The effect of SLM process parameters on density, hardness, tensile strength and surface quality of Ti-6Al-4V

AmirMahyar Khorasani\textsuperscript{a,b,\textsuperscript{*}}, Ian Gibson\textsuperscript{d}, Umar Shafique Awan\textsuperscript{a}, Alireza Ghaderi\textsuperscript{c}

\textsuperscript{a} School of Engineering, Deakin University, Waurn Ponds, Victoria, Australia
\textsuperscript{b} Department of Mechanics of Solids, Surfaces & Systems, Faculty of Engineering Technology, University of Twente, Enschede, The Netherlands
\textsuperscript{c} Institute for Frontier Materials, Deakin University, Waurn Ponds, Victoria, Australia
\textsuperscript{d} Fraunhofer Centre for Complex System Engineering, Department of Design, Production and Management, University of Twente, Enschede, The Netherlands

A R T I C L E   I N F O

Keywords:
Additive manufacturing
Hardness
Interaction plots
Relative density
Selective laser melting

A B S T R A C T

In this paper, we printed Ti-6Al-4V SLM parts based on Taguchi design of experiment and related standards to measure and compare hardness with different mechanical properties that were obtained in our previous research such as density, strength, elongation, and average surface. Then the effect of process parameters comprising laser power, scan speed, hatch space, laser pattern angle coupling, along with heat treatment as a post-process, in relation to hardness was analysed. The relation of measured factors with each other was also studied and related to hardness. The results showed an interesting similarity between hardness and density which is highly related to the formation of the melting pool and porosities within the process.

1. Introduction

Additive manufacturing has gained a lot of interest, partly because of producing lightweight structures from design data. Selective laser melting is a powder bed fusion additive manufacturing (AM) technique which produces parts from durable and expensive metallic materials [1–9]. Ti-6Al-4V is a type of titanium alloy, having two-phase alloy status. It is famous for its mechanical properties like high specific strength to weight and corrosion resistance. Moreover, it is regularly used for aerospace applications as well as in the military and medical fields [10,11].

Various investigations have revolved around SLM Ti-6Al-4 V because of its high usage in different industries; Thijs et al. studied the impact of scanning strategy and process parameters on the microstructure of Ti-6Al-4 V during SLM processing. They found that the relationship between the fracture plane and build orientation is very noticeable when the material is tested as-built. Stress relief by low temperature annealing heat treatment improves resistance against the growth of fatigue cracks and fracture toughness [12]. Zhao et al. compared the microstructure and mechanical properties of Ti-6Al-4 V alloy manufactured by SLM and Electron Beam Melting (EBM). It is evident from their work that tensile strength of SLM parts is higher than EBM because of finer α martensite. Porosity in SLM parts is associated with different scanning strategies and build orientations. Additionally, SLM and EBM Ti-6Al-4 V samples in vertical orientation show higher tensile strength and ductility as compared to horizontal orientation because of the change in tensile axial direction relative to the prior β-grain orientation [13]. Some researchers use grade 5 Ti-6AL-4 V powder in their work to investigate the growth rate of fatigue cracks and fracture toughness. Because of anisotropic residual stress distribution, the influence of fatigue crack growth and relation between fracture toughness plane and build direction were very noticeable. Annealing heat treatment and low-temperature stress-relief enhances the resistance against fatigue cracks and fracture toughness [12]. Simonelli et al. showed the tensile properties influenced by microstructure. They found that the build orientation influences tensile properties, especially ductility. Electron backscatter diffraction (EBSD) results show that intergranular fracture is present along the grain boundaries, which explains the main fracture surface features normally observed in fracture SLM of Ti-6AL-4 V [1].

