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A study on the feasibility of manufacturing high precision parts using laser powder bed fusion and finish machining

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Abstract
Additive manufacturing (AM) is a rapidly developing technology that is revolutionizing the manufacturing industry. AM allows for the rapid production of complex parts with intricate geometries that would be difficult or impossible to produce using traditional manufacturing methods. However, AM parts often exhibit lower precision and surface finish than parts produced using traditional methods. This is due to a number of factors, including the inherent nature of the AM process and the limitations of the AM machines. The purpose of this study is to investigate the feasibility of fabricating high precision parts with thin walls, as well as large complex parts that require tight tolerances using laser powder bed fusion. To improve surface finish and dimensional accuracy of the parts, various finish-machining methods were explored.
A flexspline and a helical screw were used as analogues for the thin walled and the large part respectively. A coordinate measuring machine (CMM) and a structured light scanner were used to measure the parts at different stages in the process. The thin walled flexsplines were machined using milling for the inside wall and single point turning for the outer wall. For the helix, ball milling and 5 axis grinding were tested. In addition to the finish-machining, novel work holding and locating features were also explored. It was observed that the flexsplines warped significantly during heat treatment, and the average roundness value increased by three times during the solution annealing process. A major challenge with the large helix was the shrinkage during heat treatment and aligning the part with the machine's axis when ball milling/grinding. To aid in this process, a fiduciary feature in the form of a hexagon was used. Post finish machining, tolerances in the range of eighteen micrometres with a surface finish of 0.4 micrometres Ra was obtained.
Laser powder bed fusion, surface finish, thin-walled components, thermal stress, 5-axis grinding, cnc machining

1. Introduction

Additive manufacturing is becoming popular in a wide variety of applications since it can be used to produce complex parts with geometries that cannot always be produced using traditional methods. This could be due to several reasons such as cost (including one-off parts or prototypes), materials used, and suitability of certain geometries for machining [1]. For AM to achieve widespread utilization in a production setting, the precision of the parts being produced, and repeatability of critical dimensions is critical [2]. Complex parts, especially ones with non-uniform geometries like thin-walled components, or bulk parts with large volumes are highly susceptible to variations in shape and form due to factors such as thermal stresses and shrinkage during post processing [3]. While there are methods to predict the distortions and compensate for them, they are often computationally expensive, and require a lot of physical data about the process, which might not always be available [4]–[6]. One method to improve the precision of AM parts is to use 3D optical scan measurement data to calculate the distortion from the nominal geometry. This data can then be used to modify the model so that it assumes the desired shape when distorted [7]. In this study, we investigated a hybrid approach, where the parts are printed, and a 3D scan of the parts is obtained. Depending on the deviation of the parts from the nominal geometry, the parts are finish machined using either 5-axis milling, or grinding, or both, depending on the tolerance and surface finish requirements. A strain wave gear flexspline and a helical machine shaft were used as the thin walled and the large-volume part respectively.

2. Materials and Methods

2.1. Additive Manufacturing

The flexsplines were manufactured using laser powder bed fusion (LPBF) in a Concept Laser Mlab (General Electric, Boston, USA). The material used was 17-4 PH stainless steel with a powder size distribution of 15-45 micrometres. The parts were printed in an argon atmosphere with the concave surface facing up. A 1-mm skin was added to the downfacing surfaces to enable support removal and finish machining. Figure 1 shows an as printed flexspline before post processing.

The helical machine shaft was manufactured using 18Ni300 maraging steel in an EOS M280 under nitrogen atmosphere, using powder with a size distribution of 15 micrometres – 45 micrometres. A skin of 1 mm was added to the helical shaft to facilitate finish machining and grinding. Figure 2 shows a section of the helical shaft before post processing and finish machining.

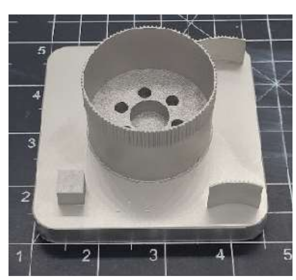


Figure 1. Photograph showing as printed flexspline on the build plate, along with metallurgical witness coupons. The ruler denotes inches.

Figure 2. Photograph showing a section of the helical shaft after printing. The hexagonal shape on the top was used for aligning the helical shaft during finish machining.

2.2. Scanning and Post Processing

The parts were scanned before and after stress relieving using a commercial scanner which uses a combination of structured light scanning and photogrammetry (Creaform HandyScan Black, Ametek, Berwyn, USA). The resulting point clouds were processed using VX Elements to obtain mesh files which were then used for all measurements and comparisons. Fiduciary stickers were used when necessary to improve scanning performance. A Zeiss DuraMax (Zeiss Group, Oberkochen, Germany) coordinate measuring machine (CMM) was also used for supplemental measurements using a 3 mm and an 8 mm diameter probe.

