Interactions between Laser Beam and Filler Metal

New opportunities for increasing the efficiency of the laser beam welding process may be achieved through a better understanding of the reflection of the laser beam from the filler metal

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ABSTRACT. One method to widen the scope of applications for laser beam welding (LBW) is to use filler metal for bridging a root opening or to control weld chemistry. Use of filler metal also reduces the relative investment of laser equipment by increasing the weldable material thickness with the highest output power of the laser. Research in the field of laser beam welding with filler metal has mainly concentrated on the effect of filler metal on the weld metal composition. The use of filler metal with laser beam welding changes the welding process by adding one more component to the process, a cold wire filler metal. This paper deals with the laser beam-filler metal interaction, in particular the beam reflections from the filler metal. Entry of the wire into the focused cone of the CO_2 laser beam causes the reflection of the laser beam. The form and intensity of this reflection depends on the wire feed rate and the laser power. Up to 57% of the incoming laser power may be reflected. The reflection's portion and direction are important, because it can increase heating and melting of the pool or unmelted edges, and therefore, affect suitable welding parameters.The focusing optics also have an effect on the reflection.

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Introduction

The application of laser welding in manufacturing is growing steadily. Today it is used in welding of gear box components and the chassis of cars. Laser beam welding is rapid, easy to automate and easy to integrate into a flexible manufacturing system. Laser beam welding improves the factory lead time and decreases the rejection rate in finished products. However, laser beam welding suffers the problem that, when compared with arc welding, the requirements for edge preparation are much more stringent. One solution is the use of filler metal for bridging the root opening.

Research on the effect of filler material in laser beam welding has mainly concentrated on the mechanical properties of the weld metal and its metallurgy (Refs. 1–3). Some research has been carried out on multipass welding (Refs. 4, 5) and the potential of filler metal making joint tolerances less severe (Refs. 6, 7). In all of these three main areas of application, the use of the filler metal during laser beam welding has been found to offer a number of advantages compared with autogenous laser beam welding. However, the interaction between the filler metal and the laser beam has not yet been fully explained.

KEY WORDS

LBW
Filler Metal
Laser Beam Reflection
Focusing Optics
Laser Power
Wire Feed Rate
Reflection Shape
Reflection Direction

Laser Beam-Filler Metal Interaction

The addition of filler metal results in the occurrence of various unique phenomena during the laser beam welding process, due to the interaction of the laser beam and the filler metal. When the laser beam impinges on the filler metal, energy is absorbed. Part of it is reported to be used to weld the wire, part to vaporize the filler metal, part of the energy is reflected from the surface of the wire, and a part passes through the wire (Refs. 4, 8). Even a keyhole has been observed in the wire, caused by the very small focused spot (Ref. 4).

The laser beam is reflected by both the solid wire and the molten drop at the end of the wire. The angle of reflection is governed by the laws of optics, and is therefore dependent on the angle of the wire and the geometry of the reflective surface. The reflective surface is defined as the intersection surface of a cylinder (the solid wire) and a cone (the focused laser beam) (Ref. 8).

The fraction of laser power reflected by the filler metal has been measured and calculated. A general heat flow formula calculates that less than 10% of the laser beam is reflected from the solid wire (Ref. 8). However, up to 35% of the power of