For enhancing the mechanical properties of AM Ti-6AL-4 V, Xu et al. worked on in-situ decomposition in which unfavourable α martensite
changed into (α + β) microstructure. The best mechanical properties are achieved by lamellar (α + β) microstructure and performance is better than most of the AM manufactured Ti-6Al-4V alloys [14]. Mertens et al. compared the mechanical properties of SLM Ti-6Al-4V alloy and 316L stainless steel manufactured under similar conditions. The behaviour of titanium alloy was more complex than steel concerning mechanical anisotropy. Titanium alloy shows more sensitivity to the internal stresses as compared to 316L stainless steel because of low thermal conductivity [15]. For biomedical applications, Murr et al. researched on mechanical behaviour and microstructure of Ti-6Al-4 V using both EBM and SLM procedures. The inclusion of α, β and α martensitic phases, compared to wrought material, increases the hardness from HRC 37 to 57 and tensile strength from 0.9 to 1.45 GPa [16]. Qiu et al. studied the microstructure and tensile properties of Ti-6Al-4 V manufactured by SLM and hot isostatic pressing (HIP). Horizontally manufactured samples show more porosity than vertically manufactured parts [17]. The HIPing process closes most of the pores and completely changes the martensite into α and β phases. Leuder et al. researched on the mechanical behaviour of SLM Ti-6Al-4 V to analyse the crack initiation and crack growth. In SLM of Ti-6Al-4 V, the process initially formed α martensite, which makes the microstructure unfavourable because it has low ductility. Porosity reduction through HIPing leads to prominent crack-initiation-phase extension and improves the fatigue strength by reducing internal stresses during crack growth [18].

Taguchi method has been used for parametric optimization of the SLM processing of Ti-6Al-4 V alloy manufacturing [10]. The regression equations showed the relation between the scanning strategy, powder thickness, laser power, scanning speed and density. The microstructure of manufactured samples was generally composed of acicular martensite, α and β phases. Taguchi method is one of the best procedures for the statistical design of experimental techniques, which considers multiple critical factors. In this method, main points are selected from comprehensive data for investigation, which are based on orthogonality and thus reduces the time and cost of the experiment.

In this work based on Taguchi, L 25 samples were designed and printed with five repetitions for each printing condition in a single build. Then the hardness was measured and compared with different mechanical tests that have been reported on previously (relative density, tensile strength, breaking elongation, and average surface) and different statistical analyses were carried out. Then the effect of process parameters on the mechanical properties was characterized and the related mechanisms extracted. Finally, using statistical analysis and based on related to rheological phenomena the similarities and differences of hardness with other mechanical properties are discussed.

## 2. Experimental set up

### 2.1. Powder material and SLM operation

According to ASTM standards, E8 and EBM samples were prepared using an SLM 125 H.L. (SLM Solutions GmbH, Lubeck, Germany), equipped with YLR-Fiber-Laser with a minimum spot size of 5 μm. Some of the process parameters were kept constant during the test which are shown in Table 1. Samples were produced using Ti-6Al-4 V powder in the form of standard tensile test dog-bones for further analysis and Fig. 1 (A) illustrates typical Ti-6Al-4 V powder used in this research, Fig. 1(B) shows the powder particle size distribution. The scan strategy is meander which is rotating based on the values on DoE between each two subsequent layers.

### 2.2. Design of experiment

With five significant parameters the number of tests in full factorial mode would become unrealistic to perform. To reduce the cost of the experiment whilst maintaining accuracy, a Design of Experiment (DOE) approach has been selected. Taguchi L25 was used to generate general results which have five levels for each factor. Table 2 outlines the factors and levels and, to increase the accuracy, the number of Replications in each column should be balanced. This DOE is called orthogonal which was used in this study.

### 2.3. Post-processing (heat treatment)

In additive manufacturing of metals, the periodic cooling and heating of subsequent layers during the build process leads to change in microstructure and storage of residual stresses within the samples. Moreover, the fast cooling rate, specifically for powder bed systems compared to blown powder, generates more intermetallic phases which can be reduced by heat treatment [19,20]. Table 3 illustrates the heat treatment conditions that were used in this experiment. In this instance, the heating and resident time were fixed at 120 min., so the heating gradient steadily increased from ambient temperature (20°) to the set temperature from 4.8 to 8.6 °C/min. The cooling rate was fixed at 5 °C/min across all samples to prevent major changes to the mechanical properties, so cooling time varied for each sample set [21].

### 2.4. Hardness testing

The DuraJet G5 macro hardness tester for Brinell hardness measurement with versatility, incremental turnaround time and repeatability was used. Before starting, the test samples were polished by alternately 80, 200, 600, and 1200 grit sandpapers. The load and indenter were selected as 30 N and 1/30 respectively. The distance between each two measurement points was 1 mm and 80 tests on each sample has been carried out and the average of these points was reported to increase the accuracy so totally 2000 points were measured.

## 3. Results

### 3.1. Statistical analysis of the obtained data

Fig. 2(A–D) shows the variation trend of all 25 samples for hardness is mostly similar to relative density. This figure also shows that less similarity is observed between average hardness, tensile strength and breaking elongation. Therefore, in the next step, the statistical analysis of hardness and relative density is shown and a comprehensive discussion will reveal the phenomena between these two parameters.

