e \Delta V_e \\ &= Q_T^n + Q_T^s + Q_T^e \end{aligned} \quad (3)$$

where, ρ : density
 C : specific heat
 V^p : volume
 $\Delta\theta$: temperature rise
 n : in a nugget
 s : in surroundings
 e : in electrodes

Thus the total heat balance including the total heat loss rate, $\dot{Q}_L$, through the model boundaries (into the cooling water) can be written as follows.

$$\dot{Q}_g \Delta t = H_f + Q_T + \dot{Q}_L \Delta t \quad (4)$$

Effect of Material Properties

Equation (4) can be rearranged as

$$(I^2 - \dot{Q}_L/R) \Delta t = (H_f + Q_T^n + Q_T^s + Q_T^e)/R \quad (5)$$

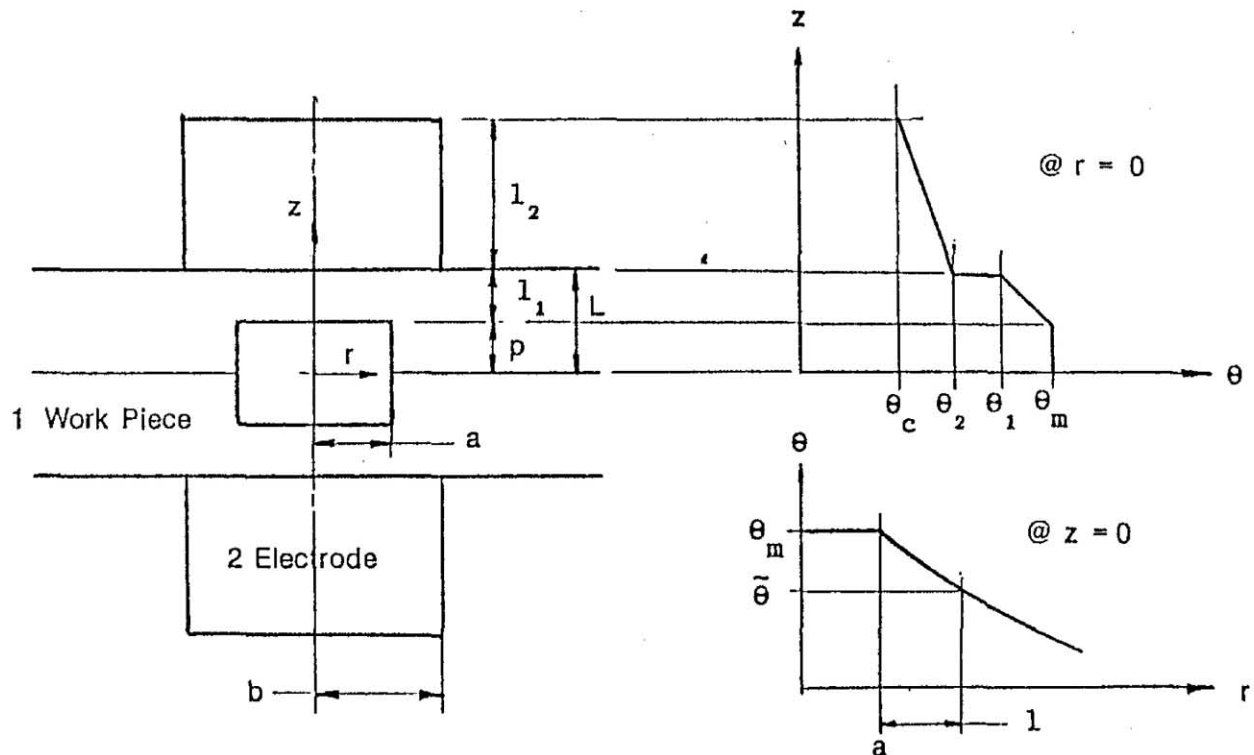


Figure 1: An Approximate Nugget Growth Model with Corresponding Temperature Profiles.

