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Weld fusion property of lotus-type porous copper by laser beam irradiation

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Abstract

Welding of lotus root like porous metals with long cylindrical pores aligned in one direction is important for new applications of porous metals. In this study, an effect of the pore growth direction on the shape of weld fusion zone of lotus-type porous copper by laser beam welding was investigated at a first attempt of the welding of lotus-type porous metals in the welding speed and laser power range of 1.67–16.7 mm s^{-1} and 2.0–3.2 kW, respectively. Significant anisotropy in the shape of weld fusion zone was observed when lotus-type copper melted in the perpendicular and parallel pore growth directions to the surface of work piece, on which the laser beam was irradiated. In the perpendicular direction, smooth weld head was obtained, but in the parallel direction, only a groove was formed instead of the weld head even at the same welding conditions of 3.33 mm s^{-1} in welding speed and 3.2 kW in laser power.

Keywords: Porous copper; Laser welding; Anisotropy; Hydrogen

1. Introduction

Porous metals have a unique combination of properties such as impact energy absorption capacity, air and water permeabilities, unusual acoustic properties, low thermal conductivity, good electrical insulating property etc. Therefore, various applications of the porous metals are steadily expanding. Such porous metals can be produced by casting, plating, powder metallurgy and sputter deposition, in which porous metals with higher porosity are used to be called as foamed or cellular structured metals. In most of the porous metals, the pores are randomly distributed as spherical. The mechanical strength is certainly low mainly due to the stress concentration [1]. On the other hand, lotus-type porous metals, whose pores are formed by supersaturated gas utilizing the difference of gas solubility between liquid and solid are aligned in one direction by unidirectional solidification, have higher strength than the conventional porous metals [2–9]. In particular, these are expected as the innovative engineering materials which yield various anisotropic properties, depending on alignment of the growth of pores.

For the industrial use of the foamed and porous metals as various parts, a reliable joining techniques such as welding is required as well as processing techniques. There have been some reports on laser and arc weldings of foamed aluminum using foaming agent, TiH_2 or $CaCO_3$ [10–13]. However, weldability of porous metals with controlled pore direction such as lotus-type porous metals has not been investigated, although the welding is necessary for fabricating the engineering materials. In this study, the laser beam with a narrow weld bead width and heat affected zone was applied to the weldings of porous metal. The lotus-type porous copper fabricated under high-pressure hydrogen gas [4–8] was chosen as the work piece. For example, it is known that the thermal conductivity of lotus-type copper with 39% porosity was 205 W m^{-1} K^{-1} in the

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direction parallel to the pore growth direction, and 141 W m^{-1} K^{-1} in the perpendicular direction at room temperature [8]. The thermal conductivity is one of the main factors controlling the shape of weld fusion zone. Therefore, it is expected that the shape of weld fusion zone is affected by the anisotropy of thermal conductivity caused by different pore growth directions. The high-pressure hydrogen gas in the original pore, which is fabricated during unidirectional solidification, ought to influence the weldability such as the pore formation in the weld metal. Thus, it is expected that the weldability of this porous copper is affected by these various factors. It is very important to clarify the basic melting property by laser beam irradiation and the effect of the growth direction of original pore on this property. The aim of this study is to elucidate effects of the pore growth direction and the hydrogen gas in the original pore on the melting property by laser beam irradiation.

2. Experimental

Electrolytic copper of 99.99% purity was vacuum-melted in a high-pressure chamber using high-frequency induction furnace. Subsequently, the high-pressure mixture gas of hydrogen and argon was introduced into the chamber. The partial pressures of hydrogen and argon were controlled to be 0.25 and 0.15 MPa, respectively. After hydrogen was dissolved into the molten copper at 1523 K to the equilibrium state, the melt was poured into the mold whose bottom plate was cooled down with water circulated through the chiller. Thus the molten copper was unidirectionally solidified upwards from the water-cooled copper bottom plat [2–7]. The obtained ingot was 100 mm in diameter and 100 mm in height. The average pore diameter and the porosity of specimens were about 0.1 mm and 30%, respectively. The work piece measuring 40 mm × 50 mm with 4 or 5 mm in thickness were cut out of the porous copper ingot with the pore growth perpendicular and parallel to the work piece surface using a spark-erosion wire-cutting machine. In reality, those pores were slightly inclined. Fig. 1 shows schematic views of specimens during laser welding.

