

## FIBER LASER-MAG HYBRID WELDING OF 780MPA HIGH STRENGTH STEEL

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### 1. Introduction

Joining process and procedures need to keep pace with new application and the development of materials. CO<sub>2</sub> laser is normally used laser in laser welding [1, 2] and laser-arc hybrid welding [3, 4] on the benefit of the low equipment cost. In laser few years, fiber laser has developed very quickly. The output power of fiber laser has increased from 100 W to multi-kilowatt in the laser six years [5]. Now, the 50 kW ytterbium-fiber laser is available [6]. Fiber lasers are a new generation of solid state lasers. In a fiber laser, the laser cavity (resonator) is contained within optical fiber and the active medium is a clad doped gain fiber. The active fiber is doped with rare earth elements such as Neodymium, Ytterbium, Erbium and Thulium. The fibers are pumped (excited) by high brightness semiconductor diodes. For IPG, fiber lasers are pumped out with ultra-long life multimode single emitter diodes that have estimated lifetimes over 100,000 hours. Single emitter diodes have longer lifetimes than diode bars, diode arrays or lamps uses in other types of lasers.

Fiber lasers has many advantages over conventional laser technologies, including high processing performance (low beam divergence, no warm up and no variation in spot size with power), high beam quality, low cost of ownership, maintenance free operation, no diodes or consumables to replace, and high wall plug efficiency, and a compact and mobile package.

The inherent efficiency of fiber lasers is unrivalled when compared to conventional laser technologies. Ytterbium fiber lasers offer 30% wall plug efficiency, compared to 2-3% for a lamp pumped YAG and 10% for a CO<sub>2</sub> laser. Fig.1 shows the comparison of the most popular industrial high power laser in several aspects [7].

High power lasers can be used for deep penetration welding in a diversity of materials since the low wave length that characterizes these lasers allows its absorption by almost all metals and alloys, and the fiber delivery system provides the necessary flexibility on the positioning of the beam. The absorption of number of metals as a function of laser radiation wavelength is shown in Fig. 2.

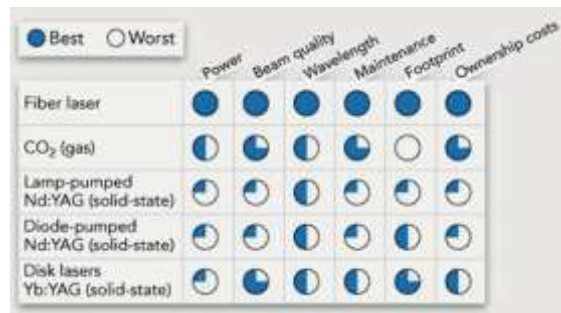


Fig. 1 Comparison of the most popular industrial high power lasers.

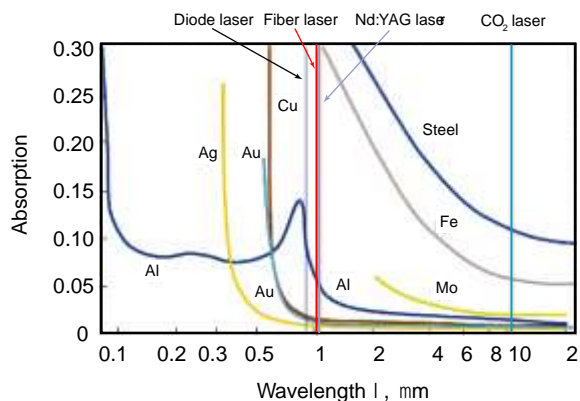


Fig. 2 Absorption of a number of metals as a function of laser radiation wavelength.

Some of researches have paid their attention on the fiber laser welding and fiber laser-arc hybrid welding. The fiber laser and fiber laser-arc are used for welding of X100 high strength steel in the research works [8, 9].

In this chapter, the effect of leading heat source of arc or laser on the bead formation was tested. The effects of laser-arc distance and MAG power on the bead formation were also studied. The phenomena of fiber laser-MAG hybrid welding were observed using a high speed video camera. The welding phenomena in fiber laser-MAG hybrid welding and CO<sub>2</sub> laser-MAG hybrid welding were compared.

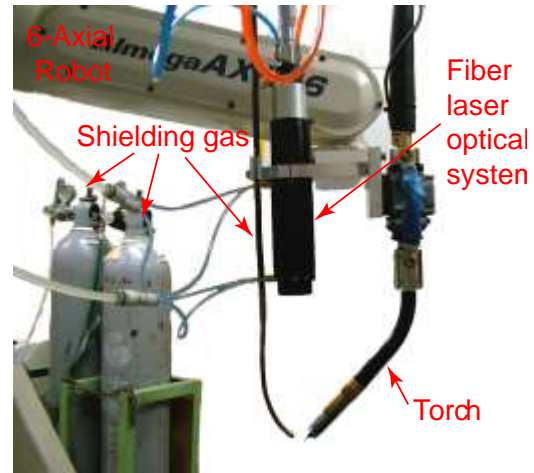


Fig. 3 Fiber laser-arc hybrid welding system.

## 2. Experimental procedure

### 2.1 Laser equipment used for hybrid welding

An ytterbium doped fiber laser equipment, IPG YLR-2000, with a maximum output power of 2 kW was used in the present work. The characteristics of the fiber laser are as follows;

Wavelength : 1070 nm

Beam parameter product (BPP) : 2.2 mm mrad

Output fiber core diameter : 150 μm

Minimum spot diameter : 152 μm ( when focal length of lens is 100mm)

### 2.2 Experimental setup

Since the fiber laser with a wavelength of 1070 nm, it can be transferred by a fiber, which makes the welding system is more convenience. Fig.3 shows the fiber laser-arc hybrid welding system developed by the authors. The laser optical system and the arc torch are fixed with special brackets and make up a hybrid welding head. The parameters concerning to the welding head, such as laser-arc distance and electrode wire extension of arc torch, can be adjusted according to the welding parameters. This laser-arc hybrid welding head is fixed to a 6-axial robot to form the welding system. It is also a fiber laser welding system when taking off the arc torch from the hybrid welding head. During the laser welding and laser-arc hybrid welding, the laser beam does not perpendicular to the surface of specimen. There is 6 degree angle between laser beam and the perpendicular line of the surface of specimen for decreasing the porosity formation [10].

