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*Melting Efficiency in Fusion Welding**

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Abstract

Basic to our knowledge of the science of welding is an understanding of the melting efficiency, which indicates how much of the heat deposited by the welding process is used to produce melting. Recent calorimetric studies of the GTAW, PAW, and LBW processes have measured the net heat input to the part thereby quantifying the energy transfer efficiency and in turn permitting an accurate determination of the melting efficiency . It is indicated that the weld process variables can dramatically affect the melting efficiency and that all fusion welding processes can be optimized to produce the same maximum melting efficiency. This limiting value is shown to depend on the weld heat flow geometry as predicted by analytical solutions to the heat flow equation and as demonstrated by the recent empirical data. A new dimensionless parameter is used to predict the melting efficiency and is shown to correlate extremely well with recent empirical data. This simple prediction methodology is notable because it requires only a knowledge of the weld schedule and the material properties in order to estimate melting efficiency.

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Introduction

Fusion welding is a metal fabrication process that heats a small volume of metal to its melting point and consequently locally heat treats the adjacent material. Because the induced thermal cycle is not uniform throughout the weldment, thermal expansion and contraction inevitably lead to yielding, shrinkage, and distortion of the weldment. Factors which can minimize the thermal expansion of the weldment will thereby reduce residual stresses, and undesirable geometrical changes. Reducing the size of the melted region will reduce the amount of shrinkage since the amount of heat required to melt the fusion zone is proportional to the volume of the fusion zone. However, the amount of heat required to melt a given volume of material is not fixed and can be minimized. A critical measure of heat deposition is the melting efficiency. Melting efficiency is defined as the amount of heat required to just melt the fusion zone relative to the net heat input deposited in the part. (1)

It has been the experience of the author that many high value added and remarkably, even heat sensitive products, are routinely welded with weld parameters that produce a low melting efficiency. Welds are inspected and deemed acceptable even though two to three times more heat may have been deposited into the part than is required for the size of the fusion zone produced, oftentimes with low production yields as a consequence. The additional cost of rework is simply not necessary when optimized weld parameters, can lead to an increased melting efficiency.

Typically for many welding applications, highly skilled manual welding has been required because of varying joint gaps that necessitate real time control of arc power in order to increase or decrease the amount of melting and smoothly bridge the gap. However, due to slow human reaction times, manual welding can only be done at relatively slow travel speeds that do not usually produce a high melting efficiency. The relatively recent emergence of both automatic and robotic welding, along with fast response seam tracking devices, weld pool imaging systems, and the better process control that these systems require, has created a unique opportunity to optimize the welding process by increasing the melting efficiency.

This paper will review our present knowledge about melting efficiency as obtained from theory, the published work of previous researchers, and from recent calorimetric based studies made at Sandia National Laboratories. Since an accurate determination of the net heat input to the part is a prerequisite to understanding melting efficiency, the latest and most reliable data available on energy transfer efficiency for the common fusion welding processes will also be reviewed. So that one can apply the subsequent information about the factors which influence melting efficiency to everyday welding applications, empirically based equations will be given which can be readily used to estimate the melting efficiency in fusion welding.

Net Heat Input Determination

In order to calculate or estimate the melting efficiency it is necessary to know how much of the energy incident on the workpiece is actually absorbed. The net heat input can be determined from knowledge of the energy transfer efficiency and the heat source power. The heat source power can usually be easily measured but the energy transfer efficiency can be difficult to estimate for some welding processes. The energy transfer efficiency (commonly known as arc efficiency for arc type processes) is defined as, the net heat input to the part divided by the energy produced by the power source.

One important reason that the factors which control melting efficiency are not well understood is that experimental determination of the net heat input to the part is a difficult task. A review of the literature reveals that a variety of calorimetric techniques have been used to measure the net heat input to the part during welding. (2,3,4,5,6) When considering experimental work in this field, it is important to distinguish the difference between net heat inputs that have been obtained from direct calorimetric measurements that can be independently calibrated, and net heat inputs that are based on temperature measurements adjacent to the weld, which rely on difficult to verify assumptions about the heat flow in that area. When available, the more reliable calorimetric measurements will be presented in this review.

Arc Welding Processes

As a result of these measurement difficulties, there has been much conflicting evidence about the magnitude of the energy transfer efficiency for the arc welding process. It appears that some significant earlier papers on this subject (3,4) wrongly concluded that the arc efficiency depends strongly on the arc current since more recent calorimetric work has clearly shown that the arc efficiency is relatively constant with current (2,5). Consequently, some researchers who have noted increases in melting due to current did not always attribute the larger fusion zone to an increased melting efficiency.

The net heat inputs used in calculating the arc efficiencies given in Fig. 1 were taken from direct calorimeter measurements and are not based on heat flow assumptions.The results indicate that the arc efficiency for the gas tungsten arc welding (GTAW) process is insensitive to current level over the range examined. In addition, since the welds for each material in this figure were made at the same machine output value, there is no dependence of the arc efficiency on the travel speed either. For the GTAW process one can assume that approximately 80% of the machine output energy will result in heat input to the workpiece regardless of the arc current or the travel speed. (2)

Similarly, the arc efficiency for the Plasma Arc Welding (PAW) process does not depend on current or travel speed. (7) The PAW arc efficiency would likely be about the same as the GTAW arc efficiency, if not for the presence of the constricting water cooled copper nozzle between the electrode and the workpiece. It has been postulated (7) that heat transfer from the arc to the nozzle is the reason that the PAW process has a lower and more variable arc efficiency than the GTAW process.

Smartt et al (5) have shown that the arc efficiency for the GTAW process drops very slightly with increasing arc gap and voltage. Although this effect is real and can be explained by increasing radiation losses, it is small and can be disregarded for conditions where the voltage does not change significantly. Table I summarizes the energy transfer efficiencies that can be expected for many of the common welding processes. The values given in the table are thought to be realistic and representative of typical processing conditions. No attempt was made to report the wide range of values found in the literature for some processes unless there is a unique and plausible loss mechanism to account for the variation. It is worth noting that the energy transfer efficiencies for most of the arc processes are about the same, which would be expected since they all transfer energy with the same electron transfer mechanism, and should have similar radiation and torch losses.

Laser Beam Welding

It is apparent from the table that the LBW process is unique in that it is the fusion welding process with the largest variation in energy transfer efficiency. Inadequate understanding of the energy transfer efficiency for the Laser Beam Welding (LBW) process has not surprisingly led to confusion in estimating the LBW melting efficiency. Unlike electron beam welding and the other arc welding processes, many factors can significantly affect the absorption of laser energy by a material including the frequency of the radiation, the reflectivity of the material, the geometry of the molten cavity, and the magnitude of the incident power density.

Fig. 2 illustrates the large variation in energy transfer efficiency that can occur with the CO_2 LBW process as a result of a change in irradiance. One can see that slight deviations in beam irradiance, brought about by part positioning errors that affect the focused spot size, can result in large shifts in the net heat input. Since it is difficult to know what the focused spot size is in LBW, the net heat input and hence the melting efficiency is never really well known. Besides this being a serious process control deficiency, the wide variation in absorption can make estimates of the net heat input extremely speculative.

A popular graphical technique for estimating the net heat input for two-dimensional heat flow welding processes like full penetration LBW and electron beam welding (EBW) was given by Swift-Hook and Gick. (8) Using this non-empirical model the net heat input can be determined from measurements of the size of the weld, the incident power, the velocity, and the material thermal properties. The much referenced concluding diagram of Swift-Hook and Gick is reproduced in Fig. 3. For completed welds where weld width and penetration depth in addition to the process parameters are known, the energy transfer efficiency and hence the net heat input, can be read directly from the diagram. The melting ratio shown in the figure is not exactly the same as the melting efficiency defined earlier since the melting ratio is based on the incident power and not on the absorbed power. This is not a significant problem though since the melting ratio can be converted to the melting efficiency by dividing it by the energy transfer efficiency. In addition to the restrictive requirement that a weld must be completed before the net heat input can be calculated, a number of simplifying assumptions (to be discussed later) in this model have limited its widespread acceptance and accuracy.

