Experimental investigation of the effect of processing parameters on densification, microstructure and hardness of selective laser melted 7075 aluminium alloy

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Abstract
The 7075 aluminum alloy of the 7xxx series largely used for structures in modern aircraft has been successfully fabricated using selective laser melting (SLM) technology. The morphology of the initial 7075 aluminum alloy powders was characterized by a Zeiss Evo 50 Scanning electron microscope (SEM). Energy Dispersive x-ray (EDX) spectrometer attached to SEM was used as a tool to obtain the chemical composition of the powders. Processing parameters including scan speed, hatch distance and constant laser power (100 and 150 W) effect on densification, microstructure and hardness were investigated. The initial powder particles were found to be elongated and non-spherical and composed of Al, Zn, Mg, Cu, and Ag without Si. The result of the influence of processing parameters on properties of the as-built samples by SLM technology indicates that higher densification of parts can be gained using higher laser power and lower laser scan speed and hatch distance due to significant reduction in the number of pores. Two major types of pores including metallurgical and keyhole pores have been identified with the keyhole pores dominating the samples processed by low laser power of 100 W. The keyhole pores increase in size at a high scan speed and hatch distances. By using higher laser power of 150 W, the keyhole pores reduced significantly while metallurgical pores appear. The result of the hardness test conducted on the samples shows that high values of hardness can be achieved with low scan speed.

1. Introduction

Aluminum possesses striking properties that make it an extremely important engineering material. Some of these properties include high electrical and thermal conductivity and high reflectivity [1, 2]. Aluminum owes high corrosion resistance because of the tenacious oxide film (Al₂O₃) which occurs naturally on its surface [3–5]. Due to high reflectivity and thermal conductivity, aluminum requires high laser power to melt [6, 7]. The 7075 aluminum alloy is an alloy of the 7xxx series with combined properties of high thermal conductivity, high strength and good mechanical properties [8, 9]. The 7xxx series alloys have high strength because they can be hardened by precipitation [1]. The 7075 alloys are built on a quaternary Al–Zn–Mg–Cu alloying system with high strength and seen as good airframe material [10, 11]. They are largely used for structures in modern aircraft where the specific strength of a high level is required [12, 13].

Additive Manufacturing (AM) techniques are used by most industries today to manufacture complete functional complex geometries from a digital model by joining material in a layer by layer mode [14–16]. Selective Laser Melting (SLM) which is a major technique in additive manufacturing generates high-density 3D parts by selectively melting and fusing metallic powder [17]. Though aluminum is a good material in the production of parts due to its mechanical properties such as low cost and weight ratio [18], it’s alloy processing by selective laser melting (SLM) to produce grade parts with the desired strength needs much attention and research is still on-going [19]. Buchbinder et al [20] and Hadadzadeh et al [21] reported the use of selective laser
melting (SLM) technology as an additive manufacturing technique for the manufacture of lightweight structured components with superior mechanical and chemical properties avoiding tooling. Siddique et al [22] also used the same technology to process AlSi12. The properties of SLM made samples are influenced by the selection of key parameters which include scan speed, hatch distance, laser power and layer thickness [23]. The SLM made samples are also affected by powder characteristics such as particle size, distribution, shape, and alloying elements [24]. Hanzl et al [25] in their research emphasized the need for proper parameter selection to improve the properties of the manufactured component by selective laser melting (SLM) technology.

So far, little has been achieved on higher densification for 7075 alloys by selective laser melting. Research work has shown higher densification by silicon additions of a certain percentage to the alloy and the use of higher laser power machines. Therefore, the possibility of processing the alloy without silicon additions to obtain higher densification also requires investigation. The 7075 alloy is an important material for use in the automotive and aerospace industries due to its high strength. It is therefore remarkable to show how the variation of process parameters influence parts by SLM so that optimized parameters can be selected or used in subsequent processes. These facts are the motivating factors that form the basis of this research.

2. Experimental

2.1. Materials
A gas atomized 7075 aluminum alloy powder obtained from the additive manufacturing laboratory of the University of Wolverhampton and manufactured by LPW UK was the major material used in this research. The morphology of the powders was characterized by a Zeiss Evo 50 Scanning electron microscope (SEM). The chemical composition of the powders was characterized by an energy dispersive x-ray spectrometer (EDX) attached to SEM.