### 2.3 Observe the phenomena of laser welding and hybrid welding

A high speed video camera shown in Fig.4 was used for observing the plasma formed by laser and metal transfer and arc during laser welding and laser-arc hybrid welding. The digital, high-speed video system records color images at the speed of 4,000 pictures per second (pps). The used high speed video camera is NAC's Memrecam fx6000 high speed video camera. NAC's Memrecam fx6000 is a fully self-contained, digital, high-speed video system that records



Fig. 4 Photograph of high speed video camera.

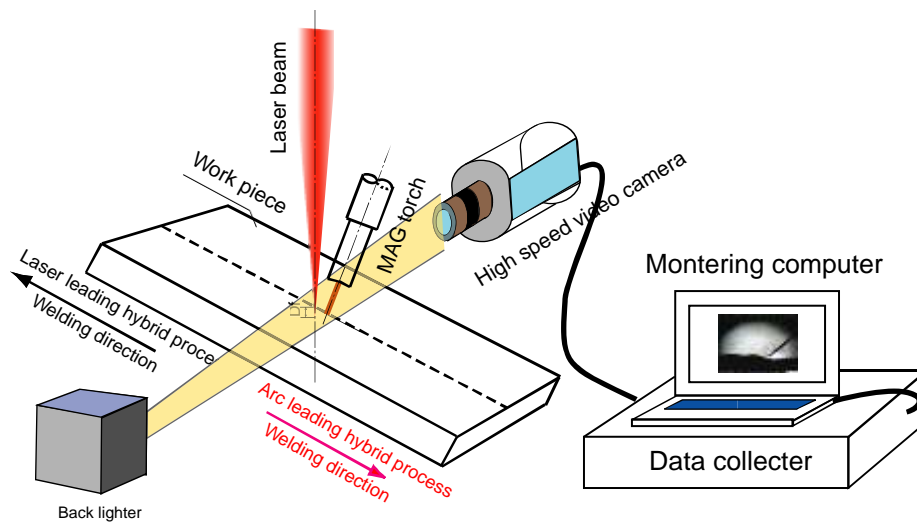


Fig. 5 Schematic of setup for observing welding phenomena during laser-arc hybrid welding.

Table 1 Chemical Compositions and tensile property of the High Strength Steel Plate and filler Wire

Materials	Elements (mass%)										Tensile properties (N/mm <sup>2</sup> )		
	C	Si	Mn	P	S	Ni	Cr	Mo	Ti	Cu	Bal.	YP	TS
Base metal	0.09	0.30	1.67	0.012	0.004	0.05	0.07	0.01	0.16	0.10	Bal.	74	
Filler wire (DS80)	0.05	0.93	2.04	0.008	0.008	2.05	0.24	0.45	0.16	0.23	Bal.	-	-

\*: Cu of electrode wire cover is also included.

brilliant color, or crisp monochrome images, with resolutions up to 512 X 512 pixels at 4,000 pps. Using an advanced CMOS sensor, the Memrecam fx6000 captures images at frame rates in excess of 200,000 pps. The extremely rugged Memrecam fx6000 is easily networked and synchronized using NAC's multi-camera control system and it is completely compatible with NAC's complete line of accessory items including 2D and 3D Motion Analysis Systems. As always, NAC allows you to obtain the ultimate performance and flexibility from these new products by providing you with unparalleled service and support, including systems integration and engineering. The setup of observation system is shown in Fig. 5.

#### 2.4 Materials used in the experiment

Materials used in these welding were 6 mm thick high strength steel plate with tensile strength of 800 MPa. Filler wires used in laser-MAG hybrid welding were 1 mm in diameter solid wire for welding 800 MPa class high strength steel. The compositions of the steel plates and solid wires are shown in Table 1.

### 3. Result and discussion

#### 3.1 Effect of leading heat source in fiber laser-MAG hybrid welding

The laser-leading and arc-leading fiber laser-MAG hybrid welding can be realized by changing the moving direction of the robot. When the laser-arc hybrid welding performs and heat sources perform in the sequence of arc-laser, the welding process is arc-leading hybrid welding process. Otherwise, the hybrid welding process is laser leading hybrid welding process. The fiber laser-MAG hybrid welding performed under the conditions of laser output power of 2 kW, defocusing distance of -2 mm, MAG current of 100 A, arc voltage of 14 V and welding speed of 15 mm/s. Fig.6 shows the bead appearance and bead profiles at laser-arc distance of 0

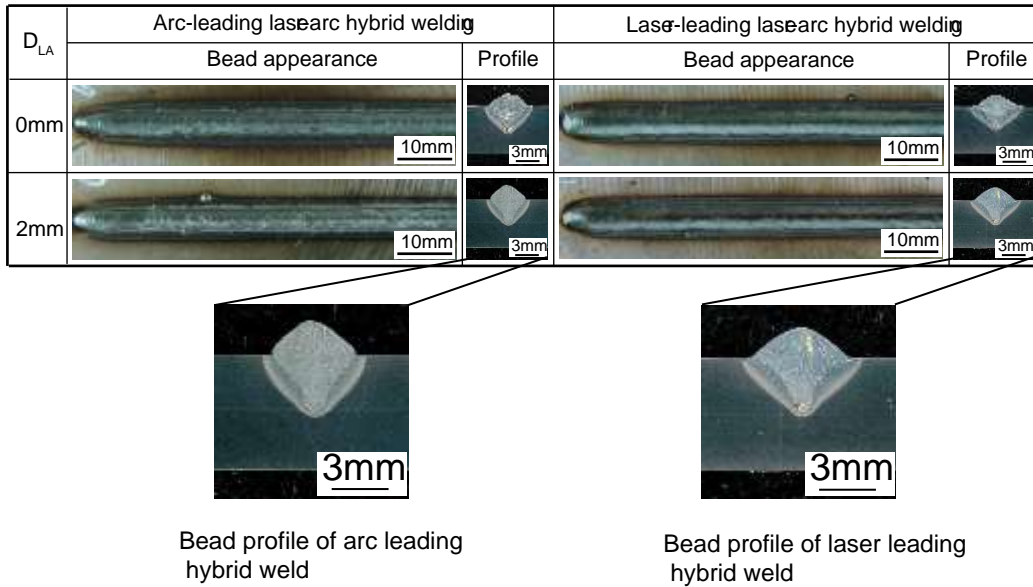


Fig. 6 Effect of leading heat source on bead appearance and bead profile in fiber laser-MAG hybrid welding. (laser power of 2 kW, defocusing distance of 0 mm, MAG current of 150 A, arc voltage of 17 V, laser-arc distance of 0 mm, welding speed of 15 mm/s.)

