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On the effect of post-processing techniques of the additively manufactured aluminum alloy parts

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Abstract. Additive manufacturing (AM) or 3D printing of metals promises a significant impact on the upcoming industrial revolution "Industry 4.0" as it is considered one of its main pillars. However, some challenges related to high initial cost and the fabricated part's quality still existed. Selective laser melting (SLM) is one of the effective techniques used for additive manufacturing to fabricate metal products. This paper presents the impact of different post-processing treatments on the microstructure and surface quality of the AlSi10Mg parts fabricated using SLM. This work illustrates the analytical view of the results obtained from two studies in a previous work by the author. A process map is presented for thermal post-processing treatment to customize the required quality and material characteristics of the AlSi10Mg parts. In addition, the shot peening results in a significant improvement for both surface roughness and hardness is illustrated. This work is a part of developing the manufacturing process of additively manufactured lightweight parts in some critical applications specifically for the metallic mirrors used in high power laser systems or wide view space telescopes.

1. Introduction

The upcoming industrial revolution known as Industry 4.0 paves a new road for advanced manufacturing. Industry 4.0 is powered by the current development in some fields, such as additive manufacturing (also known as 3D printing), autonomous robots, predictive maintenance and analytics, software integration, and cybersecurity [1]. Additive manufacturing of metals offers a variety of solutions to reduce current design and manufacturing limitations and therefore will improve part performance and customization [2].

Selective laser melting (SLM) is one of the commonly used techniques for additive manufacturing of metals, using a laser beam to melt layer-by-layer according to the generated slices from the 3D CAD model [3]. This technique can provide near-net shape objects compared to subtractive manufacturing (CNC machining), and thus will have a significant impact on workpiece development. SLM can also be used to produce efficient tools for forming and die casting technologies.

Additive manufacturing of aluminum (Al) alloys presents the production of efficient, flexibly designed, and lightweight parts using the SLM technique [4]. However, some challenges to widen SLM applications, such as obtaining consistent material properties, improving the quality of fabricated parts, and reducing their production cost, are active research issues [5]. SLM of these alloys promises a significant performance enhancement of the lightweight critical components used in different space and aerospace applications such as metallic optics and optomechanical components used for high energy laser systems [6]. However, the surface and inside defects of the additively manufactured parts present a challenge to product quality requirements.

Literature studies evaluated the SLM process parameters' impact to fabricate high quality parts. Galy et al. addressed most defects obtained from the aluminum (Al) alloy parts fabricated by SLM [5]. The selection of the SLM process parameters, such as energy density, power of laser beam, speed of laser scanning, the thickness of powder layer could affect the quality of the as-built parts [7]. Various studies in the literature presented a process optimization to improve the mechanical properties of the as-built products. Read et al. studied the impact of the SLM process parameters on the mechanical properties of AlSi10Mg parts [8]. Maamoun et al. presented a comprehensive study that illustrated the impact of the process parameters on different performance characteristics such as mechanical properties, microstructure, surface roughness, relative density, and dimensional accuracy [9,10]. Their study developed a process map that investigated the optimum process parameter range to reach the required quality of parts produced. However, higher requirements of some performance characteristics for specific AlSi10Mg products are still needed. Consequently, the post-processing of SLM produced Al alloy parts becomes an essential step to improve the microstructure characteristics and to reduce the as-built defects.

According to ASTM F3301−18, post-processing for the additively manufactured parts is a treatment that could be applied after the AM process to achieve the desired material properties or surface finish to satisfy the engineering requirements. Post-processing techniques for additively manufactured parts can be divided into surface quality improvement and elimination of the internal microstructure defects. Shot peening (SP), laser shock peening (LSP), polishing, or chemical treatment processes can be implemented to improve the surface roughness of the final product [11–16]. Thermal post-processing and friction stir processing could be applied to control the microstructure and mechanical characteristics of the fabricated parts [17,18].