2.2. Data preparation
Specimens to be produced were designed using Solidworks software for a 3D model. The file was converted into an STL when exported from Solidworks. Magics software was used to generate supports and position on the platform. An Eos RP tool was used to slice and convert STL to SLI files for use on the EOS PSW software on the machine. The settings used were standard parameters for Alsi10mg alloys. The slicing into layers is usually with the selected thickness and the file sent into DMLS software which is PSW of EOS.

2.3. Experimental procedure
The 7075 aluminum powder was processed by an EOSINT M270 DMLS machine with a continuous wave yttrium fiber laser of a maximum power of 200 W and wavelength of 1.07 μm. The beam diameter can be set to between 100–500 μm and a maximum speed of up to 7000 mm s⁻¹. The 7075 aluminum alloy powder was initially dried in an oven to remove any moisture at a temperature of 80 °C for 4 h. The SLM procedure was carried out in an Argon environment in a chamber containing an oxygen level of less than 0.1%.

2.4. Process parameter selection
The key parameters selected include; constant laser powers 100 W and 150 W, the scan speed varied in the range 100 to 500 mm s⁻¹, hatch distance in the range 0.05 to 0.3 mm, a layer thickness of 50 μm and beam diameter 100 μm. The machine used was of 200 W maximum laser power and 100 mm s⁻¹ minimum scan speed. A total number of thirty (30) samples were produced and with three samples per parameter combinations for 100 W and 150 W laser powers respectively. The samples were built in the z-direction and numbered 1–10 for easy identification as shown in figure 1. The samples built using 100 W laser powers were numbered 1–5, while those built with laser power of 150 W were numbered from 6–10. The built test samples were cubic in geometry having a dimension of 10 mm × 10 mm × 5 mm.

2.5. Characterization of as-built samples
The relative density values were determined by calculation and by micrograph and were correlated and found to have a 99.6% confidence level. The relative density by micrograph was then chosen for the research work.

An optical microscope and scanning electron microscope (SEM) were used for microstructural analysis. The polishing and etching of samples were done using Keller’s reagent at room temperature, by a solvent composed of 95 ml water, 2.5 ml HNO3, 1.5 ml HCl and 1.0 ml HF (every 100 ml solution). The stream essentials software was used for the determination of percentage porosity, pore density and maximum pore size.

Micro hardness was tested by using a Vickers hardness machine under a load of 2500 g for a dwelling time of 15 s. Micro hardness values of the polished as-built samples were taken eight times at different points on the hardness sample and averaged to give a micro-hardness value. The hardness value was compared with the
standard value. Heat treatment on the sample with the least pore and the highest density was carried out. The alloy is commonly available in T6 treatment therefore; the sample was given a T6 heat treatment by heating it to a solution temperature of 470 °C for 1 h. It was quenched immediately in cold water and aging was done at 120 °C for a time period of 24 h. This was carried out to evaluate the resultant hardness for the alloy.

3. Result

3.1. Powder characterization result

The morphology of powder particles is often studied using scanning electron microscopy (SEM). In most cases, the powder particles show spherical shape while in some cases the particles display irregular or elongated shapes. Sometimes mixed particles of different shapes are also observed [26]. Spherical, or rounded shape powder particles are more desired due to better flow behavior [27, 28]. Benson and Synders [29] reported a better flow rate with spherical powder particles. Spherical particles also give enhanced compaction and structurally better parts [10, 30, 31]. The SEM images of the initial 7075 aluminum alloy powder particles in this research are presented in figure 2(a). The powder particles of the 7075 alloy as shown in figure 2(a) are mostly elongated and non-spherical in shape. However, some of the particles have a shape close to spherical which indicates the possibility of a reduced impact on flow behavior. Moreover, properties of parts manufactured by SLM technology using powders with non-spherical shape can be improved by using high laser powers (more input energy) or simply changing other machine parameters such as scan speed and hatch spacing. Aboulkhair et al [26] in their research on Variation in morphology of AlSi10Mg powder show that the effect of elongation of powder particles on properties of SLM made parts such as density, hardness and so on can be improved by changing parameters such as input energy. We have taken into account the shape of the powders by using high laser power above 50 W.

