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## *A Dimensionless Parameter Model for Arc Welding Processes*

Phillip W. Fuerschbach  
Sandia National Laboratories  
Albuquerque, New Mexico 87185-0340

### **Abstract**

A dimensionless parameter model previously developed for CO<sub>2</sub> laser beam welding has been shown to be applicable to GTAW and PAW autogenous arc welding processes. The model facilitates estimates of weld size, power, and speed based on knowledge of the material's thermal properties. The dimensionless parameters can also be used to estimate the melting efficiency, which eases development of weld schedules with lower heat input to the weldment. The mathematical relationship between the dimensionless parameters in the model has been shown to be dependent on the heat flow geometry in the weldment.

### **Introduction**

The selection of a fusion welding process for a specific application is often influenced by the ability of the weldment to withstand the heat generated by the process and the subsequent thermal stresses and distortion. It is useful to quantify welding by the melting efficiency which indicates how much of the energy deposited by the welding process is used to produce melting. In earlier work (Ref. 1), a dimensionless parameter model has been developed for laser beam welding which facilitates the determination of the actual heat input to the part and the melting efficiency. The model has been verified through calorimetry on three different materials. The dimensionless parameters used in the model are  $R_y$ , named for N. N. Rykalin, and  $Ch$ , named for N. Christensen—researchers who first used similar parameters to analyze welding (Ref. 2,3). The parameters are defined as follows:

$$R_y = \frac{q_i v}{\alpha^2 \delta h}$$

$$Ch = \frac{v^2 A}{\alpha^2}$$

where:  $q_i$  = net power into the workpiece  
 $v$  = travel speed  
 $\alpha$  = the thermal diffusivity at the liquidus temperature  
 $\delta h$  = the enthalpy of melting  
 $A$  = the weld cross-sectional area

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Dimensional analysis postulates that all physical processes can be expressed as a relationship among dimensionless parameters. Dimensional analysis has been proven to be a powerful analysis tool in heat transfer and fluid mechanics. The excellent correlation between the dimensionless parameters in this welding model is attributed to a representation of the heat transfer mechanism that occurs at the liquid-solid interface in the fusion zone. For this reason, the universal applicability of the model to other welding processes such as plasma arc welding (PAW) or gas tungsten arc welding (GTAW) has been anticipated.

In this paper, arc welding studies where measurements of the heat input to the part were made, will be examined to determine if these welding processes can be analyzed using the laser beam welding model. By using calorimetric based data for the analysis, uncertainties related to both the arc power and arc efficiency can be eliminated.

### Experimental Background

All of the net power values reported in this study were determined from calorimetric measurements of the actual heat input to the workpiece. The measurements were made with a Seebeck envelope calorimeter in the manner described in (Ref. 4,5). The net power represents the fraction of the total arc power that is absorbed by the workpiece. The weld cross-sectional area values represent the average of several planimeter measurements made from metallographic sections of the welds. The thermophysical property values used have been taken from several sources and are shown in Table 1 along with the corresponding reference. One should note that the thermal diffusivity values are taken at the liquidus temperature.

**Table 1—Thermophysical Properties**

Material	Liquidus Temperature	Thermal Diff. (mm <sup>2</sup> /s)	Enthalpy of Melting (J/mm <sup>3</sup> )
304 stainless steel	1727K	5.7 (Ref. 6)	8.7 (Ref. 7)
1100 aluminum	933K	31.7 (Ref. 6)	2.86 (Ref. 8)
nickel 200	1726K	13.0 (Ref. 6)	9.87 (Ref. 8)

### The Dimensionless Parameter model

The relationship between the dimensionless parameters  $Ch$  and  $Ry$  for two autogenous arc welding processes is given in Fig. 1. The correlation with the dimensionless parameters and experimental data appears to be quite good and consistent with the dependence seen in (Ref. 1). The correlation equation given is based on a least squares fit of the data.

The usefulness of Fig. 1 is considerable and should be understood. When developing weld schedules, the equation given can be used to readily and accurately estimate the size of a weld for a given material, travel speed, and net power. Alternatively, the required arc



power can be determined for any combination of travel speed and weld size. Using this approach, estimates of arc current, electrode size, and equipment requirements can be made before entering the laboratory.

### Estimating Melting Efficiency

Values for these dimensionless parameters can also be used to compute an important figure of merit: the melting efficiency. The calculation is straightforward since the melting efficiency is simply the ratio of the two dimensionless parameters :

$$\eta_m = \frac{Ch}{Ry} = \frac{v A \delta h}{q_i}$$

This method enables estimates of the melting efficiency to be made for arc welds when  $Ch$  and  $Ry$  are directly calculated, or alternatively, when they have been determined with the aid of Fig. 1.

