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Effect of Assist Gas on Bead Formation in High Power Laser Welding†

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Abstract

Role of assist gas in deep penetration welding in a high power CO_2 laser welding was studied. It is found that there exsists a transition pressure above and below which three different types of bead shape are produced. When the assist gas pressure is equal to or a little higher than that of plasma blow-out from beam hole, the penetration depth becomes deepest, and over this pressure the beam hole begins to be expanded from the surface reducing the wall-focusing effect.

While at pressures higher than the transition one, whole beam hole is expanded and remelting by smooth molten metal flow increases penetration depth with no spiking and porosities.

KEY WORDS: (High Power CO_2 Laser) (Laser Welding) (Assist Gas) (Welding Phenomena) (Bead Formation) (Plasma Suppression) (X-ray Photography)

1. Introduction

As a metal-working heat source, high power laser has various characteristics suitable for high speed welding or deep penetration welding[1), 2)].

In deep penetration CO_2 laser welding, assist gas is essential to control laser plasma which reduces the penetration depth due to scattering and/or absorption of laser beam.

The authors previously reported the effect of the assist gas on the resultant weld bead at 1 kW power level and showed that the effect of the assist gas is rather than complicated; the assist gas not only reduce the influence of plasma plume but disturbes more or less the molten metal flow around the beam hole.

Systematical investigation up to higher power level is necessary for better understanding the effect of the assist gas, but has not been published so far.

In this paper some peculiarities in the bead shape formed under strong influence of the assist gas was studied in detail. The in-situ observation of the surface plasma and the shape of beam hole during welding made us clear that the assist gas not only controlled plasma plume but also changed the bead shape in the wide range of its pressure.

2. Experimental Apparatus

A 15 kW-class CW CO_2 laser (Model HPL-10, AVCO) with F/7 focusing length telescope was used and the focal spot diameter was about 1 mm. Bead-on-plate welding was performed in 18-8 stainless steel of 6-20 mm in thickness.

Helium assist gas was blown to the beam hole with a nozzle as schematically shown in **Fig. 1**. The assist gas

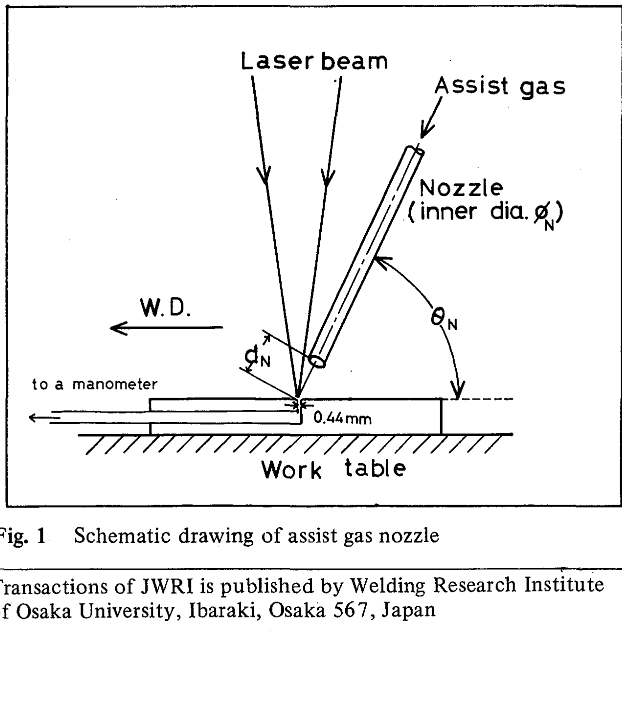

Fig. 1 Schematic drawing of assist gas nozzle

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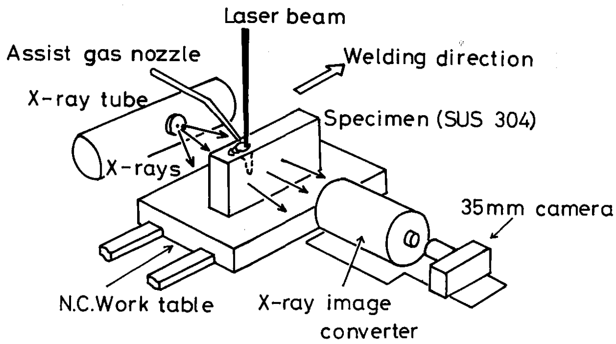


Fig. 2 Schematic drawing of X-ray photography

pressure was measured through a hole of 0.44 mm in diameter drilled in the specimen with a manometer before welding as shown in Fig. 1.