Influence of Process Parameters on Melting Efficiency

Theoretical Considerations

The same factors that affect heat flow during fusion welding will also affect melting efficiency. It is useful to identify these factors by examining the analytical solution to the conduction heat flow equation [1] for welding first given by Rosenthal. (9)

$$[1] \qquad \frac{2\pi (T-T_0)\, k\, r}{q} = \exp \frac{-V(r-x)}{2\alpha}$$

where:

q = Net Power
T = Temperature
V = Travel Speed
α = Thermal Diffusivity
k = Thermal Conductivity
$r^2 = x^2+y^2+z^2$

This quasi-steady state solution is dependent upon several simplifying assumptions which include: heat transfer by conduction only, no melting, a point heat source, and constant thermal properties. Despite these assumptions, this equation has been widely and successfully used to predict cooling rates, and the boundaries of the fusion zone for many welding processes. It is equally beneficial in indicating the parameters that will affect melting efficiency. It is apparent from [1], that the two primary process control parameters which affect heat flow in welding are the heat source power and the travel speed.

Since both of these parameters affect the rate of energy delivery to the workpiece, it is not surprising that they have a dramatic effect on the melting efficiency. The effect of travel speed on melting efficiency is intuitive if one considers that since it affects the amount of time available for heat to dissipate it must also affect the amount of melting that can take place. If energy is delivered faster than it can be dissipated, then more material will be raised to higher temperatures and more melting will occur. Similarly, the effect of power can be understood when one considers that power denotes the rate of energy delivery to the workpiece, and for a given travel speed an increase in power will result in more melting since the increased energy cannot be dissipated any faster. Increasing travel speed or power either independently or together will usually increase the melting efficiency.

These facts are best illustrated with some two dimensional heat flow diagrams presented by Rykalin (10) and shown in Fig. 4. These three diagrams represent solutions to the moving line source heat flow equation where for each case both power and velocity were increased in a way that the total heat input was kept constant. One may observe that as the travel speed and power were increased, the heat affected zone region decreased (i.e. the distance between the isotherms was compressed) and less adjacent material was unnecessarily heated. If one assumes that the melting point of this material was 1200 degrees it is apparent that the melted area increased with each grouping of power and velocity even though the heat input remained the same. Therefore the ratio of the melted volume enthalpy to the net heat input must also increase and an increase in melting efficiency will result. In metals where undesirable allotropic transformations in the heat affected zone are common, it is easy to see from these diagrams that conditions that maximize melting efficiency also will reduce the extent of these transformations. (11)

Travel Speed

Since Rosenthal first presented analytical solutions to the differential equations for moving source heat flow, (9) a number of researchers have made theoretically based predictions that melting efficiency increases with travel speed. (8,12,13,14) In related work, some welding parametric studies have found that the amount of melting increases with increasing travel speed. (3,11,15) A good illustration of the effect of travel speed on melting efficiency is shown in Fig. 5 and was given by Okada (14) using experimental data for the submerged arc welding process from Jackson and Goodwin. (11) Although the melting efficiencies in this figure were only determined from measurements of arc power and fusion zone size, they are valid, since the energy transfer efficiency for this process is believed to be relatively constant (10) just as it is for the GTAW process. The authors observed significant increases in melting efficiency as travel speed increased for each of the input powers they investigated.

Power

Note that the data in Fig. 5 also show an increase in melting efficiency with increasing input power. A similar beneficial increase in melting efficiency is known to occur with the other arc welding processes when the arc current is increased independent of travel speed. (2) The significance of weld input power in determining melting efficiency is also confirmed by Fig. 6 for bead on plate welds with the CO_2 LBW process. The results presented are from calorimetric measurements (16) and clearly show a gradual increase in melting efficiency with increasing net input power at a given travel speed.

For welding processes that do not produce a constant power delivery such as pulsed Nd:YAG LBW and pulsed current GTAW; the peak power during the pulse needs to be considered as the power parameter that affects melting efficiency. For pulsed processes, as pulse length varies, different levels of peak power will be obtained at a given average power. Consequently, the average power does not adequately indicate the higher peak power amplitude that is reached with a pulsed process. This situation is illustrated in Fig. 7 for the pulsed current GTAW process, where data are shown for welds made at two different levels of average power. For the lower average power welds, it is clear that the peak power has an important beneficial effect on melting efficiency. In contrast, for the higher average power welds, peak power does not affect melting efficiency since the melting efficiency has already been maximized. It is evident that the increased peak powers that are practical with this process can permit high melting efficiencies to be obtained at lower travel speeds than would be otherwise possible. (17)

The increased melting efficiency that results from increases in incident power has always been thought to be one of the important advantages of the EBW and LBW processes; (18,19) the output powers of these processes are often in the high power (kilowatts) range. One of the important advantages of the high power density welding processes frequently cited is that the compressed isotherms created by the high input powers and concentrated heating, can produce welds with minimum heat input. As a result of these high powers and the fast travel speeds that usually accompany them, the melting efficiencies for EBW and LBW are often very high and these processes are considered ideal for applications where only minimal heat input and distortion can be tolerated.

The beneficial effect of input power on melting efficiency is indeed genuine, but as is indicated in Fig. 6 neither a high power density welding process nor a high input power are sufficient to guarantee a high melting efficiency. It is apparent from the figure that for this material and over the power range of this laser; the highest melting efficiencies are obtained only when a specific combination of power and velocity is reached. There is evidently a coupling between power and velocity that is beneficial in attaining the maximum melting efficiency in routine welding applications.

Base Metal Influence on Melting Efficiency

Just as the rate of energy delivery to the workpiece strongly affects the melting efficiency, so too does the rate of heat dissipation in the weldment. Close inspection of [1] reveals that welding heat flow is dependent on the thermal conductivity and the thermal diffusivity of the base metal. The thermal conductivity is a material property which indicates the rate at which energy is transferred by the thermal diffusion process. Since the thermal diffusivity is determined by dividing the thermal conductivity by the specific heat per unit volume, thermal diffusivity indicates how effective a material is in transferring energy by conduction more so than in storing energy. It is therefore a more complete parameter to characterize welding, since welding is a transient heat flow process.

Thermal Diffusivity

It is intuitive that metals having higher thermal diffusivities will have lower melting efficiencies at given powers and travel speeds. One would anticipate then that faster travel speeds and higher input powers would be required when welding materials with a high thermal diffusivity, in order to compensate for the more rapid heat dissipation, and to achieve a high melting efficiency. The strong effect of base metal thermal diffusivity on melting efficiency is clearly apparent in Fig. 8 for GTAW edge welds on 304 SS and Nickel 200 (these two materials have significantly different thermal diffusivities; note the magnitudes in the figure). Since the input power for the Nickel 200 was at a level high enough to compensate for its higher enthalpy, one can reasonably conclude that the lower melting efficiencies found for Nickel 200 when compared with 304SS at equivalent travel speeds are due to the influence of the base metal thermal diffusivity.

Heat Flow Geometry

The analytical solutions for heat flow in welding given by Rosenthal are specific to the heat flow geometry that was assumed in their solution. Note that [1] is only applicable to welds that can be simulated by a point source. Heat flow in a fusion weld strongly depends on the extent and geometric shape of the surrounding base metal. (20) Some of the more common weld joints and their corresponding heat flow geometries are illustrated in Fig. 9. In each of the figures the other heat flow dimension is in the direction of heat source travel (i.e. perpendicular to the plane displayed). Upon referring to the figure one can intuitively see how the larger mass adjacent to a weld that is represented by the three dimensional heat flow geometry will increase the rate of heat dissipation over a two dimensional heat flow geometry. As a result of this change in heat flow geometry, the type of weld joint exerts a strong influence on the melting efficiency. A useful theoretical illustration of the effect of heat flow geometry on melting efficiency was given by Okada (14) and is shown in Fig. 10. The curves in the figure were determined from approximation equations for melting efficiency based on Rosenthals solutions for line source and point source welding heat flow. A line source solution requires two dimensional heat flow as in Fig. 9(b), and a point source solution requires three dimensional heat flow as in Fig. 9(a). The curves clearly show that for similar welding conditions two dimensional heat flow welds will have a higher melting efficiency than welds with three dimensional heat flow.

