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Modification using magnetic field-assisted finishing of the surface roughness and residual stress of additively manufactured components

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ABSTRACT

The choice of the sequence of manufacturing processes is a key aspect of smart manufacturing. It can determine the surface functions of the finished component, and it can revolutionize the way things are made. The focus of this paper is the post-processing—a combination of sanding, polishing, and burnishing—of 316L steel components made using selective laser melting (SLM). The integrity of the surface (including surface defects) is influenced by post-process conditions as well as the sequence of post-processes, which perform functions such as eliminating surface defects generated during SLM, altering the surface roughness, and imparting compressive residual stress.

1. Introduction

Additive manufacturing (AM) produces components by depositing material instead of subtracting or deforming material. AM technologies have been advanced since the 1980s, and they have broken out of the traditional manufacturing paradigm, especially the manufacturing of complex components in small batches [1,2]. Selective laser melting (SLM) is one of the most versatile AM processes, and it enables the production of components by binding powders such as polymers, metals, ceramics, and mixtures of these materials. Components made using SLM have applications in a wide variety of industrial areas including aerospace, automotive, biomedical engineering, etc. [3].

The powder-consolidation mechanism in SLM influences the mechanical properties, surface morphology, and surface integrity (e.g., hardness and residual stress) of products and the corresponding product functions [4]. For example, porosity, balling, cracks, and tensile residual stress are inherent in metal parts produced with SLM [5–8]. Defects common to SLM-produced components also include irregular surface morphology, distortion, geometrical inaccuracy, etc. [9–12]. Development of appropriate post-SLM processes, such as heat treatment and machining processes, plays an important role in minimizing these defects and maximizing the component performance [9,10,13,14].

Researchers have demonstrated the versatility of magnetic field-assisted finishing (MAF) and its ability to process complex geometries in various machining regimes by altering the magnetic tools. While use of magnetic abrasive or a mixture of magnetic particles and abrasive slurry results in loose-abrasive processing [15–17], use of an abrasive-coated magnetic tool results in fixed-abrasive processing [18]. Furthermore, use of magnetic pins causes plastic deformation of the surface in burnishing or peening processes [19]. Accordingly, by simply changing the magnetic tools, use of MAF enables the examination of the effects of the machining regime on the surface integrity of the SLM-processed components.

This paper presents post-processes—a combination of sanding, polishing, and burnishing by means of MAF—that alter the surface roughness and residual stress of 316L stainless steel components made using SLM. Firstly, the surface made using SLM and the modification of surface roughness are discussed. Secondly, the modification of tensile residual stress induced by SLM to compressive residual stress will be discussed, highlighting the directionality of the residual stresses.

2. Components made using selective laser melting

Fig. 1 shows a schematic of the selective laser melting process. An Yb:YAG laser with a power of 200 W within a diameter of 150 μm is applied to the 316L stainless steel powder bed. The laser scanning speed, hatch spacing, and layer thickness are 800 mm/s, 105 μm, and 30 μm, respectively. The laser-scanning direction, laser traverse direction, and part build direction are designated as the +*x*, +*y*, and +*z* directions, respectively, as shown in Fig. 1.

A photograph of a representative part (25 mm diameter, 6.7 mm thick) used in this study is included in Fig. 1. The as-built surface roughnesses *Rz* and *Ra*, measured with a stylus surface roughness tester (evaluation length: 8 mm), are in the ranges 58–130 μm and 7–17 μm, respectively. The large variations of the roughness values are due to the powder consolidation during SLM.

Residual stress analysis was conducted using an x-ray diffractometer. A Mn x-ray tube with a wavelength of 0.21 nm was used with a Cr filter. The diffracting plane selected for the stress analysis was {311}, and measurements were made assuming

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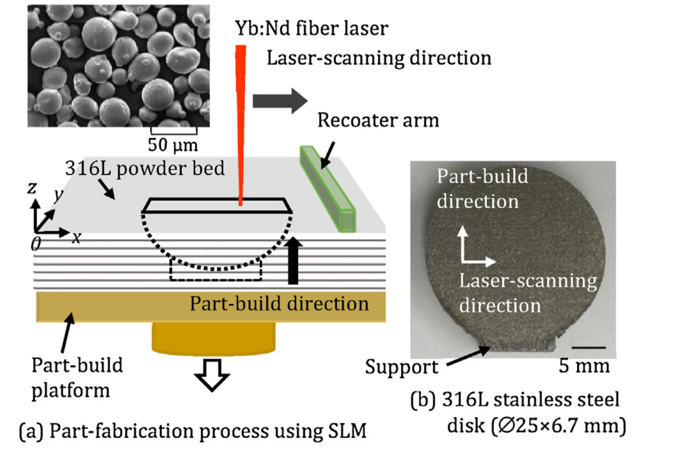


Fig. 1. Schematic of part-fabrication process using SLM and representative part.

plane stress. The residual stresses in the laser-scanning (x) direction and part-build (z) direction at the center of the surface of a representative part were measured as 206 ± 27 MPa and 45 ± 27 MPa, respectively.

3. Polishing and burnishing using MAF

Fig. 2 shows a schematic of MAF using a magnetic particle brush consisting of either (a) mixture of magnetic particles and abrasive slurry or (b) balls. The particle brush presses against the target surface when in a magnetic field generated by the magnets. Rotating the magnet generates relative motion between the particle brush and the target surface. In the case of Fig. 2(a), the surface roughness is altered as the abrasive is pressed by the magnetic particles and removes material from the target surface.