#### 3.1.1. Probability analyses

Normal probability analysis [22] is a graphical technique for analysing whether or not the obtained data has normal, Weibull distribution or something else. In this method, the data are plotted versus theoretical distribution in such a way that the points should stay around the straight line and any deviations from this line show a departure from the normal distribution. Probability plots can be plotted for different distributions to check the dispersion of the data set on each distribution. In this experiment we plotted our data for normal, Weibull and lognormal distributions and found the distribution trend of our data is similar. Therefore, in Fig. 3 the probability analysis for a normal distribution is shown. The confidence intervals on the probability plot
were selected at 95%. This is shown by outer lines on the plot and is used to find the accuracy of the individual percentile assumption. As it can be seen the dispersion of the data set for hardness is similar to relative density which corresponds to the results of Fig. 2. Moreover, the linearity of hardness and density values is closer than with the other data. Both hardness and density have some deviations on the initial data points and become much more linear further on.

### 3.2. Main effect analyses

In statistics and design of experiments, the main effect is of an independent parameter on a dependent variable (such as hardness, relative density, tensile strength, breaking elongation and average surface) averaging across the levels of any other independent variables. In accordance with any design of experiment under the analysis of variance, a mean effect analysis assesses the hypotheses for evidence of an effect of different treatments regarding fluctuations. As it can be seen in Fig. 4 the main effect plot for average hardness for each variable is almost the same as relative density which is shown using red lines. There are some small differences in the behaviour of the scan pattern angle and laser power (only in one value) which proves that the fluctuations of process parameters have a similar effect on the values of hardness and density. From Figs. 2–4(A–E) it is found that variation of process parameters for hardness is highly similar to density. However, a mean effect test only shows whether overall there is something about a particular variable that is producing the difference. Therefore, in the next step, a comprehensive discussion on the interaction effect of each process parameter on the hardness and relative density will show the tie-in and mechanisms behind these two factors.

Another difference between the mean values of relative density and hardness is related to the fluctuations. As it can be seen in Fig. 4(A) the fluctuations for relative density are bigger which shows the larger impact of process parameters on this factor. Fig. 4(A and B) also shows the highest influence on the results is associated with heat treatment, and this parameter is more dominant on hardness and density.

### 4. Discussions

#### 4.1. Interaction of process parameters on outputs by using 3D Plots

To clarify the effect of process parameters on hardness as well as understanding the relation of hardness and relative density in the SLM process the interaction of each two parameters against hardness and density was plotted. The rheological discussion shows the mechanisms behind the process and explains the governing phenomena.

#### 4.2. The effect of heat treatment on process Parameters

Fig. 5 shows the graphs to analyse the effect of heat treatment on other process parameters against both hardness and density. No specific change was observed in all sub-figures for heat treatment of 20°C–600°C. Similar to the value of density, the hardness increases in

![Image](image1.png)

**Table 2**  
Process parameters.

<table>
<thead>
<tr>
<th>Laser Power (W)</th>
<th>Scan Speed (mm/min)</th>
<th>Hatch Spacing (µm)</th>
<th>Incrementing angle (°°)</th>
<th>Heat treatment Temperature °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>600</td>
<td>65</td>
<td>36</td>
<td>20</td>
</tr>
<tr>
<td>95</td>
<td>650</td>
<td>70</td>
<td>40</td>
<td>600</td>
</tr>
<tr>
<td>100</td>
<td>700</td>
<td>75</td>
<td>45</td>
<td>750</td>
</tr>
<tr>
<td>105</td>
<td>750</td>
<td>80</td>
<td>60</td>
<td>925</td>
</tr>
<tr>
<td>110</td>
<td>800</td>
<td>85</td>
<td>75</td>
<td>1050</td>
</tr>
</tbody>
</table>