Knowledge of the influence of base metal heat flow geometry on melting efficiency is fundamental to an understanding of the science of welding and can prove to be of considerable practical value in many everyday welding applications. It is certainly no coincidence that for many small and heat sensitive welding applications such as electrical relays and specialty batteries, edge weld joint geometries (see Fig. 9) are traditionally selected. Edge weld joint geometries are routinely selected because the higher melting efficiencies provided by this weld joint design and the resulting two dimensional heat flow, are beneficial in reducing overall heat input to the part, lessening distortion, and thereby increasing product yields. A good example of the utility of this effect is illustrated in Fig. 11 where the weld size for CO2 laser welds was increased for each of four different power conditions by the addition of a notch adjacent to the weld joint. The notch is effective in creating heat flow conditions more comparable to two dimensional than to three dimensional and thereby increasing the melting efficiency and the size of the weld. In fact for many welding applications, through judicious selection of the optimum joint design, it is possible to increase the size of the fusion zone without increasing the net heat input by simply increasing the melting efficiency.

Prediction of Melting Efficiency

Theory Based Methods

Although there have been very few empirical studies of weld melting efficiency published in the literature, several researchers have developed equations and graphical techniques to predict melting efficiency (8,12,13,14) that are derived from the conduction heat flow solutions originally given by Rosenthal. (9) These methods typically will predict the melting efficiency for a weld based on knowledge of the weld process parameters, the type of base metal, and the heat flow geometry.

Wells presented the first approximation equation [2] for melting efficiency using this approach.

$$[2] \qquad M_l^{-1} = 2\left(\frac{1}{5\left(\frac{Vd}{4\alpha}\right)} + 1\right)$$

where: $M_l =$ line source melting efficiency d = pool diameter

It was derived for a line source and is based on the dimensionless parameter Vd/α. Errors in the approximation are reduced by restricting the range of Vd/α values for which the equation is valid. The equation is useful since it correctly reveals that either an increase in velocity or a decrease in material thermal diffusivity will both result in an increase in melting efficiency and that there is a maximum limiting value of melting efficiency which can be obtained as V goes to infinity. Unfortunately this equation requires knowledge of the fusion zone size in order to realistically estimate the melting efficiency and as such the equation has limited predictive benefit.

As was described earlier, the diagram (Fig. 3) given by Swift-Hook and Gick (8) can also be used to predict melting efficiency for welding power sources that produce line source heat flow. Note that the ordinate in Fig. 3 is delineated with the same dimensionless parameter as was previously given by Wells. (12) Unfortunately as was the case with the Wells approximation equation, Vd/α (as well as the other dimensionless parameter in the figure) can only be determined after the welds have been completed. Perhaps the most severe limitation of this graphical technique is the fact that a rectangular shaped fusion zone is assumed in the solution.

Indeed, a restrictive requirement on the shape of the fusion zone is common to many welding heat input studies and it often severely limits the relevance of the results to other applications.The attractiveness of melting efficiency as a measure of weld quality is compelling since it does not suffer from this limitation. Since melting efficiency is a dimensionless parameter which is simply a function of the material, the travel speed, and the power, the preferred prediction equation should not contain a functional dependence on fusion zone size. In other words, to be a more universal measure of performance for weld characterization, a melting efficiency prediction method must not require prior knowledge of the fusion zone size in order to produce an estimate.

Such a valuable approximation equation for melting efficiency [3] was given by Okada (14) for a point source and is based on the dimensionless parameter N usually attributed to Christenson (4) but first given by Rykalin. (10)

$$[3] \qquad M_p^{-1} = \exp\left(1 + \frac{1.76}{2N}\right)$$

where: $N = \dfrac{qV}{\alpha k \Delta T}$ or equivalently: $N = \dfrac{qV}{\alpha^2 \delta h}$

and:
M_p = point source melting efficiency
k = thermal conductivity
δh = enthalpy of melting
ΔT = temperature rise of fusion zone

Okada's equation is unique because it indicates the influence of all the important process parameters but without any knowledge of the fusion zone dimensions required. In addition, this equation correctly shows the important synergistic relationship between both power and velocity that was described earlier. It is apparent from [3] that an increase in either power, velocity, or both will result in an increased melting efficiency.

An Empirically Based Method

It should be noted that despite their merit in providing a qualitative understanding of melting efficiency, the preceding approximation methods are seriously limited because they have not been rigorously verified experimentally. In part because of this limitation, the dimensionless parameters used with these methods have not proven to be satisfactory indicators of melting efficiency when compared with calorimetrically determined experimental data. For example, when calorimetrically determined melting efficiencies are plotted against the dimensionless parameter used by Rykalin, Christenson, and Okada as is shown in Fig. 12, it is evident that this parameter fails to normalize the significant difference in thermal diffusivity between nickel and stainless steel. In particular, the asymptotic approach to a maximum melting efficiency that is apparent in Fig. 8, is not indicated in Fig. 12 for the nickel data. This may wrongly imply that the melting efficiency can still be significantly improved when (as shown in Fig. 8) it is clearly already close to the maximum.

One should note that the input powers used in Fig. 12 are determined from the actual energy measurements obtained from edge weld specimens contained in a calorimeter, as is the value of net heat input used in calculating the melting efficiency. The fusion zone volumes used in calculating the enthalpy of melting are also established experimentally from cross-sectional measurements of the actual welds. To be sure, these measured melting efficiencies are based on reliable calorimetric techniques (21) and as such bring a needed empirical perspective to the methods used to predict melting efficiency.

Because of the predictive limitations with the dimensionless parameter N as revealed in Fig. 12, the author attempted to match many other thermal conduction type dimensionless parameters with this empirical melting efficiency data, and also found them to be deficient in normalizing the effect of material thermal diffusivity. It was apparent that none of these groups included the liquid metal viscosity, which is known to be an important parameter in convective heat transfer processes such as fluid flow in pipes; convection in the weld pool is also considered to be important in fusion welding. (22) Although it has not yet been shown experimentally, it is reasonable to expect that metals with a low liquid metal viscosity will have an increased convective heat transfer coefficient and therefore should obtain a higher melting efficiency than other more viscous metals at the same process parameters.

Based on the expected influence of liquid metal convection, a new dimensionless parameter has been determined that has been shown to correlate much better with the experimental data presented in Fig. 12. (7) We call this parameter P, and it is given by the following expression:

$$P = q\ V / \delta h\ \nu\ \ \alpha$$

where ν is the kinematic viscosity at the melting point (m^2/s) and the value for thermal diffusivity is at the base metal temperature. As is shown in Fig.13, it is obvious that the strong material dependence has been eliminated with the substitution of this parameter and that one curve can be used to represent both materials in contrast to the dichotomous behavior illustrated in Fig. 12. This new dimensionless parameter: P, is somewhat similar to the parameter given by Rykalin [3] except that it uses both the kinematic viscosity and the thermal diffusivity in the denominator instead of squaring the thermal diffusivity. These modifications are sufficient to effectively normalize the base metal differences so apparent in Fig. 12.

With reference to Fig. 13, several points should be noted. The empirical data show an exponential increase in melting efficiency at the lower values of P and a levelling off to an asymptotic level at the higher values. This dependence is consistent with the theoretically determined equations [2] and [3] and indeed substantiates a fundamental maximum limit for melting efficiency as predicted by several researchers. The maximum melting efficiencies obtainable were first reported by Rykalin (10) as 36.8% for two dimensional heat flow and 48.4% for three dimensional heat flow. For the two dimensional heat flow conditions that are most representative of the edge welds plotted here, an asymptotic limit of 48.4% is consistent with the data in the figure. One can expect that for welds where three dimensional heat flow conditions exist, the functional dependence will be comparable and approach an asymptotic value of 36.8%, very similar in fact to Fig. 10. In contemplating this maximum melting efficiency, it is interesting to note that more than half the heat energy deposited during fusion welding is in effect always wasted, since its only purpose is to raise the temperature of the base metal!

