Characteristics of Laser Aided Direct Metal Powder Deposition Process for Nickel-based Superalloy

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Abstract. Laser additive direct deposition of metals is a new rapid manufacturing technology, which combines with computer aided design, laser cladding and rapid prototyping. The advanced technology can build fully-dense metal components directly from CAD files without a mould or tool. With this technology, a promising rapid manufacturing system called “Laser Metal Deposition Shaping (LMDS)” is being constructed and developed. Through the LMDS technology, fully-dense and near-net shaped metallic parts can be directly obtained through melting coaxially fed powder with a laser. In addition, the microstructure and mechanical properties of the as-formed samples were tested and analyzed synthetically. The results showed significant processing flexibility with the LMDS system over conventional processing capabilities was recognized, with potentially lower production cost, higher quality components, and shorter lead time.

Introduction

Laser additive direct metal deposition is an extension of the laser cladding process in that it allows three-dimensional parts directly from a 3-D CAD model to be built by cladding successive layers on top of one another in pre-determined vector paths. The development of this process has drawn tremendous interest among the rapid prototyping industry as well as the tool industry \cite{1}. The process can be utilized in many promising fields such as net shaped solid metallic parts, functionally graded materials, cellular solids, in-situ alloying parts, and parts with conformal/internal features \cite{2}.

The advantage of this technology is its ability of one-step manufacture, which greatly reduces the lead-time and investment cost of module and die design, the fabrication of hard or rare metal components, the repair of refractory and costly components, etc. Currently, a promising rapid manufacturing system called “Laser Metal Deposition Shaping (LMDS)” is being constructed and developed, and the details of this research will be further described herein.

Experiment Procedure

Experimental Setup. Fig. 1 shows the experimental setup for laser direct deposition experiment. Experimental setup is primarily composed of four components: energy supply system, motion control system, powder delivery system, and computer control system. It is only through this way that the three dimensional object can be achieved successfully.

Experimental Material. The experimental material for laser direct deposition experiment was the Ni60A alloy whose powder size is about 200 mesh. The chemical composition of Ni60A alloy is listed in Table
1. The substrate used for multi-layer laser cladding was an A3 steel plate with the dimension of 200 mm×200 mm×10 mm.

| Powder | C  | Cr  | Si  | B  | Fe  | Ni  |
|--------|----|-----|-----|----|-----|-----|
| Ni60A  | 0.5-1.0 | 14-19 | 3.5-5.0 | 3.0-4.5 | <8.0 | Bal |

**Microstructure Analysis**

Through LMDS setup, a thin-wall part used for microstructure analysis and property examination was deposited layer by layer. Fig. 2 shows the longitudinal cross-section area of the thin-wall part under a low magnification of 60× by SEM. This figure illustrates the structure of several uniform layers with the laser scanning direction and laser beam orientation denoted. For each layer, two regions are recognized: the deposition region and the remelting zone. The orientation of the dendrite of the deposition region always follows the direction from the bottom to top of each layer and slightly toward the scanning direction. The other fact about grain orientation that should be noted is that the new dendrites always nucleate at the sites of the dendrites from the former layer and inherit their orientation. Looking at the close-up view of the remelting region as shown in Fig. 3, the microstructure of the remelting region tends to become featureless and prevent the dendrites of the new layer from inheriting the orientation of those in the previous layer. This phenomenon can be explained by the solidification theory, which means that the very low solidification rate at the remelting zone causes the way of grain growth transferring from dendrite to planar. On the other hand, near the surface of the last layer, large quantities of cellular structure appear on the traditional type of dendrites as can be seen in Fig. 4. This is due to the cooling effect of the substrate, which causes the temperature gradient of the interior of the layer is remarkable in the vertical direction, whereas that of the surface of the layer is considerably weakened in the vertical direction due to the heat dissipation from the surface. Therefore, the grain growth at the interior of the layer holds preferred orientation from the bottom to top, thus forming the dendrites. By contrast, grain growth at the surface of the layer does not depend on the orientation, thereby generating the cellular structure. However, with the exception of the last layer, cellular structure does not show at the surface of the other layers. The reason for this is that the cellular structure at the surface of the previous layer become remelted when the next layer is deposited, which in turn causes the microstructure of the remelting region inclines to become featureless, showing the planar grain growth way as a result of slow solidification rate.

