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Effect of Very High Travel Speeds on Melting Efficiency in Laser Beam Welding

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ABSTRACT

Calorimetric measurements of the net heat input to the workpiece have been made to determine the effect of very high travel speeds on laser weld melting efficiency. Very high welding speeds are required in welding applications such as automotive where lasers are now applied extensively. Travel speeds as fast as 530 mm/s for continuous wave CO_2 laser welding on 304 stainless steel have been examined in this study. Melting efficiency indicates what fraction of the laser power absorbed is used to produce melting rather than undesirable base metal heating. It was found that melting efficiency initially increased then slowly decreased as fusion zone dimensions changed. Dimensionless parameter correlations for melting efficiency based on heat flow theory have been presented for both 2D and 3D heat flow geometries. The levels of melting efficiency observed are close to the maximum values that are predicted with these correlations. Determinations of the melting point isotherms and analysis of changes to the dimensionless parameters have been shown to predict the observed changes in melting efficiency. The results indicate that an enhanced melting efficiency is obtained in high speed laser welding when either the fusion zone aspect ratio or the joint geometry promote 2D heat flow.

INTRODUCTION

In order to fully utilize the high power capabilities of modern industrial lasers and to increase product throughput, manufacturers often select travel speeds for laser beam welding that are very high[1] compared to traditional arc processes. Since laser welding is considered to be an intrinsically low heat input welding process, the potentially negative effect of very high travel speeds on melting efficiency should be considered by users of the process. Melting efficiency indicates how effectively welding energy absorbed by the part is used to produce melting, rather than undesirable heating of regions adjacent to the fusion zone. Distortion, residual stresses, discoloration, and other types of thermal damage can often be reduced by welding with a high melting efficiency.

Melting efficiency (η_m) is defined as the ratio of the power necessary to just melt the fusion zone to the net power absorbed by the part. It is readily calculated from equation (1) where v is the travel speed, A is the cross-sectional area of the fusion zone, and q_i is the net power absorbed into the workpiece. The power necessary to just melt the fusion zone depends on the pool volume melting rate (vA), and the enthalpy change (δh) required to bring a unit volume of the metal from room temperature (T_r) to the liquidus temperature (T_l). The enthalpy change includes both the heat of fusion (Δh_f), and the sensible heat—a function of the specific heat (c_p) in (2). It is interesting to note from these equations that if a weld process heats the fusion zone above the liquidus temperature, the additional net power may result in a decreased melting efficiency.

$$\eta_m = \frac{\upsilon A \, \delta h}{q_i} \qquad (1)$$

$$\delta h = \Delta h_f + \int_{T_r}^{T_l} c_p(T)\, dT \qquad (2)$$

[1] We will arbitrarily bound very high speed welds to be welds greater than 100 in/min (2.5 m/min).

It has long been recognized that as both welding power and travel speed increase, melting efficiency also increases. [1] It then follows that for laser welding where the travel speeds are typically very fast, melting efficiency should be high, and the resulting thermal effects should be minimal. Recent measurements have found this to be true, and indeed the melting efficiency for laser welding can be close to the theoretical maximum. [2] For two dimensional (2D) and three dimensional (3D) heat flow conditions, the theoretical maximum melting efficiencies that can be obtained are 0.48 and 0.37 respectively. [1] As a best practice, weld procedure development efforts need to be directed towards obtaining these high levels. Weld procedure development should find the preferred levels of laser power and travel speed to achieve a high melting efficiency, and still meet other important weld requirements.

One can see intuitively that if travel speed is increased indefinitely at a fixed laser power, a condition will be reached where melting and hence melting efficiency will go to zero. In such a thought experiment, heat input to the workpiece will continue but melting must cease when the travel speed becomes excessive. A conspicuous question then follows: does melting efficiency inevitably decrease at high speed? And if so, at what speed does this occur?

Discussion of melting efficiency at high speeds by other researchers has been limited. For arc welding processes, Berezovskii [3] predicts a drop in melting efficiency will occur at high travel speed when the weld pool width becomes smaller than the arc spot. Such a decrease seems logical when the arc begins to heat a greater region adjacent to the fusion zone. This effect does not seem likely in laser welding, since the spotsize is so much smaller relative to the weld pool. Experimental data for laser welding presented by Grigoryants [4] shows a decline in melting efficiency at high travel speed for titanium and carbon steel. No discussion of the apparent drop is given. For high speed gas tungsten arc welds on thin copper cable sheathing, LaCoursier et al [5] found that the arc energy per unit length of weld declines to a constant value for weld speeds greater than 50 mm/s. Although no calculation of η_m, is given, the results demonstrate a maximum melting efficiency is reached. Most interesting, no evidence of a subsequent drop in melting efficiency is evident as speeds increased up to 120 mm/s. Recent calorimetric measurements of melting efficiency for laser welding on 304 stainless steel by Fuerschbach [2] indicate a decline in η_m occurs as travel speed increases from 50 to 76 mm/s.

