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Melting ratio in laser welding of dissimilar metals

ZHENG SUN
Laboratory of Production Engineering, Technical Research Centre of Finland, Box 111, 02151, Espoo, Finland

TAPANI MOISIO
Laser Processing Laboratory, Lappeenranta University of Technology, Box 20, 53851, Lappeenranta, Finland

Laser beam welding is a fast growing technique which offers several advantages over conventional welding processes: a small heat-affected zone and low distortion due to low heat input; welding at high speed; the fact that welding can be carried out in areas of difficult access; and possibilities for automation and robotization [1].

The industrial application potential of laser welding is actively and widely pursued. For example, it has proved to be an efficient method in the automobile industry [2–5]. However, many of the phenomena involved in laser welding require further investigation in order to provide sufficient data for controlling the process. The melting ratio is one such important factor. It is defined here as the ratio of the energy required to heat and melt the material in the weld bead divided by the energy delivered to the workpiece. The difference between these two energies represents that energy lost by thermal conduction into the base metals, and that lost by vapour phase convection and radiation to the environment [6]. Although theoretical prediction of the melting ratio has been performed, accuracy is still questionable due to the complexity of interaction of the processing parameters and insufficient data on material thermal properties, particularly at high temperatures. Different laser equipment set-up can also result in different melting ratios. In this letter, the results of melting ratio measurement for laser welding of dissimilar metals through weld bead geometry changes are reported.

Laser welding was performed using a continuous-wave CO_2 laser. The base materials used were AISI 347 stainless steel and 13CrMo44 low-alloy steel, both in the form of tubes of 43.5 mm outer diameter and 4.5 mm wall thickness. The tube-to-tube butt joints were produced in two ways—by autogenous welding (without filler) and by welding with nickel-based filler wire (ENiCrMo-3, 1.2 mm in diameter). Plasma control and shielding gas (helium) at flow-rates of 20 and 32 l min^{-1}, respectively, were used in both cases. The welding nozzle and sample arrangement are shown in Fig. 1, and the laser welding parameters are given in Table I. The autogenous welds were produced using different heat input, whereas the filler wire welds were produced with variations in both air gap width between the two base materials and the heat input. The wire feed rate was selected based on the air gap width such that the filler wire volume used was around 13% more than the gap volume, considering the formation of both face and root reinforcements. The wire feed rate was thus varied in proportion to the air gap. When calculating the heat input, a constant heat transfer efficiency of 85% was used.

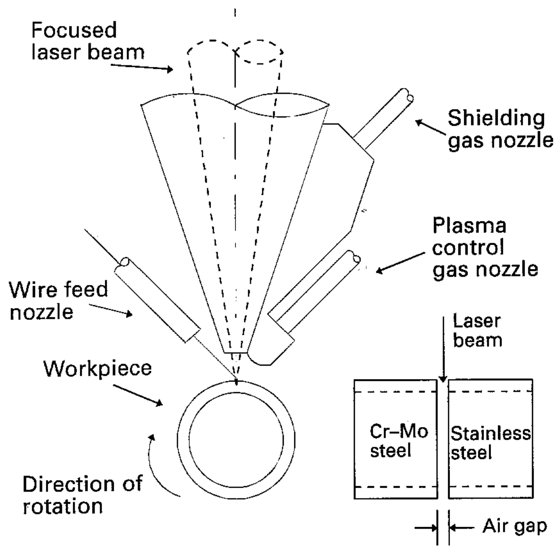

Figure 1 Laser welding nozzle and sample arrangement.

TABLE I Laser welding parameters

Weld[a]	Power (kW)	Speed (mm min^{-1})	Air gap (mm)	Wire feed rate (mm min^{-1})	Heat input (kJ mm^{-1})
A1	3.5	1250	0	0	0.14
A2	3.0	900	0	0	0.17
A3	2.5	500	0	0	0.26
F1	3.5	1250	0.2	1125	0.14
F2	5.0	1250	0.6	3200	0.20
F3	5.5	1250	0.8	4260	0.22

[a]A and F in the weld notations refer to autogenous welds and filler wire welds, respectively.