mm and 2 mm. It can be found that both of the welds achieved by laser-leading hybrid welding and arc-leading hybrid welding had a good bead appearance. The weld bead of laser-leading weld looks like a MAG weld bead because this weld bead formed finally by the MAG arc. However, the weld bead of MAG-leading hybrid welding formed finally by the laser.

As for the bead profiles, arc-leading laser-arc hybrid welding achieved a ‘V’ shape weld bead and laser-leading hybrid welding achieved a ‘Y’ shape weld bead. It can be decided that arc-leading hybrid welding achieved a better bead profile than that achieved by the laser-leading hybrid welding. One of the reasons is that the MAG arc had an action of preheating for the successive laser welding in the arc-leading hybrid welding. Another reason is the electrode orientation in laser-arc hybrid welding. In MAG welding, electrode orientation affects the weld bead shape and penetration to a great extent than arc voltage or welding speed. The MAG welding with backhand technique achieves a narrow and deep weld bead. However, the MAG welding with forehand technique achieves a wide and shallow weld bead [11].

Fig.7 shows the photographs of plasma in laser-leading hybrid welding and arc-leading

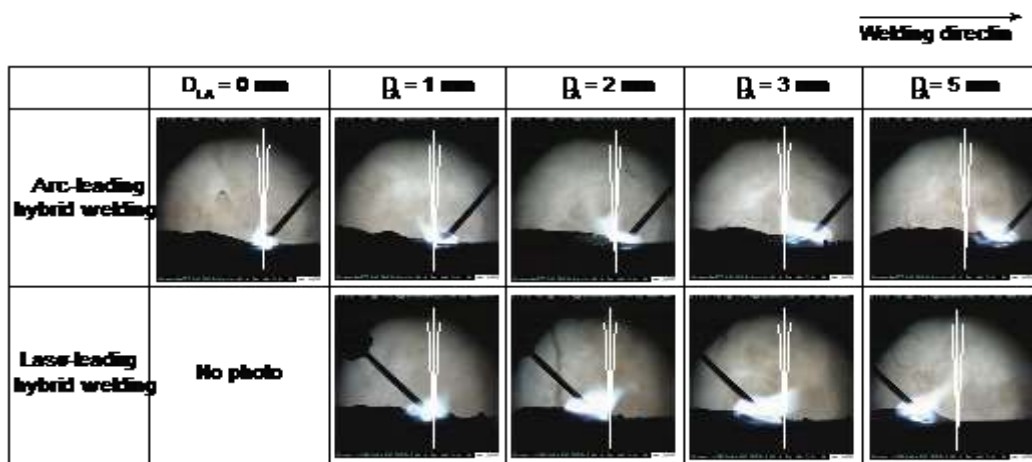


Fig. 7 Photographs of plasma induced by laser and MAG in arc-leading and laser-leading hybrid welding. (laser power of 2 kW, defocusing distance of -2 mm, MAG current of 200 A, arc voltage of 19 V, welding speed of 8 mm/s.)

hybrid welding with the laser output power of 2 kW and MAG current of 200 A and arc voltage of 19A at the welding speed of 8 mm/s. One of the phenomena is that plasmas induced by the MAG arc were absorbed by the laser beam in all of the conditions of laser-arc distance from 0 mm to 5 mm. The second phenomenon is that the volume of plasma induced in laser-leading hybrid welding was bigger than that in arc-leading hybrid welding. The reason is that the weld pool formed by laser firstly in laser-leading hybrid welding and there was some metal vapor above the molten pool. The third phenomenon is that that the plasma induced by the fiber laser was almost not found from the photos of laser-arc distance of 5 mm because of the short wave length and high absorption of the fiber laser.

### 3.2 Effect of laser-arc distance in fiber laser-MAG hybrid welding

Like the laser-arc distance in CO<sub>2</sub> laser-MAG hybrid welding, it also affects the weld bead shape and penetration in fiber laser-MAG hybrid welding. In this section, the effect of laser-arc distance on the weld bead was investigated using the laser power of 2 kW and MAG current was of 100 A, 150 A and 200 A. The laser arc distance of 0 mm, 1 mm, 2 mm, 3 mm and 5 mm was investigated.

Fig.8 shows the laser-arc distance and MAG power (MAG current and arc voltage) on the penetration. It can be found that the penetration decreased with the increase of laser-arc distance with different MAG power, for example the MAG current of 100 A, 150 A and 200 A. The penetration decreased from 4.5 mm to 3.5 mm when the laser-arc distance increased from 0 mm to 5mm. The reason is that the interaction between laser and arc became weaker and weaker with the increase of laser-arc distance. There was not interaction between laser and MAG arc when laser-arc distance was 5 mm as shown in Fig.7. Arc augmented laser welding is a welding process by adding an arc heat source to the laser beam to increase welding speed and penetration. Arc augmented laser welding can be divided into two kinds of welding process that are laser-arc hybrid welding process (laser and arc coupled as one process) and laser-arc combined welding process (without any mutual interaction between laser and arc) [12]. Actually, the laser-arc welding process can not be called laser-arc hybrid welding process according to the definition of U. Dilthey because there is no interaction between laser beam and MAG arc when the laser-arc distance was larger than 3 mm as shown in Fig.7. It also can be found that there was little plasma induced by fiber laser beam. When laser-arc distance was 0 mm, the interaction between laser and MAG arc was very strong and the deepest penetration was available in the fiber laser-MAG hybrid welding.