To help reconcile these important but disparate observations, very high speed continuous wave CO_2 laser welds were made utilizing a calorimeter to accurately measure the net heat input to the part. Analysis of the new experimental data has yielded probable explanations for variations in melting efficiency, as well as corroborated previous observations by other researchers. The experimental results will be shown to be consistent with the moving heat source solutions to the conduction heat flow equation.

Experimental Procedure

Welds were made using a Photon Sources V1200 slow axial flow CO_2 laser operating in the continuous wave mode. Because the maximum speed of the workstation XY table was limited to 100 mm/s, rotational welds were required to achieve the very high travel speeds sought. Type 304 stainless steel plates with dimensions 12.7 mm thick by 102 mm diameter with a machined surface were spun under the laser beam with a rotary fixture. Welds were made in a spiral pattern, as shown in Fig. 1, in order to obtain a reasonably long weld with substantive heating of the workpiece. Spacing between the spiral passes was adequately maintained and preheating from the preceding pass was prevented by slowly translating the rotating fixture under the laser beam. The laser beam shutter was used to start and stop the weld, as the part was already spinning before welding. The finished welds were placed immediately inside the calorimeter after welding.

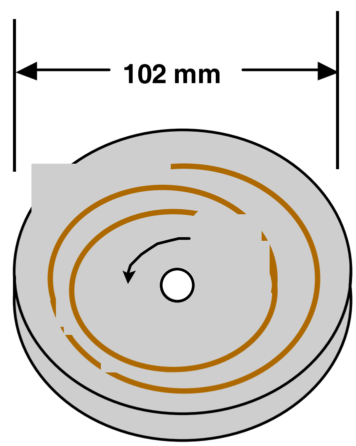

Fig. 1 — Drawing of 304 SS plate showing pattern of laser weld employed to facilitate the high travel speeds sought in the experiment.

Ten welds were made; two replicates for each of the five travel speeds. The five levels of travel speed were: 106, 212, 318, 424, and 530 mm/s. All welds were made in the continuous wave mode at 8.5 MW/cm^2. Laser output power was 930 watts. The laser beam was focused with a 2.5 in focal length aspheric ZnSe lens. The spotsize diameter with this lens and laser has been previously measured to be 0.118 mm. [6] The welds were shielded with 100% argon gas from a nozzle assembly that also houses the focusing lens. Laser output power was measured with an Optical Engineering model 25-D power probe either immediately before each weld or immediately after completion of the weld. The power measurements were taken in the laser beam as it exited the focusing lens nozzle assembly.

The net heat input to the part was measured for each weld with a Seebeck envelope calorimeter, the calorimeter walls were maintained at room temperature with a constant temperature bath. The calorimeter operates on the gradient layer principle [7] and produces a voltage output that is proportional to the flux through the walls during the time required for the weld sample to cool to room temperature. For short duration weld times, the energy losses with this experimental technique due to radiation, convection, and evaporation are thought to be 1% or less of the measured energy. [8] The calorimeter has been shown to produce a very linear response for different closure times and heat input levels. The output voltage versus time trace was recorded on a digital storage oscilloscope, then integrated to determine the energy in joules absorbed by the workpiece during the weld. Weld penetration and cross-sectional area were determined (using a planimeter) from the average of four transverse metallographic sections taken from each weld. The values of melting efficiency, η_m , were calculated from equation (1) with q_i, the net power, taken as the average for the entire weld time.