Neglecting both the heat loss and temperature rise in the electrodes and the temperature rise in the surroundings,

$$\epsilon \cdot I^2 R \Delta t = (H + \rho_n C_{pn} \Delta \theta_n) \Delta V_n \quad (6)$$

ϵ : efficiency of heat input

This is basically a lobe curve, which is a hyperbola with axes of welding time, Δt , and the square of the welding current, I . This basic lobe curve may be translated or rotated or distorted by changes in each parameter. The nugget volume, ΔV_n , is constant for a certain size of nugget. In this case, equation (6) approaches a constant value. Figure 2 represents equation (6) with two different nugget sizes. The larger nugget size shifts the lobe curve in the direction of higher currents or longer weld times.

The effect of $\rho_n C_{pn}$ and H can be considered in a similar way. Equation (6) also shows the effect of these parameters. Higher values of $\rho_n C_{pn}$ and H shift the lobe curve in a like manner as does a larger size nugget. The temperature dependence of $\rho_n C_{pn}$ will affect the lobe shape as shown in figure 3.

The effect of electric resistance can be considered as follows,

$$I^2 \Delta t = \text{constant}/R \quad (7)$$

Generally, the dynamic resistance changes in the manner shown in figure 4, at least for steel. Even though R_c drops very fast during the early weld cycles, its contribution to the thermal field seems to be great due to its large magnitude. Higher R_c values will shift the lobe curve farther to the left as shown in figure 5-a. The ratio of R_c to R_w may also affect the nugget growth mechanism due to differences in the heat generation pattern. It is also possible to see the effect of electrode pressure in equation (7). Since higher electrode pressure results in a lower R_c , the lobe curve will shift as in figure 5-a.

The heat required to raise the temperature of the material surrounding the nugget, Q_T^s , and the heat requires to raise the temperature of the electrodes, Q_T^e , can be seen in equation (5). If these terms are added to the right hand side of equation (6), the lobe curve will be shifted in the direction of higher energy input. In equation (5) one can see that the