The current paper presented the impact of different post-processing techniques on both surface and microstructure characteristics of the SLMed AlSi10Mg parts. A guideline for selecting the optimum post-processing technique along with the desired quality is also discussed.

2. Materials and methods

A gas atomized EOS AlSi10Mg powder was used. The powder was characterized according to ASTM F3049-14 [19]. An energy X-ray dispersive Spectroscopy (EDS) test was performed to investigate the chemical composition of the selected powder. Powder particle shape was detected using a Scanning Electron Microscope (SEM). A laser diffraction test was used to estimate the powder size distribution (PSD) by dispersing the powder in water.

The machine used for SLM to fabricate the AlSi10Mg parts is EOSINT M290 where the laser power reaches up to 400 W. The processing parameters are presented in table 1.

Table 1. The parameters used for the SLM process to fabricate AlSi10Mg samples.

Power of Laser (W)	Laser Scan speed (mm/s)	Distance of hatch spacing (mm)	Angle of Layer orientation (˚)	powder Layer thickness (µm)	Strategy of scan
370	1300	0.19	67	30	Stripes

The impact of thermal post-processing was investigated through three heat treatment processes by applying different heat treatment conditions. The annealing process was conducted at 200 and 300˚C. Solution heat treatment (SHT) was applied to the as-built samples at 530˚C that is held for 1 and 5 hours. T6 heat treatment was conducted on the solution heat treated samples by water quenching followed by artificial aging at 160˚C for 11 hours. Each heat treatment process parameter was performed on three samples.

Shot peening was conducted on the top surface of the AlSi10Mg samples using a 19 mm diameter single nozzle of a Lance machine. Almen intensity was detected for the AlSi10Mg sample surface which was bombarded by glass beads. A high-intensity SP 20.3 N was applied using glass beads standard of Gp50. The shot peened sample surface was covered using coverage a 200% factor to increase the area of the peened surface. A 152 mm distance was adjusted from the nozzle to the sample surface using an impact angle of 90-degree.

The surface integrity of the SP surfaces was investigated using an Alicona optical microscope. The surface roughness and waviness of the selected areas were investigated.

A 10 × 10 mm measured area was selected on the top of each sample using a lens of 10X magnification. The microstructure characterization was performed along the building direction cross-section using wire-cut samples. The procedures of polishing and etching were selected as recommended by Maamoun et al. [17].

Image analysis of samples' microstructure was tested by Nikon Microscope and SEM. A Clemex micro-hardness instrument was used to investigate the hardness of the samples before and after applying post-processing. The micro-hardness values were obtained at 200 gf load and were calculated from the average of 10 measurements conducted on each sample.

An in-situ tracking of phase change was conducted using XRD along with variable temperatures of SHT conditions. A DHS 900 domed hot stage was used to perform the XRD experiment. The sample was heated inside the domed stage under vacuum to temperatures of 30, 100, 200, 300, 400, and 530°C.

3. Results and discussion

The characteristics of the gas atomized AlSi10Mg powder were obtained according to ASTM F3049-14 as shown in Figure.1. The particle size distribution shows that the size of powder particles ranges from 2 to 80 µm as illustrated in Figure.1 (a). Spherical particle shape was determined for different particles' sizes using SEM as presented in Figure.1 (b). The spherical shape of the AlSi10Mg powder could result in a higher relative density and improve the flowability of powder compared to the irregular powder shape [20]. The chemical composition of the fresh powder used was detected using EDS analysis, the weight % of elements is listed in table 2.