Table 1 displays the chemical composition of the 7075 aluminum alloy as determined by EDX represented by the EDX spectrum in figure 2(b). The result is within the standard range for the alloy specified by the aerospace specification metals (ASM). When compared with the specification in the ASM handbook as reported by Kempen [8], it is observed that elements like Si, Mn, and Fe are missing. We have no explanation for the missing of these elements as the powder was used as received from the manufacturer. The results of the chemical composition show a significant amount of silver of about 1.74% present in the 7075 alloy powder. According to Xu et al [32], the addition of silver to 7075 alloy hinders the growth of recrystallized grains during T6 heat treatment thereby raising the strength and ductility of the alloy. They reported increasing peak values of micro hardness as the silver additions increase to 0.4% after aging at 120 degrees Celsius for 12 h.

Figure 1. Image of the built samples.
3.2. Effects of scan speed and hatch distance on densification of parts.

The result of the relative density obtained from the image processing software (stream essentials) of cross-sectioned specimens with the variable process parameters of scan speed and hatch distance at laser powers 100 W and 150 W are presented in table 2. The results were correlated and found to have a 99.6% confidence level with positive correlation and the trend is plotted in figures 3(a) and (b).

Figures 4(a) and (b) show the effect of scan speed on relative density of the samples at a laser power 100 W and 150 W respectively. It is observed that the relative density is 89.7% for a low scan speed of 100 mm s$^{-1}$ (figure 4(a)) and low hatch distance of 0.05 mm (figure 4(b)) for a laser power of 100 W. The relative density increased to 97.3% at increased scan speed of 200 mm s$^{-1}$ (figure 4(a)) and hatch distance of 0.1 mm (figure 4(b)) for the same laser power. This value of relative density was the highest for the laser power of 100 W.

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**Table 1.** Chemical composition of 7075 alloys in wt (%) by EDX.

|       | Al   | Zn   | Mg   | Cu   | Ag   | O    |
|-------|------|------|------|------|------|------|
|       | 85.03| 5.49 | 2.35 | 1.47 | 1.74 | 3.93 |

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**Figure 2.** (a) SEM image and (b) EDX spectrum of initial 7075 aluminum powder particles.
The relative density decrease as the scan speed was changed from 200 mm s\(^{-1}\) to 500 mm s\(^{-1}\) in the remaining four hatch distances of 0.1 mm to 0.3 mm. It is observed from the result that further increase in the scan speed would lead to a decrease in relative density indicating that higher scan speed results in lower relative densities.

This phenomenon was observed by Louvis et al\(^{[19]}\) in their attempt to process 6061 aluminum alloy using lower laser powers of 50 W and 100 W by selective laser melting. They used MCP realizer ytterbium fiber laser beam machines with an alternate scan strategy of 90 degrees after each layer. They reported that at high scan speeds relative densities were low due to inadequate melting of the powder.

### Figure 3.
Correlation of relative density by image processing and relative density by mass ratios at a constant laser power of (a) 100 W (b) 150 W.

### Figure 4.
Effect of (a) scan speeds (b) hatch distance on the relative density of samples using laser power of 100 W and 150 W.

### Table 2.
Result of relative density by image processing and mass ratio calculations.

| Sample no | Laser power (W) | Scan speed (mm s\(^{-1}\)) | Hatch distance (mm) | Relative density (%) by image processing | Relative density (%) by mass ratios |
|-----------|----------------|----------------------------|---------------------|------------------------------------------|-----------------------------------|
| 1         | 100            | 100                        | 0.05                | 89.7                                     | 88.9                              |
| 2         | 100            | 200                        | 0.1                 | 97.3                                     | 95.4                              |
| 3         | 100            | 300                        | 0.15                | 93.7                                     | 90.0                              |
| 4         | 100            | 400                        | 0.2                 | 83.3                                     | 83.1                              |
| 5         | 100            | 500                        | 0.3                 | 63.7                                     | 64.2                              |
| 6         | 150            | 100                        | 0.05                | 99.8                                     | 96.6                              |
| 7         | 150            | 200                        | 0.1                 | 99                                       | 96.1                              |
| 8         | 150            | 300                        | 0.15                | 98                                       | 94.5                              |
| 9         | 150            | 400                        | 0.2                 | 93.8                                     | 91.6                              |
| 10        | 150            | 500                        | 0.3                 | 83.9                                     | 80.3                              |
For the laser power of 150 W (figures 4(a) and (b)), the highest value of the relative density of 99.8% was achieved using a scan speed of 100 mm s\(^{-1}\) (figure 4(a)). This is slightly different from when the laser power of 100 W was used with the highest relative density achieved at a scan speed of 200 mm s\(^{-1}\). This signifies that at a higher laser power and lower scan speed, relative density increases. The relative density decreases as the scan speed and hatches distance increases. In all, the scan speed range for which relative densities were high for both laser powers was between 100–200 mm s\(^{-1}\). Kempen [8] in a related study on 7075 alloy reported a relative density of only 95% using laser power of 200 W and a scan speed of 1400 mm s\(^{-1}\) due to crack formations. Although the laser power was higher than the one used in this research, the scan speed was also very high. If the scan speed were reduced, the relative density may have been higher too meaning that the scan speed is a very significant parameter to the densification of parts. Therefore, from the results of this research, it can be observed that the highest relative densities can be realized by using higher laser power and lower laser scan speed and hatch distance.