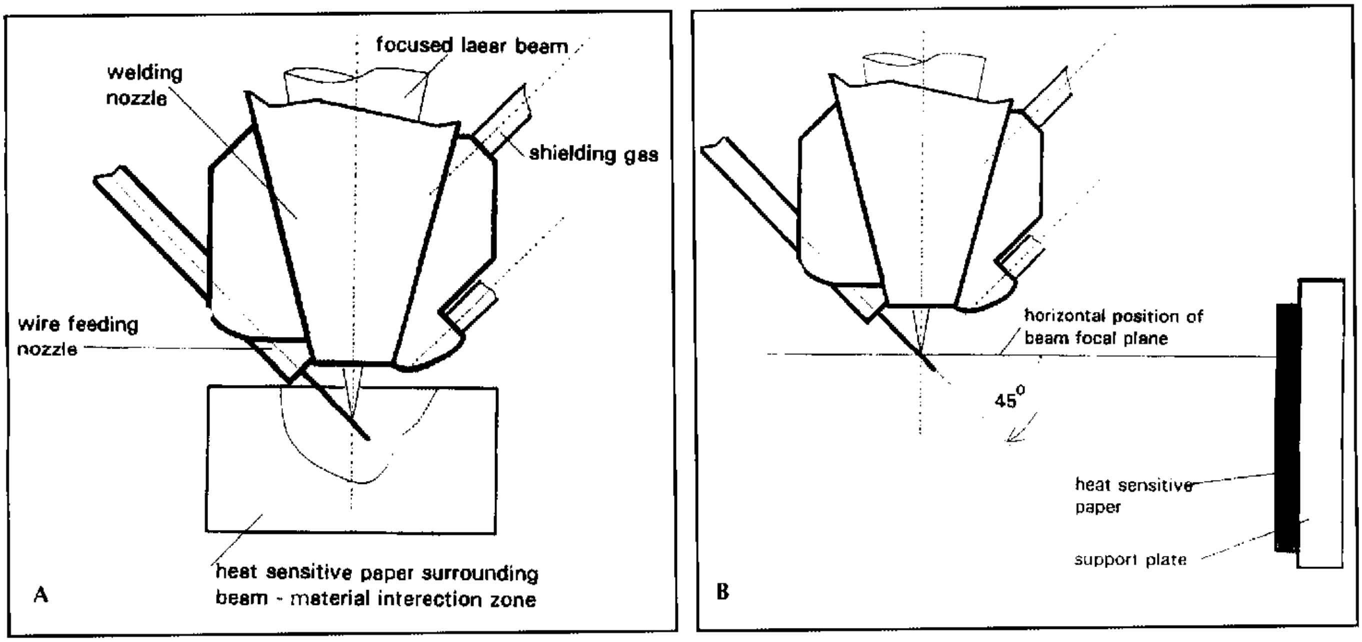

Fig. 1 — Experimental setup for detecting: A — the direction of a reflected laser beam; B — the shape of a reflected laser beam.

the laser beam can be reflected, the fraction decreasing with a decrease in the wire feed rate (Ref. 4). The reflection from the melt drop is about 70% of the total reflection from the wire (Ref. 4).

The absorption of a laser beam by the workpiece has been reported to be as high as 80% in multipass laser welding with filler metal (Ref. 4). The increase in absorption observed during filler metal welding compared with the autogenous welding is supported by reports which found that an increase in welding speed can be achieved when using filler metal (Refs. 7, 9).

Experimental Procedure

The laser used in the experiments was a Rofin-Sinar RS 6000, CO_2 laser with a TEM_{02*} beam mode. The diameter of the raw laser beam was 44, 44 and 40 mm with laser powers of 3, 4 and 5 kW, respectively. The filler metal was fed at an angle of 45 deg to the focal plane of the CO_2 laser beam. The length of free wire, *i.e.*, the distance between the tip of the wire feed nozzle and the beam-wire interaction point, was 5 mm. The filler metal was a commercially available copper-coated GMAW wire 0.8 mm in diameter, suitable for welding of mild steel.

The presence of base metal hinders the measurement of both the intensity and form of the laser beam reflection during welding. Experiments were therefore carried out without a base metal. The process parameters used (wire feed rate and laser power) were those typically used to weld steel thicknesses in the 3- to 5-mm range, with filler metal for bridging a butt joint root opening. The shielding gas was introduced by coaxial nozzle with the laser beam. Shielding was performed with helium gas at 20 L/min flow rate.

The laser beam was focused using a paraboloidal mirror of 150-mm focal length. In some experiments, a paraboloidal focusing mirror of 300-mm focal length was used in order to study the effect of the focusing system. The experimental setup is illustrated in Fig. 1.