The technique for the X-ray filming of beam hole during welding developed by the authors[3] was used to observe the shape of beam hole which was filmed by a 35 mm camera as shown in **Fig. 2**

3. Results and Discussion

3.1 Effect of the assist gas

A series of experiments were performed at various beam powers (6–12 kW), speeds (0.5–3 m/min.) and focal positions with fixed nozzle parameters (ϕ_N = 3 mm, d_N = 11 mm, θ_N = 65°). The focal position a_b is defined by lens-work distance divided by focal length. The change in bead with assist gas pressure at W_b = 12 kW, v_b = 1 m/min., a_b = 0.998 and 1.000, for instance, is shown in **Fig.**

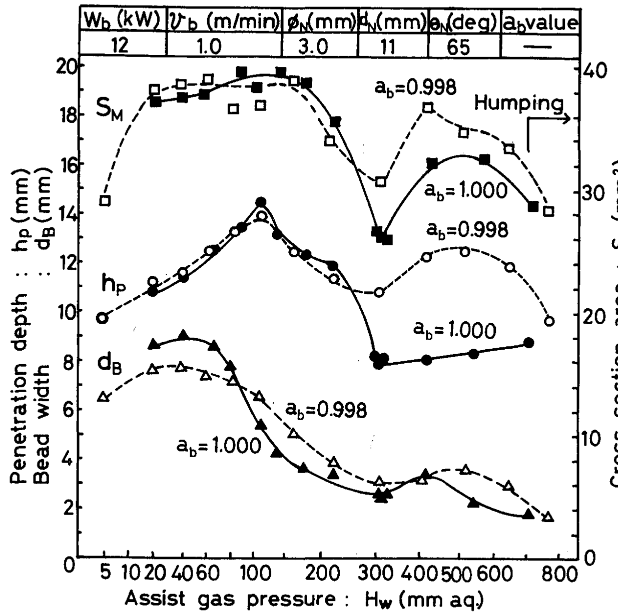


Fig. 3 Dependence of dimensions of bead shape on assist gas pressure; W_b = 12 kW, v_b = 1 m/min., ϕ_N = 3.0 mm, d_N = 11 mm, θ_N = 65° and a_b = 0.998 & 1.000

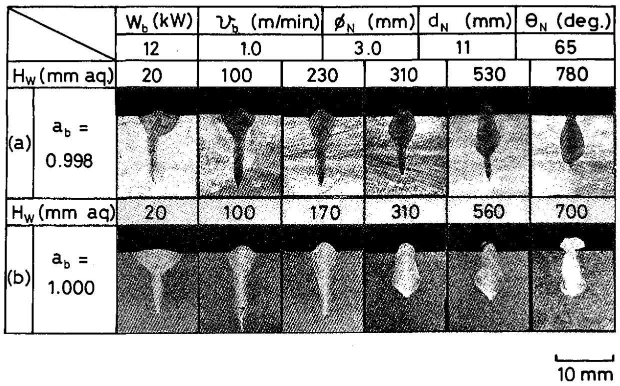


Fig. 4 Typical bead shapes in Fig. 3
(a) a_b = 0.998 (b) a_b = 1.000

3 and typical bead cross sections are also photographed in **Fig. 4**. From these results, the effect of the assist gas pressure on bead formation are summarized as follows;

(1) There exists "Transition pressure", (for example 310 mm aq. in Fig. 3), below and above which the penetration depth increases.

(2) At pressures below the transition pressure, a "winecup" like shape bead tends to be produced and the ratio of the cup-part area to the whole bead area has a peak value at a certain pressure. The maximum penetration depth is reached in this pressure region.

(3) In the higher pressure region than the transition pressure, an "egg" like shape bead is obtained at a_b = 1.000 and a wedge is seen under the egg shape at a_b = 0.998. The penetration depth of an egg shape bead is shallower compared with other types and increases gradually with the assist gas pressure. The penetration depth of an egg + wedge shape bead is smaller or equal to the maximum value of a winecup bead. It also has the peak value at a certain pressure.

(4) At too high pressure a humping bead is obtained and the wedge under an egg shape almost disappeares.

(5) Bead cross sectional area has a peak value in both regions and it always lowers to have the minimum value near the transition pressure.

(6) As for bead width, it also has the maximum value at a certain pressure in the lower pressure region, which does not correspond to that of the maximum penetration depth. It decreases rapidly as the assist gas pressure is increased.

(7) Porosities and spiking in penetration depth are observed at the bottom of the wedge bead, but no porosities are seen in an egg shape bead without spiking.