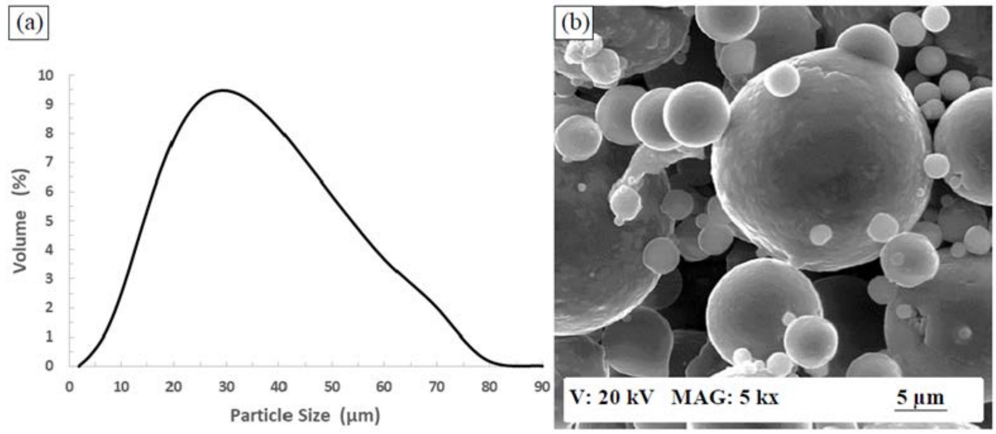

Figure 1. AlSi10Mg powder characteristics; a) particle size distribution, b) Powder morphology.

Table 2. The chemical analysis (wt. %) obtained from the AlSi10Mg powder using EDS.

Si	Mg	Fe	Cu	Sn	Pb	Zn	Al
10.6	0.36	0.4	0.09	0.06	0.06	0.05	Balance

Figure. 2 shows the images obtained by the optical microscope for the as-built AlSi10Mg etched samples along the building direction (Z-direction), the parallel plane to the layers (X-Y plane).

These images illustrate the melt pool shape obtained after the material solidified. Figure. 2 (a) shows that the melt pool shape is affected by the Gaussian shape of the laser beam through the formation of the semi-elliptical melt pool shape.

The laser scan pattern is clearly appeared in Figure.2 (b) where the intersection angle between the melt pool shapes represents the orientation angle between the building layers. Figure. 2 confirms the microstructure inhomogeneity of the additively manufactured AlSi10Mg samples.

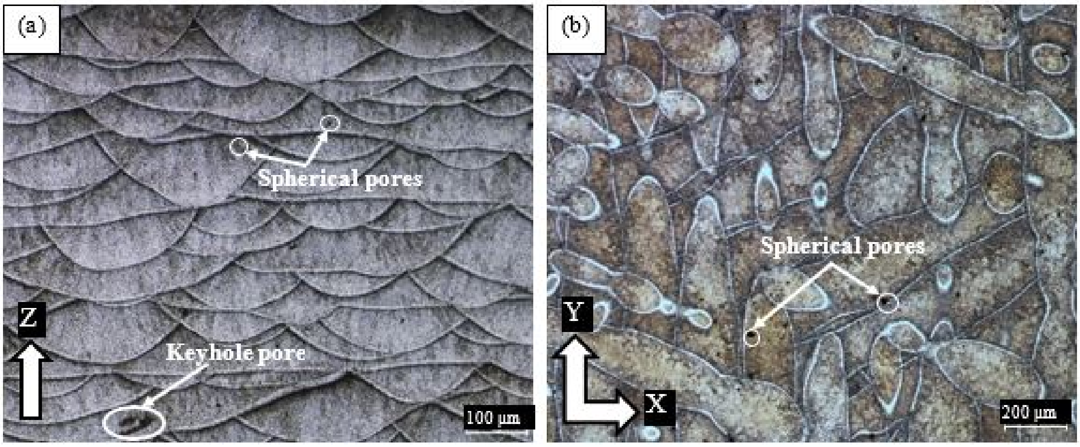

Figure 2. The as-built AlSi10Mg microstructure images: a) along Z-direction (building direction), b) through the x-y plane (the parallel plane to deposited layers) [17].

The observations of the defects above the upper surface of the additively manufactured sample are demonstrated in Figure.3 (a). These main defects are represented in the effect of balling phenomena Figure.3 (b), unmelted powder particles Figure3. (c), the effect of laser scan tracks Figure.3 (d), and the open pores on the sample surface Figure.3 (e).