The laser beam was delivered using a 600-μm diameter optical fiber. The focal length for Nd:yttrium–aluminum–garnet (Nd:YAG) laser with a 1064 nm wavelength was 100 mm. The diameter of the laser beam at the focus point was 300 μm. The laser beam was irradiated at an 80° forward angle relative to a work piece surface to prevent damage to the optics by a reflection of laser beam. Argon was used as a shielding gas with a flow rate of 5.0×10^4 m^3 s^{-1}. The welding of the work piece was conducted using a Nd:YAG laser unit with a maximum output power of 3.2 kW in continuous wave mode. The welding speed and the laser

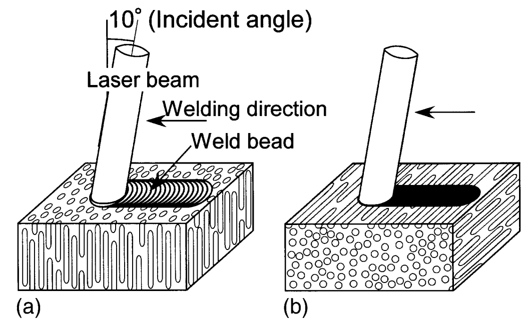


Fig. 1. Schematic views of specimens during laser welding in the porous copper with the pore growth (a) perpendicular and (b) parallel to the work piece surface.

beam power were controlled in the range of 1.67–16.7 mm s^{-1} and 2.0–3.2 kW, respectively. The welded specimen was radiographed in order to detect the pores in the weld metal. The cross-section of the welded specimen was observed by optical microscopy to determine the shape of the weld fusion zone and the porosity. The weld bead after welding was drilled in 3-mm diameter in the vacuum chamber, and the residual gas in the pores was analyzed using a mass spectrometer (ANELVA Corporation, AGS-7000).

3. Results

Fig. 2 shows a relation between the welding speed and the penetration depth of the weld bead in depth at the thickness of 5 mm from the work piece surface when the laser beam power of 3.2 kW was irradiated on both types of sample (a) and (b) shown in Fig. 1. The penetration depth in both directions decreases with increasing welding speed. The penetration depth in the parallel direction (filled square) is always shallower than that in the perpendicular direction (filed circle). Fig. 3 shows the top view of the specimens after laser welding in the thickness of 5 mm at the constant laser beam

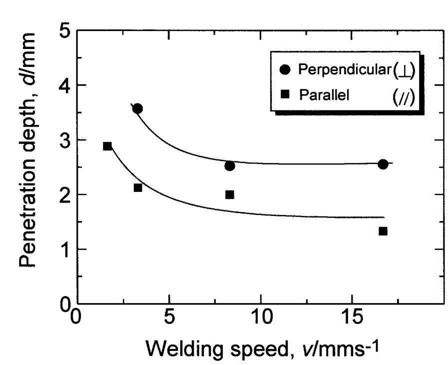


Fig. 2. Relation between welding speed and penetration depth of the weld bead in depth at the thickness of 5 mm from the work piece surface when the laser beam power of 3.2 kW was irradiated on both types of sample (a) and (b) shown in Fig. 1.