### 3.3. Effect of energy density on densification behavior of parts

The densification behavior of samples produced by SLM is also greatly influenced by the laser energy input or density [33]. It, therefore, means that for SLM parts (samples) to achieve full densification, sufficient energy input is required. "The laser energy density \( E (J \text{ mm}^{-3}) \) which is the energy supplied by a laser beam in unit volume was calculated using equation (1) and the result tabulated in table 3.

\[
E = \frac{P}{vht}
\]

(1)

From the equation, \( p \) is the laser power (W), \( v \) is the scan speed (mm s\(^{-1}\)), \( h \) is the hatch distance (mm) and \( t \) is the layer thickness (mm).

The results in table 3 and figure 5(a) for the samples built with 100 W laser power show that the energy density decrease with increase scan speed for all the samples. The result also shows that as energy density increase from 13 J mm\(^{-3}\) to 100 J mm\(^{-3}\), the relative density also increases to a maximum of 97.3%. However, the relative density decreases to 89.7% when the energy density reached 400 J mm\(^{-3}\). The decrease in the relative density was due to the solidification cracks and large pores observed in the micrograph in figure 6(a) of the sample at 100 mm s\(^{-1}\) and hatch distance of 0.05 mm [1]. Kempen [8] in a study of A360 aluminum alloy observed that at an ‘optimal energy input per unit length’, the melt pool becomes stable and higher relative densities are obtained. The maximum relative density for these samples was achieved by using the energy density of 100 J mm\(^{-3}\) at the scan speed of 200 mm s\(^{-1}\) which seems to be optimal for these samples as well. Higher laser energy was therefore required to produce a stable melt pool that will eliminate or reduce the large pores and cracks. The lowest relative density is obtained using the least energy density of 13 J mm\(^{-3}\). This is expected since the laser energy input is not adequate to completely melt the aluminum powders as seen in the large keyhole pore in the micrograph of the sample built using 500 mm s\(^{-1}\) scan speed in figure 6 and the largest maximum average pore size of 1235.29 \( \mu \text{m} \) in table 4. Higher laser energy was therefore required to provide sufficient liquid phase for the complete melting of the powders. Hanzl et al [25] reported that the laser energy is majorly influenced by

| Energy density (J mm\(^{-3}\)) | Relative density (%) by image processing 100 W laser power | Porosity (%) |
|--------------------------------|----------------------------------------------------------|--------------|
| 400                            | 89.7                                                     | 9.97         |
| 100                            | 97.3                                                     | 2.75         |
| 44                             | 93.7                                                     | 6.29         |
| 25                             | 83.3                                                     | 16.6         |
| 13                             | 63.7                                                     | 36.0         |
| 600                            | 99.8                                                     | 0.17         |
| 150                            | 99                                                       | 0.95         |
| 67                             | 98                                                       | 1.99         |
| 38                             | 93.8                                                     | 6.17         |
| 20                             | 83.8                                                     | 16.4         |
Figure 5. Plot of relative density and energy density at a constant laser power of (a) 100 W (b) 150 W.

Figure 6. Micrographs of polished as-built 7075 alloy at different scan speeds at 100 W laser power; (a) 100 mm s\(^{-1}\), (b) 200 mm s\(^{-1}\), (c) 300 mm s\(^{-1}\), (d) 400 mm s\(^{-1}\), (e) 500 mm s\(^{-1}\).