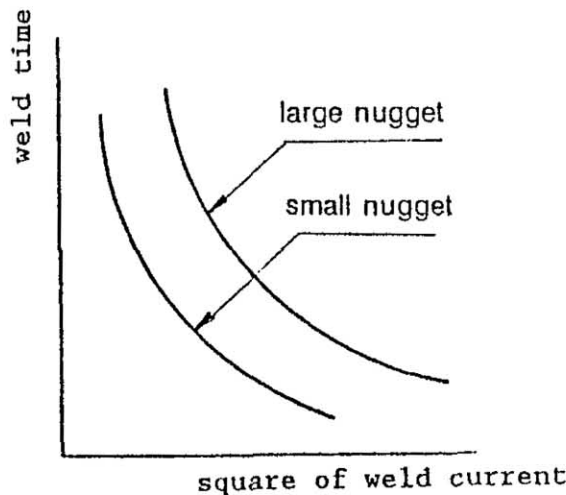


Figure 2: Basic Lobe Curve

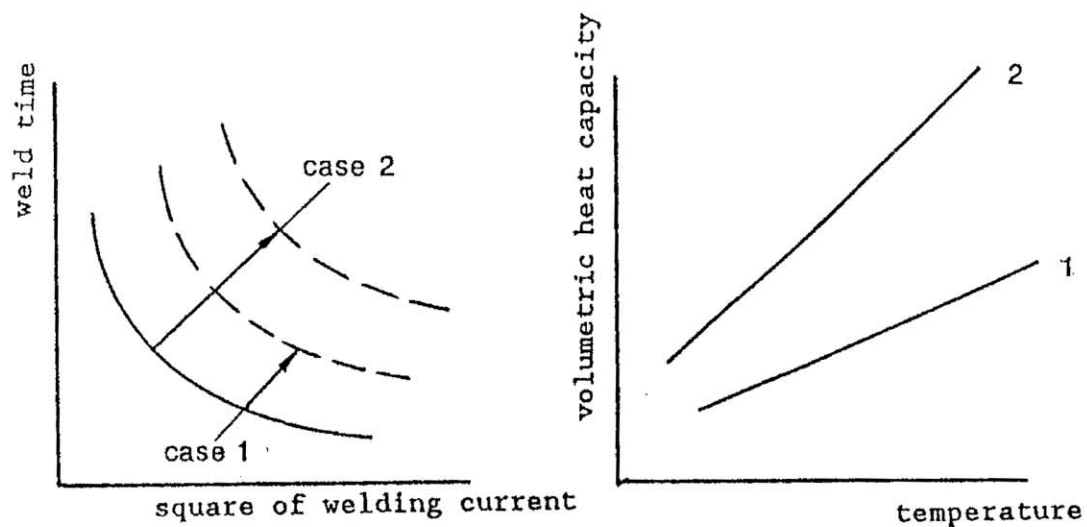


Figure 3: Effect of ρC_p Change.