**Table 3**  
Heat treatment condition (20 means no heat treatment).

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Heating time (min)</th>
<th>Resident time</th>
<th>Cooling time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>600</td>
<td>120</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>750</td>
<td>120</td>
<td>120</td>
<td>150</td>
</tr>
<tr>
<td>925</td>
<td>120</td>
<td>120</td>
<td>185</td>
</tr>
<tr>
<td>1050</td>
<td>120</td>
<td>120</td>
<td>210</td>
</tr>
</tbody>
</table>
600 °C and then decreases for temperatures ranging 800–925 °C and then sharply decreases for 1050 °C. This increasing trend might be associated with decomposition of the α’ for stress relieving. This intermetallic appears due to the high cooling rate in the SLM process [16,19,20,23]. α’ is harder and subsequently the intermetallic phase disappears in mill annealing and stress relieving, and due to lower mass of α’, density improves. Over this range the density shows to have a reduction trend specifically for temperatures above 1000 °C. At this temperature micro-flow might be occurring on the surface that is associated with temperature concentration and lower mass due to balling and residual particles [19,20,24]. The mentioned trend occurs for samples that were processed at lower than 70 J/mm³ energy density. The amount of α’ martensite in these samples, due to lower temperature and the cooling rate, is lower. Therefore, the mean value of hardness for low energy density samples that is shown in Fig. 5(A) is about 12% less than as-built samples with higher energy density. Fig. 5(C and D) show the microstructure of as-built and coarse for beta heat treatment was observed.

It is reported that by changing energy density the temperature also changes [14,23,25]. This effect causes remelting of the previous layer, which generates α’ martensite and explains why there is a change in hardness for heat treatment temperatures above 600 °C with decomposition of α’ into α and β [14,23,25].

Increasing heat treatment temperature leads to decreasing the value of hardness that is observed in Fig. 6(A–D). This can be related to the slow cooling rate and increasing the grain size and coarsening of α-phase [21]. Decomposition of the α’ martensite and nucleation of α precipitates in α + β annealing is a result of increasing the value of secondary α, so the total percentage of α and bigger grain size was obtained. β annealing compared to stress relief and mill annealing has a lower hardness that is related to increasing the grain size and decomposition of α’ martensite to secondary α. The hardness value of α + β annealing was higher than β annealing due to the higher volume fraction of β and bigger grain sizes. Also, coarsening of α phase in β annealing leads to decreasing the average hardness [16,26,27].

SLM is operated under controlled conditions (first vacuum then argon), but a small amount of nitrogen and oxygen was found in the bulk of the material. When α + β heat treatment has carried out these elements, due to lower melting temperature, are flowing. The separated flow has a stochastic trend, and so nitrogen and oxygen are mixing with Ti, Al and V by different amount on the surface of the samples, and this leads to decreasing the hardness [23,28,29].

Fig. 6 shows the interaction of heat treatment versus laser power and scan speed for both hardness and density. With high scan speed, less hardness and density were obtained that can be associated with wettability and Rayleigh instability. Melting pool temperature is calculated using Eq. 1 [23].
Where $C_1$ and $C_2$ are Planck distribution constants and $\lambda$ is laser wavelength. Scan speed and melting pool temperature have opposite proportion so higher scan speed causes lower temperature and higher surface tension (according to the thermocapillary effect) [30,31].

$$T_{np} = \frac{C_2}{\lambda \ln \left( \frac{C_1 \delta H_s}{4 \rho \lambda^3} + 1 \right)}$$

(1)

Where $\gamma^*$ is constant for each liquid, $T_c$ is critical temperature and $T_0$ is a reference value for temperature. Therefore, the value of surface tension for solid-liquid phase and liquid-gas phase ($\gamma_{SL} + \gamma_{LG}$) is bigger and based on Eq. 3 the chance of generation of droplets increases [23,30,31].

$$\gamma = \gamma^* \left( \frac{T_c - T_0}{T_c} \right) \left[ 1 - \left( \frac{C_2}{(T_c - T_0) \lambda \ln \left( \frac{C_1 \delta H_s}{4 \rho \lambda^3} + 1 \right)} - \frac{T_c}{T_c - T_0} \right)^n \right]$$

(2)

This phenomenon leads to low wettability and a higher chance of balling which are known to be a common defect in metal AM and increases pores and reduces density and hardness [23,32]. Fig. 6(A and B) shows that with lower laser power, less hardness and density are obtained.

When using lower laser power according to Eq. 1, less energy is transferred to the melting pool and the temperature decreases. This leads to lack of fusion and generation of big pores, so hardness and density also decrease. In this case, the hardness and density reduce down to 250HB and 95% respectively.

Fig. 6(C and D) illustrates that higher hardness and density were found with heat treatment ranging 600 °C–800 °C. Lack of wetting leads to decreasing hardness and density in higher scan speed, and therefore more porosity is generated. This leads to a radical reduction of hardness.
and density specifically at high heat treatment temperature (due to the micro-flow effect). The results are a reduction of density to 95% and hardness to 250HB.