Fig.9 shows the effect of laser-arc distance on the weld bead width in fiber laser-MAG hybrid welding. Bead width of hybrid welds increased with the increase of MAG power using the same output laser power. The bead width increased from 4~5 mm to about 8 mm when the MAG current increased from 100 A to 200 A. However, at the same laser output power and MAG power (MAG current times arc voltage), the bead width

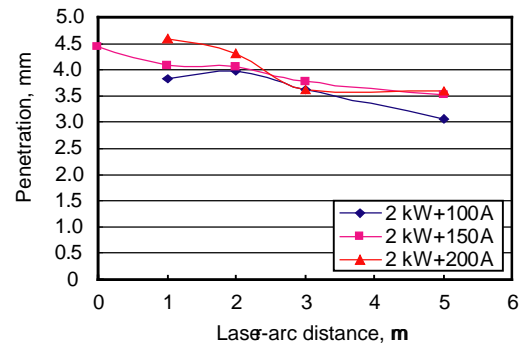


Fig. 8 Effect of laser-arc distance and MAG power on penetration. (Welding speed of 8 mm/s.)

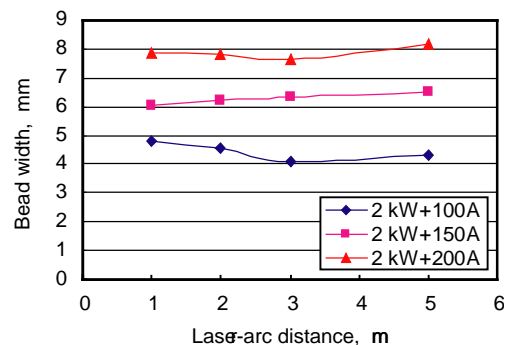


Fig. 9 Effect of laser-arc distance and MAG power on bead width. (Welding speed of 8 mm/s.)

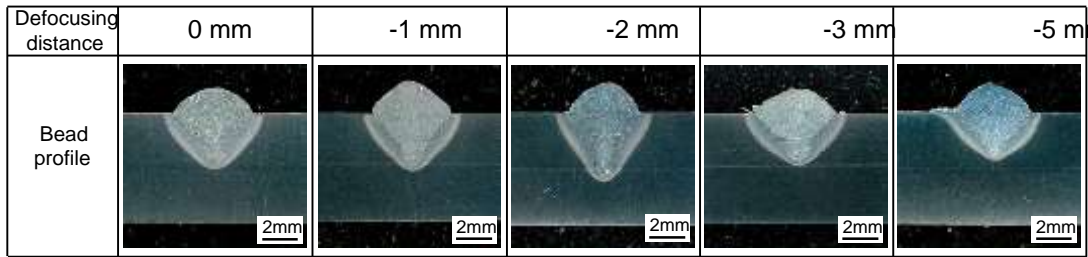


Fig.10 Macrograph of weld bead profile when defocusing distance changed from 0 mm to -5 mm in fiber laser-MAG hybrid welding.

changed within 1 mm when the laser-arc distance changed from 0 mm to 5 mm. That means that MAG power affects hybrid weld bead heavily. It is thought that the increased melted filler affected the weld bead width when the MAG power increased in those experiments. As for the laser-arc distance, it affected the bead width slightly comparing with the MAG power.

### 3.3 Effect of defocusing distance of laser on weld bead in hybrid welding

Although the depth of focus of fiber laser is longer than that of CO<sub>2</sub> laser using the same focusing lens with 200 mm focal length. The defocusing distance of laser beam affects the welds in laser welding. In this section, the effect of defocusing distance of laser beam on weld bead is investigated.

Figs.10 and 11 show the macrographs and penetration of the weld bead profiles achieved under defocusing distance from 0 mm to -5 mm at the welding speed of 15 mm/s and MAG current of 150 A, arc voltage of 17 V and laser output power of 2 kW. From this figure, it can be found that the defocusing distance affected the bead penetration strongly although the defocusing distance affected penetration slightly in fiber laser welding. When the defocusing distance changed from 0 mm to -2 mm gradually, the penetration increased from 2.9 mm to 3.6 mm. However, the penetration decreased from 3.6 mm to 2.4 mm when the defocusing distance changed from -2 mm to -5 mm. It seems that defocusing distance of -2 is the suitable parameter for laser in fiber laser-MAG hybrid welding when the other conditions are MAG current of 150 A, arc voltage of 17 V and laser-arc distance 0 mm.

Fig.12 shows the schematic of arc-leading fiber laser-MAG hybrid welding process. Because the surface of molten pool is lower than the upper surface of specimen during the

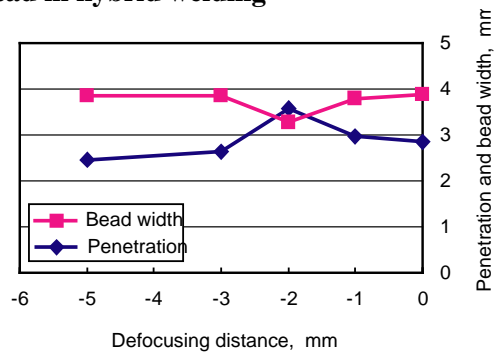


Fig. 11 Effect of defocusing distance on penetration and bead width in fiber laser-MAG hybrid welding.

