Distortion prevention of axisymmetric parts during laser metal deposition

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Abstract. One of the main problem of large parts manufacturing using laser metal deposition (LMD) is the high residual distortion. Effects of layer-by-layer evolution of stresses and strains was studied by finite-element simulation. It was shown that distortion of axially symmetrical parts can be successfully predicted by the developed simulation procedure. Required dimensional accuracy of additively manufactured parts can be achieved by the optimization of deposited part size and shape in order to compensate volume shrinkage during layers solidification. The corresponding simulation procedure was developed and validated. Another major problem is prevention of distortion during deposition of thick flange on the surface of thin shell structures. In this case the following procedure was proposed and studied: on the first step spacer ring introduces in the shell, then deposition of the flange is carried out and on the last stage whole structure is heat treated in order to remove residual stresses.

1. Introduction

Every year, engineers are developing ever more complex mechanisms and parts of machines to increase their efficiency and productivity, optimize the shape and materials used, however, this affects the increase in the laboriousness of production of such products, for example, aircraft engines or devices from the aerospace industry. Moreover, the overall dimensions of engines used in aircraft construction are quite large and can reach 3 meters in diameter with a wall thickness of several centimeters. The production of engine casings is a complex and time-consuming task, so rapidly developing additive technologies seek to solve and simplify the task of manufacturing such parts [1-5].

In particular, Institute of Laser and Welding Technologies (ILWT), Peter the Great St.Petersburg Polytechnic University was tasked to produce a prototype of the gas turbine engine support made of titanium alloy, a diameter of more than 800 mm with a wall thickness of 3 mm and thick flange – about 15 mm – on it. However, this presents some difficulties, due to the process of metal melting and its further crystallization, as is known, leads to the appearance of internal stresses into the part and its deformation. Therefore, we put forward two hypotheses: in the case the product is produces without supports, the product itself must have sufficient rigidity to has internal stresses resis tance during the manufacture, whereby cracks on the product and its destruction are avoided; In the case where the product cannot retain internal stresses without deformation or failure, we need to use supporting structures. We have developed and applied an innovative way to add extra rigidity to a thin-walled structure using internal supporting structures. The point of this approach is that the body of the necessary shape and size is first made, then a special support device is inserted into it, the so-called spacer pan, which adds extra rigidity to the construction and prevents the destruction of a thin-walled product, after
which the flanges and other elements are grown on the surface of the housing. Next, it is necessary to make a heat treatment of the product, remove the special support device and send the product to the final treatment.

Both hypotheses were tested, the results of the study compared with the results of the simulation, the data were analyzed, based on it, a decision on the possibility of producing large-sized thin-walled parts from titanium alloys using laser metal deposition (LMD) technology with and without supporting structures and on distortion prevention of axisymmetric parts were made.

2. Experimental part

The experiments were carried out using ILWT’s laser metal deposition setup (Figure 1).

![Figure 1. Laser metal deposition setup with an operator.](image)

It consists of the following main parts:
- a 5 kW fiber laser IPG LS-5 coupled with chiller Riedel PC 160;
- a powder feeder Oerlikon Twin 10-C;
- a six-axis robot manipulator Fanuc coupled with a two-axis positioner Fanuc;
- a welding laser head IPG FLW-D30 with a coaxial slit nozzle;
- a sealed chamber of a 6 m³ volume with the possibility of obtaining an argon atmosphere with a purity of ≈ 100 ppm oxygen content.

A series of three trials was carried out using this setup:

1) Thin-walled cylinder of IN625 on the substrate of low-alloy steel. There are scheme and appearance of this part on Figure 2. It was deposited on the following process parameters:

- Laser power: 1.5 kW;
- Deposition rate: 30 mm s⁻¹;
- Beam radius: 1.2 mm;
- Number of layers: 246;
- Cylinder radius: 100 mm.
Figure 2. Schematic (a) and photo (b) of the deposited cylinder of IN625.

2) Thin-walled cylinder of Ti-6Al-4V on the substrate of the same alloy. There is a scheme of this part on Figure 3. It was deposited in 100 % argon atmosphere on the following process parameters:

- Power: 1.6 kW;
- Deposition rate: 30 mm s⁻¹;
- Beam radius: 1.2 mm;
- Number of layers: 600;
- Cylinder radius: 420 mm.

Figure 3. Scheme of the deposited cylinder of Ti-6Al-4V

Subsequently residual distortion of the build parts was measured by the Shining 3D EinScan-Pro laser scanner and Geomagic software was used for data processing. Due to the comparison of the geometric dimensions of the theoretical model and the manufactured product, the first hypothesis was partially disproved: large-sized products have sufficient rigidity to resist internal stresses, but the latter
cause unacceptably large deformations. Therefore, it is necessary to use supporting structures to impart extra rigidity to thin-walled structures.

