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Residual stress modification and surface enhancement of PBF-LB/M components via particle blasting and plasma electrolytic polishing

Neel Kamal Gupta[1]*, Toni Böttger[1], Christian Schimpf[2], Henning Zeidler[1]

[1]*Institute for Machine Elements, Engineering Design and Manufacturing (IMKF), Technische Universität Bergakademie Freiberg, Freiberg, Germany*
[2]*Faculty for Materials Science and Materials Technology, Technische Universität Bergakademie Freiberg, Freiberg, Germany*

**Corresponding Author: neel.gupta@imkf.tu-freiberg.de*

Abstract

Powder Bed Fusion – Laser Beam/Metals (PBF-LB/M) is one of the most versatile additive manufacturing techniques for fabricating complex metal geometries with high design freedom. Despite these advantages, components produced via PBF-LB/M typically exhibit significant tensile residual stresses due to rapid melting and solidification, along with a poor surface finish caused by partially fused particles and surface irregularities. These drawbacks not only limit the fatigue life of the component but also necessitate additional post-processing steps to achieve functional performance. Plasma electrolytic polishing (PEP) has emerged as a promising surface finishing technique for PBF-LB/M parts, providing a substantial reduction in surface roughness while imparting a glossy appearance. However, prior to PEP, particle blasting serves as an essential intermediate treatment. Particle blasting not only reduces the initial roughness and oxide layer on the as-built surface but also effectively relieves tensile residual stresses by converting them into a more desirable compressive state. This transition is critical for enhancing the mechanical reliability and longevity of the manufactured components.

In this study, the influence of particle blasting on PBF-LB/M components is systematically investigated. The results show that residual stresses, which are heterogeneous and tensile in the as-built state, become uniform and compressive after particle blasting. Furthermore, the treatment removes loosely adhered particles and surface asperities, creating a stable foundation for subsequent polishing. When followed by PEP, a substantial improvement in surface finish is achieved, confirming that particle blasting acts as a crucial bridging step between printing and final functional deployment of PBF-LB/M components.

Keywords: Additive Manufacturing, Particle Blasting, Plasma Electrolytic Polishing, Residual Stresses, Surface Finish.

1. Introduction

Additive manufacturing (AM) has evolved from prototyping to direct functional components since its commercialisation in the late 1980s. According to ASTM ISO standards, there are seven classes of AM [1], which can be applied to a wide variety of materials. Directed energy deposition (DED) and powder bed fusion (PBF) are the two most popular classes of AM for metallic components, with each having its benefits and challenges [2]. DED provides a high deposition rate but induces significant residual stress, which affects component usage and requires machining as a necessary step for dimensional accuracy [3-4]. In contrast, powder bed fusion of metals using laser beam (PBF-LB/M) has a lower deposition rate, yet produces high-quality parts suitable for many applications, requiring minimal machining for high-precision features [2]. However, the surface finish of such components is critical and requires post-processing to enhance their properties. Various mechanical and chemical processes exist to enhance surface quality, and in most cases, mechanical-based processes are inferior due to the complexity of the components, making chemical-based processes the preferred option. Electrochemical-based post-processing is one of the available options; however, due to its hazardous operation involving corrosive and toxic acids, which are also non-recyclable [5], plasma electrolytic polishing (PEP) is a more suitable alternative. PEP offers faster processing with environmentally friendly, chemically neutral, non-toxic water-based electrolytes [6-7].

Residual stresses have always been seen to be critical for metal AM due to repeated heating and cooling cycles, and exhibit tensile residual stress on the surface, which also affects the fatigue life of the components. Compressive stress, achieved through various mechanical operations, is thus required to remove the locked-in residual stress from the components. Hammering/peening is commonly used for DED components [8], while particle blasting (PB) is suitable for small to medium-sized components, making it a suitable choice for PBF components [2].

This study focuses on the effect of PB on PBF-LB/M components, with a particular emphasis on the residual stress behaviour of both as-built and particle-blasted components. The effect of PB on surface roughness has also been studied, as the impact of the particle alters both residual stress modification and initial roughness, making PEP a more efficient process and reducing the surface roughness.

2. Materials and methods

The materials used in this study were pure aluminium and stainless steel of grade SS 316L. Aluminium samples were used to fabricate the test samples at different angles, as shown in Figure 1. The parameters used for sample preparation were: laser power, 370 W; layer thickness, 0.04 mm; hatch distance, 0.14 mm; and scanning speed, 1300 mm/s. These samples were treated with particle blasting, which has a planetary motion-based setup and a mixture of spherical and irregular stainless-steel particles. The speed for blasting varied from 9000 (maximum) to 4000 (minimum) RPM, with a maximum time of

30 minutes at maximum speed, followed by 5 minutes at each reducing speed from 8000 to 4000 with an interval of 1000 RPM.