Ball burnishing is known to modify the surface geometry as well as impart compressive residual stress at the processed surface [20]. In the case of Fig. 2(b), the balls facilitate surface material flow and plastic deformation. This alters the surface texture and subsurface structure, which corresponds to the residual stress.

In this study, three 25.4 mm diameter, 12.7 mm thick Nd–Fe–B magnets are attached to the main spindle of a 5-axis high-speed machining center. The main spindle rotates at 600 min^{-1}, and the circular motion is offset by 5 mm. This creates an epitrochoidal motion of the particle brush, resulting in polishing of the entire target surface. In the case with balls, an additional steel pole tip is attached to the Nd–Fe–B magnet. The major role of the steel pole tip is to prevent the magnet from cracking due to the pressure conveyed by the balls. Hereafter, the methods of Fig. 2(a) and (b) will be referred to as *magnetic field-assisted polishing* (MAP) and *magnetic field-assisted burnishing* (MAB), respectively.

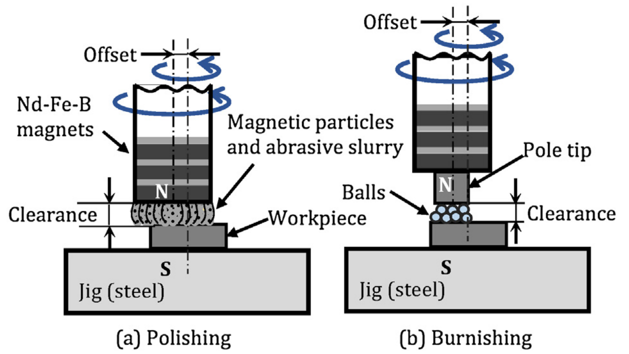
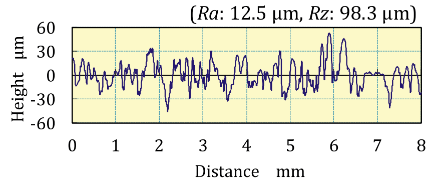


Fig. 2. Schematics of magnetic field-assisted finishing processes.

Table 1
Experimental conditions.

Conditions	A	B	C
Magnetic particles	G14 steel grit: 6 g	G25 steel grit: 4 g	−50/+100 mesh iron particles: 4 g
Magnetic abrasive	80 μm mean diameter (Alumina abrasive <10 μm) 1.5 g	1 g	1 g
Diamond abrasive	120 μm mean size		N/A
Clearance	3 mm	2 mm	
Magnet	Nd–Fe–B magnet (ϕ25.4 × 12.7 mm)		
Magnet revolution	600 min^{-1}		
Magnet feed	Circular motion (5 mm offset, 1 mm/s feed rate)		
Workpiece	ϕ25 × 6.7 mm 316L stainless steel disk 		
Lubricant	Soluble-type barreling compound		

4. Modification of surface roughness using MAP

Table 1 shows the experimental conditions. The roughness Rz of surfaces generated using SLM often exceeds 100 μm, and the roughness profiles consist of hard protrusions due to the powder consolidation during SLM. Large magnetic particles (which are unable to penetrate the surface topography past the peaks) are required to selectively remove materials from the peaks of the target surface to smoothen the surface. The surface finishing process was designed with three phases: course (Condition A), medium (Condition B), and fine polishing (Condition C). For the course polishing, G14 (1.4 mm) steel grit mixed with magnetic abrasive (80 μm mean diameter) and 100–125 μm diamond abrasive were used to remove the initial surface layer. The surface roughness Rz was measured in five places using a stylus roughness tester. Once the surfaces became smooth, the surface roughness Sz was evaluated using an optical profiler. The material removal was obtained as the change in weight before and after finishing measured with a micro-balance (0.01 mg resolution).

Fig. 3 shows a representative case of the changes in the surface roughness Rz and material removal with processing time. The

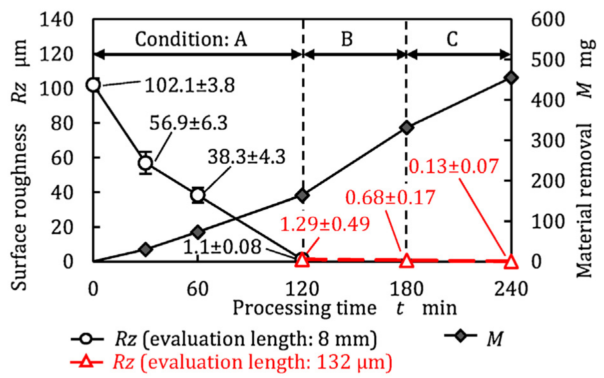


Fig. 3. Changes in surface roughness and material removal with processing time.

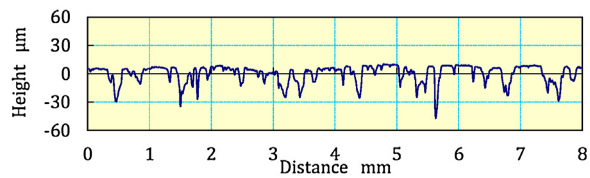


Fig. 4. Roughness profile of the surface finished for 60 min under Condition A (Ra: 7.35 μm, Rz: 57.4 μm).