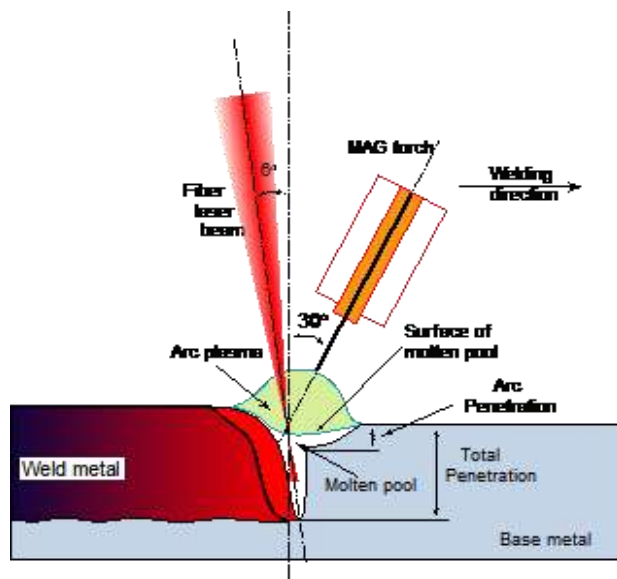


Fig. 12 Schematic of fiber laser-MAG hybrid welding process. (Arc leading process, DLA equaling to 0 mm.)

laser-arc hybrid welding [13], defocusing distance of minus is better for getting deeper penetration. In other words, the focused point of the laser bead in the base metal is better for getting deeper penetration. On the other hand, there is little plasma induced by the fiber laser beam during the laser-MAG hybrid welding as shown in Fig.7. The volume of plasma induced by MAG arc and laser beam was not bigger than that produced by MAG arc when the laser-arc distance was 0 mm, 3 mm and 5 mm. That means the lost laser energy in the plasma did not increase when the laser-arc distance changed when the laser-arc distance was 0 mm. And the laser beam can interact with MAG arc completely when the laser-arc distance is 0 mm. That is the reason of the deepest penetration gotten when the laser-arc distance was 0 mm.

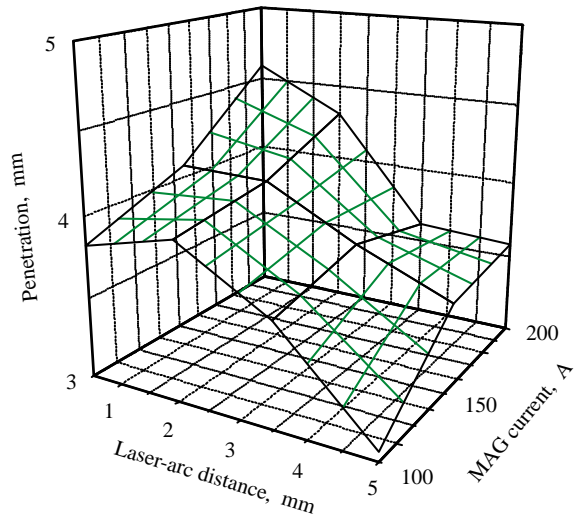


Fig.13 Effect of MAG current and laser-arc distance on the penetration in fiber laser-MAG hybrid welding

### 3.4 Effect of MAG power on the weld bead

The fiber laser-MAG hybrid welding performed keeping the laser output power constant, 2 kW, and changing the MAG current at 100 A, 150 A and 200 A at the welding speed of 8 mm/s. The relationship among penetration, MAG current and laser-arc distance is shown in Fig.13. It shows that the penetration increased with the increase of MAG current and with the decrease of laser-arc distance. The deepest penetration was about 4.6 mm when the laser-arc distance was 0 mm and MAG current was 200 A. The shallowest penetration was about 3.1 mm when the laser-arc distance was 5 mm and MAG current was 100 A. The reason is that the MAG power increased with the increase of MAG current and the interaction between laser beam and MAG

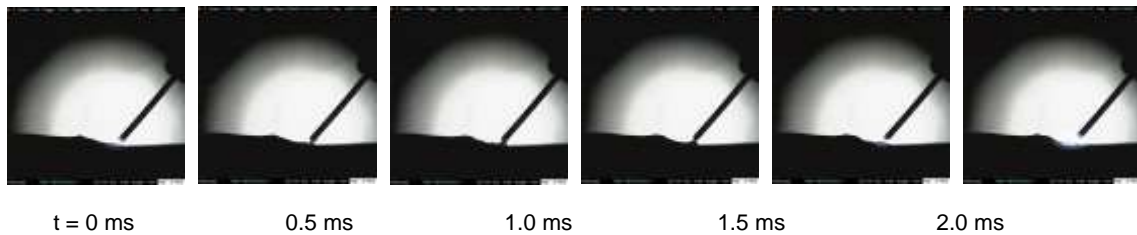


Fig. 14 Photographs of metal transfer at the welding current of 150 A, 17 V in MAG welding.

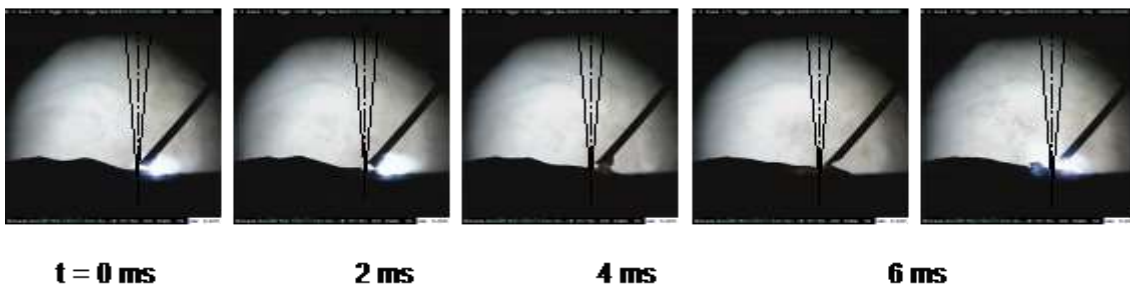


Fig. 15 Metal transfer in fiber laser-MAG hybrid welding. (MAG current of 150 A, arc voltage of 17 V, fiber laser output power of 2 kW, laser-arc distance of 0 mm.)

arc is best when the laser-arc distance was 0 mm as shown in Fig.7.

### 3.5 Metal transfer in fiber laser-MAG hybrid welding

Ordinarily, the metal transfer in MAG welding is short circuiting transfer when the arc current at the range of 100 A to 200 A. Fig.14 shows a example of short circuiting transfer at the MAG current of 15 A and arc voltage of 17 V using the fx-6000 NAC high-speed video camera at the speed of 4000 pictures per second.