Predicted values of melting efficiency were calculated using Rosenthal's [9] moving heat source solutions to the conduction heat flow theory, along with the aid of desktop computer. In order to calculate melting efficiency, it is necessary to determine the cross-sectional area of the melted region for a specified power and travel speed. The line source (2D) and semi-infinite plate (3D) steady state heating solutions are given in equations (3) and (4), where T is the melting temperature (for the melt contour), T_0 is base metal temperature, k is thermal conductivity, t is thickness of workpiece, α is thermal diffusivity, r is the resultant distance to a point on the melt contour from the origin, and x is the component in the direction opposite to the movement of the heat source (where $r^2 = x^2+y^2$, y being the lateral coordinate). K_0 is the Bessel function of order 0. Thermophysical property values for 304 stainless steel used in the analyses are: T_l= 1727K, α = 5.7 mm^2/s, k = 34.1 W/mK, and δh= 9.4 J/mm^3. Since the specific heat, c_p is a complex function of temperature, an empirical value of δh was used for (2).

$$\frac{2\pi (T-T_0)kt}{q_i} = e^{\left(\frac{vx}{2\alpha}\right)} K_0\left(\frac{vr}{2\alpha}\right) \quad (3)$$

$$\frac{2\pi (T-T_0)kr}{q_i} = e^{-\left(\frac{v}{2\alpha}(r-x)\right)} \quad (4)$$

For the 2D case, one solves for the melt contour coordinates, $r, x, y,$ corresponding to the maximum width ($2*y_{max}$). Uniform heating is assumed through the thickness of the plate. A is then the rectangular approximation, ($2y_{max}t$.) Since everything in the heating equation, except position (r, x) is specified, y_{max} is obtained by first solving (3) iteratively for $r_{min} =| x_{min}|$, and $r_{max} = x_{max}$ to determine the endpoints of the contour; then incrementing r between these two values and solving for the x coordinate analytically, then y from $y^2 = r^2 - x^2$; and finally choosing y_{max}.

For the 3D case, the melt contour is considered a *body-of-revolution*. One solves for the melt contour coordinates, r, x, y, z, corresponding to the maximum width. It is assumed that the coordinates y,z lie on the semi-circular cross-sections. A is then approximated as $\pi y_{max}^2/2$ (or $\pi z_{max}^2/2$). As before, everything except position (r, x), is specified. It is necessary to solve (4) iteratively for the contour end point $r_{min} =| x_{min}|$ (x_{max} is known from inspection). The rest of the solution proceeds identically to the 2D case.

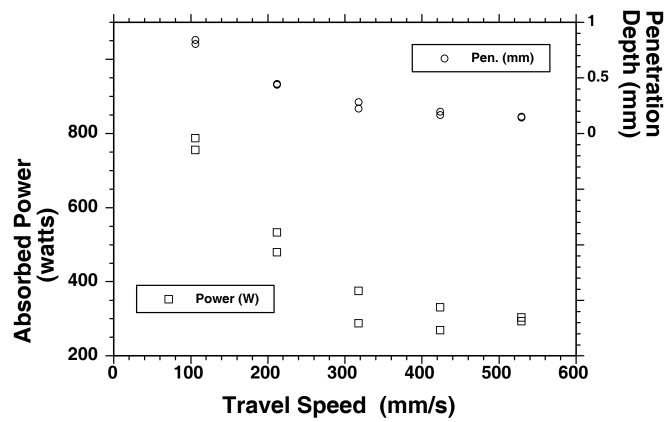

Fig. 2 — Both the net input laser power and the weld penetration decrease as travel speed increases, all welds made at 8.5 MW/cm^2.

RESULTS AND DISCUSSION

AN ENHANCED MELTING EFFICIENCY.

The laser power absorbed by the workpiece (q_i) is shown in Fig. 2. The decrease in absorbed power is likely due to a drop in energy transfer efficiency (beam absorption) associated with a progressively shallower fusion zone as speed is increased. [10] The decrease in fusion zone depth also shown in Fig. 2 is simply related to a decrease in the laser linear output energy from 8.7 J/mm at the low speed to only 1.7 J/mm at the highest speed. As a practical matter, to maintain a more constant linear output energy at the very high travel speeds evaluated in this experiment, a significantly more powerful laser would have to be used. If we examine η_m in equation (1), we can note that despite a decrease in q_i, η_m does not necessarily increase, since the resulting fusion zone size (A) must also be taken into account.

The combined result of the changes illustrated in Fig. 2 on laser beam melting efficiency is given in Fig. 3. The experimental results in Fig. 3 indicate the potential of travel speed for both positive and negative effects on melting efficiency. Note that melting efficiency at first increases, then begins to slowly decrease as the travel speed becomes faster. We will discuss the causes of the observed increase and decrease subsequently, but first let us consider the magnitude of the measured values.