Another way to estimate melting efficiency is with the dimensionless parameter  $Ry$ . The traditional approach for quantifying the heat input to the part in arc welding involves calculating the linear heat input (the ratio of the arc power to the travel speed). However, this factor does not realistically indicate the effectiveness of a welding process in creating melting as is demonstrated in Fig. 2. One can see from this figure that the energy required to melt the fusion zone is not solely influenced by the heat input rate. The efficiency of the welding process in creating melting must also be considered; that is, the heat input rate must be modified by the melting efficiency. Since melting efficiency is a nonlinear function of both  $q_i$  and  $v$ , this step is often neglected in welding analysis.

The dimensionless parameter  $Ry$  has been found to be extremely effective in estimating melting efficiency. The strong correlation between melting efficiency and  $Ry$  can be seen in Fig. 3 for both the PAW and GTAW processes. Because the correlation has a thermodynamic basis, the type of heat source (i.e. the welding process) has little effect on the dependence. In addition, because  $Ry$  is dimensionless, and contains the material parameters important in welding,  $Ry$  facilitates the direct comparison of the welding behavior of widely different metals.

The effect of heat flow geometry on melting efficiency can also be represented with  $Ry$ . The correlation curves shown in Fig. 4 are fitted to data taken for two different weld joint types. One can see that at high values of  $Ry$ , melting efficiency asymptotically approaches a maximum value. It has been shown that this maximum value depends on the heat flow geometry (Ref. 7). For the welds in Fig. 4 that are edge welds, the heat flow is constrained to be two dimensional, whereas for the bead on plate welds given, the heat flow is three dimensional. The theoretical maximums for two dimensional and three dimensional heat transfer are 0.48 and 0.37 respectively.

### Conclusions

1. A dimensionless parameter model previously developed for CO<sub>2</sub> laser beam welding has been shown to be applicable to autogenous arc welding processes.

2. The ratio of the dimensionless parameters has been shown to be equivalent to the melting efficiency.
3. The mathematical relationship between the dimensionless parameters in the model has been shown to be dependent on the heat flow geometry in the weldment.

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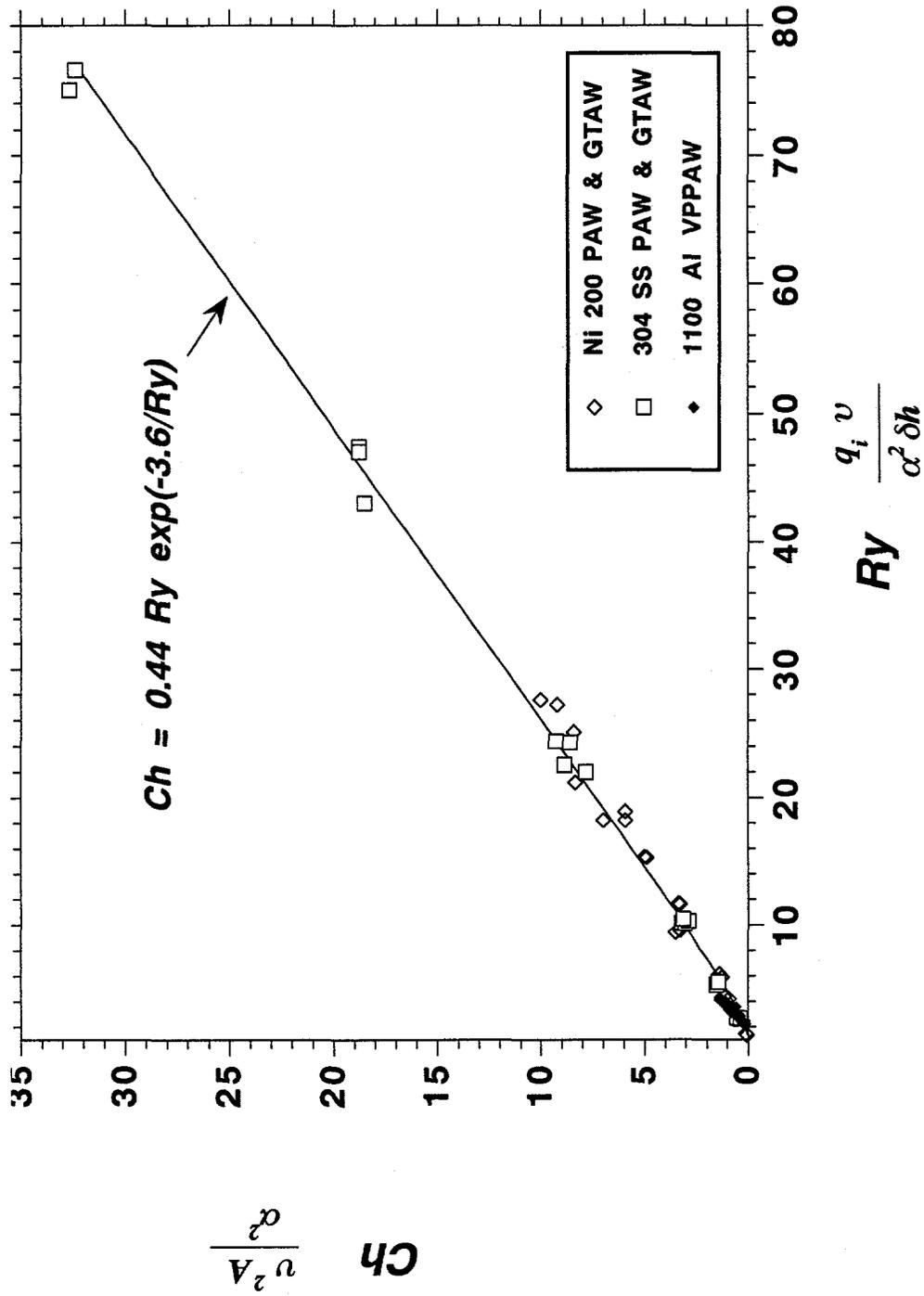


