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Penetration Characteristics and Plume Behavior in Laser-Arc Hybrid Welding[†]

NAITO Yasuaki*, MIZUTANI Masami** and KATAYAMA Seiji***

Abstract

Hybrid welding using a YAG laser combined with a TIG arc was carried out on Type 304 stainless steel plate with various distances from the laser beam axis to the electrode for the establishment of high-efficient high-quality welding. It was consequently found that the optimum distance between the laser axis and the electrode for the production of deeper penetration was different between the backward welding and the forward welding. To establish the reason and the hybrid welding phenomena, arc plasma, laser-induced plume, evaporation spots and molten pool behavior during welding were observed using a CCD camera. Plasma plume behavior was found not to be different. The deepest weld bead could be produced when the YAG laser beam of high power density was targeted on the molten pool made stably with the TIG arc.

KEY WORDS: (Hybrid Welding), (TIG Arc), (YAG Laser), (Penetration)

1. Introduction

In recent years, laser-arc hybrid welding¹⁻⁵⁾ has been receiving considerable attention because of deeper penetration¹⁾, wider gap tolerance^{1), 2)} and a smaller amount of porosity^{2), 3)}. The effect of the various welding parameters on weld penetration and porosity formation in the laser-arc hybrid welding has been reported^{2), 3), 5)}. However, it seems that the effect of the welding parameters on weld penetration in the hybrid welding using YAG laser has not been reported, and physical phenomena are not well understood.

In this study, therefore, the effect of the distance from the beam axis to the electrode on weld penetration was investigated in hybrid welding with YAG laser combined with TIG arc, and was compared with the welding results obtained with TIG arc only or YAG laser only. To understand the hybrid welding phenomena and factors affecting penetration, the behavior of the arc plasma and laser-induced plume as well as the

relationship between a laser target spot and the molten pool made with TIG arc only was observed using a CCD camera during arc and hybrid welding.

2. Material and Experimental Procedures

The material used in this study is Type 304 austenitic stainless steel of 5 mm thickness, possessing the chemical compositions of 18.35%Cr-8.56%Ni-0.05%C-0.51%Si-0.89%Mn-0.027%P-0.001%S. The low content of S is considered to exert a smaller effect of surface tension-driven force on the melt flows in the molten pool.

In this study, a YAG laser machine (the maximum power $P_0 = 1.8$ kW) and a TIG welder (the maximum current 300 A) were used. TIG electrode, which contains Ce_2O_3 , is 3.2 mm in diameter. **Figure 1** shows experimental set up of laser beam and TIG torch. The laser beam was irradiated on the plate perpendicularly. Ar shielding gas was supplied from the TIG torch nozzle.

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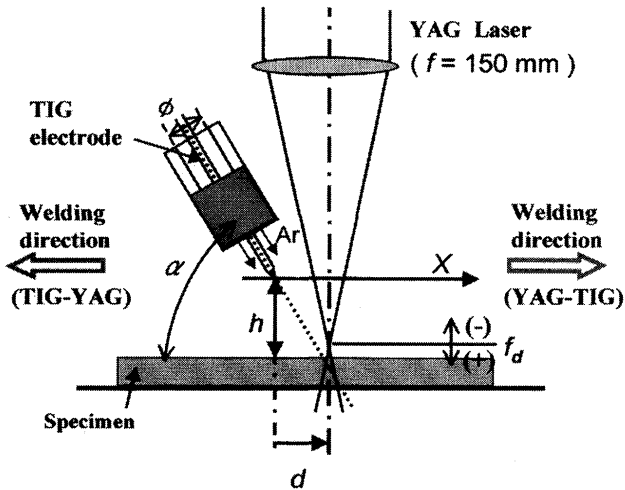


Fig. 1 Schematic diagram of experimental setup.