The flexsplines were solution annealed at a temperature of 1040°C for 30 minutes under argon and air cooled to room temperature. They were then hardened using H900 heat treatment, which involves holding the parts at 480°C for 1 hour under argon, and then air cooling to room temperature. To prevent oxidation of the walls during air cooling, the parts were wrapped in 304 stainless steel heat treatment foil.

The maraging steel helical shaft was vacuum annealed at 940°C for 2 hours and then cooled under vacuum to room temperature. The helical shaft was not hardened as it was not a design requirement for the part, and to make machining easier.

2.3. Finish Machining

For flexsplines with extra material on the inner wall, the flexsplines were machined using a Mazak Integrex i-100ST (Yamazaki Mazak Corporation, Oguchi, Japan) milling and turning centre while they were still on the build plate. The flexsplines were then cut off, and the bottom surfaces were turned to remove the support and obtain the final part. Expansion clamps were used to hold the flexsplines from the now machined inner wall.

To ensure precise positioning of the helical shaft, a temporary 60 mm hex was printed as a reference point since locating off the flutes was not feasible due to the geometry. Achieving an adequate surface roughness and reducing tool path calculation time were accomplished through a stepover of 10 micrometres. Additionally, pre-finishing process on a Mazak machine centre effectively removed an additional 250 micrometres of material, resulting in a substantial reduction in the required grinding time to achieve the desired final dimensions.

Additional tests were conducted on the Mazak machining centre to compare ball milling and single-point grinding. The objective was to assess geometric accuracy and surface roughness. The use of a Mill/Turn machining centre had the

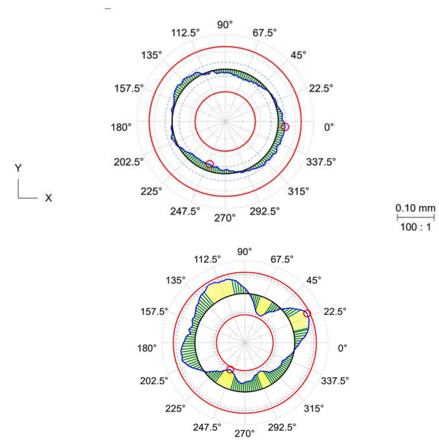


Figure 3. Colour maps showing the deviation of the flexspline from nominal before heat treatment (left) and after heat treatment (right).

potential to reduce manufacturing costs and consolidate processes in a single machine, subject to meeting the required tolerances [8]. A 10 mm 8-flute AlTiN ball endmill was employed for 3D surface milling, chosen based on its fit within the helical shaft's flute without causing material gouging. The selected coating and flute were optimized for high-speed steel milling. This same process, with an increased stepover, was used for pre-finishing the helical shaft prior to grinding. The finish milling of the helical shaft involved 50 micrometres step-over, preceded by a 250-micrometer step-over pass to eliminate 3D printing roughness.

3. Results

3.1. Flexspline

To determine the appropriate scaling factors in the X, Y and Z axes, two test builds were performed. The parts were measured on the CMM before and after heat treatment, and a shrinkage value of 1.0034 was obtained. Graph 1 shows the average diameter values taken at different heights at the three stages of the flexspline. The highest thermal distortion was observed after solution annealing, which could be attributed to the high cooling rates during air quenching and the residual stresses from the printing process causing the thin walls to warp. However, the level of warping seen in the cup was deemed non-critical for the required application. Figure 3 shows heatmaps of a before and after heat treatment. Figure 4 shows roundness of the flexsplines before and after heat treatment. The average roundness value of the flexspline increased from 0.051 ± 0.012 mm to 0.129 ± 0.036 mm after heat treatment.

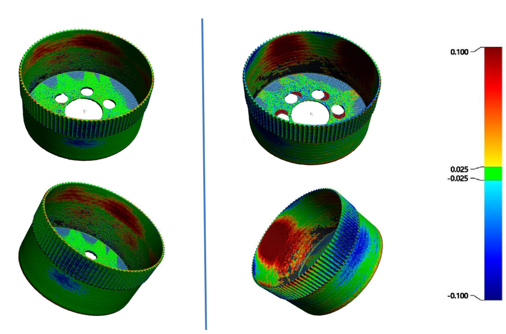
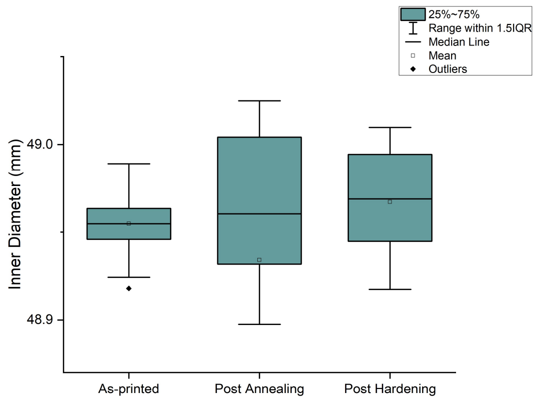


Figure 4. CMM scans showing the roundness of the flexspline before heat treatment (top) and after heat treatment (bottom). The scale bar denotes ±0.1 mm and the tolerance band is ±0.025 mm.