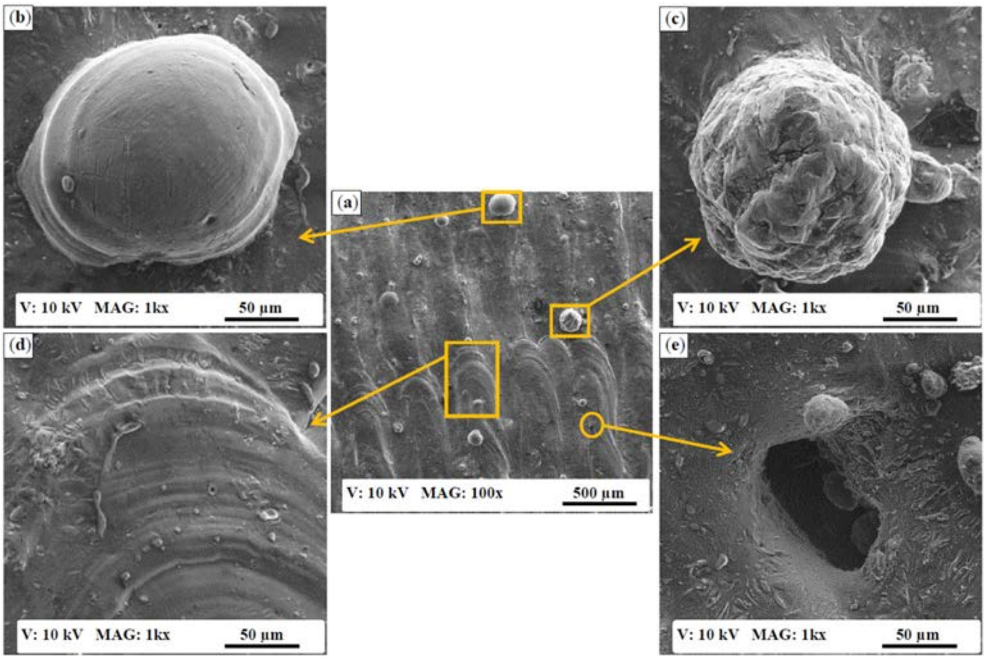

Figure 3. The surface defects observed on the top surface of the as-built AlSi10Mg samples; a) balling, b) partially or unmelted powder particle, c) laser scanning track effect, d) open pore on the sample surface [11].

The SLM process parameters used are the optimized process parameters as presented in the most recent studies [9,10]. However, inhomogeneity of the microstructure and surface defect still exists. The post-processing of the as-built parts becomes necessary to achieve the desired part quality for some critical applications.

Thermal post-processing affects the microstructure of the as-built parts related to the applied parameters as shown in Figure.4. The developed map shows that the microstructure homogeneity can be obtained using SHT or T6 HT. The microhardness gradually decreased after annealing up to 50% after SHT due to the decomposition of the Si network structure characterizes the as-built microstructure. However, the microhardness increased after the T6 treatment reaching almost the microhardness values obtained from the additively manufactured parts.