Fig. 1 — Dimensionless parameter model for VPPAW Al welding and constant current arc welding of 304SS & Ni 200

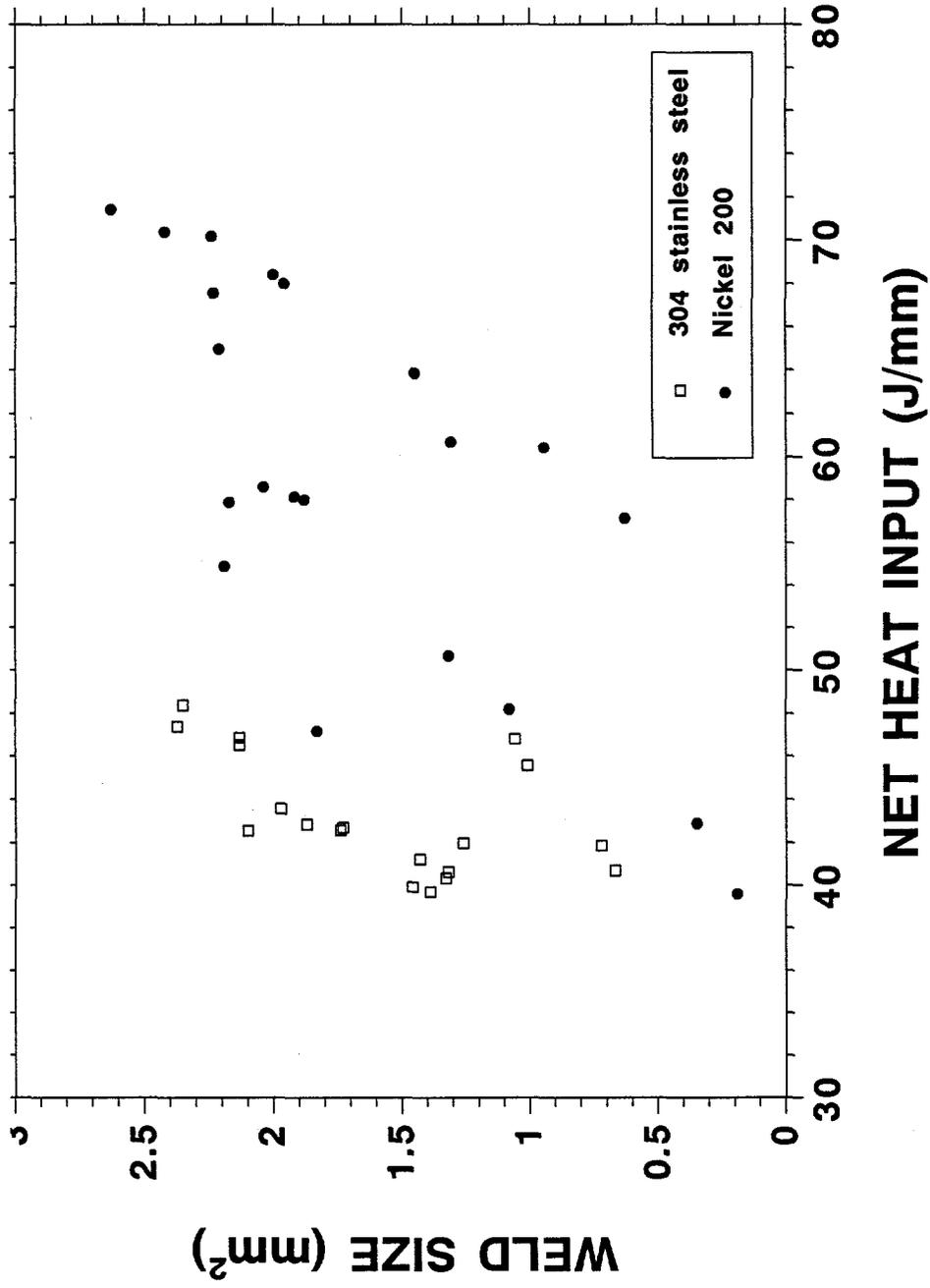


Fig. 2 —Lack of correlation between arc