Graph 1. Box plot showing the change in the value of the internal diameter of the flexspline between the different heat treatment steps. The increase in diameter is caused by the wall shrinking during heat treat.

3.2 Helical shaft

Figure 5 shows heatmaps of the scanned helical shaft compared to the nominal geometry before and after finish machining. By comparing the shaft after heat treatment to the nominal, a scaling factor of 1.0028 was obtained. To avoid additional complications, the helical shaft was machined using a 3-axis toolpath, with the helical shaft rotating in the spindle and a milling head following the contour of the individual lobe sections. A clear difference can be seen between the inner root section of the lobes and the outer section, which might have been caused by the way the tool engaged when milling, with the edge of the tool engaging in the inner portions, as opposed to a tangential engagement with the radius of the ball nose endmill in the outer portions. This resulted in the outer portions of the helical shaft being smaller than the desired geometry. The surface roughness of the final helical shaft was 0.3 micrometre Ra measured perpendicular to the milling direction. To process an entire helical shaft using a 50-micrometre step over, the machine required 8 hours and 32 minutes and was purely limited by spindle speed. Although we were not able to get a full griding timed results, predictions show that a full helical shaft would have taken upwards of 32-48 hours.

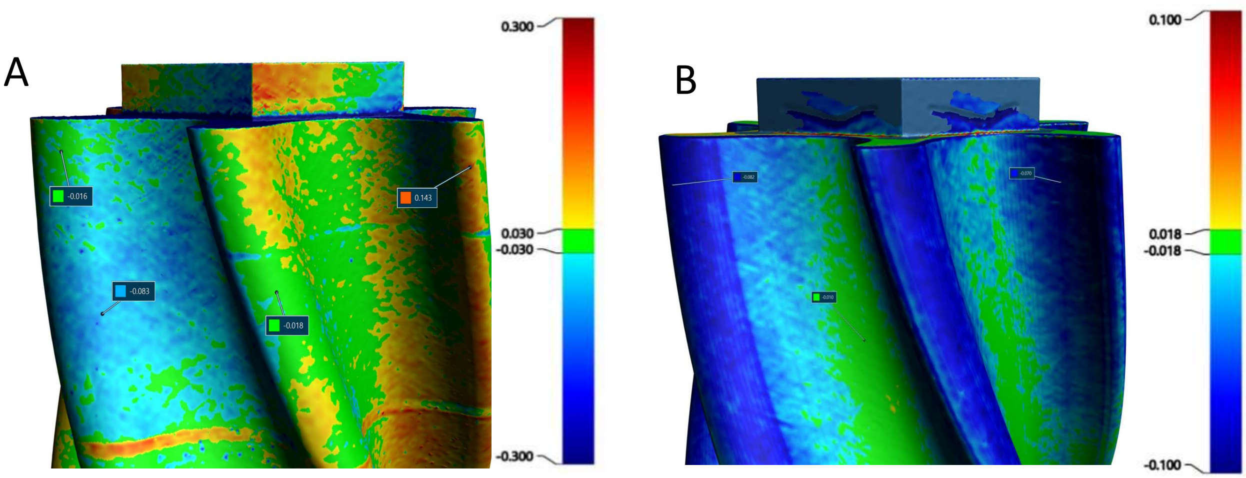


Figure 5. Heatmaps showing the deviation of the helical shaft geometry from nominal: (A) As printed (B) After final machining. Note the difference between scale bars.

4. Conclusion

In this study, we looked at manufacturing two high precision parts with different characteristics using a combination of LPBF and finish machining. For the thin-walled component, the biggest issue was thermal warping, which was not uniform across various samples of the same geometry, making it hard to compensate for. Adding additional material to the critical features and machining them later helped improve the accuracy. However, this might not always be possible. In the future, using the scan data to modify the geometry such that the gears deform into the nominal geometry will be explored.
The biggest issue with the helical shaft was shrinkage of the bulk geometry and machining the complex cross sections. To reduce the number of axes moving in the machine to increase accuracy, a simple 3-axis rotary style tool path was chosen to process the helical shafts. A 5-axis tool path may have produced improved finishes by tilting the cutting edge but may have induced more inaccurate than the 18-micrometre tolerance would have allowed. Further research could compare various CAM packages and cutting tools to see the variation in accuracy. A visual scallop could be seen on the surface of the part but cannot be felt of measured with our instrumentation. A smaller tool and step over could assist in reducing this but would result in longer machine time. Additionally, clear marks can be seen in the part from the direction the tool was traveling. If the tool was traveling along the flute of the helical shaft, this could have been reduced. Our machine was very limited by spindle speed at only 12,000 RPM. 40,000 RPM would be much more appropriate and would produce an improved surface finish in addition to reduced machine time [9].

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