The exponential dependence seen in Fig.13 can be more simply represented with a linear equation by plotting the natural logarithm of melting efficiency versus the inverse of P as is shown in Fig. 14. Note that the data in this figure are for two dimensional heat flow conditions and that three different welding processes have been included, which can all be correctly fit with the same linear regression equation. Although limited to one material, some calorimetric measurements for the high current GTAW process are available (2) that represent the three dimensional heat flow case. These results are plotted in Fig. 15 together with the GTAW and PAW edge welds given in Fig. 14. It is apparent from the figure that the difference in both the Y intercepts and the slope between the two heat flow cases will limit the melting efficiency for the three dimensional case to a lower value than is possible for the two dimensional case for all values of P.

Another apparent consequence of Fig. 15 is that the maximum melting efficiency is not dependent on the base metal thermal diffusivity. The data in Fig. 8 are not extensive enough to discern this point but due to the functional relationship exhibited in Fig. 15 and the widely dissimilar properties of these two alloys, the figure suggests the existence of a common maximum for all type metals which is consistent with all of the theory based predictive methods presented earlier.

The equations given in the figure can be readily used to predict melting efficiency and are unique in that they are based on experimental measurements and do not require any presumed knowledge about the dimensions of the fusion zone. Since the dependence of melting efficiency on a dimensionless parameter (that takes into account both the process parameters and the material properties) has been experimentally characterized with these equations, it is now possible to readily determine the melting efficiency for any fusion welding process contingent only on knowledge of this parameter and the type of weld joint geometry.

Since the melting efficiency for the ordinary arc processes and the more advanced and higher power density LBW process can all be described with the same predictive equations as given in Fig. 14, one might reasonably conclude that the LBW process has no clear advantage over these processes in producing low heat input welds. In terms of melting efficiency alone this is a true statement; all fusion welding processes are limited by the same laws of physics and cannot produce welds with melting efficiencies greater than 48.4%. However, as is shown in Fig. 16, the high power density processes such as LBW and EBW have unique capabilities in producing welds with shapes and sizes not achievable with conventional arc processes. As a result, the high power density welding processes can produce some welds with high melting efficiencies that could not be made otherwise. But it is evident from Fig. 16 that the maximum melting efficiency obtainable with the LBW process is no higher than that obtainable with any of the arc welding processes. Clearly the selection of a high power density fusion welding process for a particular application should be based on more than just a requirement for a low heat input process. If similarly shaped welds can be produced with an arc process then it is doubtful that the welds can be made with a lower heat input simply by using a laser or electron beam.

Concluding Remarks

It is likely that the increasing availability of computers for manufacturing process control will eventually lead to the widespread use of welding expert systems and computer models for many welding applications. Since these computer models are based on the same conduction heat flow theory that has been used to predict melting efficiency and has been experimentally verified, the results from these models should correctly account for melting efficiency. In other words, the analysis of melting efficiency is already built into most computer models. Unfortunately it is not often evaluated and discussed as an important measure of weld quality.

Perhaps using the methods outlined in this review paper, and with new confidence in the constancy and validity of the energy transfer efficiency, more engineers and researchers will attempt to estimate and report the melting efficiency for fusion welding applications. More widespread knowledge of the magnitude of melting efficiency can only lead to its improvement and an enhancement of overall weld quality.

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Table I — Typical Values of Energy Transfer Efficiency for Common Fusion Welding Processes

Welding Process	Energy Transfer Efficiency (%)	Ref.
SAW	90	(10), (14)
EBW	85	(8)
GMAW	85	(14)
GTAW	80	(5), (15), (20)
SMAW	75	(14)
PAW	50-75	(7)
LBW	20-90	(17)

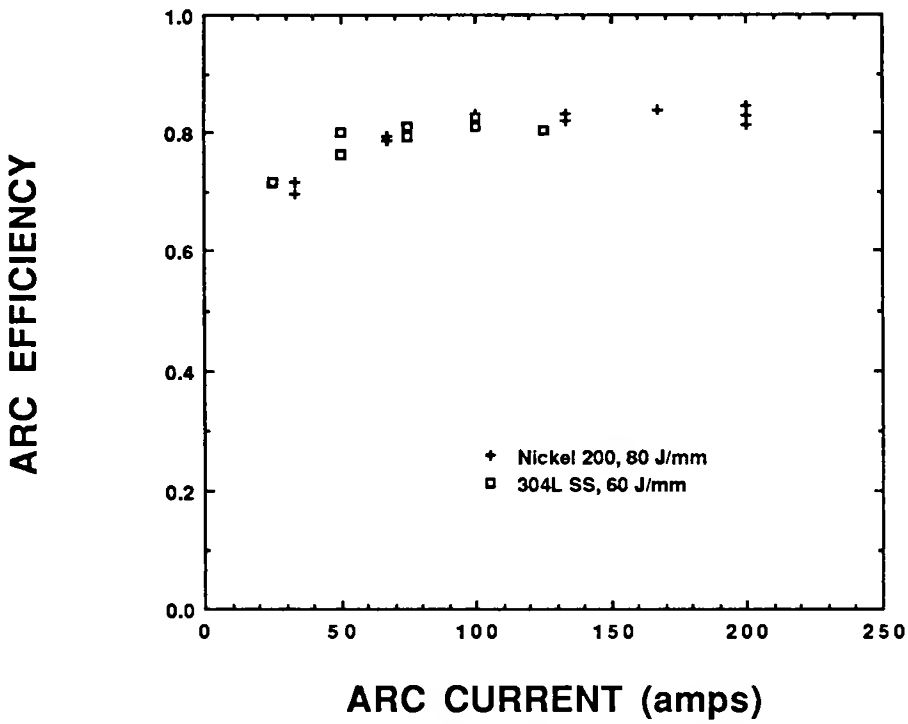

Figure 1: Independence of arc efficiency on current level for the GTAW process. At approx. 8 volts. (7)

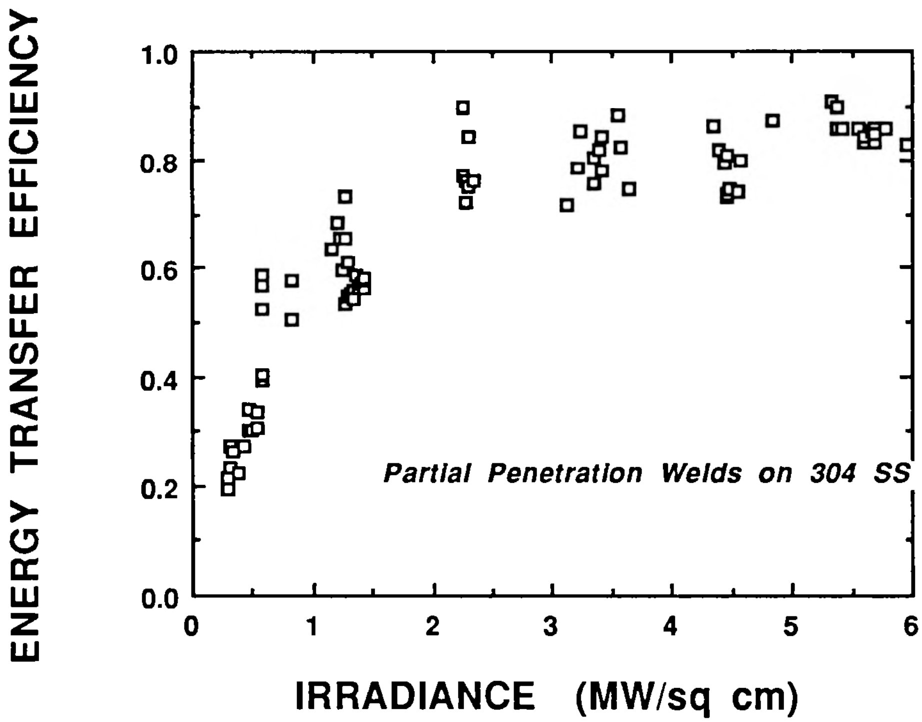

Figure 2: Effect of incident power density on the energy transfer efficiency for continuous wave CO_2 laser beam welding. (16)