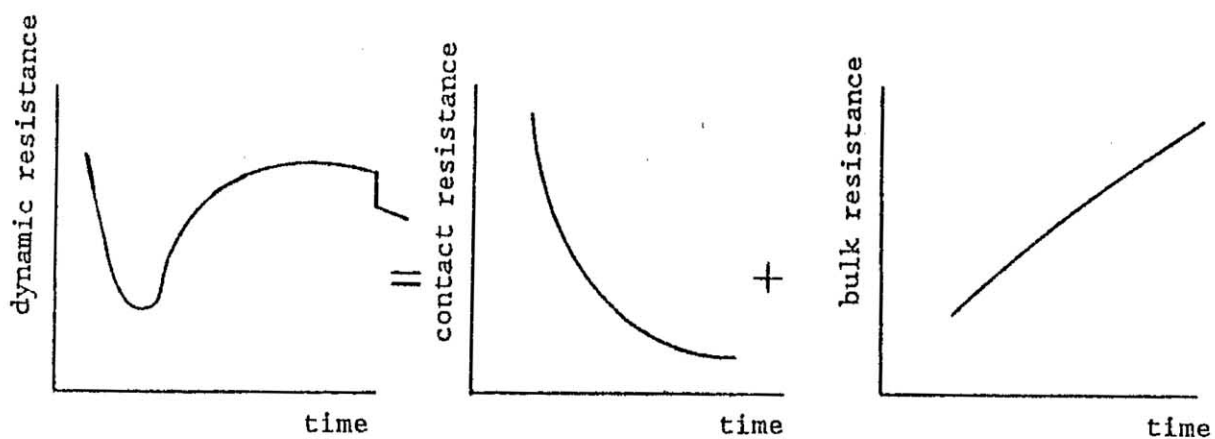


Figure 4: Typical Dynamic Resistance Change

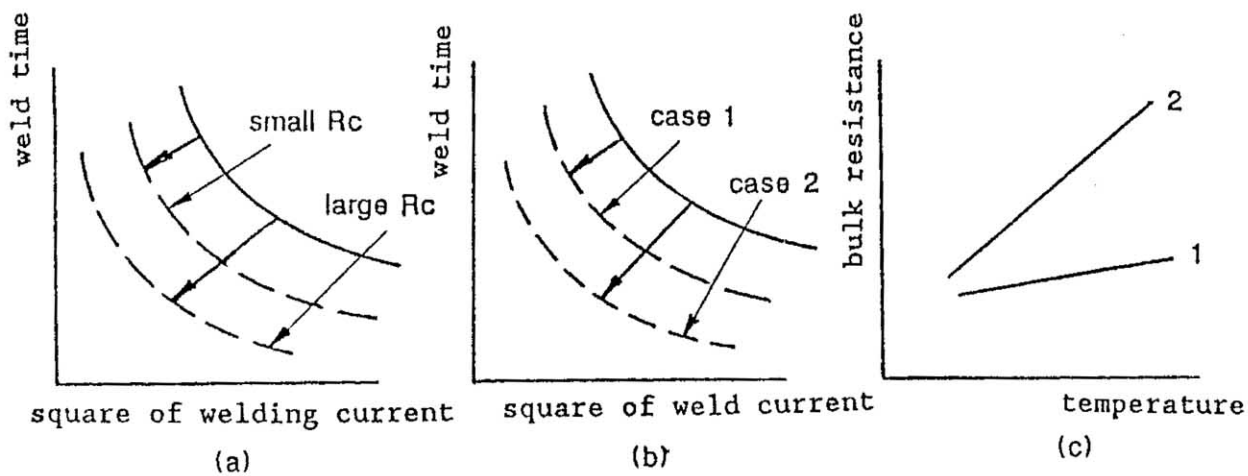


Figure 5: Effect of Resistance Change.

extent of this shift is determined by the ratio of the amount of heat required for heating of the electrode and the work piece divided by the electrical resistance (i.e. the ratio of heat capacity to electrical resistivity, σ). This is an important parameter in the characterization of nugget growth mechanisms and lobe curve.

Effect of Geometry and Heat Loss

Considering the total heat loss rate, equation (6) changes to

$$(I^2 R - \dot{Q}_L) \Delta t = \text{constant} \quad (8)$$

This shifts the lobe curve in the high current direction by $\dot{Q}_L/R$, which is actually a function of the thermal properties of the material and of the geometry. This is shown in figure 6. Here, one can see that the ratio of the heat loss rate to the resistance (i.e. the ratio of thermal conductivity to electrical resistivity σ) can be a important parameter in the characterization of nugget growth and weld lobe shape.

The total heat loss rate of the nugget, $\dot{Q}_L^n$, is the sum of the axial heat loss rate through the electrodes, $\dot{Q}_a$, and the radial heat loss rate through the work pieces, $\dot{Q}_r$. The thermal conductivity of the copper electrode is much greater than that of the work piece materials (this is not the case for aluminum welding) and the time scale of the process is on the order of 1/10 second (5 to 20 AC cycles). In this time scale the heat diffusion distance in the electrode is about 3 mm while it is 1 mm in the steel. When the electrode face thickness is very thin (e.g. less than 3 mm) the heat generated in the electrodes and that transferred from the work piece will be carried away by cooling water while the nugget develops. In this case the heat dissipation in the axial direction is influenced by the heat transfer characteristics of the cooling water. If the electrode face thickness is greater than 3 mm, the heat transferred from the work pieces and that generated in electrode itself will be used to heat up the electrodes. Hence a smaller portion of the heat may be carried away by the cooling water during nugget development. In any case, if it is assumed that the temperature build up in the electrodes has already been reached when melting starts in the nugget, the heat flux in the axial direction can be thought to be balanced during nugget growth with θ_i as a interface temperature at the work piece side. Therefore, the heat loss rate, $\dot{Q}_L$, into the cooling water will be roughly equal to the axial heat loss rate, $\dot{Q}_a$.

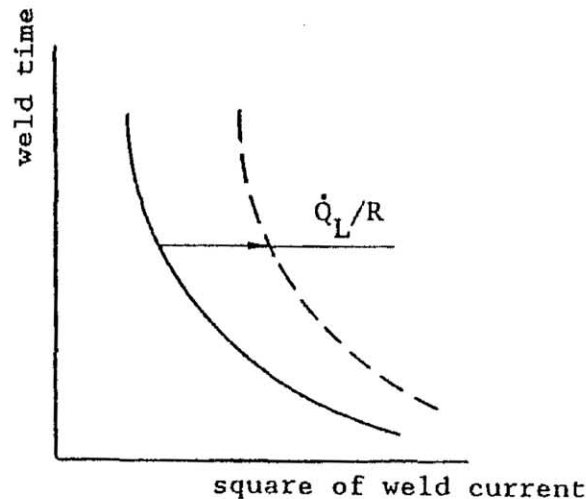


Figure 6: Effect of Heat Loss

The heat loss in the axial direction is assumed to be proportional to the square of the nugget radius. The temperature profile between the interface and the melting front is assumed to be linear. Then the axial loss rate is,