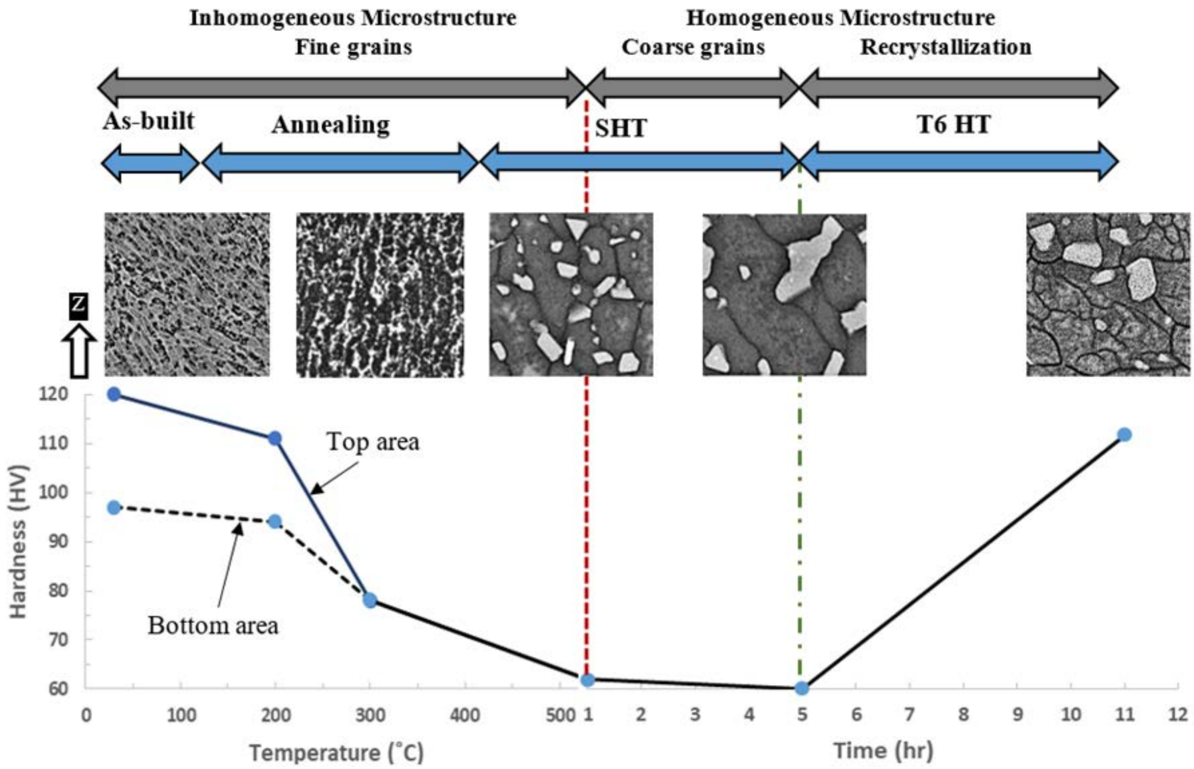

Figure 4. Microhardness map illustrating the impact of heat treatment post-processing on the microstructure along the building direction cross-section of the AlSi10Mg fabricated samples [17].

Figure.5 shows the XRD analysis of the in-situ phase change tracking under variable SHT conditions. The results illustrate that no phase change was obtained under the applied temperatures. The obtained results validate the Al and Si grain size change that was significantly obvious in the process map presented in Figure.4. In addition, the peak broadening of Al and Si increase along with the increase of temperature confirms the gradual decrease of microhardness values illustrated in Figure.4 [21].