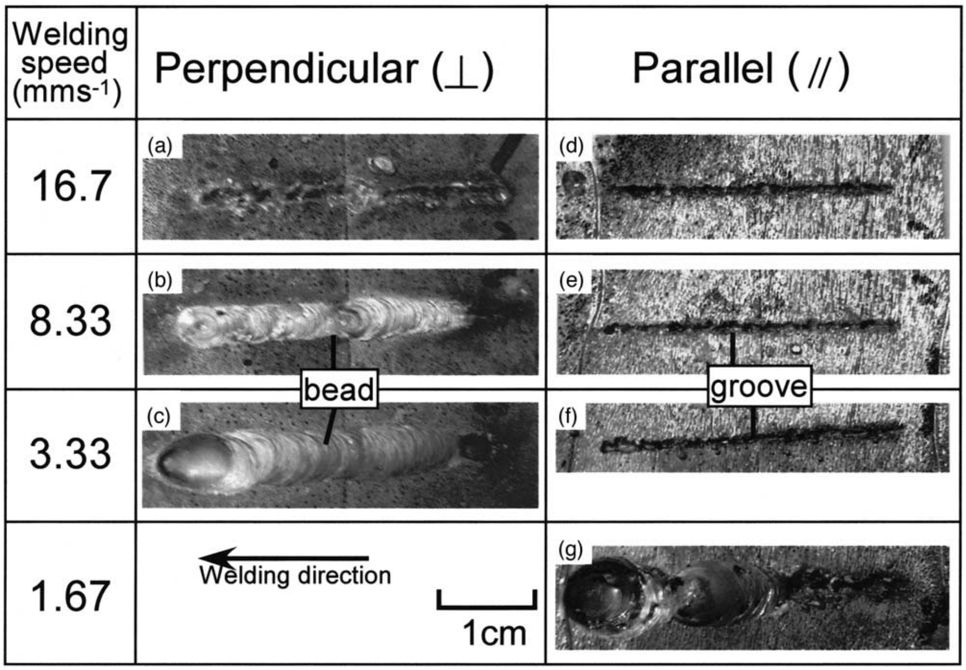


Fig. 3. Top view of laser welded specimens at different welding speeds with 3.2 kW constant laser power in 5 mm thickness, in (a)–(c) perpendicular and (d)–(g) parallel to the pore growth directions. Welding speed: (a) and (d) 16.7 mm s^{-1}, (b) and (e) 8.33 mm s^{-1}, (c) and (f) 3.33 mm s^{-1} and (g) 1.67 mm s^{-1}.

power of 3.2 kW in the welding speed range of 1.67–16.7 mm s^{-1} in (a)–(c) perpendicular and (d)–(g) parallel pore directions. In the perpendicular direction, only the groove was observed in the condition of 16.7 mm s^{-1} as shown in Fig. 3(a). The weld beads were found below the welding speed of 8.33 mm s^{-1} as shown in Fig. 3(b and c), while a smooth weld bead was observed at the welding speed of 3.33 mm s^{-1}. In contrast, in the parallel direction, no weld bead was made in the welding speed range from 3.33 to 16.7 mm s^{-1}, and a smooth weld bead on all specimens was not observed. At the welding speed of 1.67 mm s^{-1}, the weld bead was formed only at the end of weld, though nonuniform. Those indicate that the formation of the weld bead has strong anisotropy of pore direction in relation to the irradiation direction of laser beam.

The effect of the laser power on the penetration depth in the thickness of 4 mm for two pore directions at the constant welding speed of 3.33 mm s^{-1} was shown in Fig. 4. The penetration depth of the weld bead in the perpendicular to the pore growth direction shows a sharp rise at the laser beam power of 2.4 kW. On the other hand, the penetration depth in the parallel to the pore growth direction increases gradually in comparison with that in the perpendicular. These facts indicate that the keyhole formed at the laser irradiated point in the perpendicular to the pore growth direction may be attributed to the metal vaporization [14] more than the laser beam power of 2.4 kW, but not in case parallel to

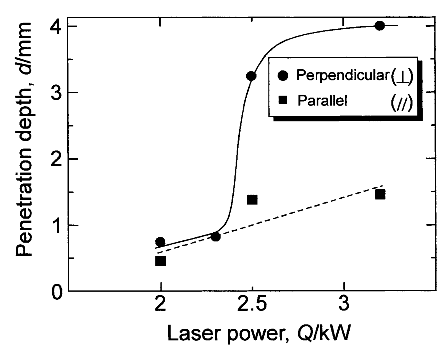


Fig. 4. Effect of laser power on penetration depth of weld bead for perpendicular and parallel to the pore growth direction in depth of 4 mm thick from the work piece surface at 3.33 mm s^{-1} welding speed.

the pore direction. Fig. 5 shows the cross-section of laser welds perpendicular to the welding direction in the thickness of 4 mm in the welding speed of 3.33 mm s^{-1} at the laser beam power of 3.2, 2.5 and 2.0 kW (a)–(c) perpendicular and (d)–(f) parallel to the pore growth directions. As shown in Fig. 5(a), the weld part at the laser beam power of 3.2 kW in the perpendicular case was completely melted through the bottom; shortly, the fully-penetrated weld bead was formed. The shape of the fusion boundary is nearly straight. The straight line of the fusion boundary is nearly parallel to the direction of the original pores. Some large and many small pores in the weld metal were observed in the weld bead. The weld metal at the laser beam power of 2.5 kW in the