Initial trials concerned the investigation of the angle of reflection by placing a cylinder of a heat-sensitive paper around the beam-wire interaction point. A short laser energy pulse (1 kW/10 ms) was then focused on the surface of the filler metal and the angle of reflection was detected by the heat-sensitive paper — Fig. 1A. The paper reacted to the incident CO_2 laser beam as follows:

The paper turned grey-black-brown-white, with increasing incident beam intensity or interaction time. In cases of excessive power, after turning white, the paper started to burn. The distance between paper and laser beam was 45 mm.

The form of reflection was then investigated by placing heat-sensitive paper on a flat surface such that it was the target for the reflection — Fig. 1B. The paper was fixed to one side of an acrylic plate, which was placed a distance of 170 mm from the beam-wire interaction point. The shutter was opened at the same time as wire feeding was initiated. A processing time of 10 s was used to study the effect of wire feed speed on reflection at various power levels. Wire feed rates of 1 to 8 m/min for 3 kW of laser power, 1 to 10 and 14 m/min for 4 kW, and 1 to 16 m/min for 5 kW of laser power were used in the trials. Experiments with the 300-mm focal length mirror were carried out with a laser power of 5 kW and wire feed rates of 9 to 14 m/min. Since an excessively high beam intensity set the heat-sensitive paper on fire, the form of the reflection could only be measured with laser powers of 3 and 4 kW. The range of wire feed rate that could be studied with the equipment used was restricted by the wire feeding equipment. Process times of 1 to 3 s were used when measuring the form of the reflection, since longer times invariably damaged the heat-sensitive paper.

The power of the reflected beam was detected by placing a black body power gauge (Laser Craft P10K) in the path of the reflection, close to the beam wire interaction point (distance 70 mm), such that the whole reflection was absorbed by the gauge. The measurement time was 10 s.

Results

The angle, form and power of the reflection, as well as the effects of the wire feed rate and laser parameters such as beam power and focal length of the optic were examined in the experiments.

The filler metal was directed at the focal point at an angle of 45 deg to the laser beam. The experimental arrangement shown in Fig. 1A revealed the angle of the reflection from the wire. The reflection was revealed on the opposite side of the laser beam compared to the

Table 1 — Fraction of Beam Reflected for Various Power-Wire Feed Rate Combinations

	Focal Length 150 mm						Focal Length 300 mm	
	Laser Power 3 kW Reflection		Laser Power 4kW Reflection		Laser Power 5 kW Reflection		Laser Power 5 kW Reflection	
Wire Feed Rate m/min		%	kW	%	kW	%	kW	%
1	0.35	12	0.35	9	0.20	4		
2	0.55	18	0.35	9				
3	0.75	25	0.60	15	0.30	6		
4	1.40	37	1.00	25	0.60	12		
5	1.40	47	1.10	28	0.45	9		
6	1.40	47	1.45	36	0.65	13		
7	1.15	38	1.30	33				
8	1.70	57	1.30	33	0.70	14		
9			1.30	33	0.95	19	2.10	42
10			1.80	45	0.95	19	2.10	42
11					0.90	18	2.00	40
12					1.10	22		
13					1.20	24	2.40	48
14			1.40	31	1.25	25	2.70	54
15					1.70	34		
16					1.85	37		

Paraboloidal focusing mirror focal lengths 150 and 300 mm.

wire approximately horizontally on the same level as or a little below the focal point of the laser beam. It was normally symmetrical on both sides of the level of the laser beam and wire — Fig. 2. This reflection direction was roughly independent of the laser power and the focusing optics. The wire feed rate had a little effect on the angle of the reflection. As can be seen in Fig. 2A to D, an increase in wire feed rate concentrates the reflection to just below the level of the focal point.

The shape of the reflection was either an oval (Fig. 2A) or a mushroom, comprising a cap and a base — Fig. 2B. The shape was clearly dependent on wire feed rate. The transition value for the wire feed rate was about 2 m/min, above which the shape appeared as a mushroom, and below which an oval was formed. Up to a rate of 5 m/min, the color of the heat-sensitive paper was relatively uniform, which can be interpreted as an indication of uniform intensity.