Table 4. Pore size and counts result at different scan speed, laser power, and hatch distance using stream essentials software.

| Sample no | Laser power (W) | Scan speed (mm s\(^{-1}\)) | Hatch distance (mm) | Average maximum pore size (\(\mu m\)) | Average pore count |
|-----------|-----------------|----------------------------|---------------------|--------------------------------------|-------------------|
| 1         | 100             | 100                        | 0.05                | 868.1                                | 107.6             |
| 2         | 100             | 200                        | 0.1                 | 288.7                                | 139               |
| 3         | 100             | 300                        | 0.15                | 305.2                                | 450.6             |
| 4         | 100             | 400                        | 0.2                 | 760.6                                | 250.6             |
| 5         | 100             | 500                        | 0.3                 | 1353.29                              | 182               |
| 6         | 150             | 100                        | 0.05                | 93.22                                | 15.2              |
| 7         | 150             | 200                        | 0.1                 | 260.58                               | 112.3             |
| 8         | 150             | 300                        | 0.15                | 184.1                                | 152               |
| 9         | 150             | 400                        | 0.2                 | 192.9                                | 253.3             |
| 10        | 150             | 500                        | 0.3                 | 392.5                                | 215.3             |
laser power and scan speed and that laser energy, in turn, influences the melting temperature which is responsible for the volume of liquid phase provided in the ‘melted components’. Table 3 and figure 5(b) shows how relative density and energy density at a constant laser power 150 W are related. It shows that as energy density increase from 20–600 J mm$^{-3}$, the relative density also increases. The highest relative density of 99.8% was achieved using the lowest scan speed of 100 mm s$^{-1}$ and the highest energy density of 600 J mm$^{-3}$. This is in agreement with the study on Al–Cu–Mg alloys as reported by Zhang et al [33]. They reported that a higher temperature is obtained as a result of the increase in the energy density attributed to the low scan speed. The higher temperature according to them provided a low viscous and sufficient liquid phase spread, thereby enhancing the ‘metallurgical bonding of adjacent layers’. The long stay of the liquid phase due to the low scan speed allows for sufficient ‘flow between dendrites and backfill the dendrites shrinkages’ [34, 35]. However, the lowest relative density of 83.9% is realized using the lowest energy density of 20 J mm$^{-3}$ with the highest scan speed of 500 mm s$^{-1}$. The relative density at this scanning speed is higher than that achieved at a constant laser power of 100 W due to increased energy density as a result of a higher laser power of 150 W. It is observed that the maximum relative density of 99.8% is possible with a higher laser power of 150 W and a low scan speed of 100 mm s$^{-1}$ thereby increasing the energy density. This is in agreement with Loh et al [36] where they reported that higher energy deposition depends on cases of higher powers and lower speeds resulting in larger penetration and width of the melt.

3.4. Effect of scan speed and hatch distance on microstructural properties of parts
The effect of process parameters on the porosities of the samples is shown in table 4. As can be seen in table 4, porosity increases as hatch distance increases. The result agrees with the study by Louvis et al [19] that with a reduction in the overlapping area of the melt tracks adjacent to each other, porosity occurs particularly when the hatch distance is large. A study by Aboulkhair et al [23] showed that lack of overlap also increases fraction gaps and as the hatch distance increases, the overlap also decreases. Therefore, the best overlap is realized at hatch distance of 0.05 mm and 0.1 mm. These values of hatch distance have also been shown in this work to yield the highest densities for both laser powers.

Figure 6 presents the micrographs of samples produced using lower laser power of 100 W. The micrograph showed that at increased scan speed and hatch distance, porosity increases. The result is close to a model prediction of porosity conducted by Read et al [37], which showed that at lower laser power and increased scan speed, porosity increases. They reported that the effects of the laser power on porosities were more pronounced at a higher scan speed and that the effect of the scan speed on the porosities was more pronounced at a lower laser power. The reason according to them was due to the reduction in the energy into the material due to lower laser power and increased scan speed. This consequently reduced the melt pool forming porosities as a result of inadequate consolidation. According to Read et al [37], increased hatch distance can lead to the formation of porosity as a result of inadequate overlapping between adjacent scan tracks resulting in partial consolidation. They argued that porosity can be reduced if the laser power, scan speed, and hatch distance are controlled. However, it was noted that other factors like turbulence in the melt pool and evaporation can also cause porosity. They concluded that for porosity to be eradicated or reduced a higher laser power be accompanied and low scan speed and hatch distance be applied. This phenomenon is evidenced in table 4, and the micrographs in figures 6 and 7. At the highest scan speed of 500 mm s$^{-1}$, laser power of 100 W, and hatch distance of 0.3 mm, the largest pore was obtained with the average maximum pore size of 1235.39 μm. This is due to the high rate of solidification owing to the high scan speed with low laser power resulting in un-melted powders.