heat input and fusion zone size for PAW and GTAW processes

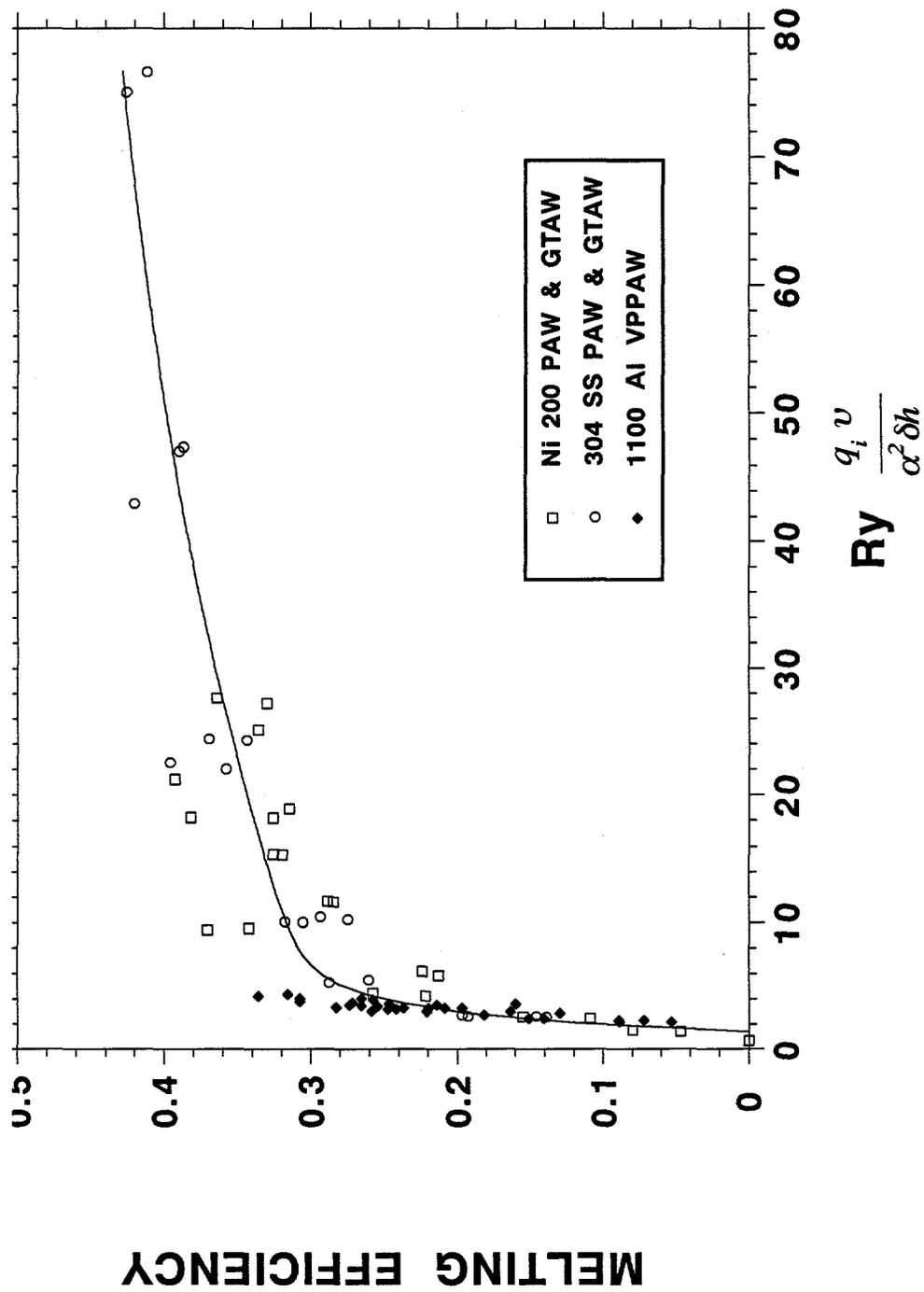


Fig. 3 — Dependence of edge weld melting efficiency on the dimensionless parameter  $Ry$