In the results at the other nozzle conditions, there was no confliction with above results.

From these results, it is clearly understood that the assist gas not only controlls plasma plume to increase penetration depth but also effects the behaviour of the molten metal to change bead shape. A winecup shape bead with the maximum penetration depth obtained in the lower pressure region is expected to apply to full penetration welding and an egg shape bead without porosities and spiking in the higher pressure region is also applicapable to partial penetration welding.

3.2 Discussion for the optimum welding condition

Observation of plasma plume above workpiece surface and the shape of beam hole on photographs were performed at $W_b = 8$ kW, $v_b = 1$ m/min. and $a_b = 1.000$ with nozzle parameters $d_N = 11$ mm, $\phi_N = 3.0$ mm and $\theta_N = 65°$.

The change of bead cross sectional dimensions with the assist gas pressure and typical photographs of welding and cross sectional dimensions of bead are shown in **Figs. 5, 6,** and 7. As shown in Fig. 5, although pressures for the maximum penetration depth and the transition pressure tend to decrease with decreasing laser power, the effect of the assist gas pressure on the penetration at this welding condition are almost same as Fig. 2.

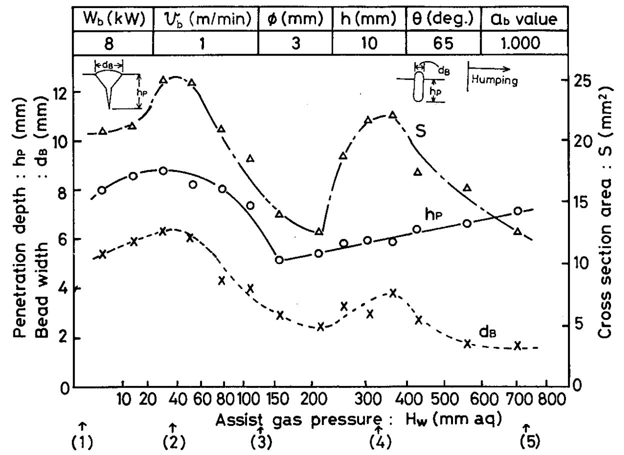
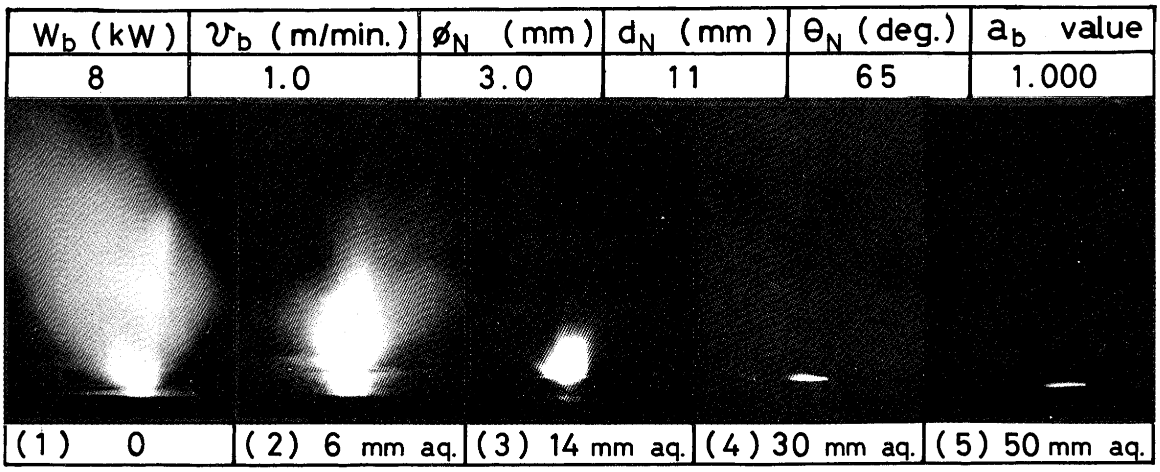


Fig. 5 The change of the cross sectional demensions of bead; $W_b = 8$ kW, $v_b = 1$ m/min., $a_b = 1.000$, $\phi_N = 3.0$ mm, $d_N = 11$ mm and $\theta_N = 65°$



(1) $H_W = 0$, (2) $H_W = 6$ mm aq., (3) $H_W = 14$ mm aq., (4) $H_W = 30$ mm aq., (5) $H_W = 50$ mm aq.