Another transition in the shape of the reflection was observed when the rate of wire feeding was increased substantially. When the highest rates of wire feeding were used, the shape of the dark part of the reflection become more round — Fig. 2C and D. A lighter area in the middle of the reflection, which indicates a higher intensity than a darker color, still appears with the shape of a mushroom. The transition for this change appeared to be dependent both on the rate of wire feeding and the laser power. When using laser powers of 3 and 4 kW, the transition was observed with wire feed rates of approximately 5 and 7 m/min, respectively. The level of the focal point of the laser beam always coincided with the top (cap) part of the reflection.

The total power of the reflection was measured after the shape and direction of the reflection were defined. The results are shown in Table 1. It can clearly be seen that the reflected power increased with the wire feed rate used. With low wire feed rates (1 m/min), the reflected power was only up to 10% of the total focused beam power. In contrast, with the highest rates of wire feeding (10 m/min), the reflection could be more than half the total laser beam power. The trend was similar for all the power levels used.

The total reflection decreased with an increase in laser beam power at a constant wire feed rate, even if the absolute reflected powers are compared. This trend is clear for all wire feeding rates. For example, a wire feed rate of 1 m/min resulted in reflections of 0.35 and 0.2 kW with laser beam powers of 3 and 5 kW, respectively. A rate of 8 m/min resulted in 1.7- and 0.7-kW reflections with laser powers of 3 and 5 kW, respectively — Table 1.

The focal length of the focusing mirror also had a significant effect on the reflected power. An increase in focal length from 150 to 300 mm more than doubled the reflected power with all wire feeding rates — Table 1.

Discussion

Shape and Direction of Reflection

The shapes of reflections from the filler metal were found to depend on the wire feed rate — Fig. 2. These can be explained by the state of the metal. The oval shape is formed by a reflection from a molten drop at the end of the wire. The mushroom shape is a mixed-type reflection, where the cap is created by a reflection from the solid wire and the base is, as with an oval reflection, reflected from the molten drop. A reflection from the solid wire is suggested (Ref. 8), and an experiment using acrylic has been described, which gave a mushroom-shaped reflection (Ref. 4). This work is supported by both of these observations.

The transition in the shape of the reflection suggests that with a low feed rate the wire melts almost immediately on entering the laser beam. With the higher feed rate, the wire remains unmelted longer on entering the beam and a reflection from the unmelted wire becomes visible, creating a cap-shaped reflection at the top of the oval-shaped reflection from the melted edge of the wire, forming a mushroom — Fig. 2B.

The angle of reflection was found to be horizontal, taking the form of an arc to the level of the focal plane of the beam. This is as expected and represents a reflection from the cylinder (solid wire) according to the laws of optics. It should be remembered that the wire was directed at the angle of 45 deg to the vertical focused laser beam, an arrangement which would be expected to give a horizontal reflection.

When using higher rates of wire feeding, the oval part of the reflection (the base of the mushroom) was concentrated to an area closer to the horizontal level of the beam focal plane than with lower rates — Fig. 2. This can likely be explained by examining the forces acting on the molten drops in the laser beam. At low wire feed rates, the molten drops of metal have little kinetic energy, and they drop deeper in the focused beam and reflect the beam lower in the heat-sensitive paper than the drops of metal which have higher energy because they originate from the wire with higher feeding rates.

The shape of the molten front of the filler metal cannot be established from the experiments described here. The parameters that affect the shape depend on the focused spot diameter, the wire diameter and the power distribution in the focused spot. The regularity of the direction of the reflection indicates that the solid-liquid front shape must be stable and does not depend to a great extent on heat input. Due to the high energy density at the center of the focused spot, it can be assumed that the molten edge is cylindrical in shape, such that the middle of the wire is melted earlier than the edges.