In the fiber laser-MAG hybrid welding, the same MAG conditions including welding speed, MAG current, arc voltage were used as in MAG welding. Fig.15 shows the photographs of metal transfer in fiber laser-MAG hybrid welding. It shows that the metal transfer in fiber laser-MAG hybrid welding was also short circuiting transfer. However, the metal transferring time increased. It was about 4 ms from the high speed video. And there was some spatter produced in the photographs (the last photograph in Fig.15).

Fig.16 shows the metal transfer in fiber laser-MAG hybrid welding when the laser-arc distance changed from 1 mm to 5 mm at the MAG current of 100 A and arc voltage of 15 V. It shows that there was not so much different in metal transfer with the laser-arc distance changed from 1 mm to 5 mm at the MAG current of 100 A and arc voltage of 15 V. Even the MAG current and arc voltage increased to 150 A, 17 V and 200 A, 19 V, the metal transfer was also short circuiting transfer. However, the stability of metal transfer was different, in other words, the spatter produced under

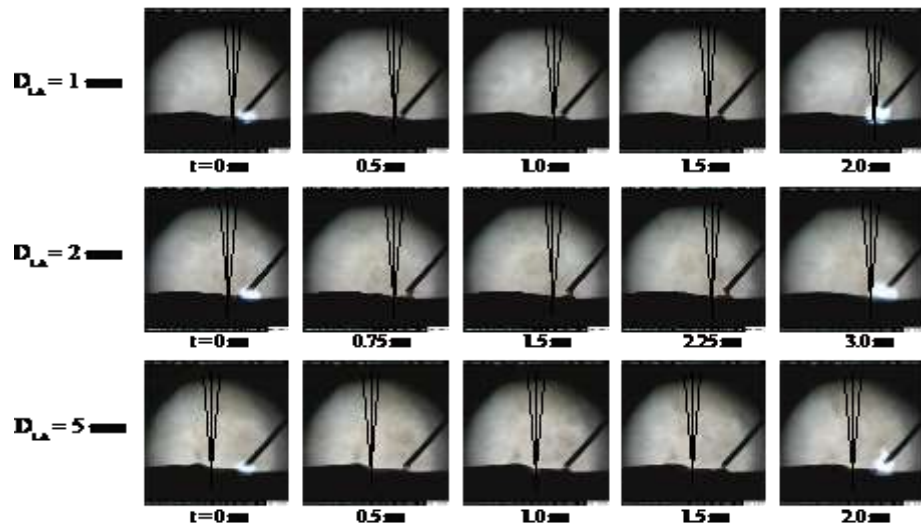


Fig. 16 Metal transfer in fiber laser-MAG hybrid welding of different laser-arc distance (MAG current: 100A, Arc voltage: 15V, Laser power: 2kW)

Fig.17 shows a comparison of the metal transfer in MAG welding and laser-MAG hybrid welding with laser-arc distance of 1 mm and 5 mm. The table below summarizes the metal transfer characteristics for different welding conditions.

Time (ms)	0	0.5	1.0	1.5	2.0
MAG welding					
Laser-MAG hybrid welding $D_{LA} = 1$ mm					
Laser-MAG hybrid welding $D_{LA} = 5$ mm					

Fig. 17 Comparison of the metal transfer in MAG welding and laser-MAG hybrid welding with laser-arc distance of 1 mm and 5 mm.



some welding conditions.

As shown in Fig. 16, there was no spatter produced at the end of metal transfer with the laser-arc distance of 1 mm, 2 mm and 5 mm. And the metal transfer was short circuiting transfer. But, with the increase of MAG current, the spatter produced. At the MAG current of 200 A, spatter produced at the laser-arc distance of 0 mm and 1 mm. There was not spatter produced when the laser-arc distance over 2 mm at the MAG current of 200 A. The MAG welding had not spatter when the MAG current was 200 A and 19 V as shown in Fig. 17. The reasons are that the overheating of the neck between the solid wire and the droplet or the molten pool and forces acting on the neck.

Fig.18 shows the schematic of forces dropped on the neck between droplet (or molten pool) and electrode and the heat produced by the electrical resistance. The forces acting on the neck are the gravity of the droplet or the melted solid wire between the neck and molten pool, magnetic force produced by the welding current and the surface tension. Those forces make the diameter of the neck small and small.

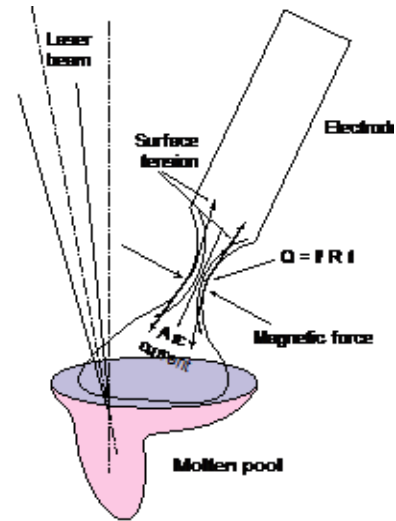


Fig. 18 Schematic of forces on the neck between droplet and electrode in laser-MAG hybrid welding.

At the same time, the electrical resistance between electrode wire and the molten pool became bigger and bigger because the electrical is inversely proportion with the cross-sectional area as formula (1). It is well know that the cross-sectional area is in direct proportion with the squared diameter of the neck as formula (2). And the Joule heat will increase quickly because the joule heat is in direct proportion with the electrical resistance. So, the Joule heat will in inversely proportion with the squared diameter.

On the other hand, the melted solid wire was heated to a high temperature by the laser because of the short laser-arc distance. The metal of the neck between solid wire and the droplet will be evaporated and than the exploration occurred. The spatter produced at those conditions.

### 3.6 Comparison of fiber laser-MAG hybrid welding and CO<sub>2</sub> laser-MAG hybrid welding

Laser-arc distance		0 mm	2 mm	m 6 m
Cross section	Fiber laser-MAG			
	CO <sub>2</sub> laser-MAG			

Fig. 19 Cross section of fiber laser-MAG and CO<sub>2</sub> laser-MAG hybrid welds.

