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学位論文の要旨

Abstract of Thesis

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学位論文題目 Title of Thesis（学位論文題目が英語の場合は和訳を付記）

High-efficiency and High-quality Laser Welding of Difficult-to-weld Materials
(溶接困難材料の高効率・高品位レーザ溶接)

学位論文の要旨 Abstract of Thesis

Recently, rapid developments in the automotive, aerospace and electronics industries have necessitated miniaturization and digitization of components, and increased demand for sheet metal joining technology. To realize sustainable development of society, effective use of energy through reduction of weight of products and efficient energy transmission is required. Hence, use of materials with excellent electrical conductivity, such as copper; and high strength-to-weight ratio, such as aluminum alloys, is highly demanded. The applications of copper and aluminum alloys in various industrial fields call for metal joining technology as a functional requirement for various products, but conventional joining methods result in welding defects. Laser welding is a good method for joining these materials, since precise control of energy input is possible by the process parameters. However, copper and aluminum alloys have high reflectance and high thermal conductivity, thus they are difficult to weld using lasers. Combination of high thermal conductivity and low melting point makes it difficult to achieve good welding quality with high energy utilization. In order to adapt laser welding to copper and aluminum alloys, improvements in efficiency and welding quality were investigated using pulsed Nd:YAG lasers and adjustable ring-mode (ARM) fiber laser.

Normally, the laser absorption rate varies depending on the temperature; as a material becomes hot, the absorption rate increases. However, in laser welding of aluminum, the absorption phenomena become very unstable upon reaching the melting point. Consequently, a lot of spatter is generated, and deep penetration welding with good surface quality becomes a challenge. In addition, with a high welding speed, the humping phenomenon leads to deterioration of the surface quality. To overcome these challenges, a method to stabilize the welding phenomena and improve penetration at a high welding speed was described.

Experimental and numerical investigations on overlap welding of aluminum alloy were performed using ARM fiber laser. ARM fiber laser offers a dynamic adjustable beam profile with two parts namely; center part and ring part, hence enabling unique intensity distribution. The influences of laser power and intensity distribution were clarified by evaluating the geometry and appearance of weld bead. In addition, the influences of supply direction and flow rate of nitrogen shielding gas were clarified. The weld bead was evaluated in terms of its width, height, penetration depth and surface roughness. Further to experimental work, a three-dimensional thermal model based on finite element method (FEM) was developed, to dynamically simulate the laser welding process of aluminum alloy. The FEM model employed a combination of surface heat source with top-hat mode distribution, and volumetric heat source with Gaussian distribution. The developed model could calculate the temperature fields, and it agreed well with the experimental results. High-speed welding of aluminum

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alloy without humping could be achieved by using appropriate intensity distribution. Dual-mode irradiation of center and ring power made it possible to stabilize the welding process. High-quality welding characterized by deep penetration, small bead height and width, and low surface roughness could be achieved in dual-mode welding, using appropriate low flow rate of shielding gas, supplied from the back. The ring power ensured good temperature distribution, while the center power helped to achieve sufficient deep penetration by enhancing faster and sufficient keyhole formation. Therefore, laser welding using suitable intensity distribution proves to be a reliable high-speed joining method for aluminum alloy, with the possibility of obtaining high-quality weld beads.

Laser welding of copper is characterized by low and unstable energy absorption around 1000 nm wavelength, hence it is difficult to obtain good welding quality. When copper is processed using 1064 nm Nd:YAG laser, there is need to employ very high output power in order to melt the copper material, since most of the laser energy is reflected. It is difficult to obtain a stable process even after reaching the melting point, since the absorptivity is still low. Shorter wavelength such as 532 nm has a possibility of highly efficient process for copper but use of 1064 nm wavelength system is desired in industrial applications, because of its affordable cost and high reliability. To improve efficiency and welding quality with 1064 nm laser, techniques to enhance process stability have been proposed.

Since the surface state of copper affects the absorption phenomena, effects of surface undulations, such as concave shape and surface roughness were investigated. Further, processing was carried out at the transitional region between heat conduction welding and keyhole welding. Laser absorption rate and molten volume were increased by creating appropriate concaves and by controlling the surface roughness. Stable micro-welding process with deep penetration and good surface quality was achieved under transitional processing condition. It was clarified that control of surface texture is effective to improve the process stability when using 1064 nm laser, and approximately 30 μm surface undulation would be proper to achieve high and stable absorption rate, and large molten volume.

It is expected that superposition of 532 nm and 1064 nm Nd:YAG lasers might also lead to a stable absorption phenomena, since 532 nm laser shows high and stable absorption by copper. Therefore, processing by superposition of the two lasers was investigated through experiments and numerical simulations. Since appropriate surface undulations will lead to a stable process by 1064 nm laser, 532 nm laser was utilized to create the surface undulations, then followed by irradiation of 1064 nm laser. The influence of irradiation delay for 1064 nm laser and power density were clarified. Superposition with a short irradiation delay of 200 μs, and appropriate high power density of 532 nm laser, was effective in stabilizing the process. Therefore, with a careful setting of process parameters in superposition, the process can be stabilized and good surface quality of weld bead with deep penetration and no porosity can be obtained.

This research work presents unique techniques to achieve high-quality and high-efficiency welding of copper and aluminum alloy materials using lasers. Stabilization of the process in laser welding of aluminum alloy is achieved by control of intensity distribution, even at high welding speeds. In copper micro-welding, stabilization of the absorption phenomena is achieved by control of surface texture, and superposition of different and suitable laser wavelengths.