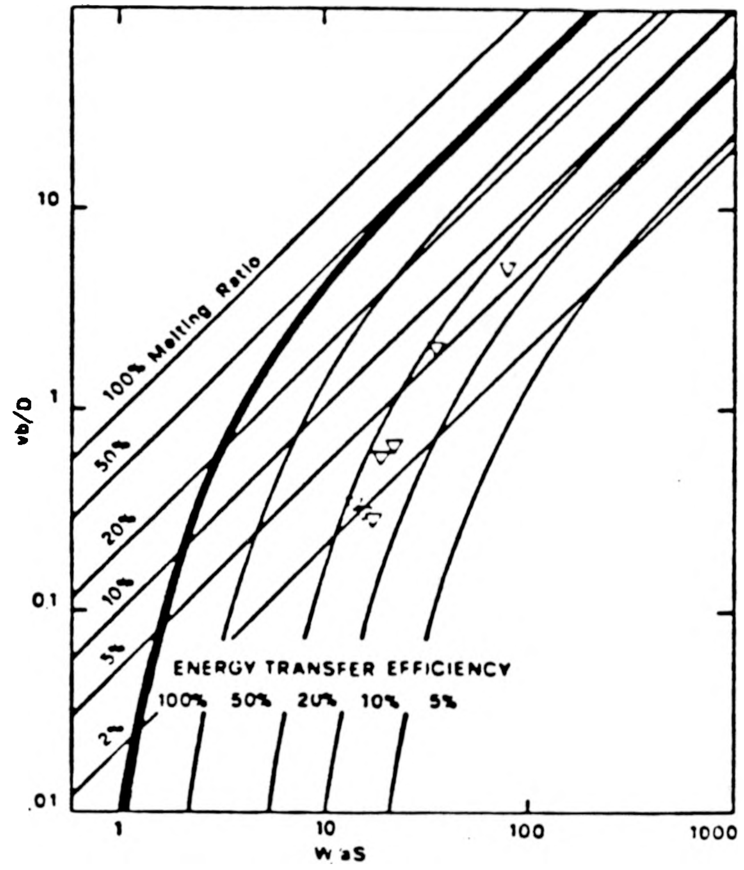

Figure 3: Graph for estimating energy transfer efficiency and melting efficiency for line source welding processes. (8)

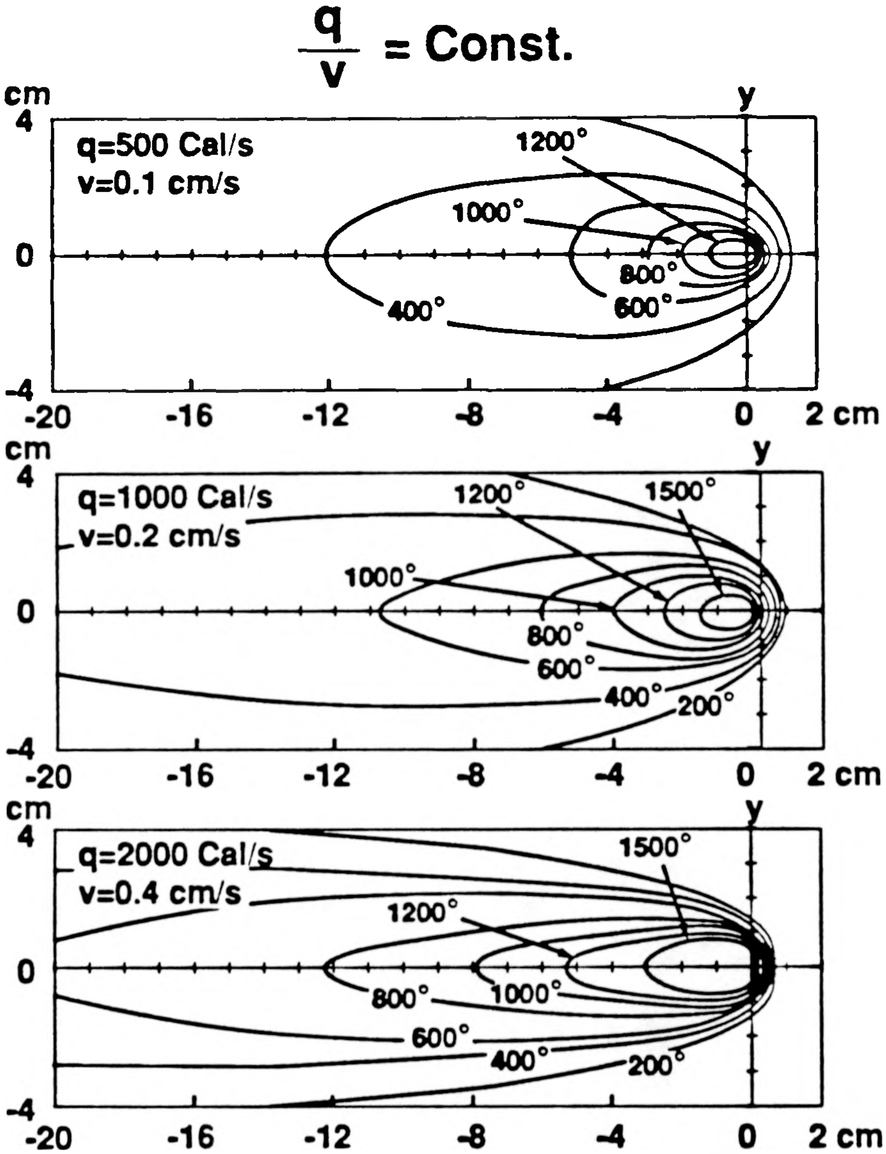

Figure 4: Top view of welding temperature isotherms for three weld schedules, each with the same net heat input but yielding a different melting efficiency. (10)

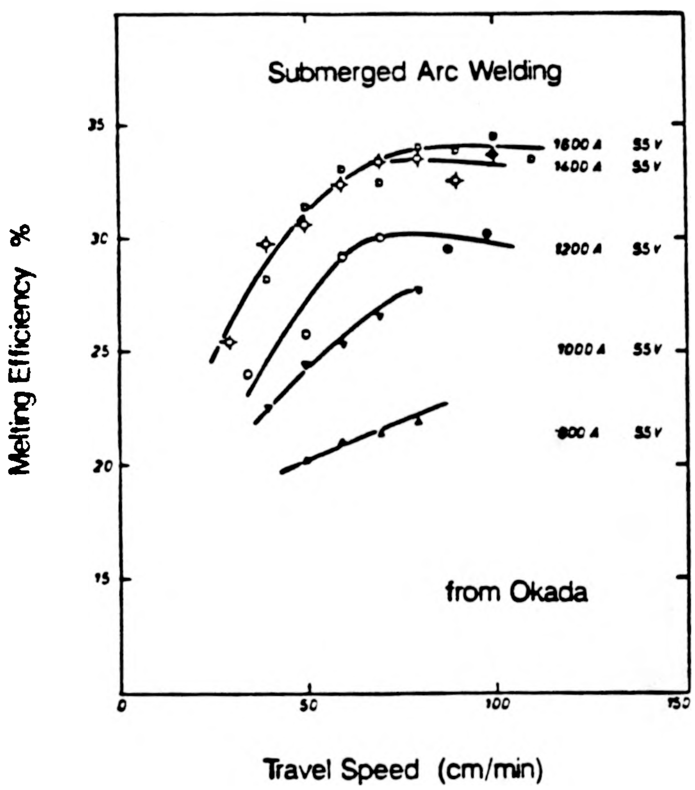

Figure 5: Effect of travel speed on melting efficiency at different input powers for the SAW process. (14)