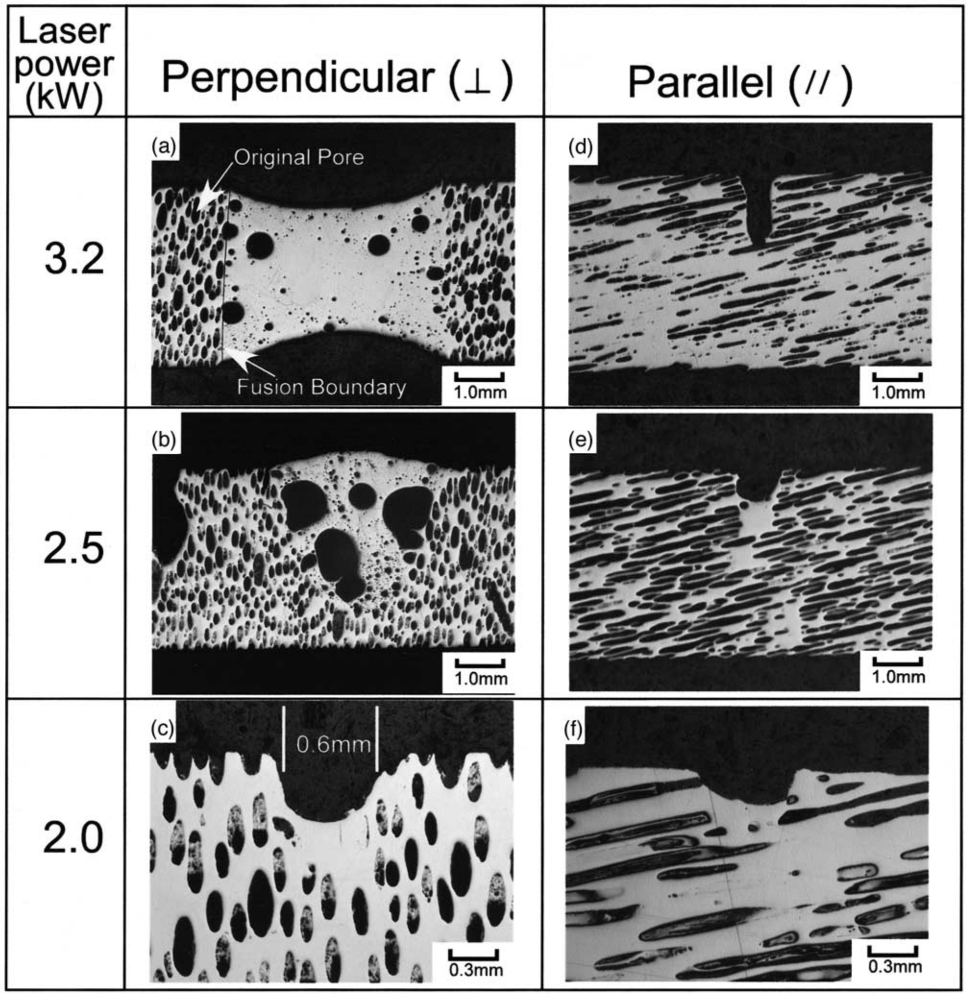
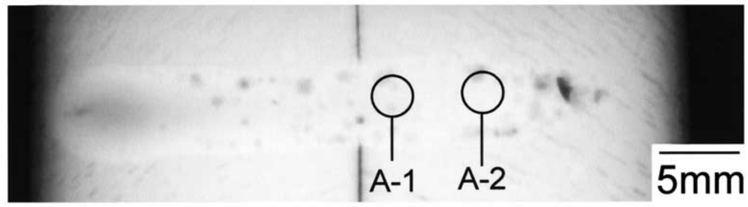


Fig. 5. Cross-section of laser weld perpendicular to the welding direction in 4 mm thickness in the welding speed of 3.33 mm s^{-1} at the laser beam power of 3.2, 2.5 and 2.0 kW (a)–(c) perpendicular and (d)–(f) parallel to the pore growth directions, which slightly inclined to the work piece surface with about 10°.

perpendicular shown in Fig. 5(b) did not melt through the opposite side. Some larger pores evolved by the weld were observed in the weld metal. At the laser power of 2.0 kW shown in Fig. 5(c), the weld metal was not observed, and the diameters of the grooves formed instead of weld bead were about 0.6 mm. In the parallel direction case, the shape of groove was similar to Fig. 5(c), though the groove depth increased with increasing laser power. Obviously, the shapes of the weld bead and the groove exhibit anisotropy with respect to the pore growth direction. Thus, the weldability of the porous copper in the perpendicular direction is more significant than that in the parallel direction.