In the hybrid process, the welding was performed in the DCEN mode. The main welding conditions are the laser power (on the plate): $P_l=1.7$ kW(cw), the defocused distance: $f_d=0$ mm, the welding speed: $v=10$ mm/s, the arc current: $I_a=100$ A, the electrode height: $h=2$ mm, the distance between beam axis and electrode: $d=2$ mm, the angle: $\alpha=55$ deg, and the Ar shielding gas at the flow rate: $R_g=5.0$ or 6.7×10^{-4} m³/s. In this paper, backward welding with a YAG laser beam followed is called TIG-YAG welding for convenience sake. Similarly, forward welding with the leading YAG laser beam is called YAG-TIG welding.

The tip of the electrode was set as the origin when the distance between the beam axis and the electrode (d) and the position of molten pool are measured. During hybrid welding, arc plasma and laser-induced plume were observed with a CCD camera at the sampling time: 1/30 s and the shutter speed: 1/10,000 s.

3. Experimental Results and Discussion

3.1 Effect of distance from beam axis to electrode on penetration characteristics

The effect of the distance between the beam axis and the electrode (d) on the penetration was investigated. After welding, weldability was evaluated and penetration depths were measured by investigating etched cross sections of weld beads.

Figure 2 shows cross-sectional photos of welds made by the TIG-YAG or YAG-TIG welding, and the penetration depths are indicated as a function of the electrode-beam axis distance, d in Fig. 3. In the TIG-YAG welding, the penetration becomes deeper and the bead width becomes narrower as the distance d is long within 5 mm. On the other hand, in the YAG-TIG welding, the penetration is the deepest at $d=1$ mm and is shallow at the distances of 5 to 9 mm.

From these results, it was found that an optimum distance between the laser axis and the electrode for the production of deeper penetration existed and was different in the process between the TIG-YAG and the YAG-TIG welding.

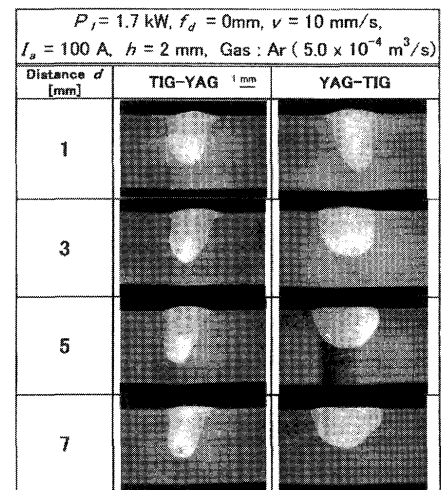


Fig. 2 Cross sections of Type 304 stainless steel subjected to laser-arc hybrid welding at various distances, d .

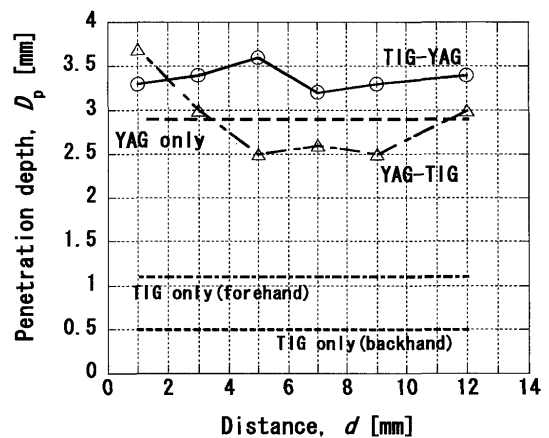


Fig. 3 Influence of distance d on penetration depth in laser-arc hybrid welding of Type 304.

3.2 Observation results of arc behavior during hybrid welding

In order to understand the difference in melting characteristics between TIG-YAG and YAG-TIG welding, the laser-induced plasma/plume and arc behavior were observed. The observation result by CCD camera during TIG-YAG welding is given in Fig. 4. During TIG arc welding ($t=0$ s), the arc was extending backwards, and the molten pool existed in the back of the position where a laser was targeted. However, when hybrid welding started, the molten pool was generated in the position irradiated with the laser. Part of the arc moved near to this molten pool. During hybrid welding ($t=0.3\sim$ s), the arc moved violently around the keyhole surface. Figure 5 shows the observation result by CCD camera during YAG-TIG welding. When hybrid welding started, the molten pool was generated in the position irradiated with the laser, and part of the arc moved to this molten pool. During hybrid welding ($t=0.3\sim$ s), as well as TIG-YAG welding, the arc was violently moving around the keyhole surface. This reason can be explained by considering the instability of the direction of a plume ejected, if it is assumed that part of the arc flows along the plume ejected from the keyhole.