3) Thin-walled cylinder of Ti-6Al-4V with thick flanges on the substrate of the same alloy. There is an appearance of this part on Figure 4. Based on the previous trials and simulation data it was decided to produce the part in two steps: build the thin-walled cylinder using optimised deposition path at first; insert extra-rigid supports, which pushes to outside, into the cylinder and deposit thick flanges on cylinder side. It was deposited in 100 % argon atmosphere on the following process parameters:

- Power: 2.3 kW;
- Deposition rate: 20 mm/s;
- Beam radius: 1.75 mm;
- Wall thickness: 4.2 mm;
- Flange thickness: 10 mm.

Figure 4. Photo of the deposited cylinder of Ti-6Al-4V with flanges

Residual distortion of the build part was also measured by the Shining 3D EinScan-Pro laser scanner and Geomagic software was used for data processing.

3. Simulation part
The sequentially-coupled heat conduction analysis in transient mode followed by elastic-plastic large displacement analysis has been performed using finite element method. Deposition of material during LMD was simulated using so-called element birth technique. In this method, elements for the yet to be deposited are deactivated at the beginning and then gradually activated of “born” into the solution domain (Figure 5). Finite element model of deposited parts was 2D axisymmetric. The temperature-dependent mechanical properties for IN625 [6] and Ti-6Al-4V [7] was used in Figure 6.
4. Results and discussion

4.1. Residual stress and distortion of the deposited cylinder of IN625

Effects of radius variation of the deposited cylinder on distortion and temperature field along the cylinder generator of a constant height are shown in Figure 7. As can be seen, the effect of increasing cylinder radius is to increase residual radial displacement and curvature of the sidewall. It can be explained by a large amount of the deposited metal in one layer due to higher circumference on the one hand and the lower thermal gradient along sidewall on the other. Colder metal prevents the temperature expansion of the solidify deposited layer and leads to the generation of higher shortening plastic stain and thus higher distortion. The lower radius, the greater temperature gradient and the peak temperature before the deposition of the current layer. It leads to the more uniformly shrinkage and less warping.
Figure 7. Residual radial displacement along the cylinder generator as a function of cylinder radius (a); Temperature distribution along the cylinder generator before the deposition of the last layer (b).

Analysis of residual stresses in build cylinder of 700 mm radius revealed that the highest tension hoop and axial stress amounted to $(1.15-1.2)\sigma_{0.2}$ near the substrate (Figure 8a, b). It can be explained by the high stiffness of the substrate and increasing in bending moment with increased wall height. It was also revealed that axial plastic strain is tension and attains 1.5-2.0% (Figure 8c). This leads to the conclusion that if deposited material has a weak ductility (e.g. titanium alloys) there is a high probability that the fracture could occur in this region. Residual radial stress is neglectfully small due to thin sidewall of the cylinder.

Figure 8. Distribution of normalised hoop stress (a), normalised axial stress (b) and axial plastic strain (c) in the sidewall cross section of the cylinder of 700 mm radius.

4.2. Analysis of distortion of Ti-6Al-4V cylinder

During the first experimental trial deposition path completely agree with part generator shown in Figure 3. Measured mismatch along generator between build part and required shape is shown in Figure 9. It can be seen that deviation is negative and amounted to about 5 mm, that is unacceptable. The next experimental trial was carried out according to the optimised deposition path obtained by the numerical simulation. In this case, the peak mismatch amounted 1 mm only on the small area of the part whereas an average deviation is only 0.2 mm (Figure 9b).
Figure 9. Scheme of fabrication part deviation from deposited part (a) and distribution of mismatch between required model and build part obtained using non-optimised deposition path (b)

Figure 10. Scheme of fabrication part deviation from deposited part (a) and distribution of mismatch between required model and build part obtained using optimised deposition path (b)

4.3. Analysis of distortion of Ti-6Al-4V cylinder with thick flanges
Cause of non-uniform residual distortion and heat influence on the built cylinder during flanges cladding unexpected deviation were appeared and registered. Despite of optimised deposition path and extra-rigid supports the deviation were significant, although at the support-mounted places distortion were the least.

Figure 11. Distribution of mismatch between required model and build part obtained using optimised deposition path.
5. Conclusions
1) The effect of increasing cylinder radius is to increase residual radial displacement and curvature of the sidewall.
2) The highest tension hoop and axial stress amounted to 1.15-1.2 times of yield stress near the substrate.
3) If deposited material has a weak ductility (e.g. titanium alloys) there is a high probability that the fracture could occur in the sidewall near the substrate.

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