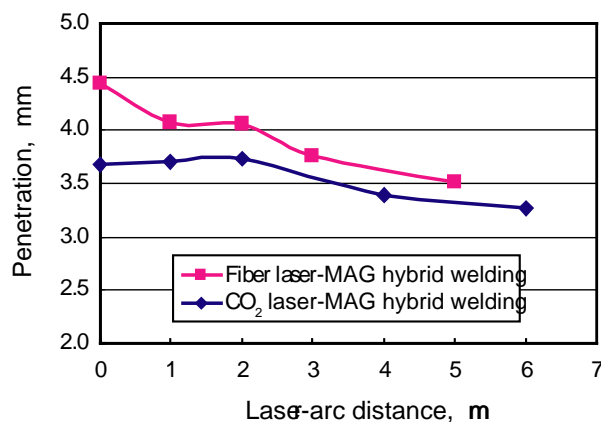


Fig. 20 Effect of laser-arc distance on penetration in fiber laser-MAG and CO<sub>2</sub> laser-MAG hybrid welding.

$$R = \rho \frac{L}{A} \dots \dots \dots (1)$$

where:

$L$  is the length of the conductor, measured in meters.

$A$  is the cross-sectional area, measured in square meters.

$\rho$  (Greek: rho) is the electrical resistivity (also called specific electrical resistance) of the material, measured in ohm · meter.

### 3.6.1 Effect of welding process on the weld bead shape

In this section, CO<sub>2</sub> laser-MAG hybrid welding and fiber laser-MAG hybrid welding performed to weld 9 mm thick and 6 mm thick high strength steels with 2 kW laser power and 140A x 16.5V and 150A x 17V MAG power, respectively. MAG leading laser-MAG hybrid welding process was

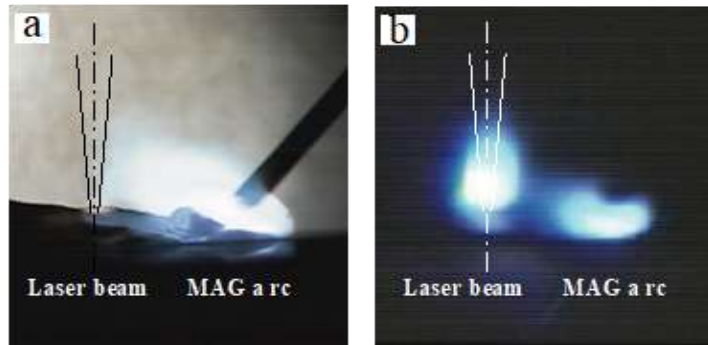


Fig.21 Photos of plasma produced by laser and arc in fiber laser-MAG hybrid welding (a) and CO<sub>2</sub> laser-MAG hybrid welding (b) at laser-arc distance of 5 mm.

$$A = \frac{\pi D^2}{4} \dots \dots \dots (2)$$

where:

$A$  is the cross section area, m<sup>2</sup>;

$D$  is the diameter of the cross section, m;

$\pi$  is a constant, 3.14.

adopted in these performances. Fig.19 shows some of cross sections of CO<sub>2</sub> laser-MAG and fiber laser-MAG hybrid welds. It can be found that the nail shape weld bead appeared in CO<sub>2</sub> laser-MAG hybrid welds when laser-arc distance was 0 mm and 2 mm. When the laser-arc distance was 6 mm, the nail head disappeared in CO<sub>2</sub> laser-MAG hybrid welding. However, the bead shows ‘V’ shape cross section when the laser-arc distance was 0 mm in fiber laser-MAG hybrid welding. Even when the laser-arc distance was 2 mm or 6 mm, the bead shape is acceptable. The reason is that there was more energy arriving at the substrate materials in fiber laser-MAG hybrid welding than that in CO<sub>2</sub> laser-MAG hybrid welding.

$$n_c = \frac{10^{21}}{\lambda^2} \dots \dots \dots (3)$$

Where:

$n_c$  is the cut-off density of laser radiation.

$\lambda$  is wavelength of laser,  $\mu\text{m}$ .

$$E_{lost} = \frac{n_{laser}}{n_c} \dots \dots \dots (4)$$

Where:

$E_{lost}$  is the lost laser energy in plasma, %;

$n_{laser}$  is the actual electron density of plasma.

The relationship between penetration and welding speed is shown in Fig.20. With the increase of laser-arc distance, the penetration of welds decreased in fiber laser-MAG hybrid welding and CO<sub>2</sub> laser-MAG hybrid welding. But the penetration decreased quickly when the laser-arc distance increased from 0 mm to 2 mm. However, the penetration showed a bit increase when the laser-arc distance increased from 0 mm to 2 mm in CO<sub>2</sub> laser-MAG hybrid welding. The penetration decreased at the same trend in fiber laser-MAG hybrid welding and CO<sub>2</sub> laser-MAG hybrid welding as the laser-arc distance larger than 2 mm. But, the penetration of fiber laser-MAG hybrid welds is deeper than that of CO<sub>2</sub> laser-MAG hybrid welds about 0.3 mm. This phenomenon can be explained by the plasma produced by laser and arc.

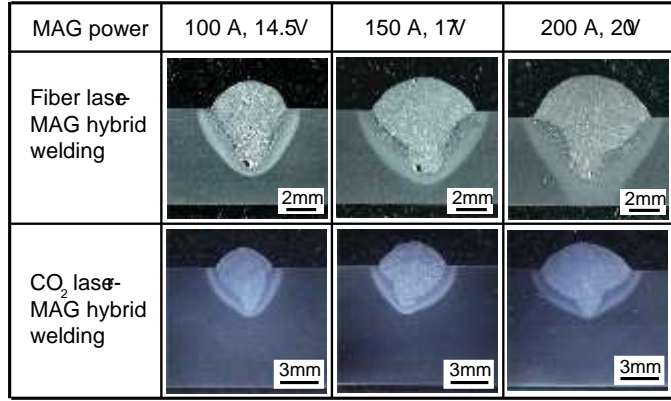


Fig. 22 Cross sections of welds under different MAG power in fiber laser-MAG and CO<sub>2</sub> laser-MAG hybrid welding processes.