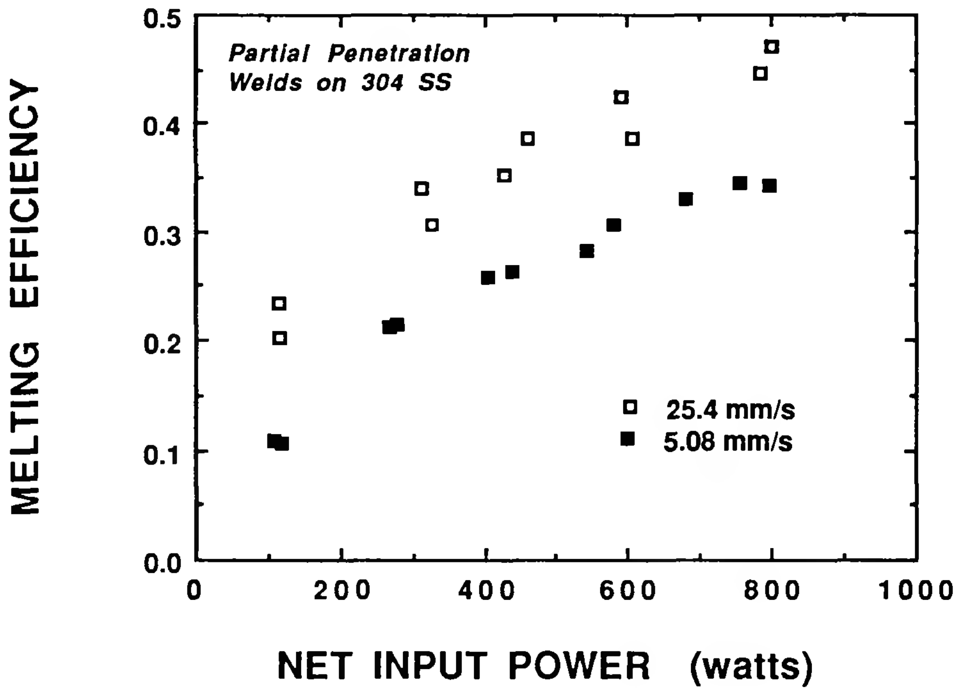

Figure 6: Dependence of melting efficiency on input power for continuous wave CO_2 laser beam welding. (16)

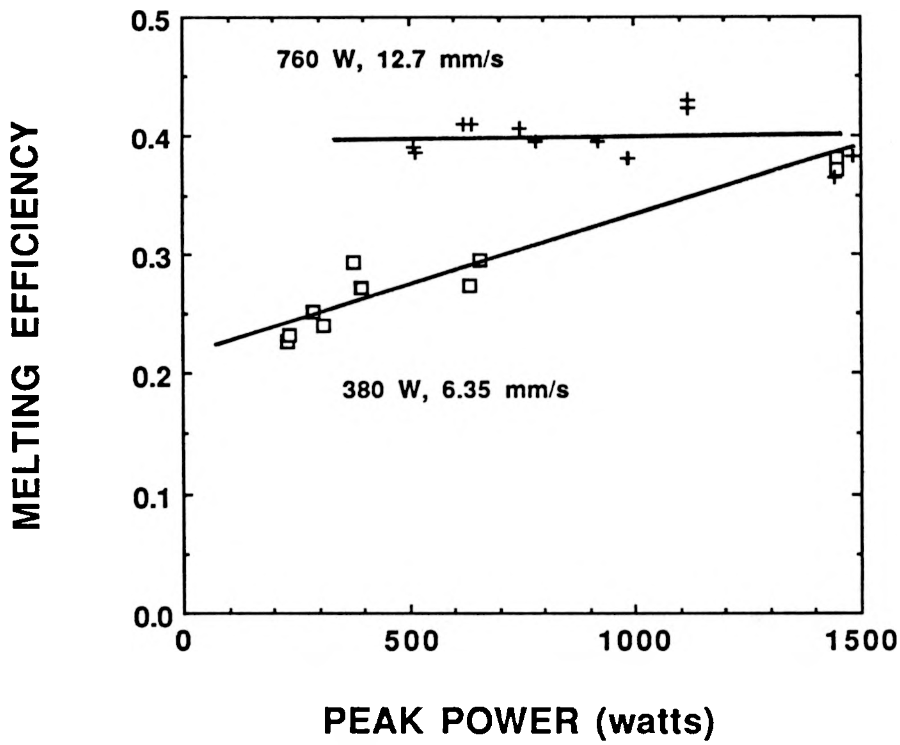

Figure 7: Effect of peak power on melting efficiency for the pulsed current GTAW process at two travel speeds. (20)

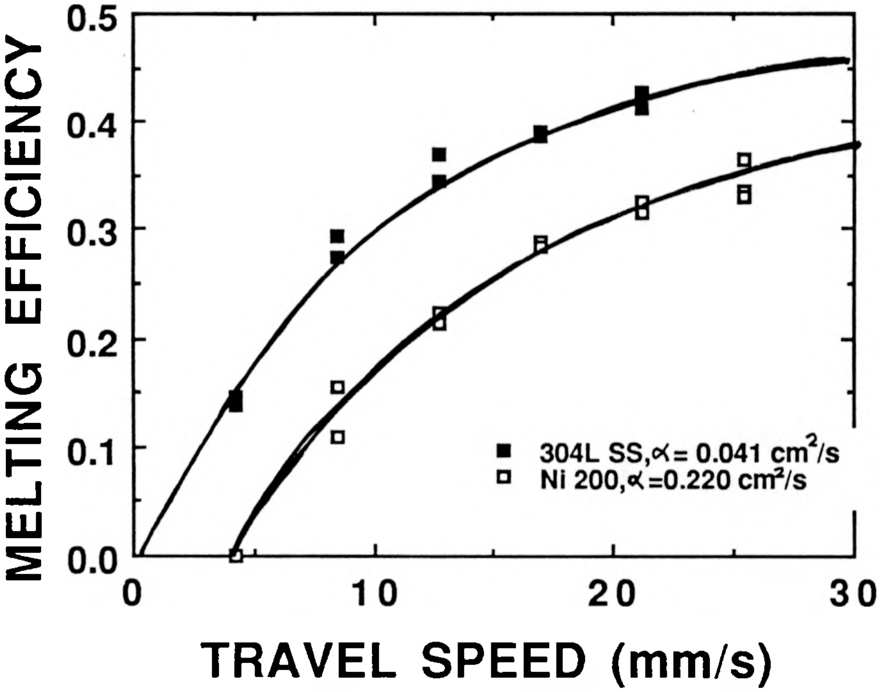

Figure 8: Strong influence of base metal thermal diffusivity on melting efficiency. GTAW edge welds. (7)

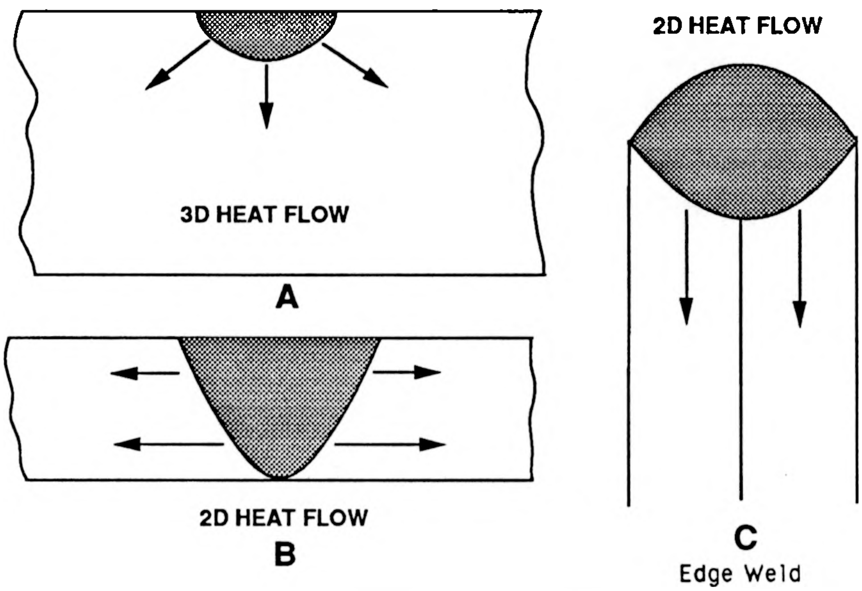

Figure 9: Dependence of heat flow geometry on weld joint design.