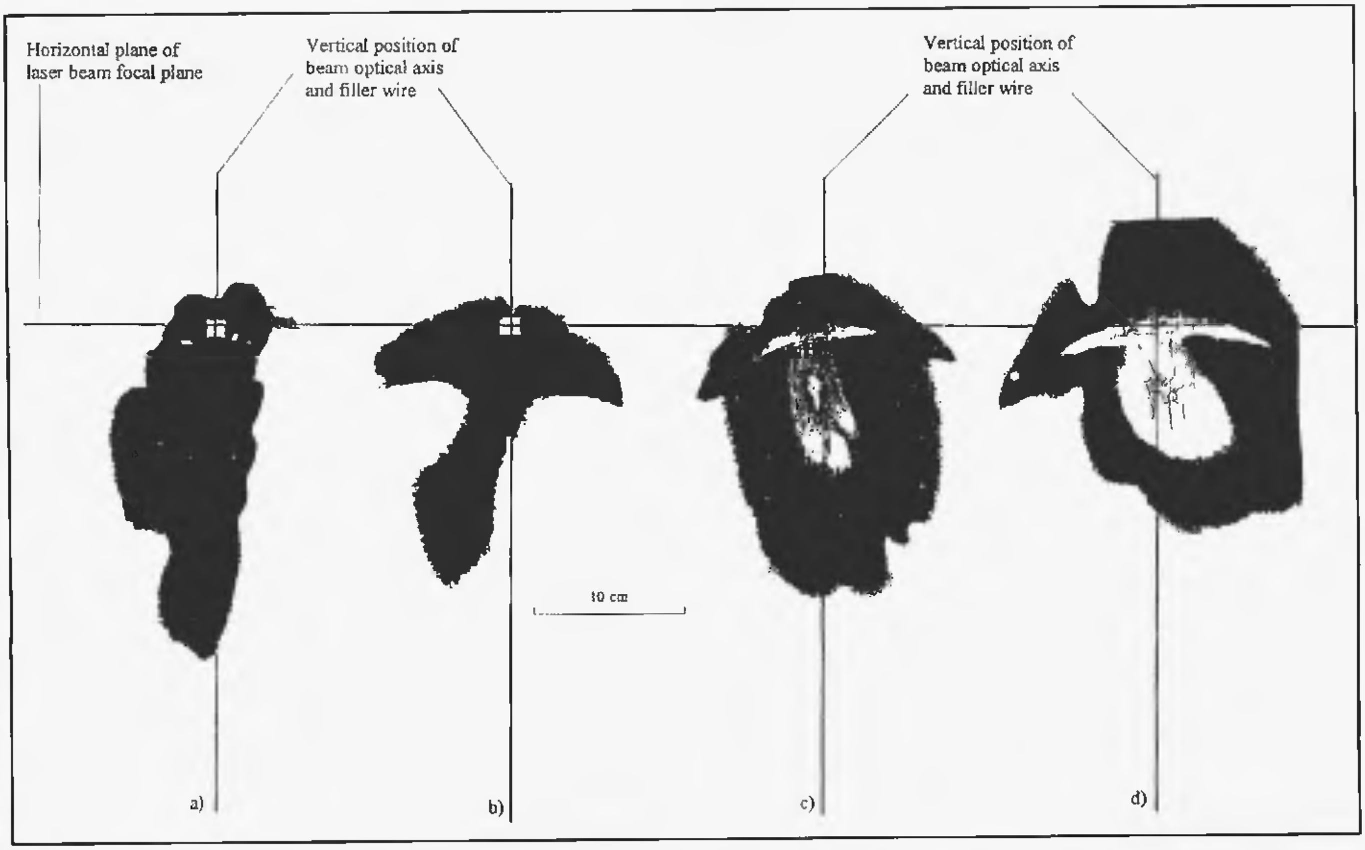

Fig. 2 — The effect of wire feed rate on the shape of the reflection. A — laser power 3 kW, wire feed rate 2 m/min; B — laser power 4 kW, wire feed rate 5 m/min; C — laser power 3 kW, wire feed rate 8 m/min; D — laser power 4 kW, wire feed rate 14 m/min.

Fraction of Beam Power Reflected

The fraction of beam power reflected of the laser beam from the filler metal was found to increase with the wire feed rate — Fig. 3. Since the reflectivity of a metal is higher in the solid state than the liquid state, and increases with a decrease in temperature as the wire feed rate increases, a greater portion of the wire has time to penetrate the focused beam, and the reflectivity is higher.

The laser beam power also affected the fraction of power reflected, the higher power showing a lower reflected power at a constant wire feed rate — Table 1. This can also be explained by the temperature of the reflected surface. When the power is increased at a constant wire feed rate, the reflection occurs from a hotter surface of a lower reflectivity. Therefore, the reflected power is also lower at higher laser beam powers.