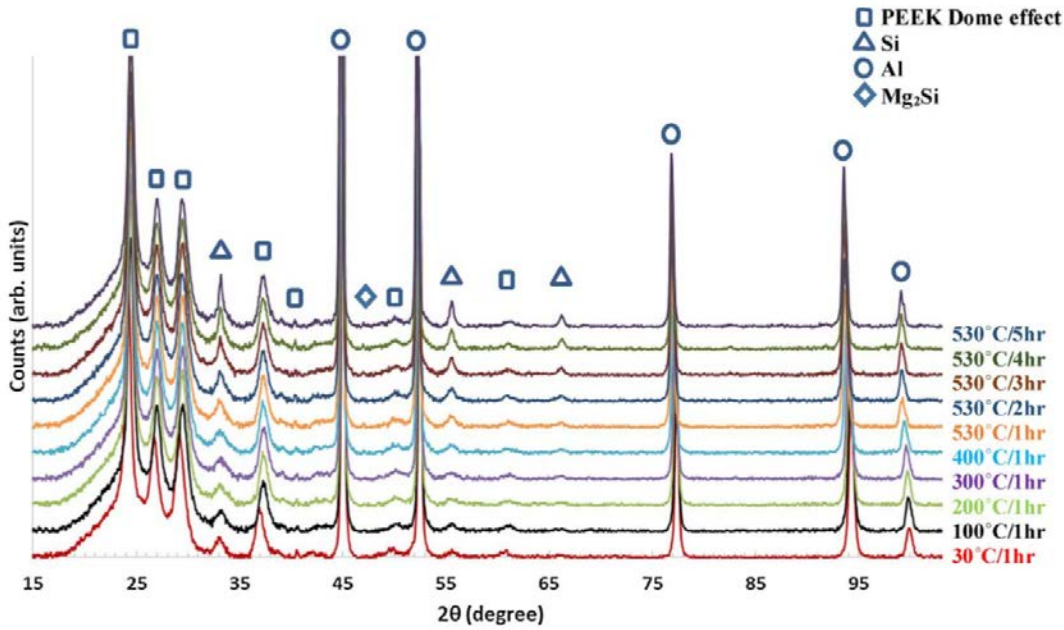

Figure 5. In-situ XRD phase pattern of the AlSi10Mg sample through variable SHT temperatures.

The shot peening significantly improves the as-built surface characteristics as illustrated in Figure.6. Thus was obtained due to the uniform pattern of the Gp165 glass beads applied at 200% surface covering factor using the optimized Almen intensity of 22.9A.

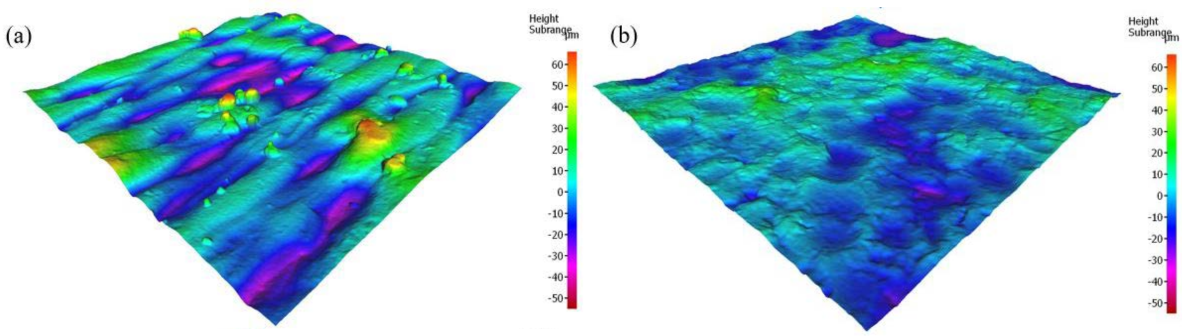

Figure 6. The surface texture of the AlSi10Mg sample; a) additively manufactured, b) shot peened.

Surface hardening and highly compressive stresses were investigated. SP generated severe plastic deformation on the sample surface which results in high compressive stresses. Figure.7 illustrates the surface hardening of the shot-peened area which extends into a depth of 500 µm from the sample surface.

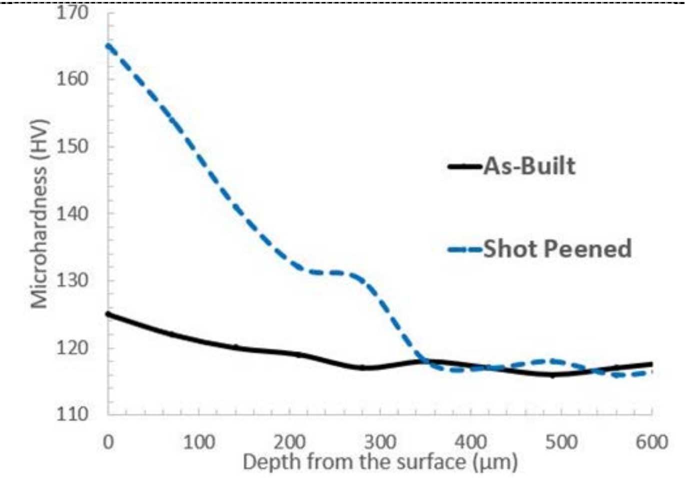

Figure 7. The microhardness profile in depth from the surface of the AlSi10Mg sample before and after SP.