Fig. 6 Plasma plume above workpiece surface for different assist gas pressure in Fig. 5
Photography condition: F = 32, ND2.ND4.ND8 filters, 1/60 sec.
Neopan F (Fuji Color) ASA 32

A bright and columnar plasma is clearly observed in plasma plume without the assist gas as shown in Fig. 6. Dynamic behaviour of the plasma plume filmed by the authors[4] shows that it goes out intermittently from the beam hole. The brightness and size of whole plasma plume, however, is seen to be decreased rapidly by blowing a small amount of assist gas, 6 mm aq. Bright plasma, however, is observed to remain at the entrance of beam hole even a pressure of 30 mm aq., and then a winecup shape bead with the maximum penetration depth is obtained. As the pressure increasing to be 50 mm aq., weakened plasma light is observed only in the beam hole and the penetration depth begins to be decreased. This indicates that the assist gas pressure overcomes the pressure of the vapor out-coming from the beam hole to remove the vapor from the high intensity beam region. The authors previously showed with 1 kW-class CO_2 laser beam that the penetration depth becomes deepest when the assist gas pressure is equal to or a little higher than the ionized vapor pressure in the beam hole[5]. This plasma removing mechanism is confirmed to work in 15 kW-class CO_2 laser welding from present results.

As shown in Fig. 7 the plasma plume and the work-

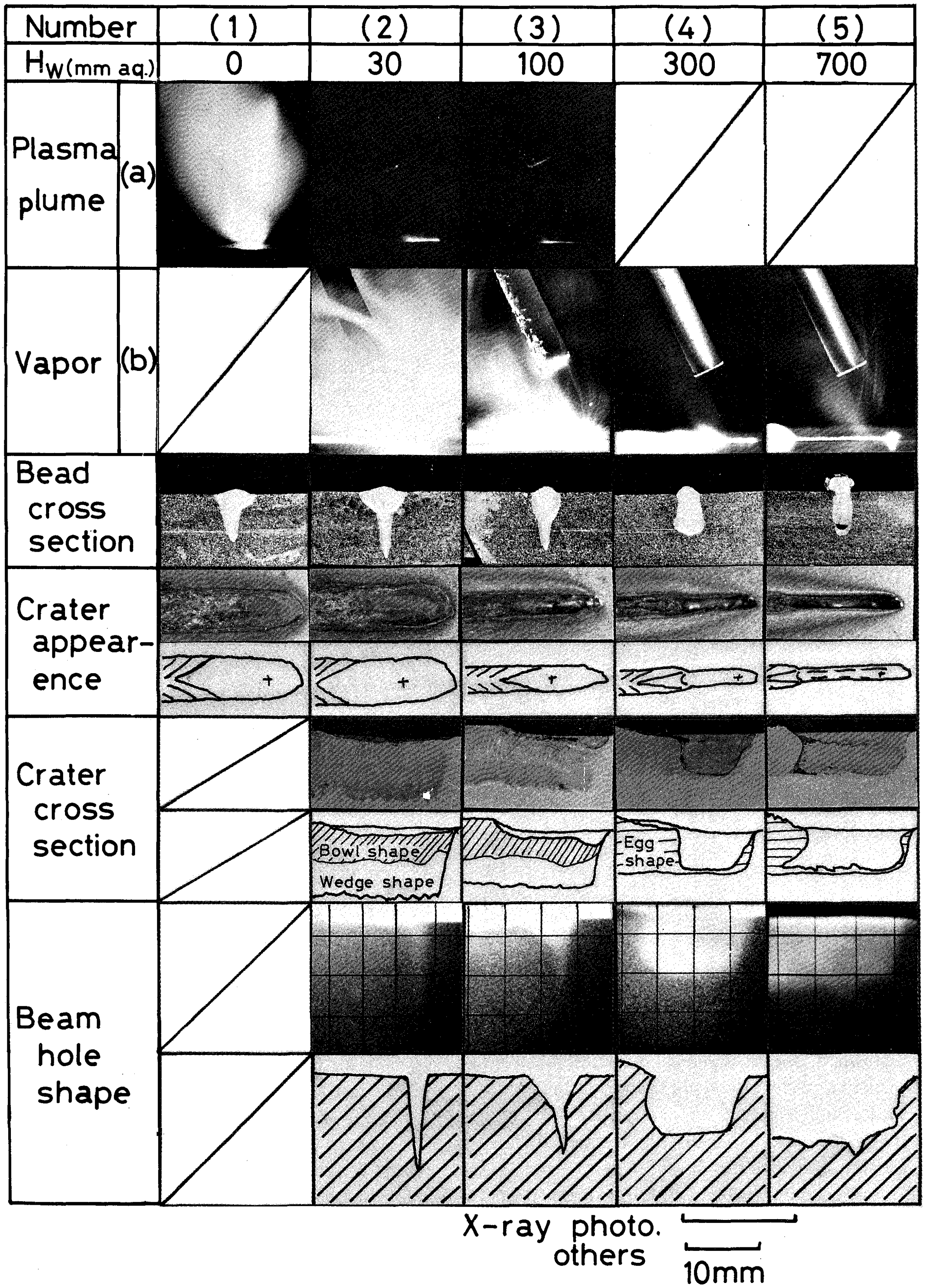


Fig. 7 Typical photographys of plasma plume and vapor cloud above workpiece surface, bead cross section, crater appearance, crater cross section and beam hole shape by X-ray photography in Fig. 5.

Photography condition: (a) F = 32, ND2.ND4.ND8 filters. 1/60 sec. Neopan F
(b) F = 11, 1/60 sec, Neopan F

piece surface were photographed with two different irises. While condition (a) was adopted to observe bright plasma plume, the behaviour of vapor and the formation of bead above workpiece surface was taken at condition (b). Brightness of vapor and plasma decreased rapidly with the assist gas pressure and in the higher pressure region a small amount of plasma light is observed at the front wall of the beam hole and vapor blows out along the back wall of the beam hole. This indicates that an expanded beam hole is sustained steadily by the pressure of the assist gas.

Typical hollows expanded by the strong assist gas pressure are seen in the photographs of resultant crater appearances and their cross sections when the assist gas pressure becomes higher compaired with plasma pressure, while the appearances of crater obtained at pressures below a pressure of 30 mm aq. is similar to the one observed in arc welding. From observing that if a hollow is formed or not, it may be decided whether the assist gas pressure is higher than the plasma pressure or not and we can use this phenomenon as an index to obtain the optimum assist gas pressure for the deepest penetration depth without observing the cut and etched bead cross section.