The focal length of the reflected mirror also had a very clear effect on the fraction of reflected power. At constant laser beam power and wire feed rate, a doubling of the focal length roughly doubled the fraction of reflected power. This can be explained by the difference in the focused laser beam intensity. When the focal length increases, the focused spot size increased, and therefore, the intensity of the focused beam decreases. Thus, the heating effect on the wire is lower, and the wire remains in the solid state to a greater depth in the focal cone causing an increase in the reflectivity in a similar way to the increase in wire feed rate and a decrease in laser beam power.

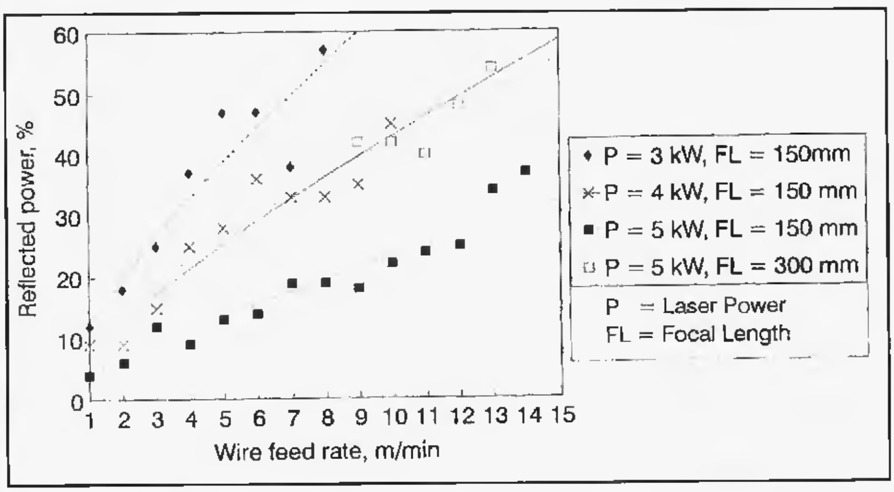

Fig. 3 — Effect of laser power and wire feed rate on the fraction of laser beam reflected.

Practical Importance of the Results

Measurements of the shape, direction and power of the reflected beam were made without the use of a base material, but with using typical welding parameters, (wire feed rates, laser beam powers, shielding gas and optical systems), the results can be expected to be relevant to real welding applications.

An increase in welding speed can be achieved through the use of filler metal compared with autogenous welding (Refs. 7, 9). The results of this work offer two explanations for this observation.

First, in autogenous welding a part of the beam escapes through the keyhole and is lost without heating the weld metal. In contrast, interaction of the beam with the filler metal reduces this. Second, the plane of reflection from the filler metal was horizontal or slightly below. When wire is fed into the leading edge of the keyhole, the reflected beam impinges the trailing edge of the keyhole, providing additional heating. Therefore, the reflection can be assumed to lengthen the weld pool, making it narrower, enabling a higher welding speed to be used.

The results favor feeding of the filler metal into the leading edge of the keyhole because of the advantageous effect on the welding speed. However, in some cases there is a need to preheat the joint edges prior to welding. This can be achieved by feeding the wire into the trailing edge of the weld pool.

The focal length of the optic can be used as a parameter to control reflection during optimization of the welding process.

Conclusions

Reflections of a laser beam from a filler metal wire has been investigated using parameters typical of practical welding with filler metal. The results allow the following conclusions to be drawn:

1) The direction and shape of the reflection of a multikilowatt CO_2 laser beam from a filler metal can be characterized by a simple technique that uses heat-sensitive paper.

2) When using a filler metal oriented at an angle of 45 deg to the laser beam, the wire reflects the beam in a horizontal plane to the opposite direction of the wire. The shape of the reflection is dependent on the laser power and the wire feed rate.

3) The fraction of the beam reflected by the filler metal wire increases with an increase in the filler metal feed rate, a decrease in the laser power, or an increase in the focal length of the focusing mirror.

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