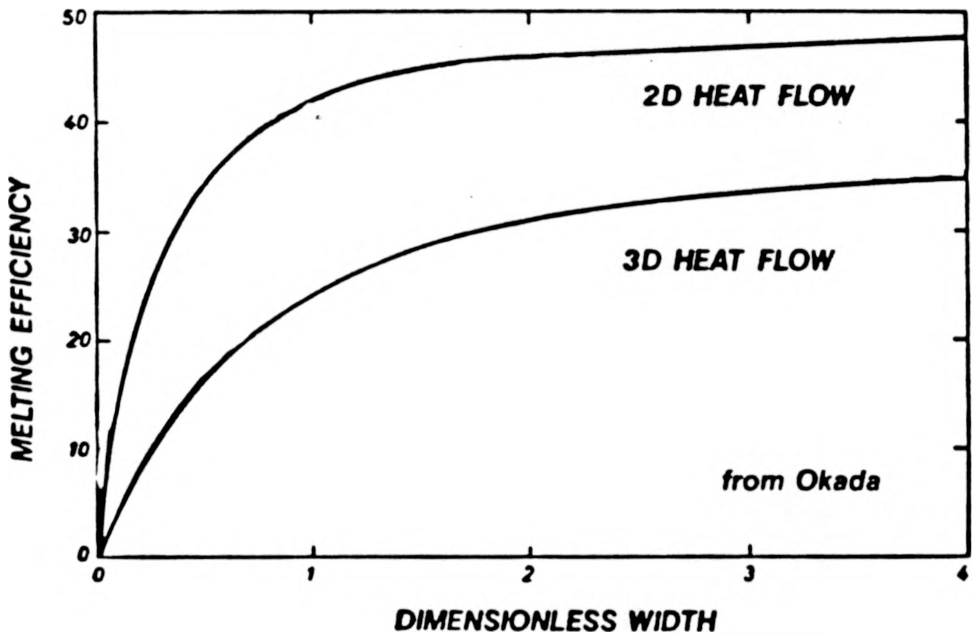

Figure 10: Theoretical melting efficiency, illustrating effect of base metal heat flow geometry. (14)

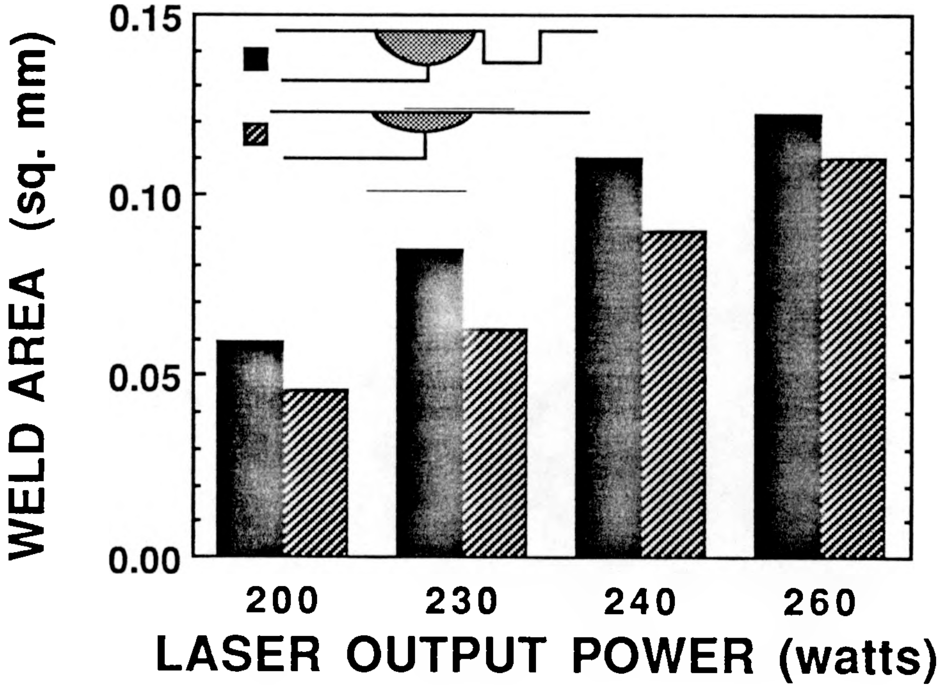

Figure 11: Increase in melting due to addition of groove adjacent to weld joint for continuous wave CO_2 laser beam welding. (16)

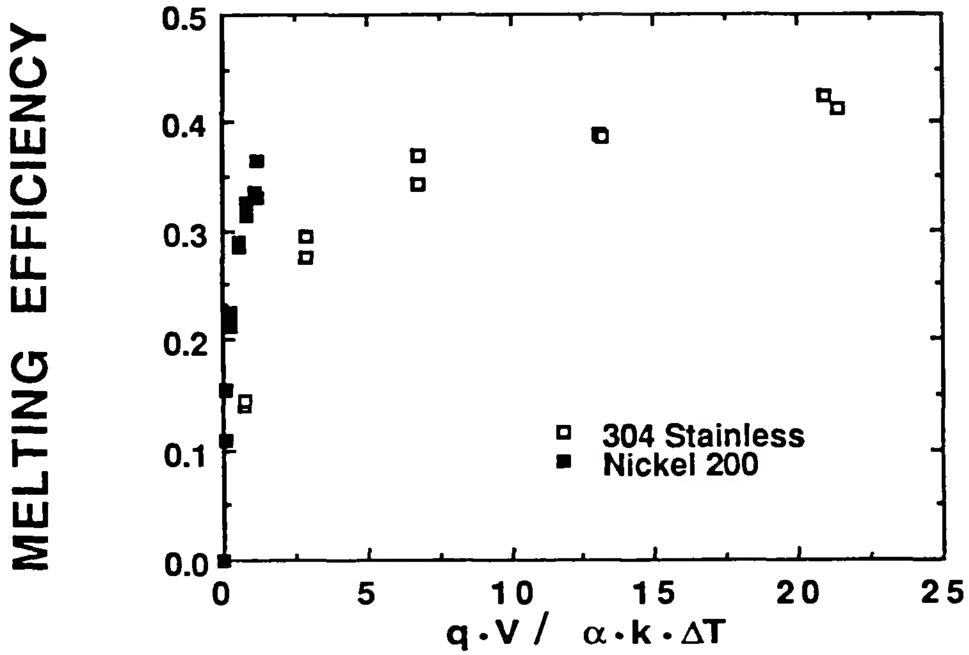

Figure 12: Lack of correlation between experimentally measured melting efficiency and a commonly used dimensionless parameter.

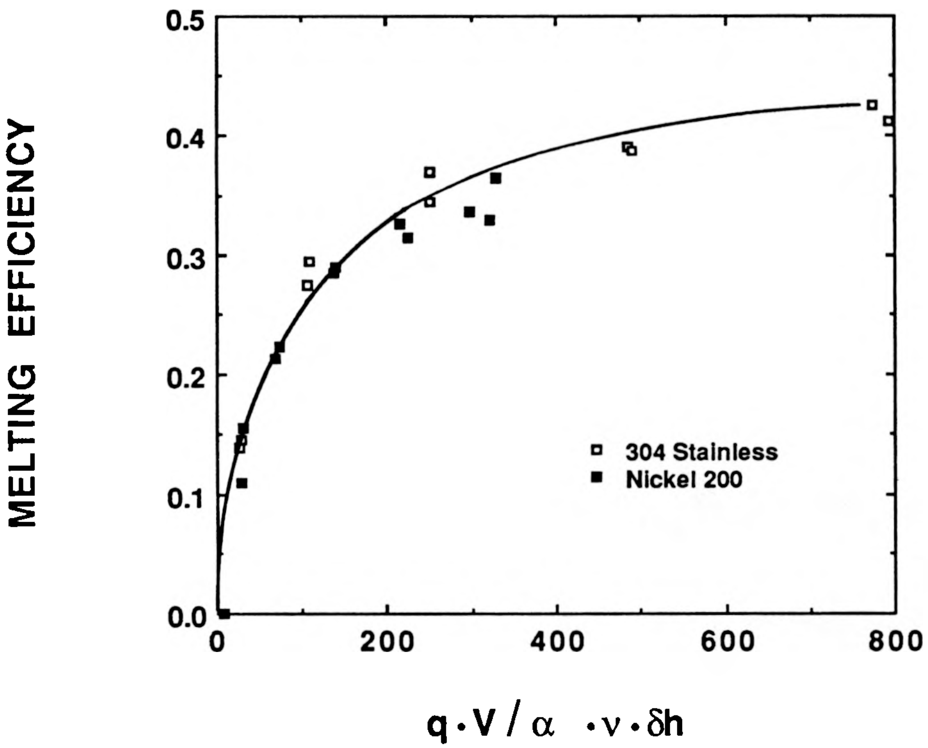

Figure 13: Functional relationship between experimentally measured melting efficiency and a new dimensionless parameter. (7)

