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Anisotropic fusion profile and joint strength of lotus-type porous magnesium by laser welding

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Abstract

The effect of pore growth direction on the weld fusion zone profile and the mechanical property of lotus-type porous magnesium joints were investigated by laser welding through experiments and numerical simulations. The dependencies of the pore growth direction on the weld fusion zone profile were evaluated on the basis of the temperature distribution calculated using the ABAQUS FE code with user subroutines. The calculated weld fusion zone profiles were in good agreement with the experimental results, thereby suggesting that thermal conductivity affects weld fusion zone profiles significantly. Moreover, the effect of pore growth direction on the joint strength of lotus-type porous magnesium was investigated. The anisotropy of the tensile strength of the lotus-type porous magnesium with regard to the pore growth direction was observed. The joints with pores parallel and perpendicular to the tensile direction were fractured at the fusion boundary and the base metal, respectively.

Keywords: Porous magnesium; Laser welding; Solidification; Hydrogen; Numerical simulation; Mechanical property

1. Introduction

In recent years, the development of porous metals and their applications in industries have been carried out worldwide. Such porous metals can be produced by casting, plating, powder metallurgy, and sputter deposition. The porous metals with higher porosities are called foamed or cellular-structured metals. For example, foamed aluminum with TiH_2 as the foaming agent has a unique combination of properties such as lightweightness and high impact energy absorption [1,2]. However, its mechanical strength is clearly low mainly due to the stress concentration [3] because the pores are spherical and randomly distributed. On the other hand, lotus root-like (lotus-type) porous metals with pores formed by a supersaturated gas, which utilizes the difference between the gas solubilities of liquids and solids and are aligned in one direction by unidirectional solidification, possess higher strengths than the conventional porous metals [4–7]. The strength of lotus-type porous metals, as determined by tensile tests, depends on the porosity and the pore growth direction, which is relative to the tensile direction. This can be attributed to the significant stress concentration at the pore wall when the pore growth direction is perpendicular to the tensile direction. Lotus-type porous metals are expected to serve as innovative engineering materials with various anisotropic properties, depending on the alignment of the pore growth direction.

For the industrial use of foamed and porous metals in various components, reliable joining technologies such as welding as well as processing technologies are indispensable. There have been some reports on the arc welding of cellular aluminum sandwich plates [8], laser welding and arc welding of foamable aluminum [9], arc welding of aluminum-based foam materials [10], laser welding of aluminum foams [11], diffusion bonding of closed-cell aluminum foams [12], and laser-based welding of cellular aluminum [13]. Our previous study [14] indicated that lotus-type porous copper with the pores perpendicular and parallel to the specimen surface owing to the difference in laser energy absorption on the specimen surface demonstrated significant melt anisotropy and thermal conductivity anisotropy. The difference in the laser energy absorption was considered to be the main factor because copper has a high reflectivity,

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and multiple reflections could be observed at the perpendicular pores.

Lotus-type porous magnesium, which is expected to be employed in various applications as a lightweight material, exhibits a lower reflectivity for a laser beam and lower thermal conductivity as compared to lotus-type porous copper. Therefore, it is expected that anisotropy of thermal conductivity affects the melting property of lotus-type porous magnesium much more than the difference in the laser energy absorption. From this viewpoint, the melting property is discussed in this study on the basis of comparisons between the numerical simulations and the experimental observations. Moreover, the tensile strength of lotus-type porous copper depends on the pore growth direction relative to the tensile direction because of the stress concentration at the pore wall. Therefore, a similar dependence of the tensile strength on the pore growth direction is expected for lotus-type porous magnesium. The objectives of this study are to elucidate the effect of pore growth direction on the melting and mechanical properties of welded joints with different pore growth directions.

2. Experimental procedure

Magnesium of 99.9% purity was vacuum melted in a high-pressure chamber by high-frequency induction heating. After melting, high-pressure hydrogen gas was introduced into the chamber. The pressure of hydrogen was maintained at 0.9 MPa. After hydrogen dissolved in molten magnesium at 1053 K for 1.2 ks and equilibrium was achieved, the melt was poured into the mold. The bottom plate of the mold was cooled with water circulating through a chiller. Thus, the molten magnesium was unidirectionally solidified vertically upward from the water-cooled copper-bottom plate [15,16]. The obtained ingot was 100 mm in diameter and 100 mm in height. Specimens of dimensions 40 mm × 40 mm with a thickness of 1.8 mm were cut out of the porous magnesium ingot with the pore growth perpendicular and parallel to the specimen surface using a spark erosion wire cutting machine (Brother Industries Ltd., HS-300). The average pore diameter and porosity of the samples were about 0.15 mm and 35%, respectively.