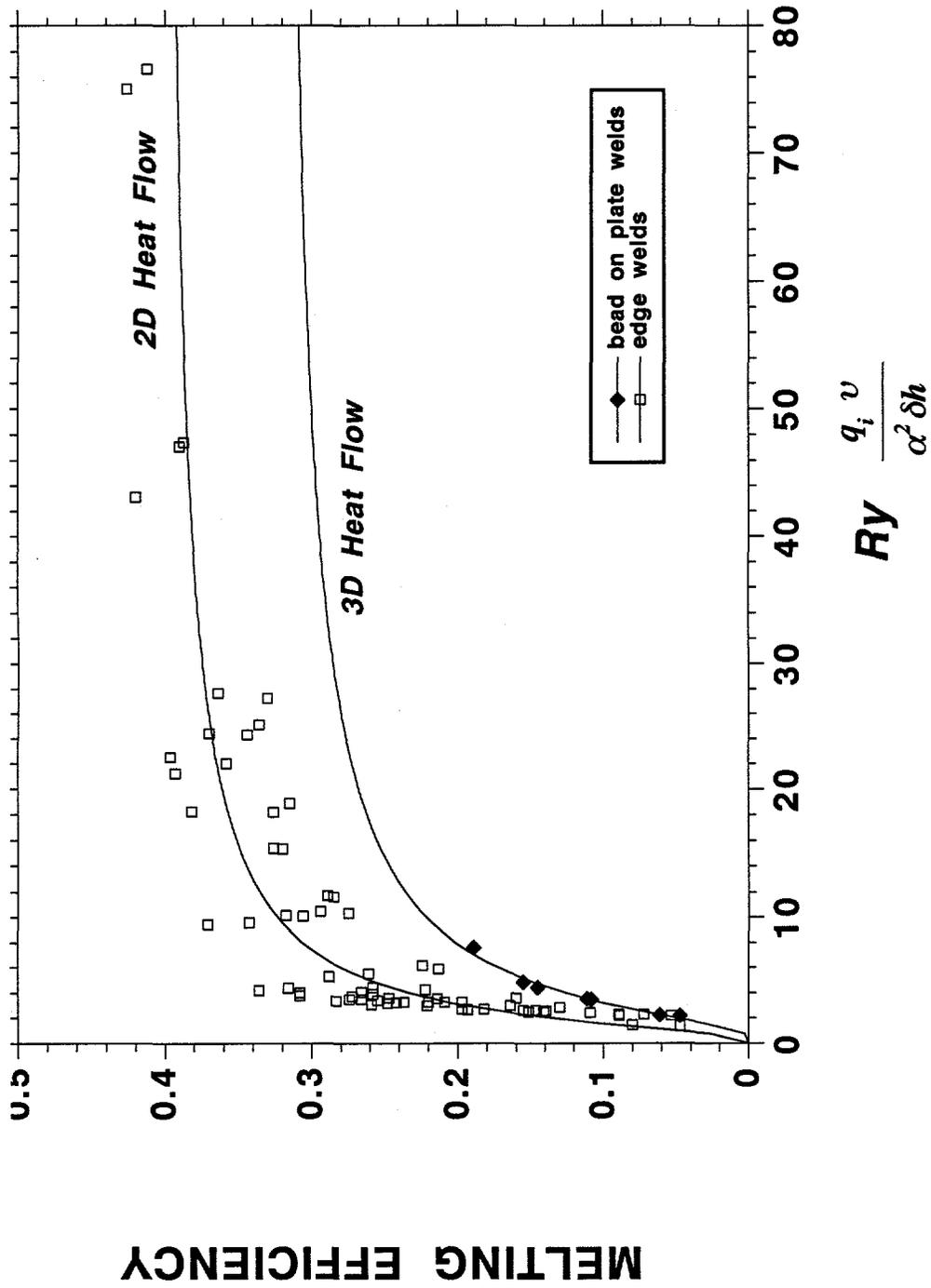


Fig. 4 — Dependence of measured melting efficiency on heat flow geometry for autogeneous GTAW and PAW welds