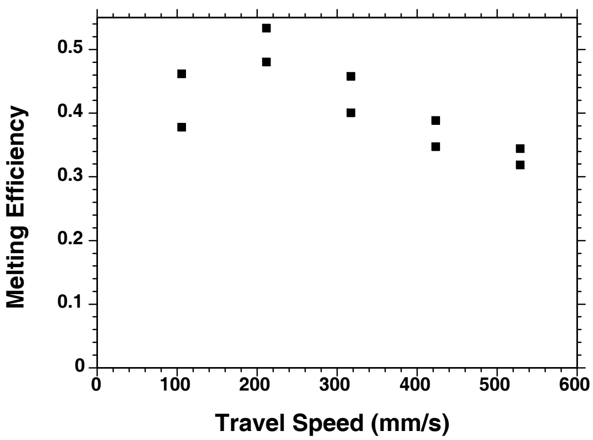

Fig. 3 — Effect of travel speed on measured melting efficiency for very high speed laser welding.

Despite the extremely high travel speeds investigated, the melting efficiency values are still very high relative to many typical laser welds made at lower travel speeds. [2] Note that welds at 212 mm/s (equivalent to 500 in/min, and 12.7m/min) are considerably faster than welds commonly regarded as very high speed (i.e. 2.5-8 m/min). The experimental results in Fig. 3 clearly indicate that a high and close to ideal melting efficiency can be obtained while welding at high travel speed. The evident uncertainty of the data in the figure is explained by the considerable difficulty in accurately measuring the small weld heat inputs and weld size fluctuations. The maximum melting efficiency obtained is reasonably consistent with the theoretical maximum of 0.48 predicted for 2D heat flow conditions. The maximum 2D level is reached even though these are small welds on a relatively thick plate, where one would expect 3D heat flow to occur and η_m should be no higher than 0.37.

Previous melting efficiency measurements of similar laser welds [2] have shown that because of a high depth to width ratio, laser welds on thick sections can yield enhanced melting efficiency levels that are quasi-2D—more typical of a 2D heat flow geometry than of the 3D geometry which should govern for partial penetration welding in thick sections. The high levels presented in Fig. 3 show a similarly enhanced melting efficiency—such high levels for partial penetration welds are a compelling benefit of the laser welding process.

INITIAL INCREASE IN MELTING EFFICIENCY.

The initial increase in Fig. 3 can be predicted from heat flow analysis using the moving heat source solutions (3), (4), to the conduction heat flow equation. A dimensionless parameter first given by Rosenthal [9] can be used to correlate with melting efficiency for 2D heat flow. We will designate the parameter as: *Ro*, after D. Rosenthal; it is given in (5) where t is plate thickness, and ΔT is the temperature difference between the base metal and the melt contour. Similarly, for the 3D problem, the dimensionless parameter, *Ry* in (6), named after N. Rykalin is useful in predicting melting efficiency. [2]

$$Ro = \frac{q_i}{t\,k\,\Delta T} \qquad (5)$$

$$Ry = \frac{q_i\,\upsilon}{\alpha^2\,\delta h} \qquad (6)$$

Figures 4 and 5 illustrate the dependence of melting efficiency on these parameters for 2D and 3D heat flow respectively. The curves were generated by solving equations (4) and (5) for a given material at multiple sets of power and velocity, then calculating the fusion zone area and the corresponding melting efficiency. These model curves are helpful in examining the effect of changes in process parameters on melting efficiency. As one would expect, the theoretical maximum values of melting efficiency discussed earlier are predicted by the moving heat source models used to generate the curves in Figs. 4 and 5.

For the general 2D heat flow problem illustrated in Fig. 4, it is apparent that η_m increases with increasing values of *Ro*. However, since travel speed is not explicitly contained in *Ro*, melting efficiency for 2D heat flow is only improved by welding with a higher power per unit thickness(q_i/t), and speed is really unimportant. Nonetheless, for welds that are made at very high travel speeds, high power will inevitably be required, and therefore, indirectly, a high melting efficiency is likely.

For the general 3D heat flow problem illustrated in Fig. 5, the dependence of melting efficiency on travel speed can be inferred directly from a somewhat different dimensionless parameter, *Ry*. In this case, laser power and travel speed will have the same effect on melting efficiency since they both occur in the numerator of *Ry.* Increasing travel speed independently, as in this experiment, will increase *Ry,* hence η_m should increase, whether the power is increased or not.