Figure 8 shows that SP significantly results in high stresses. The high compressive residual stresses generated could lead to enhance mechanical properties and fatigue strength.

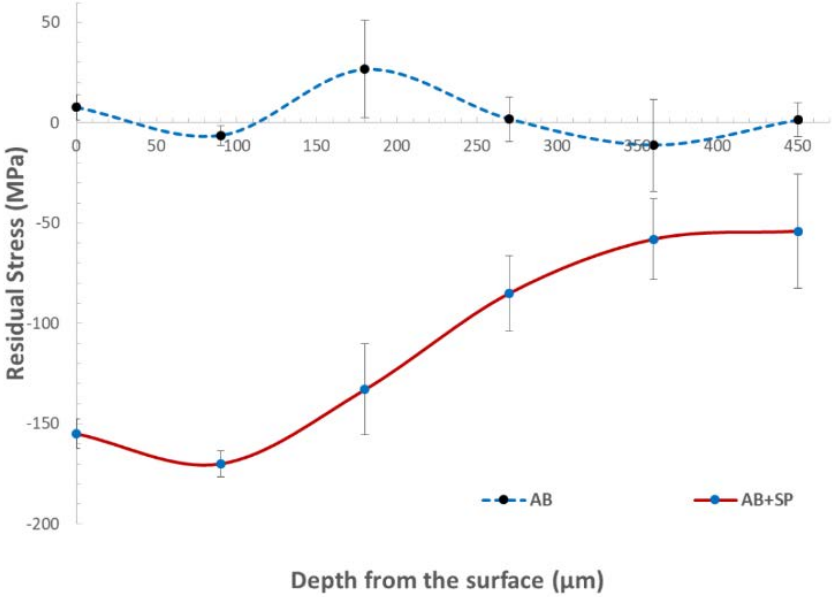

Figure 8. The residual stress profile along the cross-section of the shot peened and as-built AlSi10Mg samples [11].

4. Summary and conclusion

The current study shows the impact of different post-processing treatments for the additively manufactured AlSi10Mg parts fabricated by SLM. It was found that post-processing treatment is considered an essential step to solve the issues of microstructure inhomogeneity and to improve the as-built surface quality by reducing the defects obtained. AlSi10Mg powder was characterized according to ASTM F3049-14; then the parts were fabricated according to the optimized SLM parameters obtained by the authors from another study. The results can be summarized as follows:

- Microstructure inhomogeneity of the additively manufactured parts was illustrated through different areas and orientations. An anisotropic material structure could be obtained due to this microstructure inhomogeneity.
- The defects obtained on the as-built part surface were characterized.

- Heat treatment of solution heat treatment at 530 ˚C and T6 treatment eliminates the microstructure inhomogeneity obtained from the as-built AlSi10Mg parts.
- SHT also increases the ductility and improves the microstructure homogeneity. The microhardness was reduced by 50% compared to the values measured from the SLMed conditions. However, T6 HT resulted in a higher rate of microhardness with a homogenous and refined microstructure.
- A microhardness map was developed through different heat treatment conditions to assist in satisfying the design requirements of the desired part characteristics. The trend obtained from this map was validated using the in-situ XRD tracking of the phase change along SHT.
- SP eliminates the defects on the top of the peened surface of as-built parts and improves the shot-peened surface roughness.
- After SP, surface hardening was achieved along with generating high in-depth compressive stress up to 500 µm from the sample surface. Thus could improve the mechanical properties and of the processed parts.

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