（様式２）

学位論文の概要及び要旨

氏　　名　James Mutuku Mutua 印

題　　　目 3D Additive Manufacturing, Microstructure, and Mechanical Properties of High Performance Materials

(高性能材料の三次元積層造形、微視組織と機械的性質に関する研究)

学位論文の概要及び要旨

During product development, nothing communicates an idea more than a model. 3D additive manufacturing (AM) technologies are used to generate and optimize design models as a proof of concept before actual product fabrication. Through these processes, prototypes and/or fully functional parts can be generated using different materials including polymers, metals, ceramics, and composites. At inception, AM technology was developed to solely produce plastic prototypes from liquid photopolymer resins. However, with time different AM processes such as binder and material jetting, material extrusion, powder bed fusion, direct energy deposition, sheet lamination, and hybrid systems have been used extensively in real time rapid prototyping of product models to provide early error detection and correction during manufacturing process. To date, the technology has advanced and is now capable of producing complex, near-net shaped objects from a wide variety of materials. Specific materials have been developed and used directly to make end-use parts in areas such as aerospace, automobile, medicine, and tool/die making etc. Some of the as-built AM parts have inferior mechanical properties compared to conventionally manufactured ones. This may be due to intrinsic material properties, choice of AM process and associated process parameters, the microstructure inherited from rapid cooling, and any subsequent heat treatment subjected to them. Moreover, improper combination of process parameters results in less dense and porous products which do not meet design specifications. Therefore, materials, AM process, and process parameters must be carefully selected to yield requisite properties. In addition, appropriate post treatment must be carried out to improve these properties so as to suit design constraint.

The objective of this study was to determine the effects of various 3D printing process parameters on the quality of the products, and to identify the optimum process parameters and material properties during fused deposition modelling (FDM) of carbon fiber reinforced plastic composites and metal 3D printing of steels. High performance materials including CFR-ABS composites, 18Ni (300-grade) maraging and SUS316L stainless steels were processed through FDM and selective laser melting (SLM), respectively. The FDM and SLM process parameters were optimized and high-quality FDMed/SLMed products were obtained.

In the FDM of CFR-ABS composites, the effects of process parameters, *i.e.,* printing speed, layer thickness, and raster direction on the microstructure and mechanical properties of 3D printed ABS and CFR-ABS materials were investigated. It was found that low and high printing speed resulted in low tensile strength and ductility while small layer thickness resulted in high tensile

strength. However, increasing the layer thickness led to decreases in both tensile strength and ductility. In addition, specimens printed at a raster direction of 0° had better mechanical properties compared to those at 45° and 90°. Reinforcing ABS with carbon fibers led to better dimensional stability, decreased tensile strength, and onset of brittleness. The best printing conditions were found to be printing speed of 3200 mm/min, layer thickness of 0.1 mm, and raster direction of 0°. This resulted in relatively high tensile strength of 55.86 MPa and 49.03 MPa for 3D printed ABS and CFR-ABS specimens, respectively.

The optimization of SLM process parameters including laser power, scan speed, pitch, and spot diameter, and their influences on the densification behavior, surface morphology, microstructure, and mechanical properties of SLMed18Ni (300-grade) maraging steel have been investigated. A process map for the SLM of maraging steel was constructed and the process parameter optimization has been realized. The results indicate that, there exists a relatively large processing window, where sound products with relatively high relative density and good surface quality can be obtained. For example, the optimum process conditions were found to be scan speed of 700 mm/sec, laser power of 300 W, overlap rate of 40%, and energy density of 71.43 J/mm^3. These resulted in a maximum relative density of 99.8% and good surface quality with a roughness value of Ra= 35 μm. Besides, the as-built SLMed parts were found to have higher hardness values (330-403 HV) compared to the wrought counterparts (280 HV). This was due to the fine microstructure obtained during SLM.

The influence of post heat treatment on microstructure and mechanical properties of maraging steel has also been extensively investigated in this research. As-built specimens contained martensite matrix with trace amount of austenite phase. The quantity of austenite phase increased during aging treatment due to reversion of martensite to austenite. Solution treatment/aging resulted in elimination of the austenite phase and formation of intermetallic precipitates in the martensite matrix. The as-built and aged specimens exhibited almost the same average grain size, while solution treatment/aging resulted in grain growth of the martensite matrix and a significant change in grain orientation. The results indicated that the SLMed specimens with the building direction parallel to the loading direction had much lower elongation than those with the building direction perpendicular to the loading direction. The maximum tensile strength and hardness obtained were 2033 MPa and 618 HV respectively, after solution treatment at 820 °C for 1 h and aging at 460 °C for 5 h.

Finally, select process parameters including laser power, scan speed, pitch, and spot diameter were varied and their effects on relative density, surface quality, microstructure, and hardness of SLMed SUS316L stainless steel were examined. The optimized process parameters that resulted in high-quality SLMed products with relative density of 99.2%, surface roughness of 9.95 μm, micro-hardness of 241 HV were found to be: laser power of 320 W, scan speed of 700 mm/sec, pitch of 0.12 mm, spot diameter of 0.2 mm, overlap rate of 40%, and energy density of 77.92 J/mm^3. A process map for the SLM of SUS316L steel has been constructed. Relatively high relative density and good surface quality parts can be obtained in a constricted range of laser power (150-320 W) and scan speed (650-750 mm/sec).

The optimized process parameters on 3D printing of CFR-ABS composites, SLM of 18Ni maraging and SUS316L stainless steels, and the generated process maps for maraging steel and SUS316L will help in deeper understanding of the processing-structure-property-performance in AM processes and contribute new knowledge towards a comprehensive material property database and testing methodology on FDM and SLM as key AM processes.