### 3.6.2 Plasma formed in hybrid welding process

When the focused laser beam irradiates onto the surface of specimen, a part of the radiation is absorbed by the material and a part is lost by reflection, radiation, conduction and plasma absorption. In laser-arc hybrid welding, the laser energy absorbed by the plasma produced by laser and arc in laser-arc hybrid welding is very important aspect. Metal vapors are transparent to the laser beam at low vapor temperatures and begin to absorb the beam strongly as the vapour temperature increases [14]. The Roles of both arc plasma and laser plasma are important for bead formation in hybrid welding process [15].

In laser-MAG hybrid welding processes, the plasmas produced by laser and arc were observed by a high speed video camera at the speed of 4000 pictures per second. Fig.21 shows the pictures of fiber laser-MAG hybrid welding and CO<sub>2</sub> laser-MAG hybrid welding in the case of laser-arc distance of 5 mm in arc leading hybrid welding processes. The plasma produced by fiber laser was not found as Fig.21(a), however, that produced by CO<sub>2</sub> laser has very large volume and high brightness as Fig.21(b). The reason is the different wavelengths of fiber laser and CO<sub>2</sub> laser. The role played by the wavelength is important because the characteristics of laser induced plasma are heavily dependent on the processes which take place in the region whose electron density is close to that for cut-off of the radiation [16]. The cut-off density electron of laser radiation can be calculated by the sample formula (3):

For CO<sub>2</sub> laser, wavelength,  $\lambda$ , is 10.6  $\mu\text{m}$ , the cut-off electron density,  $n_c$ , is  $10^{19}$ . For fiber laser, wavelength,  $\lambda$ , of 1.07  $\mu\text{m}$ , the cut-off electron density,  $n_c$ , is  $10^{21}$ . Assume that the absorption of laser radiation by the plasma is in direct corresponding to the electron density, the lost energy of laser can be calculated as:

When the  $n_{lost}$  has the same value, the lost energy of fiber laser in plasma is about 1% of that of CO<sub>2</sub> laser beam.

On the other hand, in the two laser-MAG hybrid welding processes, fiber laser produced very little plasma during welding; however, there was a lot of plasma produced in the CO<sub>2</sub> laser-MAG hybrid welding as shown in Fig.21. There will be more laser energy reached at the substrate in fiber laser-MAG hybrid welding than that in CO<sub>2</sub> laser-MAG hybrid welding.

### 3.6.3 Effect of MAG power on bead formation in CO<sub>2</sub> laser- and fiber laser-MAG hybrid welding

Keep the laser output power content, 2 kW, change the MAG current and then the arc voltage, the bead cross section of welds are shown in Fig.22. It can be found that the fiber laser-MAG hybrid welds had a better shape than that of CO<sub>2</sub> laser-MAG welds. In the range of MAG power changed from 100A, 14.5V to 200A, 20V, the wine cup shape weld bead did not appeared in fiber laser-MAG hybrid welding. However, the wine cup shape weld bead appeared when the MAG power increased from 150A, 17V to 200A, 20V. Even at the low MAG power of 100A, 14.5V, the weld bead showed a little bit wine cup shape.

Fig.23 shows the relationship between penetration, bead width and MAG power in fiber laser-MAG and CO<sub>2</sub> laser-MAG hybrid welding. With the increase of MAG power in hybrid welding, the penetration increased in fiber laser-MAG hybrid welding. However, the penetration increased with the MAG current increased from 100A to 160A. And then the penetration decreased with the increase of MAG current form 160A to 200A.

The bead width increased with the increase of MAG current from 100A to 200A in fiber laser-MAG hybrid welding and CO<sub>2</sub> laser-MAG hybrid welding. That means the laser type affects the bead shape and penetration in laser-MAG hybrid welding processes. Using short wavelength laser can increases the penetration in laser-arc hybrid welding processes.

#### 4. Conclusion

From the experimental result and discussion, it can be concluded as the following:

1. A better weld bead is gained by arc-leading fiber laser-MAG hybrid welding.
2. Laser-arc distance in fiber laser-MAG hybrid welding affects not only the weld bead, but also the metal transfer and spatter produced during the welding.
3. MAG power affects the bead shape and penetration. With the increase of MAG power, the penetration increased in the experimental range, 100 A ~ 200 A.
4. Deeper penetration and narrower bead width welds can be available in fiber laser welding than that in CO<sub>2</sub> laser welding according to the shorter wavelength and higher absorption of fiber laser.
5. Short wavelength fiber laser produces little plasma than the long wavelength CO<sub>2</sub> laser in hybrid welding process.
6. The plasma produced by the laser in laser-arc hybrid welding affects the weld bead shape and the suitable laser-arc distance. The suitable laser-arc distance is 0 mm in fiber laser-MAG hybrid welding, however, it is 2 mm in CO<sub>2</sub> laser-MAG hybrid welding.
7. Using high energy density fiber laser in laser-arc hybrid welding can get better bead shape weld beads than using CO<sub>2</sub> laser when the welding performed with different MAG power, such as from 100A to 200A.

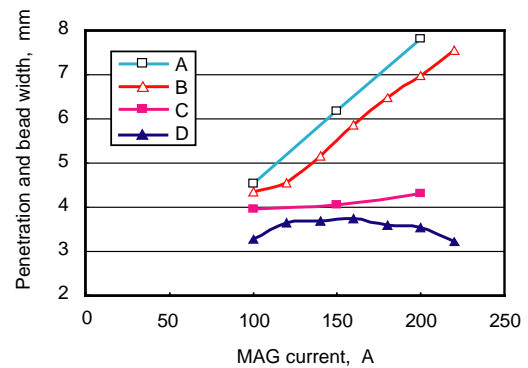


Fig. 23 Effect of MAG power on penetration and bead width in laser-MAG hybrid welding. A-bead width of fiber laser-MAG hybrid welds; B-bead width of CO<sub>2</sub> laser-MAG hybrid welds, C-penetration of fiber laser-MAG hybrid welds, D-penetration of CO<sub>2</sub> laser-MAG hybrid welds.

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