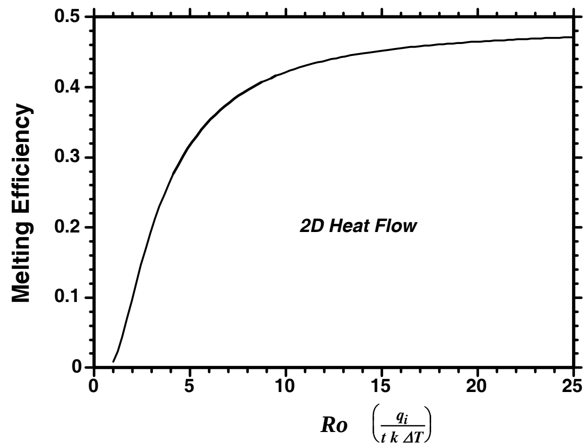

Fig. 4 — Dependence of melting efficiency on the dimensionless parameter Ro. From the line source steady state heating solution (3).

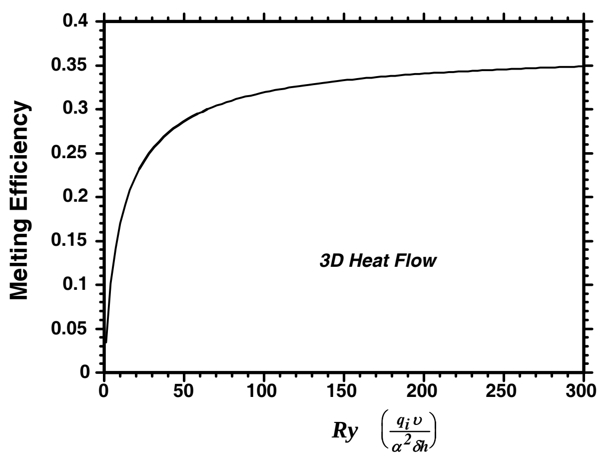

Fig. 5 — Dependence of melting efficiency on the dimensionless parameter Ry. From the semi-infinite plate steady state heating solution (4).

If 3D heat flow is assumed for our experimental welds, then the initial increase in η_m observed in Fig. 3 is entirely consistent with changes in *Ry* , since travel speed was increased significantly.

In contrast, if 2D heat flow is assumed, we must consider the change in power per unit thickness. For quasi-2D laser welds, penetration depth can be used to approximate thickness. Analysis of the net power and corresponding penetration depths in this experiment indicates that the power per unit thickness is increasing, hence *Ro* is increasing even as the net power declined. As for the 3D heat flow case, the initial increase in η_m seen in Fig. 3 is predictable for 2D heat flow due to changes in the applicable dimensionless parameter.

DECREASE IN MELTING EFFICIENCY.

The conduction heat flow models illustrated in Figs. 4 and 5 indicate that melting efficiency does not inevitably decrease but continues to asymptotically approach maximum values as either power, travel speed, or both increase. This constancy that the theory predicts at high travel speeds is corroborated by the unvarying arc energy requirements seen by LaCoursiere et al. [5] It seems likely that many other high production rate fusion welding applications also benefit from the constancy in melting efficiency that occurs at very high travel speed. The intuitive drop in melting that one would expect if travel speed was increased independently to an exceedingly high value, may quite simply result in infinitely small welds that still possess a high melting efficiency. If we reconsider our earlier thought experiment along with equation (1), a decline in melting (*A*) does not necessitate a decline in melting efficiency, since ν is increasing concurrently.

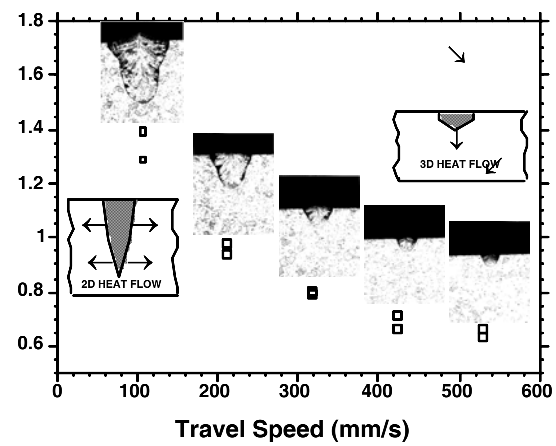

Fig. 6— Change in fusion zone geometry as travel speed increased in the experiment.