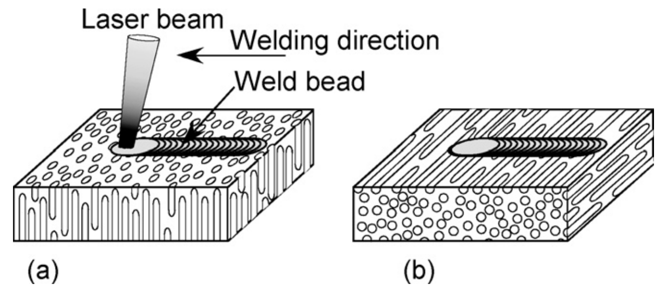

Fig. 1. Schematic views of specimens during laser welding in the porous magnesium with the pores (a) perpendicular and (b) parallel to the specimen surface.

Fig. 1 shows schematic views of specimens during laser welding. The specimen was welded using a Nd:yttrium–aluminum–garnet (Nd:YAG) laser with a maximum nominal output power of 3.2 kW in the continuous wave mode. The wavelength of the Nd:YAG laser beam is 1064 nm, and the beam is delivered by using an optical fiber of diameter 0.3 mm. This laser beam is irradiated on the surface of the specimen at an angle of 80° to prevent damage to the optics by reflected laser beams. Argon was used as a shielding gas with a flow rate of $5.0 \times 10^{-4}\,m^3\,s^{-1}$. The welding speed was maintained to be $83.3\,mm\,s^{-1}$. In this study, the process parameters selected were the laser beam power and the diameter of the laser beam at the focus point. The power of the nominal laser beam and spot diameter were varied in the range of 0.8–2.5 kW and 0.3–0.6 mm, respectively.

The cross-sections of the welded specimen were observed with an optical microscope in order to determine the profile of the fusion penetration. Fig. 2 shows the geometry of tensile

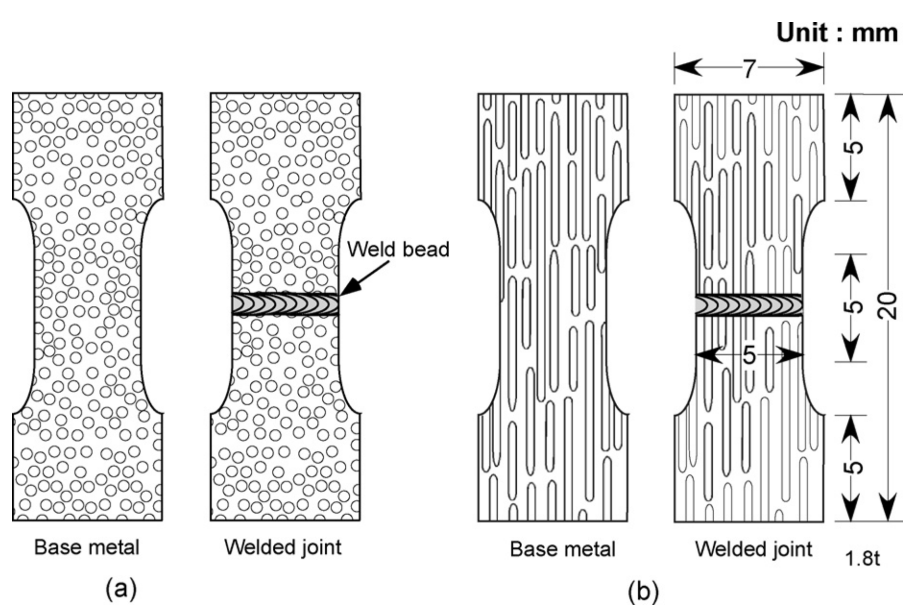

Fig. 2. Geometry in the tensile test specimens of base metal and welded joint with the pores (a) perpendicular and (b) parallel to the specimen surface.