$$\dot{Q}_a = k_1 (\theta_m - \theta_1) \pi a^2 / l_1 \quad (9)$$

Where, k_1 : thermal conductivity
 θ_1 : melting temperature
 θ_m : interface temperature at work piece
 l_1 : distance from melting interface to electrode contact surface
 a : nugget radius

The heat required for the temperature rise in surrounding nugget material, $\dot{Q}_r$, is thought to be determined by the heat flux out of the nugget, $\dot{Q}_r$, and the heat generation in surrounding material itself. The temperature distribution in this region is assumed to be mainly determined by $\dot{Q}_r$ when the nugget has grown to sufficient size. If the heat loss through the work piece is assumed to be proportional to the area of the nugget side wall, then,

$$\dot{Q}_r = k_1 (\theta_m - \bar{\theta}) 2\pi a p / l \quad (10)$$

Where, $\bar{\theta}$: characteristic surrounding temperature
 l : characteristic heat diffusion length

The thermal conductivity, k_1 , included in the heat loss equations changes with temperature while the interface temperature, θ_1 , is also affected by geometry and interfacial characteristics. This is also affected by the heat generation pattern due to the electrical resistivity change with temperature.

The interface temperature change is shown in figure 7, assuming a steady state heat flux balance without heat generation included. As the distance l_1 decreases with growing nugget size, the interface temperature rises with nugget growth.

A rough comparison of heat loss in two directions can be made considering growth of the nugget. The ratio of axial heat loss, $\dot{Q}_a$, to the radial loss, $\dot{Q}_r$, is,

$$\frac{\dot{Q}_a}{\dot{Q}_r} = \frac{(\theta_m - \theta_1) a l}{(\theta_m - \bar{\theta}) 2 p l_1} \quad (11)$$

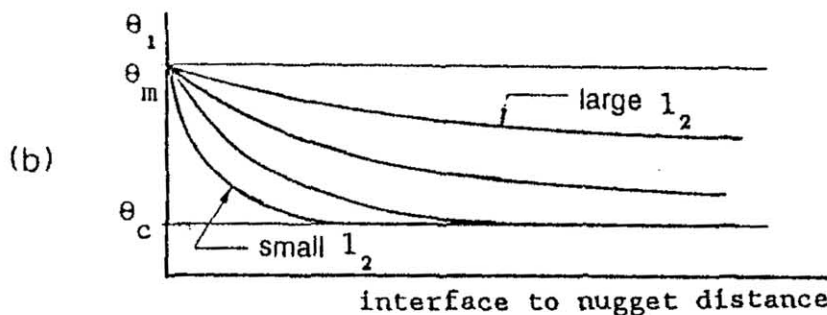


Figure 7: Change of Interface Temperature Due To a Geometrical Change.

Assuming nugget size growth is proportional to the geometry of the electrode and the thickness as explained in the model development section,

$$p = a\beta L/b \quad (12)$$

where, p : penetration
 β : final penetration to work piece thickness ratio
 (about 0.8)
 b : electrode contact surface radius

Then the final ratio becomes,

$$\frac{\dot{Q}_a}{\dot{Q}_r} = \frac{(\theta_m - \theta_1)b l_1}{2(\theta_m - \bar{\theta})\beta L l_1} \quad (13)$$

