論　文　の　要　旨

題目　Development of Additive Manufacturing Technology using High-power Diode Laser and Hot-wire Method

（高出力半導体レーザとホットワイヤ法を用いた高能率 AM 技術の開発）

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Recently, additive manufacturing (AM) is a family of new techniques that have developed rapidly in various industries, such as aerospace, automobile, and marine due to the time-saving characteristics, high material utilization rate, and high design flexibility. Different from traditional subtractive and formative manufacturing processes, AM technology has the potential to build complicated structures with near-net-shape from the three-dimensional (3D) model in layer-upon-layer forms. According to the raw materials, Metallic additive manufacturing (MAM) technologies are mainly classified into powder-feeding metal additive manufacturing (PMAM) and wire-feeding metal additive manufacturing (WMAM). PMAM provides thin-scale parts with a low laser consumption, high dimension accuracy, high flexibility, and good surface quality. However, the MAM method that uses recycling powder also has some weaknesses, such as oxidation and pore defect formations, low deposition rate, and materials waste. The use of wire materials can improve the deposition rate and material utilization rate significantly compared with the use of powder materials with a lower utilization rate. Thus, WMAM technology has been successfully applied in fabricating large geometries and high near-net-shape ratio metallic components.

WMAM technology can be categorized into three types according to the heat source: wire and arc additive manufacturing (WAAM), electron beam freeform fabrication (EBF^3), and laser additive manufacturing (LAM). Although wire and arc additive manufacturing has the advantages of a high fabrication efficiency, low equipment cost, large component manufacturing capability, and defect-forming prevention compared with other AM technologies, it has challenges, such as control of heat input, low cooling rates, large distortion, and surface fouling. Development of the EBF^3 method has been accelerated because of its ability to manufacture high-quality near-net-shape components with better mechanical properties. This method also has problems, such as a low deposition rate, the requirement for a vacuum environment, and a high equipment price. The LAM method has been applied widely and uses a high-energy density laser that is irradiated on a substrate or previous layer. However, the conventional MAM process that uses cold wire materials remains an ongoing challenge because of the high reflectivity on some materials, the inability to control base metal melting and cold wire melting independently, and small process condition tolerances. Therefore, the LAM method combined with a hot-wire system is interesting because of its high productivity and controllability.

The objective of this thesis was to develop a high-efficiency and high-quality additive manufacturing technology using a combination of a high-power diode laser and hot-wire method with three types of metallic materials: Stainless steel, Ni-based alloy, and 5xxx-series Aluminum alloy. In hot-wire laser additive manufacturing (HLAM), a laser beam with high controllability serves as the main heat source, and another heat source is Joule heat that is generated by a hot-wire current, which heats the filler cold-wire to its melting point independently from the heat input of the main heat source for base metal melting.

Firstly, a simple calculation method to predict the appropriate wire current was proposed and confirmed by hot-wire feeding experiments without laser irradiation. The results of theoretical calculation and experimental value of the appropriate heating current were investigated. In order to clear the experiment verification, this experiment used a high-speed camera to observe the hot-wire heating phenomenon. As a result, the appropriate hot-wire current for heating the wire tip to nearly its melting point for four wires (SUS308L, SUS630, Inconel625, and A5356WY) was obtained. It is found that the hot-wire heating current is an important parameter to achieve stable and smooth wire feeding. Excessively low and high wire currents result in insufficient wire-tip temperature with poking on the base metal surface and fusing and spatter formation, respectively. In the calculation method, the appropriate current value under different conditions (e.g. wire feeding speed, temperature-dependent specific heat, temperature-dependent specific gravity, and temperature-dependent specific electrical resistivity) was studied in detail. As a result, the wire temperature increment in segment length L is positively correlated with the square of the wire current I, and negatively correlated with the wire feed speed V_F and the diameter of filler wire. Moreover, the estimated current is in good agreement with the experimental values over a wide range of wire feeding speeds from 0 to 20 m/min for all four filler materials, considering both heat loss from heat convection and heat generation by contact resistance.