X-ray radiograph of the work piece after welding with the welding speed of 3.33 mm s^{-1} at the laser beam power of 3.2 kW was taken in depth of 4 mm thick, which is shown in Fig. 6(a). The drilling points were determined in the open circle including the shadow of the weld pores such as A-1 and A-2. Fig. 6(b) shows the drilling time and the distance from the weld bead surface dependence of mass spectral intensity of residual gas detected from the pores in weld metal (Fig. 5(a)) with the welding speed of 3.33 mm s^{-1} at the laser beam power of 3.2 kW in depth of 4 mm thick. When the drilling depth increased to more than 0.5 mm, various kinds of gases were clearly detected at the same time with high intensity, which were evolved from the large weld pore at this point. These gases are identified as H_2, H_2O, N_2, Ar and CO_2 by the mass spectrometer. No obvious change in the intensity was detected during drilling for other gases up to 100 mass numbers. The gas concentration was determined using a net intensity, which was eliminated the difference between the peak intensity and the background intensity in depth of 0.5 mm from the surface. The background of hydrogen is higher than other gas, because small amount of hydrogen was always detected and some hydrogen peaks with comparably high intensity were detected in depth of 0.4

(a)



(b)

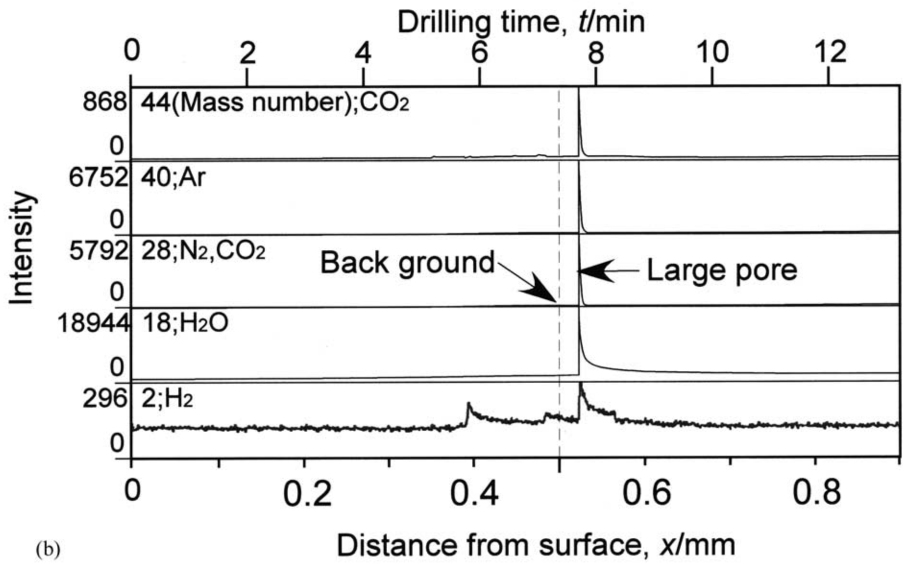


Fig. 6. (a) X-ray radiograph of the work piece after welding with the welding speed of 3.33 mm s^{-1} at the laser beam power of 3.2 kW in depth of 4 mm thick. The drilling points determined in the open circle including the shadow of weld pore such as A-1 and A-2. (b) Dependence of mass spectral intensity of gas detected from A-2 on drilling time and the distance from the weld bead surface.

Table 1
Results of residual gas analysis in pore of weld metal in the perpendicular direction at 3.2 kW laser power

Detected gas (vol.%)	Weld bead				
	A-1	A-2	B-1	B-2	C
Thickness (mm)	4.0		5.0		5.0
Welding speed (mm s^{-1})	3.33		8.33		3.33
H_2	–	1.5	–	8.6	3.8
H_2O	6.5	69.2	12.5	66.3	59.3
N_2	14.5	8.9	14.0	3.1	11.1
Ar	77.4	18.2	73.2	21.1	22.1
CO_2	1.6	2.1	0.3	0.9	3.6

and 0.48 mm. These may correspond to small weld pores which were formed during welding. Table 1 shows the results of gas analysis in the pore of the weld metal at some specimens perpendicular to the pore growth direction. The weld beads A, B and C shown in Table 1 correspond to the welded work pieces shown in Fig. 5(c), Fig. 3(b and c), respectively. The major component of A-1 and B-1 was argon comprised beyond 73 vol.%, and other components were 14 vol.% nitrogen and water. The major component of A-2, B-2 and C was water comprised about 60–70 vol.%, and other components were about 20 vol.% argon, several to 10 vol.% nitrogen and several volume percent hydrogen.