Assuming the nugget front revises its position at every half cycle (1/120 sec) in AC welding,

$$\bar{\theta}/\theta_m = 0.9, \quad \text{when } l=0.2 \text{ at } -\sqrt{\alpha}/50,$$

α : thermal diffusivity of work pieces

$$\frac{\dot{Q}_a}{\dot{Q}_r} = \frac{(\theta_m - \theta_1)b\sqrt{\alpha}}{10 \theta_m \beta L l_1} \quad (14)$$

As l_1 reaches its final value abruptly, and if l_1 and θ_1 are assumed constant, the heat loss ratio in equation (14) is proportional to the parameter b/L^2 . The effect of this parameter on the heat loss ratio is plotted in figure 8-a. The ratio is also a function of the thermal diffusivity, α .

The total heat loss can be described as follows using equations (9), (10) and (12).

$$\dot{Q}_L^n = \dot{Q}_a + \dot{Q}_r = k_1 \pi a^2 [(\theta_m - \theta_1)/l_1 + 10(\theta_m \beta L)/(b\sqrt{\alpha})] \quad (15)$$

As the nugget diameter, a , increases with time, the rate of heat loss in the nugget, $\dot{Q}_L^n$, increases in a quadratic manner. But this should be compensated by changing the axial temperature gradient in the work piece, $(\theta_m - \theta_1)$, which seems to decrease with time. The thermal conductivity also affects the total heat loss as shown in figure 8-b.

It is almost certain from this analysis that the electrode geometry and the work piece thickness are very important factors not only in the distribution of the heat generation rate but also in determining heat dissipation characteristics of resistance spot welding. Generally, as one welds thinner sheet metal, the temperature gradients in the sheet become steeper and a greater portion of the total heat is lost to the electrodes.

Discussion

The ratio of the axial heat loss rate to the radial heat loss rate changes in proportion to the parameter b/L^2 . By reducing the thickness by half, the ratio increases by a factor of four. This means that a thinner work piece will lose an even greater fraction of the heat by conduction

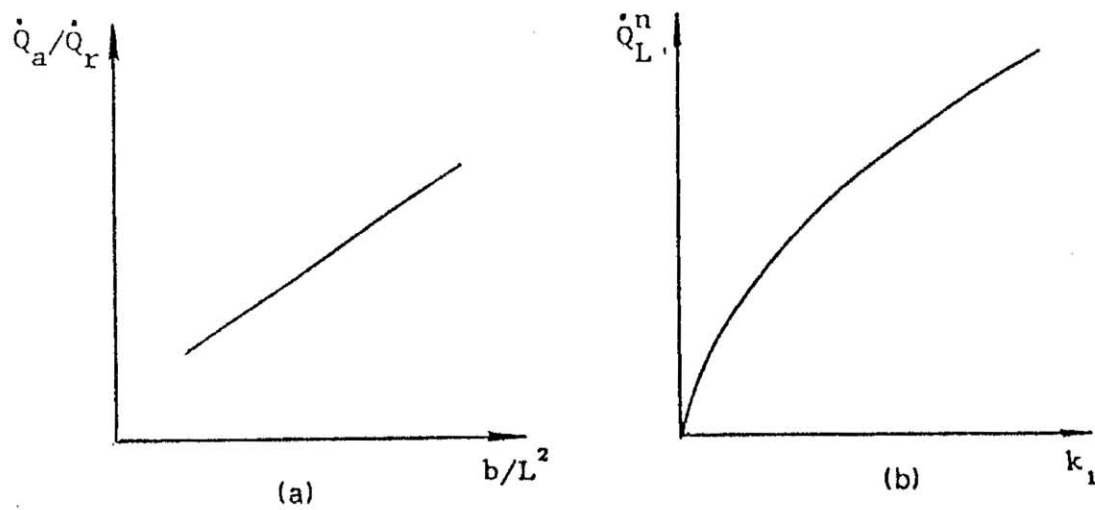


Figure 8: Characteristics of Heat Loss.

into the electrode. Thus, heat transfer through the electrode-work piece interface will dominate the nugget growth mechanism in thin sheet welding. A very small variation in the contact characteristics may result in great inconsistency in weldability. This will be more pronounced as the work piece thickness becomes less. This may also increase the maximum temperature which the electrode achieves or the length of time at this temperature. In addition, this may cause a large reduction in electrode life especially in galvanized steel welding.