By increasing the laser power to 150 W but maintaining the same scan speed and hatch distance, the maximum average pore size reduced significantly to 392.5 μm; a more than 300% reduction. This was due to the increased laser power that provided more energy in the material for the melting of powders. All the built samples show different forms of porosities accompanied by some cracks in the micrographs shown in figures 6 and 7. These porosities were of different sizes and shapes. Aboulkhair et al [23] reported two forms of porosities namely metallurgical and keyhole pores. The metallurgical pores are caused by hydrogen and are formed at low scan speeds from trapings of gases in the melt pool. They are of smaller sizes usually less than 100 microns with spherical morphology. The keyhole pores are irregular in shape, larger in size usually above 100 microns and are formed due to ‘rapid solidification of the metal’ with inadequate gap filling with the molten metal [15]. It can be observed from figures 6(a)–(e) that keyhole pores dominated in all the samples with very few or negligible metallurgical pores. This may be a result of the high rate of solidification and low laser power used as there was no sufficient melt pool for gas trapings [23]. As a result of the low laser power and rapid solidification, most of the powders were not melted due to the small amount of melt pool formed. As the scan speed increases, the keyhole pores also increase in sizes. It is also observed that the keyhole pores actually started from the sample with low scan speed of 100 mm s$^{-1}$ accompanied with cracks seen in figure 6(a). In figure 6(b), there is a
reduction in the number of pores and even cracks which is the reason for the highest density obtained for samples built with 200 mm s\(^{-1}\) scan speed. The largest pore size obtained from the micrograph is 1235.29 microns obtained in the sample in figure 6(e) with a scan speed of 500 mm s\(^{-1}\). This shows that at higher scan speed, the keyhole pores will increase in size due to un-melted powders thereby resulting to lower densities. This may also be the reason why this sample had the lowest density as shown in table 2.

Figure 7 shows the cross-section of 7075 alloys built with scan speed ranging from 100 to 500 mm s\(^{-1}\) using laser power of 150 W. It shows a decrease in the size of imperfections which includes pores and cracks at lower scan speeds. It is also observed that keyhole pores that dominated in all the samples built using laser power of 100 W reduced greatly in number and size but with some metallurgical pores observed with cracks. The reason is that the increase in laser power provides more wettability so as to enhance powder melting during the SLM process. The presence of cracks may be due to the susceptibility of the alloy to solidification cracking.

There is also a significant reduction in the number and size of both keyhole and metallurgical pores in the sample built using a scan speed of 100 mm s\(^{-1}\). The same sample, when built with the laser power of 100 W, has greater pores. The significant reduction in the size and number of pores also increases the densities of samples as observed in table 2. This is in agreement with literature that increased laser power and reduced scan speed and hatches distance results in a decrease in pore size and number.

The above discussion on the microstructure of the SLM made samples is further supported by figures 8–11. The sample with the highest density (figures 8 and 9) and the least density (figures 10 and 11) for the two laser powers used was analyzed using the LEXT confocal optical microscope (figures 8 and 10) and scanning electron microscope (SEM) in figures 9 and 11. The sample with the highest relative density was built with a constant laser power of 150 W at a scan speed of 100 mm s\(^{-1}\) and at a hatch spacing of 0.05 mm. While the other samples with the least relative density were built with laser power of 100 W and 150 W at a scan speed of 500 mm s\(^{-1}\). The optical microscopy images of the sectioned samples were taken on the top surface parallel to the build plane which is the XY plane and parallel to the build direction which is the XZ plane where Z direction is the build direction.

Figure 8(a) observed in the XY plane parallel to the build plane shows a layered pattern that is regular and represents partially laser tracks conforming to the x/y scanning strategy. The melt pools were observed to be oriented both in the horizontal and vertical directions. There are columnar grains formed epitaxially and some are along the build direction. It shows a non-uniform microstructure all through the sample material. This is due to the formation of the columnar grains which occurred during the period of solidification after the heat transfer from the top surface down to the bottom during laser irradiation on the powders. The formation of the grains was also due to the existence of a temperature gradient between the powder bed surface and the build platform. The growth and formation of the columnar grains are in the direction of the ‘positive temperature gradient’.