Through this calculation method, the appropriate current of filler material could be obtained under various wire feeding speeds. The final aim of this study is to a combination of the diode laser irradiation and hot wire method. Thus, the hot-wire laser AM by using SUS308L wire was investigated at first. High-speed imaging was performed to monitor clear wire melting phenomena and molten pool formation during AM processing by combining hot-wire feeding and diode laser irradiation. The two-layer and three-layer deposited samples were then proposed and evaluated. As a result, a process windows for a laser power from 3 to 5.5 kW, process speeds from 0.3 to 0.5 m/min, and a wire feeding rate from 20 to 40 were obtained. A large width above 10 mm and a high deposition rate above 800 cm^3/h were achieved. There are many parameters involved in the process conditions, including laser power, process speed, wire feeding rate, and energy heat input, mainly affect the melting phenomenon and bead appearance of three-layer deposition. It is found that the energy heat input was proposed as being key to obtaining adequate and stable melting phenomena. Each wire feeding rate from 20 to 40 had a lower limitation of energy heat input from 35 to 60 J/mm^3 to create sound deposited layers. Moreover, the effects of laser spot size on a bead shape and cross-sectional characteristics were investigated. As a result, a sufficiently high wire feeding speed (rate) should be used according to the laser beam width and processing speed before optimizing other parameters in the proposed HLAM process.

Then, the AM conditions for the three types of wires (SUS308L, Inconel625, and A5356WY) were also investigated using the appropriate wire current calculated using the proposed method. It is found that the laser power and process speed affected the effective width and effective height and maximum height, respectively. The wire feeding rate had the biggest effect on height and the near net shape rate. The optimized AM process parameters were obtained from the viewpoint of higher material utilization and more stable bead formation according to cross-sectional evaluations. As a results, sound three-layers and cross-sections without any defects were obtained for the three materials types using the optimized process parameters. A wide effective width of 9–11 mm, and a high wire feeding speed of 12–20 m/min (deposition rate of approximately 800–1300 cm^3/h) were achieved. Moreover, three large wall-type parts with the effective width of ~10 mm, effective height above ~40 mm, and length above ~200 mm were fabricated by using optimized process conditions, and tensile tests were performed. Large-wall samples for the three materials types with a maximum height of 42.4-59.3 mm and a high near net shape rate of 75-84% were obtained by using only 15 layers. A sufficient tensile strength of 265–713 MPa and elongation of 23-66% were achieved. However, the thin-wall of various materials also need to apply in special industries.

Finally, a hot-wire with narrow diode laser spot AM technique was investigated for the deposition of 630 stainless steel. The effect of processing conditions including the wire feeding position, defocus length and welding direction on the stability of deposition along with the effect of the energy density distribution and process speed. As a result, the wire feeding position significantly affected the stability of the HLAM process. The wire feeding position that is too close ($D \leq 0$ mm) or too far ($D \geq r$ mm) from laser beam center results in wire dripping or wire stubbing, respectively. When the wire feeding position ($0 < D < r$ mm) was appropriate, the homogeneous width deposited metal without any defects could be obtained. A process map between the energy heat input and wire feeding rate was established for predicting the suitable defocus length. The sound bead with no defects could be fabricated under the suitable energy heat input ranging from ~10 to 21 J/mm^3 when the wire feeding rate is from 6.7 to 10. The substrate can be melted with the limitation of energy heat input was ~10.5 J/mm^3. Compared with hot-wire leading, the laser leading process that pushed a forward flow of the liquid metal and acids the backward flow along the edges of the molten pool. The laser leading condition can significantly avoid the humping defects and improved the shape of the bead. The effect of process speed on the neat net shape rate and microstructure of the deposited three-layer was also investigated. It is found that the microstructure of the materials fabricated at difference process speed was evaluated. The phases of 630 stainless steel deposited three-layer mainly composed of a large number residual δ-ferrite and a small amount of γ-austenite. The deposited metals solidify in F mode, and the morphologies of ferrite are vermicular, skeletal and lathy.