In the higher pressure region of 300 mm aq., the crater is a narrow dich and the bead width increases suddenly at the back of the hollow where the molten metal driven by the assist gas flows out to the workpiece surface and solidifies. This indicates that the surrounding of the beam hole is remelted by the molten metal flow, that is expected to cause the increase of the cross sectional area of an egg shape bead without spiking and porosities in the higher pressure region as shown in Fig. 5.

The shape of beam hole in the higher pressure region taken by the X-ray photography also gives a similar shape to the hollow of crater cross section. It is clearly observed that the front wall angle of the expanded beam hole is lower than that of the wedge shape beam hole. Thus it is expected that a reduction in the wall-focusing effect[6] occurs in the expanded beam hole to decrease the penetration depth, since this effect indicates that a narrow beam hole leads to an increase of the laser beam energy density within the beam hole by the refocusing of beam owing to its high reflectivity to metal[7].

An irregular flow of the molten metal in the beam hole and non-uniform solidification in the bead are observed at a pressure of 700 mm aq. where a humping bead is obtained. Taking into account the decrease of bead cross sectional area and the increase of hollow cross sectional area in this pressure region, it is expected that the heat conduction loss along the expanded beam hole and the cooling of the non-uniform flow of molten metal by too high a value of the assist gas pressure causes an irregular solidification forming a humping bead.

4. Conclusions

Effect of the assist gas on bead formation were tested using 15 kW-class CO_2 laser and the role of the assist gas in deep penetration welding was discussed. The results obtained in this study are summarized as follows:

(1) The assist gas increases penetration depth by suppressing plasma plume and can change bead shape with its pressure.
There exists a transition pressure above and below which three different types of bead shape, winecup, egg and egg with wedge are produced. In the lower pressure region the deepest penetration with winecup shape is obtained. In the higher pressure region an egg shape bead with penetration depth a little smaller than that of winecup bead is obtained without spiking and porosities. The wedge part is produced when the beam power density is high enough at the bottom of egg shape bead to provide another sub-beam hole. When the assist gas pressure is too high, a humping bead is produced.

(2) It is confirmed in high power laser welding up to 15 kW that the penetration depth becomes deepest when the assist gas pressure is equal to or a little higher than the pressure of plasma blow-out from beam hole.

(3) At assist gas pressures higher than that of the maximum penetration depth, the upper part of beam hole begins to be expanded in the direction of welding to reduce the wall-focusing effect, thereby decreasing penetration depth.

(4) At pressure higher than the transition pressure, whole beam hole, which was found to be almost the same as the resultant crater, is expanded and then remelting by smooth molten metal flow increases penetration depth with no spiking and porosities.

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