Figure 8(b) in the Z direction shows a half-cylindrically shaped melt pool with the ends of the melted laser tracks.
arranged closely together developing a bond between adjacent layers. Zhang et al.[33] also reported a similar melt pool structure on Al–Cu–Mg alloys. They observed a melt pool that was cylindrical which according to them was caused by the ‘Gauss energy distribution thermal flux of laser aligns layer by layer which is the trend of the SLM technology’. The presence of the melt pool is also revealed in SEM micrographs in figure 9.

Figure 8. Optical images for samples with the highest relative densities built with a laser power of 150 W, a scan speed of 100 mm s\(^{-1}\): (a) the top section in the XY plane parallel to the build plane; (b) XZ plane parallel to the build direction.

Figure 9. SEM micrograph of the sample with the highest relative density built with the laser power of 150 W and scan speed of 100 mm s\(^{-1}\): (a) melt pool structure; (b) showing the boundaries of the melt pool at a higher magnification; (c) showing the core of the melt pool at a higher magnification.
Figure 9(a) revealed a tiny long crack and some other few ones. It revealed two types of grain structure; the core and boundaries of the melt pool. The boundary is the whitish bright color seen while the core is the darker side. Figures 9(b) and (c) revealed the details of the melt pool at a higher magnification and it was observed that the core of the melt pool consists of a fine microstructure, while the boundary consists of a coarse microstructure.

Figure 10 shows optical micrographs of the samples with the least relative densities built with the laser powers of 100 W and 150 W at scan speeds of 500 mm s\(^{-1}\) in the XY and XZ plane. Figure 11 shows the SEM micrographs of the same samples. Both micrographs reveal the presence of large cracks and pores. The large pores show powders that were not melted due to the high scan speed. Due to the high scan speed of 500 mm s\(^{-1}\) used, the melt pool could not be sustained and hence large pores in the form of keyhole pores and cracks were formed for both laser powers. In figure 10(a), the pores were larger due to the low applied laser power of 100 W. The laser energy input was not enough to melt the powders completely. However, the large pores were reduced in the case of the higher laser power of 150 W as shown in figures 10(b) and (c) and table 4. The melt pools as observed in all the samples have the same orientation as discussed in the case of 100 mm s\(^{-1}\) scan speed but the laser tracks show some kind of disconnections. The neighboring melt pools were not overlapped as in the 100 mm s\(^{-1}\) due to the large pores and cracks.

3.5. Effect of energy density on microstructural properties of parts

Table 3 and figure 12(a) show the result and plot of porosity against energy density at a constant laser power of 100 W respectively. The plot shows that at a low energy density of 13 J mm\(^{-3}\), porosity was at the highest with 36% due to large un-melted powders and no consolidation. Porosity decreases as the energy density increases. However, as energy density exceeded 100 J mm\(^{-3}\), and reached 400 J mm\(^{-3}\), porosity increases. At this point, keyhole pores and cracks were observed as seen in the micrograph in figures 6, 10 and 11. This result agrees with the study of AlSi10Mg by Read et al [37] which reported that when energy density was lower than 50 J mm\(^{-3}\), porosity was high due to no consolidation. However, they stated that porosity decreases with an increase in

![Figure 10. Optical micrographs for samples with the least relative densities built with (a) 100 W/500 mm s\(^{-1}\), (XY plane (b) 150 W/500 mm s\(^{-1}\), (XY plane (c) 150 W/500 mm s\(^{-1}\), Z-direction.](image-url)
energy density, but when the energy density exceeds 60 J mm$^{-3}$, there is a scattering of the porosity till it reached 120 J mm$^{-3}$. They observed the formation of keyhole pores and defects in the material which was attributed to vaporization.

The result and plot of porosity against energy density at a constant power of 150 W are shown in table 3 and figure 12(b) respectively. The plot shows that porosity decreases with an increase in energy density. The maximum porosity content of 16.14% was observed in the sample of 500 mm s$^{-1}$ scan speed with the least energy density of 20 J mm$^{-3}$. This is a more than 100% reduction in the pore content compared to the case of 100 W constant laser power. The lowest pore content was found in the sample of 100 mm s$^{-1}$ scan speed having
a maximum energy density of 600 J mm\(^{-3}\). This may be attributed to the higher laser power and low scan speed which amounted to the high energy density achieved. Therefore, increasing laser energy density decreases the percent porosity.