These samples were studied for the residual stresses in both the as-built and post-PB conditions. The residual stress measurement was conducted on an X-ray diffraction-based setup with the following parameters: Wavelength, Cu 1.54056 Å; two-theta angle, 114.5°; and beam optics, 2 mm point focus. Further, another test specimen was fabricated using SS 316 material with the following parameters: laser power, 230 W; layer thickness, 0.04 mm; hatch distance, 0.11 mm; and scanning speed, 900 mm/s. These samples were sufficiently large to conduct surface roughness measurements, as the larger surface area provides minimal chances of error. The residual stress and surface roughness measurements were conducted on the top surface. PEP was performed on a bath-based, 80kVA high-voltage setup; a schematic representation is shown in Figure 2. The surface roughness measurement was conducted using Mahr, Marsurf CM explorer microscope with Mountains version 11 as the user interface.

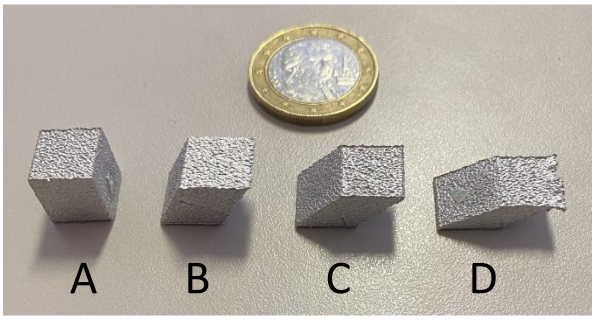

Figure 1. Aluminium samples for residual stress analysis

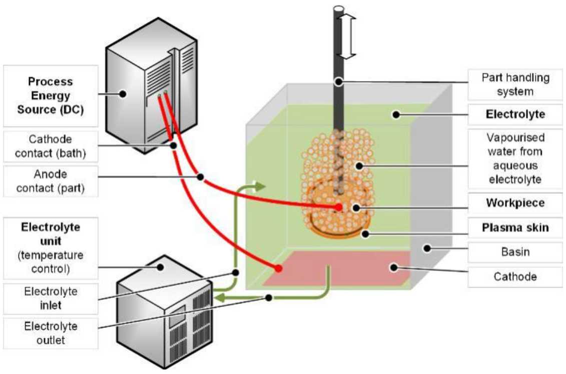

Figure 1. Schematic representation of PEP setup [6]

3. Results and discussion

The residual stress values measured on the top surface are presented in Table 1. It can be observed that in the as-built condition, the residual stress is tensile in nature and after particle blasting, the nature of stress is compressive due to the application of compressive loading during particle blasting.

Table 1: Residual stress values for each sample on the top surface

Samples	Residual Stress (in MPa)			
	As built		After PB	
	σ_{xx}	σ_{yy}	σ_{xx}	σ_{yy}
A	51	48	-34	-39
B	48	42	-42	-52
C	40	39	-45	-45
D	42	41	-35	-35

This was the basis for further experiments, which demonstrated that particle blasting helps reduce tensile residual stress. For further analysis, the samples were treated with particle blasting before undergoing PEP for surface enhancement. PEP parameters were optimised by varying different factors at various levels. Furthermore, the optimised parameters were used to conduct the tests, and three steel samples were tested for their roughness values at three different stages: as-built, after particle blasting, and after PEP. The Surface roughness was considered for measurement as it covers a wide area and is not direction-dependent, unlike the case of line roughness, and presents a better surface morphology. Within surface roughness, S_q (root mean square) values were studied, as Sq is more sensitive to peaks and valleys than Sa (arithmetic mean). The average surface roughness for three samples was reported as 13.7 µm in as-built conditions, 7.5 µm after particle blasting, and 2.7 µm after PEP. A clear indication of particle blasting states that, apart from residual stress relaxation, significant changes in roughness values were observed from 13.7 to 7.5 µm. Furthermore, polishing the particle-blasted sample results in lowering the roughness to 2.7 µm. As PEP is an effective method for reducing surface roughness, its effectiveness is reflected in the results, with the addition of PB leading to further enhancement of efficiency.

4. Conclusions and future scope

PB effectively eliminates tensile residual stresses and promotes the formation of a more uniform compressive residual stress state through the application of compressive loading by bombarding particles. This process further reduces the initial surface roughness by removing partially sintered powder and mitigating surface features associated with the lack of remelting. PEP is recognised as an effective surface enhancement technique, and the results demonstrate that integrating PB further improves the efficiency of the PEP process. Furthermore, additional experiments with varying parameters are planned to further investigate potential improvements in residual stress and surface roughness.

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