In equation (15), the axial heat loss rate, $\dot{Q}_a$, is proportional to $k_1 a^2/l$ and the radial heat loss rate, $\dot{Q}_r$, is proportional to $\sqrt{k} a^2$. According to these relationships the shift of the expulsion lobe boundary will be larger than that of the minimum nugget boundary due to the difference in the nugget size, a . Therefore, if the thermal conductivity of the metal is increased, the lobe width will be increased along with a translation of the lobe in the direction of high energy input.

Material with high contact resistance, R_c , requires relatively less heat input. This may be due to the early temperature build up within the system before the start of nugget formation. This may also increase the lobe width, possibly due to an early start of nugget formation at low current levels. Specifically, the increase in the lobe width may be due to the larger increase in the total heat loss produced by larger size nuggets and the longer heat dissipation time.

The change of work piece bulk resistance, R_w , to a higher value will move the lobe position in the direction of lower energy input. From equation (6), it can be seen that this shift is greater when the nugget size is large. This will reduce the lobe width.

It is obvious that the lobe will shift in the direction of high energy input if the value of volumetric heat capacity, ρC_p , is increased. This can be easily seen from equation (5). If nugget size P is considered, the shift will be greater with a larger size nugget. Thus, a wider lobe width is possible if a material with a high volumetric heat capacity, ρC_p , is used.

It is seen that the ratio of material properties $\rho C_p/\sigma$ and k/σ could be important factors which affect the lobe shape. The increase in the

volumetric heat capacity, ρC , and thermal conductivity of the work pieces, k , will increase the lobe width and will require a larger total heat input. On the contrary, an increase in electrical resistivity will decrease the lobe width and the total amount of heat necessary to form a nugget. Therefore, these two ratios can be used as parameters to describe the weldability of a specific material. In general, it can be said that a material with large values of these ratios will have a wider lobe width and will require a higher energy input.

Different combinations of weld time, Δt , and weld current, I , will have different effects on the lobe shape. Welding with high current at short nugget growth times will result in a smaller heat loss to the surroundings. On the contrary, long weld times with lower currents will produce greater heat loss. As this will demand a higher heat input for the same sized nugget, the slope of the lobe curve in this region will become steeper. This can also explain the reason why the lobe is wider in the long weld time region.

Thus far it was assumed that heat transfer through the electrode-work piece interface is not a rate controlling step. If the interface has very high thermal resistance, the heat loss to the electrode will be reduced and the lobe width will decrease. This may be the case with hard materials such as high strength low alloy steel compared to a low carbon steel. The experimental data in reference 10 support this argument (10).

Conclusion

A parametric heat flow analysis of the resistance spot welding process shows that:

1. The ratio of the heat loss rate in the electrode compared to the heat loss rate in the work piece is a function of the electrode diameter divided by the square of the work piece thickness.
2. Thinner gage welding is more sensitive to the contact variations
3. Thinner gage sheets increase the electrode surface temperature
4. The ratio of thermal conductivity and heat capacity to electrical resistivity is a characteristic number which is representative of the ease of spot weldability of a given material. The increases in thermal conductivity and heat capacity of the sheet metal increase the lobe width while increases in electrical resistivity decrease the lobe width.
5. Welding with a high electrical contact resistance will increase the lobe width provided that increasing this resistance does not produce expulsion at the electrode-sheet interface.
6. The wider lobe width of long time - low current welds can be explained by the larger amount of total heat dissipation due to the longer weld time and the larger heat loss area of larger nuggets.

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