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TABLE II Thermal properties used for calculating the melting ratio

	Melting temperature (K)	Density (kg m^{-3})	Specific heat capacity (J kg^{-1} K^{-1})	Latent heat (J kg^{-1})
13CrMo44	1723	7920	620	271960
AISI 347	1673	7750	620	271960
ENiCrMo-3	1623	8480	600	292880

The cross-sectional area of the weld metals was determined from macrographs of the welds. The weld profiles were cut out from these pictures and weighed, to an accuracy of 0.1 g. From the known magnifications of the macrographs and the specific weight of the paper used, the weld cross-sectional areas were calculated. Three sections were examined for each weld and the average was used to give the cross-sectional area of the weld metal.

In autogenous welds, the fractions of stainless steel and low-alloy steel in the weld metal were calculated according to the Cr and Ni contents, measured by energy dispersive X-ray spectrometer (EDS) using a scanning electron microscope, and the compositions of the base steels. When filler wire was used, the fractions of each part (including filler wire and both base steels) in the weld metal were calculated by considering the filler wire cross-sectional area and the measured cross-sectional area of weld metals as well as the Cr and Ni contents of each part.

The melting ratio (R_m) can be expressed as

$$R_m = \frac{\rho_{ss}A_{ss}(C_{ss}\Delta T_{ss} + H_{ss}) + \rho_{la}A_{la}(C_{la}\Delta T_{la} + H_{la}) + \rho_{wi}A_{wi}(C_{wi}\Delta T_{wi} + H_{wi})}{\frac{P}{S}}$$

in which ρ is material density, A is cross-sectional area, C is average specific heat capacity for the temperature interval, ΔT, which is the difference between the ambient temperature and the melting temperature, H is latent heat, P is laser power and S is welding speed. The subscripts "ss", "la" and "wi" represent stainless steel, low-alloy steel and filler wire, respectively. The thermal properties of the materials used in the calculation are taken from the literature [7, 8], and are listed in Table II. The calculated melting ratios of the welds as a function of heat input for both autogenous and filler wire welds are given in Fig. 2.

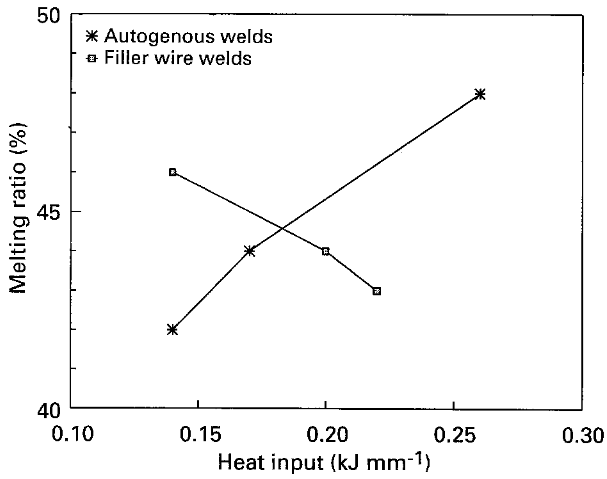

Figure 2 Melting ratio as a function of heat input.

Two tendencies were observed in the melting ratios calculated. Firstly, the melting ratio was found to increase with an increase in heat input in autogenous laser welding. Secondly, the melting ratio decreased with increasing heat input in filler wire welding. Note that in these filler wire welds, the air gaps increase with an increase in heat input at the same time. This may be one of the reasons, since the increased air gap may reduce the absorption of heat by the workpiece. This result indicates that the effect of air gap width is stronger than that of heat input in the present study. Although such tendencies are found from these calculations, their extent is difficult to confirm quantitatively, in view of the inaccuracy of calculation caused by errors in the thermal properties assumed. In fact, high-temperature material properties presented in the literature vary considerably and are dependent on temperature.

Swift-Hook and Gick [9] defined the melting ratio as the amount of energy needed to form the weld bead in relation to the energy delivered by the laser power, and concluded that the maximum value theoretically possible is 48.3% for an energy transfer efficiency of 100%. In this set of experiments, the energy transfer efficiency is assumed to be 85%. This leads to a maximum value for the melting ratio of 41%. The melting ratios shown in Fig. 2 agree quite well with this value, considering the inaccuracies mentioned above.

Melting ratio is an important factor which can provide useful data for selecting the processing parameters for a particular application. For instance, in this study, once the laser power at the workpiece and welding speed were known, the weld bead size could be estimated, and vice versa. However, this is only valid for this equipment arrangement. A different laser set-up may have a different energy transfer efficiency, and thus a different melting ratio would be obtained.

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