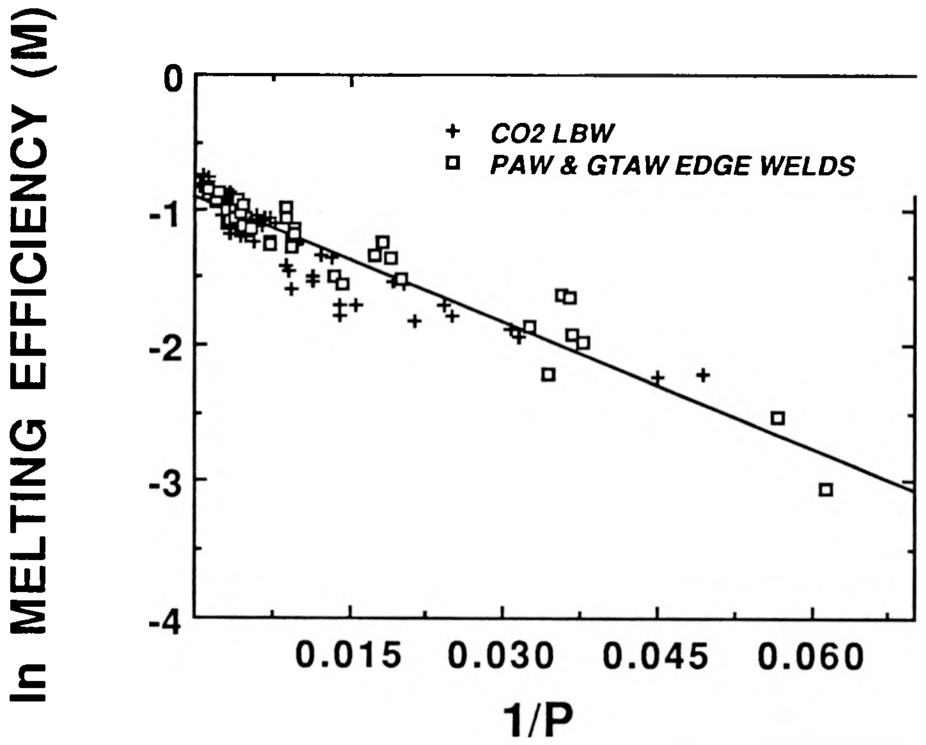

Figure 14: Linear dependence of the natural logarithm of melting efficiency with inverse P for two dimensional heat flow.

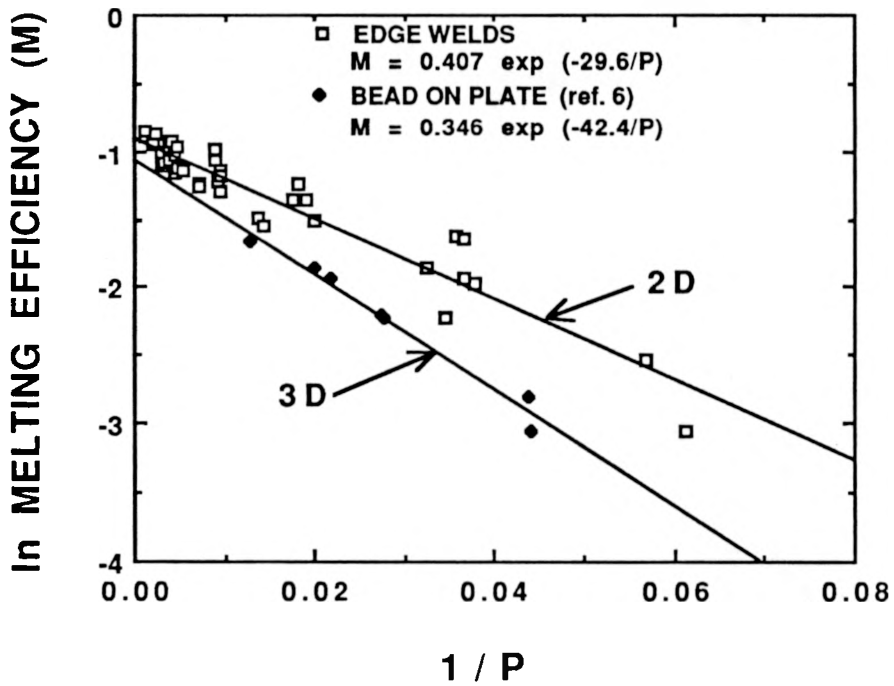

Figure 15: Effect of heat flow geometry on melting efficiency prediction equations. (7)

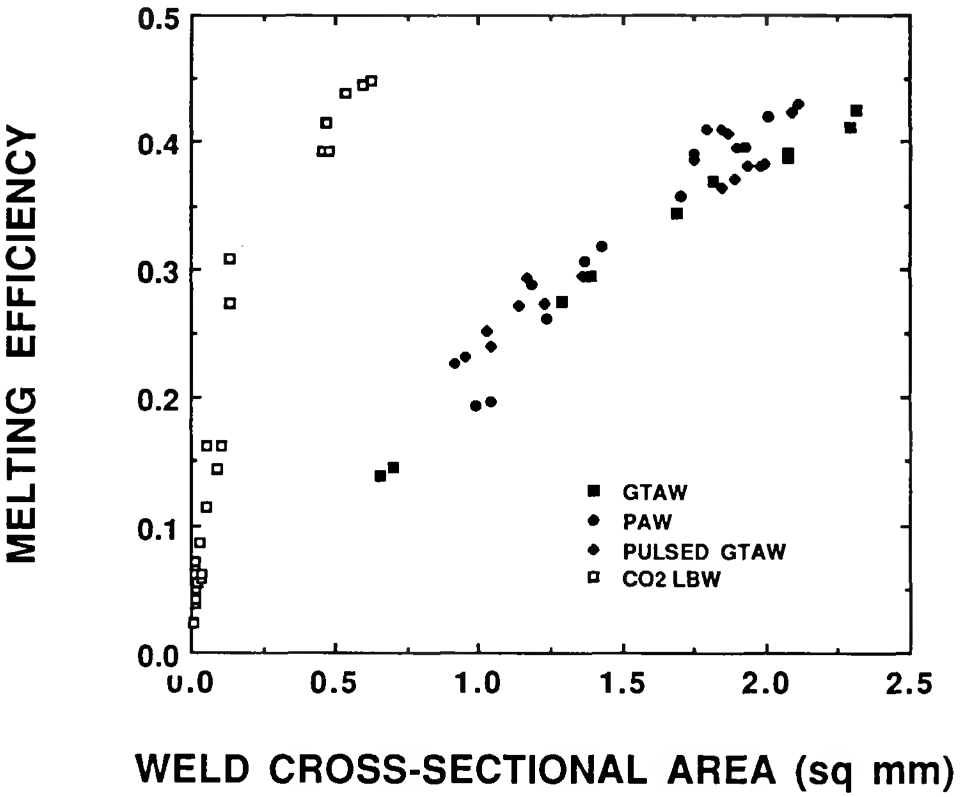

Figure 16: Capability of the LBW process to weld at high melting efficiencies and small weld sizes. (16)