Fig. 7(A and B) show the interaction of hatch space and heat treatment versus hardness and density. Small hatch space starts with lower density related to high overlap. Also, Fig. 7(A) shows that most hardness fluctuations are related to the variation of heat treatment. This also shows that heat treatment had the stronger impact which is proved by mean effect diagrams (Figs. 4 and 5). By increasing hatch space, hardness increased and then reduced. In the overlap area, the material is mushy and no micro-flow motion occurs due to higher viscosity. In this case, higher heat penetration due to lack of Marangoni’s convention leads to the generation of bubbles and vapour in the melting pool. The bubbles tend to escape from the melting pool and the interaction of vapour force, versus hydrostatic pressure + surface tension (Fig. 8) leads to the formation of keyholes and decreasing hardness. The vapour pressure has a direct relation with the diameter of the keyhole and in lower diameter, higher pressure on the pores leads to the generation of high force and as shown in Fig. 8 the vapour moves to the topmost surface of melting pool to escape and overcome to hydrostatic and surface tension forces, thus creating keyholes.

In higher than optimum hatch spaces lower hardness was obtained. This is related to higher energy dispersion over a bigger surface and lower remelting of subsequent layers. Fig. 7(D) shows nonlinear behaviour for the interaction of scan pattern angle and heat treatment versus hardness. Here, two-dimensional graphs were plotted to clarify this situation (Fig. 9). In this figure, the best hardness is related to area 2, which occurs around the stress relieving temperatures and shows the impact of heat treatment on hardness. In lower scan pattern angle higher hardness was seen and by moving across the Y-direction the average value of hardness decreases.

This can be related to higher overlap between subsequent layers. When the lower scan pattern angle is selected, then the hatch space is much more coincident with the former layer. In this case, the overlap area of the second layer is mostly sitting on the first layer and two further laser crossings occur. Therefore, this leads to double remelting on the overlap of the former layers and possible removal of keyholes and pores. As a result, the hardness improves [19,20].

Fig. 4. Main effect analyses (A) Average hardness (B) Relative density (C) Tensile strength (D) Breaking elongation (E) Average roughness.
4.3. The effect of scan pattern angle on process parameters

Figure (A) shows for the interaction of scan pattern angle and laser power the best hardness (higher values) was obtained with lower scan pattern angle and higher laser power. Also, with low laser power and high scan speed, hardness reduced to 250HB which is about 15%
reduction. This area suffers from a lack of re-melting and fusion and these two phenomena strengthens the correlation. A similar trend was obtained for the density that is shown in Fig. 10(B).

Fig. 10(C and D) show the similar trend for interaction between scan speed and pattern angle. Some peaks occurred in the higher scan speed and low pattern angle for both hardness and density. This can be associated with better coverage of overlaps of previous layers that leads to double remelting, and reduction of some defects such as cracks, keyholes and pores. This effect seems to compensate for the lack of wettability in higher scan speeds.

Fig. 10(E and F) illustrate the effect of hatch space and scan pattern angle on hardness and relative density. Higher hardness was achieved in the optimum area of hatch space and lower values of pattern angle. This figure demonstrates pattern angle is more influential in hardness compared to hatch space. In rheology of the melting pool the work of adhesion is another important factor affecting the porosity and hardness. In solid-liquid interfaces like melting pool and solidified layer,
according to Young’s law and Young-Dupré’s relation, Eq. 4 is obtained [23].

\[ W_a = \gamma (1 + \cos \theta) \]  

(4)

where \( \theta \) is the radius of the meniscus with the normal line to the surface. This shows that work of adhesion is a direct function of surface tension. According to Planck’s distribution and thermocapillary effect, when selecting small hatch space, the surface tension and work adhesion in hatch-to-hatch decreases and this mechanism causes reduction in initial adhesion between the solidified layer and melting pool. Due to high pressure laser pulses the melt pool becomes unstable and the gradient of fluid flow has non-zero values (Eq. 5):

\[
\nabla \vec{u}_0 = \frac{\partial u_{0x}}{\partial x} \mathbf{i} + \frac{\partial u_{0y}}{\partial y} \mathbf{j} + \frac{\partial u_{0z}}{\partial z} \mathbf{k} \neq 0
\]

(5)

Totally, this phenomena generates waves and causes dropping of unmelted powder particles in the melting pool, which can form porosity in subsequent layers.