At first examination, the results of this experiment in Fig. 3 might be thought to contradict the heat flow models shown in Figs. 4 and 5. Unlike the η_m increase discussed above, the η_m decrease is not consistent with the models displayed in Figs. 4 and 5. Nevertheless, the theory is still valid here. The decrease in melting efficiency shown in Fig. 3 can be explained by a gradual change in the weld heat flow geometry from 2D to 3D. A change in fusion zone shape is the root cause of the variation in heat flow geometry. The change in heat flow direction is illustrated in the two sketches included with Fig. 6. The figure also shows the calculated aspect ratio along with a representative weld metallographic cross-section for each condition. As the local amount of energy available to produce melting is reduced, the fusion zone aspect ratio changes to a shape that conducts heat quite differently. For the high aspect ratio welds, heat flow occurs primarily in two dimensions—to the sides, and in the direction of weld travel. For the low aspect ratio welds, heat flow occurs in three dimensions—to the sides, downward, and in the direction of travel. As noted above, the maximum value of melting efficiency for 3D heat flow is limited to 0.37; the welds in Fig. 3 are gradually declining in magnitude to that level. It is postulated that the drop in melting efficiency observed in this experiment would not occur if sufficient laser power were available to maintain a fusion zone aspect ratio greater than 1.0. Observed drops in melting efficiency at high speed noted by Fuerschbach and Grigoryants [2,4] can similarly be explained by changes in fusion zone aspect ratio.

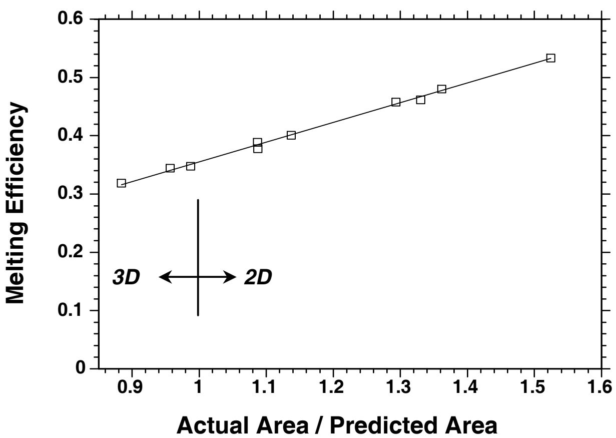

Fig. 7 — As melting efficiency decreases, weld size is better predicted with the 3D heat flow geometry model.

Further evidence of an enhanced melting efficiency and a decline to levels more typical of 3D heat flow is given in Fig. 7. The predicted weld area for each representative condition of travel speed and net power was calculated using the 3D moving heat source solution (4). Since 3D values will generally under-predict the actual amount of melting in laser welding, most of the area ratios given in Fig. 7 are greater than 1.0. At the highest melting efficiency, it is apparent that the actual weld area is at least 50% greater than one would expect for a 3D geometry weld. As the actual weld area decreases to a value more typical of 3D heat flow (i.e. the area ratio approaches 1.0), the melting efficiency approaches a level close to 0.37, which is again the theoretical maximum predicted.

Very high travel speed does not alone decrease melting efficiency. If sufficient laser power is available, then quasi-2D heat flow and a corresponding high melting efficiency can be obtained at any speed. No drop as seen in Fig. 3 should occur. The dimensionless parameters in Fig. 4 and 5 can guide us in choosing these optimum levels. It should be mentioned that the decline in melting efficiency observed in this experiment is not representative of practical laser welds. We deliberately chose the highest levels of travel speed that would still produce a measurable weld. Nonetheless the experiment has been an instructive example of the benefits obtainable with quasi-2D laser welds. In more typical high speed laser welding applications, the weld pool geometry either displays a high aspect ratio or fully penetrates a thin plate—both conditions represent 2D heat flow and should result in ideal melting efficiency. Certainly, the strong demand for high power lasers and their widespread application at very high travel speeds are directly related to the tangible benefits that result when welding with high melting efficiency.

SUMMARY AND CONCLUSIONS

1. Analysis of measured melting efficiencies for very high speed laser welds (106-530 mm/s) have indicated the process conditions necessary to enhance melting efficiency, and the conditions that may degrade melting efficiency.
2. Dimensionless parameter correlations for melting efficiency based on moving heat source solutions to the conduction heat flow equations have been presented for both 2D and 3D heat flow geometries.
3. A small initial increase in melting efficiency in the experiment was found to be consistent with changes to the applicable dimensionless parameters which occurred as travel speed was increased.
4. Subsequent decreases in melting efficiency at higher and higher travel speeds were attributed to gradual changes in the heat flow geometry from 2D to 3D, a condition that is not representative of typical high travel speed laser welds.
5. For laser welds that retain a high aspect ratio, an enhanced melting efficiency is obtainable, and is not degraded by the very high travel speeds often seen in high production rate manufacturing.

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