**Mechanical Properties of the Parts**

**Tensile Test Results.** The uniaxial test was conducted for the thin-wall part using tensile tester. For the thin-wall part, the specimens were prepared so that the tensile directions can be varied both
in parallel and perpendicularly to the scanning directions of the layers, as shown in Fig. 5.

The tensile test was carried out with the specimens broken in the middle position. After tensile test, the fracture surfaces for both specimens showed a gray, rough and necking morphology. As illustrated in Fig. 6, a large number of dimples with various shape and size are distributed on the fracture surfaces, which indicates that the fracture characteristic of as-formed Ni60A samples is the ductile fracture behavior. Ductile fracture occurs as the stress reaches the fracture strength. The mechanical properties such as yield strength, ultimate tensile strength and elongation percentage of the tensile samples loaded with the different tensile directions are listed in Table 2.

The tensile test results also show that the part deposited by laser direct deposition is anisotropic. The yield strength and ultimate strength with the scanning direction parallel to the tensile direction were much greater than those with the scanning direction perpendicular to the tensile direction, which can be explained by the grain boundary strengthening mechanism. In the case of the scanning direction parallel to the tensile direction, most of the dendritic boundaries were normal to the tensile direction and block the dislocations so as to withstand additional load. However, since the deformation at the grain boundaries was restrained, at a small strain, the fracture will occur along the grain boundaries. On the other hand, for the case of the scanning direction perpendicular to the tensile direction, good ductility could be obtained since the orientation of dendrites is parallel to the tensile direction so that it is easier for dendrites to be elongated.

Especially, fracture always occurs at the remelting layer, namely at the bonding position between the adjacent layers, which might be caused by the weak bonding strength and the different nature between the remelting region and its adjacent layers. As a result, the elongation percentage with the scanning direction perpendicular to the tensile direction becomes nearly twice as great as that with the scanning direction parallel to the tensile direction. Therefore, the anisotropy of the mechanical properties of deposited parts should be considered when designing the structure of the part so as to meet requirement of the mechanical properties.

**Hardness Test Results.** The sample for hardness test was sectioned in the middle of the deposited thin-wall part with a cross-section normal to the scanning direction. The hardness of the deposited stainless steel part was measured along the height direction of the part. The distance between two adjacent test points in the height direction was approximated as 5 mm. The

| Material                          | Yield Strength (MPa) | Ultimate Strength (MPa) | Elongation Percentage (%) |
|----------------------------------|----------------------|-------------------------|----------------------------|
| Deposited Ni60A (Parallel)       | 385                  | 572                     | 9.6                        |
| Deposited Ni60A (Perpendicular)  | 224                  | 338                     | 18.5                       |
experimental results are shown in Fig. 7.

The hardness values for the deposited Ni60A part are in the range of HRC 55-61, which is somewhat less than those measured in the traditional single laser cladding experiment. The annealing effect due to the reheating of the subsequent layers is the principal reason for the decrease in hardness. Another possible explanation is that the preheating of the previous layer may reduce the cooling rate of the molten metal and therefore the hardening effect while cooling will be minimized. However, since the ductility of the part is inversely proportional to the hardness, it is improved in the laser direct deposition, which is desirable as the body of a metal part. As shown in Fig. 7, the hardness values are relatively high near the top surface of the thin-wall part and close to the surface of the substrate. Furthermore, the intensive cooling functions from the external environment and the substrate contribute to the increase in hardness at the top and bottom of the part.

![Fig. 7 Hardness distribution in the height direction within the laser fabricated Ni60A part](image)

**Parts Produced with LMDS Setup**

Based on our experiments, several fully-dense Ni60A metal parts were fabricated using the LMDS setup, four of which are exhibited in Fig. 8. All of them demonstrate fine appearances and surface quality. Furthermore, they are free of porosity, fully-dense, and near-net shaped. In addition, rapid solidification during deposition ensures the fine microstructure and perfect properties with the as-fabricated metal parts.

**Conclusions**

A direct laser metal deposition process was incorporated into the LMDS setup. The process was not restricted by the material and shape of the deposited metal powder. Thin-wall Ni60A part was successfully fabricated by LMDS technology. There was no crack or porosity in the part and the dendrites oriented from the bottom to the top of each layer with slightly toward the laser scanning direction. The tensile test results for Ni60A samples showed that the mechanical properties of the deposited part were anisotropic and they were affected by the microstructure distribution. Finally, a number of metal parts were produced using the LMDS setup. These parts illustrate the capability of the system to fabricate fully-dense and near-net shaped parts without any tools, dies, or clamps.

**References**

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