4. Discussion

4.1. Mechanism of pore formation

It is generally considered that the pores in the laser weld bead of dense materials are formed by shielding gas trapped in the weld pool due to keyhole instability by vaporized molten metal [15]. Therefore, it is likely that argon of shielding gas was detected as a main component. The detected nitrogen may result in the gas from the air which trapped together with the shielding gas. In this study, however, the presence of large amount of water and small amount of hydrogen is not explainable in term of keyhole instability only. The reason why those components are present in the pores is that high-pressure hydrogen gas was remained in the closed original pores in the porous copper formed during the unidirectional solidification under high-pressure condition. It is considered that at remelting of work piece by laser welding, remained hydrogen gas in the original pore was released into molten weld metal and then coalesced into the large pore which generated by keyhole instability. Subsequently, the hydrogen gas reacted with oxygen containing in air trapped with the shielding gas, and then water vapor was evolved. Besides, there is small amount of hydrogen gas without reacting with oxygen in the some pores. Nitrogen gas in air also was trapped, but remained in the pore because of no reaction with molten copper. Similar reason was supposed in case of CO_2 gas formation. Therefore, the large pores in the weld metal are formed by the gases, which are the shielding gas, the vaporized copper, the air trapped with the shielding gas and the hydrogen gas in the original pores, trapped in the weld metal owing to keyhole instability.

In addition, there are many small weld pores in the weld metal in which the gas could not be analyzed. Only the low intensity peaks of hydrogen were detected in depth of 0.4 and 0.48 mm as shown in Fig. 6. Therefore, it is expected that the gas in the small weld pores is hydrogen. It is estimated that these pores are formed by the supersaturated hydrogen, which is supplied from the original closed pores, in molten copper as weld metal during solidification of the weld metal.

4.2. Anisotropy of the weldability

In the case of the pore direction parallel to the work piece surface, regardless of the same condition of laser welding as that of the perpendicular pore direction, these specimens show the grooves with little molten copper, which was quite different from the melting property in the case of the perpendicular pore direction. The reason may be considered to the following. The laser beam mostly reflects on the copper surface due to the high reflectivity of copper [16,17]. In the perpendicular pore direction, however, a part of laser beam deeply penetrates into open pores because the growth direction of original pore nearly equals to the incident direction of the laser. In this case, the multiple reflections of the laser beam at the pore wall increases the amount of heat input absorbed to the specimen. In addition, two-dimensional thermal conductivity on the parallel plane to the specimen surface is low, and this assists the melting of the specimen, especially at lower welding speed as shown in Fig. 3(c). On the other hand, the amount of heat input absorbed in the parallel direction is less than the former case, and the small amount of copper melts because of no multiple reflection and high reflectivity of copper. Moreover, this molten copper in the weld pool is blown out by high-pressure hydrogen gas released from the original closed pore.

In the laser beam welding of lotus-type porous copper plat, the pore growth direction should be perpendicular to the work piece surface. When the lotus-type porous copper plate with the original pore parallel to the work piece is used, the surface treatment for increasing the laser beam absorption should be required.

5. Conclusions

The melting property of lotus-type porous copper has been studied using Nd:YAG laser welding in the range of 1.67–16.7 mm s^{-1} welding speed and 2.0–3.2 kW laser power at argon shielding gas. The obtained results are summarized as follows,

(1) There is the pore anisotropy in the melting property by laser beam irradiation when the work pieces were melted in the perpendicular and parallel pore directions to the work piece surface on which laser beam was irradiated.

(2) The weld bead can be obtained at the lower laser beam power in the perpendicular pore direction to the work piece surface than that in the parallel pore direction. In the condition of 4 mm specimen thickness, 3.33 mm s^{-1} welding speed and 3.2 kW laser power, the specimen obtained a smooth surface, low porosity and fully-penetrated weld bead. In the parallel pore direction, no smooth weld head was made in all conditions.

(3) Some large and many small weld pores were made in the weld metal. The gases in these pores are dozen volume percent H_2O and Ar, several to 10 vol.% N_2 and several volume percent H_2 and CO_2, which was determined using mass spectrometer. The large pores in the weld metal are formed by the gases trapped in the weld metal in connection with keyhole instability. These gases are shielding gas, vaporized copper, air trapped with shielding gas and hydrogen gas remained in the original pore.

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