The formation position of the molten pool made by the TIG arc before TIG-YAG welding ($t=0$ s) was $X=2\sim 8$ mm. But the formation position of the molten pool before YAG-TIG welding ($t=0$ s) was $X=1\sim 3$ mm. Thus it was found that the position of the molten pool made by the TIG arc welding before TIG-YAG welding differed from that produced by the TIG arc welding before YAG-TIG welding. And the position of the molten pool made by the TIG arc welding before TIG-YAG or YAG-TIG welding was almost in agreement with the distance d where the penetration was the deepest in respective hybrid welding. These results suggest that the penetration becomes deep when the distance between the TIG molten pool and the laser-target position is small. Therefore, the reason why deeper penetration is obtained can be explained by considering the natural concentration of an arc, the reduction in laser reflection, due to the

molten pool generated, and small heat conduction losses to reach a melting point.

On the other hand, in the YAG-TIG welding, the penetration depth from $d=5$ mm to 9 mm is shallower than that of the YAG laser welding. It is conjectured that the keyhole closed or the direction of the liquid flow changed.

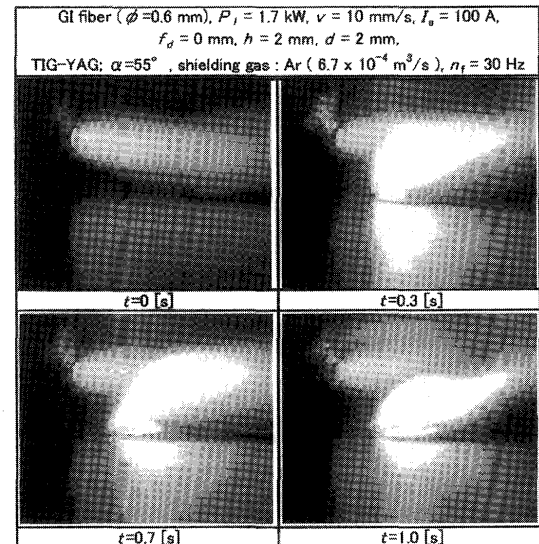


Fig. 4 Observation results of arc behavior during TIG-YAG hybrid welding of Type 304.

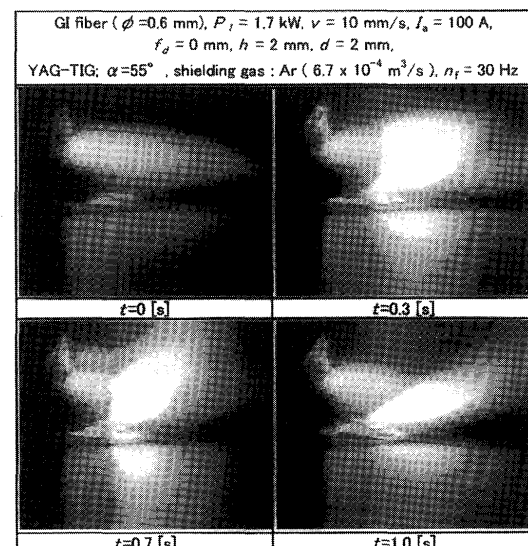


Fig. 5 Observation results of arc behavior during YAG-TIG hybrid welding of Type 304.

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4. Conclusions

The following conclusions were derived from the results and discussion.

- (1) During hybrid welding, the arc moves violently around the keyhole surface.
- (2) The deepest penetration is achieved by separately selecting the proper distance between laser axis and the electrode in the YAG-TIG and TIG-YAG hybrid welding.
- (3) In the hybrid welding, it is expected that deeply penetrating weld is obtained when the laser-target position is in agreement with the location of the molten pool produced with a TIG arc.

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