4.4. The effect of other parameters on density

Fig. 11(A and B) shows that with higher scan speed and lower laser power, hardness and density reduce to 250 HB and 95% respectively. This area is a fertile ground for porosity since the energy density has very small values and so the chance of formation of big pores due to lack of fusion is higher. On the other side, higher scan speed leads to Rayleigh instability specifically in the low energy area, and porosity increases and hardness decreases. Scrutinizing Fig. 11(A) shows some peaks happened toward a certain direction along the maximum value of laser power, which proves this parameter is more influential than scan speed on the value of hardness.

In terms of the interaction of laser power and hatch space from analytical 3D graphs, the complex behaviour was obtained. Contour plots in 2D have been plotted to show the linear behaviour of the process (Fig. 12). This figure shows that increasing hatch space up to a certain point (darker area) improves the density. Larger hatch space leads to larger contact between the melting pool and solidified layer. Therefore, according to Eqs. 6 and 7, surface energy and subsequently work adhesion increases.

\[
E_{SL} = \gamma_{SL} S_C
\]

(6)

\[
E_i = E_1 + E_2 = (\gamma_1 + \gamma_2) S_C
\]

(7)

Where \( S_C \) is contact area of melting pool with a solidified layer, \( E_1 \) is melting pool energy, and \( E_2 \) is energy of solidified layer. This leads to the more stable melting pool and lower porosity and higher hardness. Higher than a certain amount (a selected region in Fig. 12 (A and B)), due to the higher dispersion of energy density and lower re-melting effect on former layers, the value of density and hardness reduce [21,23,33,34]. Also, the lower density and hardness areas are observed...
in Fig. 12 with the lighter colour that is related to a larger overlap area with a smaller hatch space. It is reported in the above-mentioned references that overlapping areas absorb greater energy. This energy penetrates further into the material and, according to Fig. 8, increases the chance of keyholes and reduces density and hardness.

Fig. 11(E and F) show that lower hardness and density were found for higher scan speed and hatch space. Both factors reduce the value of energy density and therefore lack of wettability and energy in this region results in increasing pores and reduction of density to 95% and hardness to 250HB.

By considering $R_{\text{drop}}$ as a droplet radius, Eq. 8 shows the pressure in the droplet.

---

**Fig. 11.** Interaction plots for hardness and density for other process parameters.

**Fig. 12.** Effect of laser power and hatch space on hardness by 2D plot (A) hardness, (B) Density.
\[ P_1 = P_0 - \frac{2}{R_{\text{dop}}} \gamma \left( \frac{T_C - T_0}{T_C} \right) \left[ 1 - \frac{C_2}{(T_C - T_0) \lambda \ln \left( \frac{C_1 \Delta T_0}{T_C - T_0} + 1 \right)} - \frac{T_C - T_0}{T_C - T_0} \right]^n \]  

(8)

Low scan speed and hatch spacing raise the pressure in the droplet and, due to thermocapillary effects, the surface tension also increases and bursting and dross can occur, which increases the chance of porosity for subsequent layers, as proved by Eq. 8.

5. Conclusions

In this research, based on ASTM standards, a relevant DoE was chosen and 25 samples with five repetitions for each were printed. The process parameters were laser power, scan speed, hatch space and scan pattern angle, and were selected in five repetitions. To tailor mechanical properties, heat treatment also was selected as one of the variables for these levels. Based on the mentioned DoE, samples in the form of cylindrical samples were printed. They were selected in five levels. Based on the mentioned DoE, samples in the form of cylindrical samples were printed. They were selected in five levels. The results were characterized based on the rheology of the melting pool and formation of pore structures. Higher laser power and lower scan speed produced higher hardness due to better energy transfer and good melting pool quality. Also, for lower than optimum hatch space values, due to larger overlap, hardness decreased. For higher than an optimum hatch spacing, on account of dispersion of beam energy, the hardness also reduces. Low scan pattern angle produces better hardness due to double remelting of overlap of previous layers. Stress relieving improved the hardness for samples with a lower energy density which is related to the formation of less \( \alpha' \) martensite for as-built samples. Increasing the temperature of heat treatment leads to increasing grain size and reduction of hardness.

Future work will be directed toward analysing process parameters on the value of shrinkage and dimensional deviations. Monitoring the melting pool temperature and characterising it with rheological phenomena would be another direction for upcoming research to explain the temperature profile and find the link with mechanical properties and process parameters.

References