### 3.6. Micro hardness of as-built 7075 alloys by SLM

The hardness of as-built 7075 alloys by SLM was measured to determine the level of alloy’s resistance to plastic deformation [38]. Hardness is also the degree to which a material can resist surface indentation [39]. The hardness value was measured from the XY plane. Hardness test was conducted on the densest sample of the as-built 7075 alloys using Vickers hardness testing machine and the test yielded an average value of 93.5 HV. This value is low compared with the standard value of 175 HV for Al7075-T6. The reasons for the low value may be due to some cracks found in the sample by optical microscopy, and the absence of silicon in the chemical composition of the alloy. The presence of silicon causes a reduction in the melting temperature and assist in the processing of materials by SLM and as a result, enhanced fluidity [40]. However, the hardness value is 25.5 HV higher than that reported by Kempen [8] in a study of SLM 7075 wrought aluminum alloy. A lower hardness value of 80.2 HV has been reported for 7075 aluminum alloy processed by high-pressure die casting [41]. This casting method has been regarded to produce better mechanical properties. However, the result of SLM 7075 parts showed better properties as compared with a 13.5 HV difference. Similar results were obtained by Kempen [8] who found that the Vickers hardness value of Al366.0 built by SLM was 30 HV higher than that of the high pressure die casting.

Sistiaga et al [40] reported a micro hardness value of about 130 HV for as-built Al 7075 aluminum alloy processed by SLM with 0.727% silicon content. The alloy was processed with a laser power of 300 W and a scan speed of 1000 mm s\(^{-1}\) by a developed LM Q machine. The high hardness value may be attributed to the silicon content and the used process parameters. According to their study, silicon additions improved the hardness of the alloy. The highest hardness value of 159 ± 9 HV was also obtained with a silicon content of 4% with no cracks which is 30 HV lower than conventional Al7075-T6. Although, it was reported that high numbers of cracks were present in the samples with 1 and 2% silicon addition and was stated to be the reason for their low hardness when compared with the standard value of 175 HV for Al7075-T6. Therefore, it can be concluded that a certain amount of silicon additions to 7075 alloy increases the hardness of the alloy.

The Relationship between relative density and hardness was also investigated and the result displayed in table 5 and figure 13 for samples built with laser power of 150 W. It could be observed from table 5 and figure 13 that as relative density increases, hardness also increases. This is because denser material contains fewer pores and hence a harder material.

### 3.7. Effects of heat treatments on the hardness of 7075 alloys by SLM

Since Al7075 alloy is found in the T6 condition, T6 heat treatment was performed on the alloy to improve the hardness property. Heat treatment has been shown to be a method of improving the mechanical properties of aluminum alloys. Hardness is also a verification of heat treatment. Based on the earlier discussed study that higher hardness is obtained from higher densities, the sample having the highest relative density was heat treated to study the improvement on the hardness. The average hardness value obtained after eight measurements from the XY direction was 90.7 HV (table 5). Surprisingly the hardness value decreased instead of it to increase when compared to the as-built sample value (table 5). The decrease may be attributed to over-aging of the alloy especially with the percentage of silver in the alloy. It has been reported that heat treatment of 7075 alloys with silver additions reduces the process of precipitation and achieves high mechanical properties within a short time [42]. Xu et al [32] observed in a study of cast 7075 alloys after T6 treatment, that the micro-hardness decreases after hardening beyond the above period of hours for which the peak micro-hardness values were obtained and it was attributed to over aging. The highest hardness obtained in their study was with the sample having the highest percentage of silver which was attained within the shortest aging period of 12 h. The decrease in hardness also confirmed the study reported by Sistiaga et al [40] after applying a modified T6 (solution treatment at 470 °C for 2 h, water quenched, and aged at 150 °C for 6 h) heat treatment on Al7075 aluminum.

| Scan speed (mm s\(^{-1}\)) | Relative density (%) | Hardness (HV) of as-built 7075 alloy sample (before heat treatment) | Hardness (HV) of sample after T6 heat treatment |
|---------------------------|----------------------|-------------------------------------------------|-----------------------------------------------|
|                           |                      | 93.5                                            | 90.7                                          |
| 100                       | 99.8                 | 83.4                                            | —                                             |
| 200                       | 99.0                 | 76.4                                            | —                                             |
| 300                       | 98.0                 | 75.4                                            | —                                             |

Table 5. Result of hardness at selected scan speed for laser power of 150 W.
They observed a significant decrease in hardness from 130 HV to about 120 HV when compared to the as-built sample with 0.727% silicon content. They attributed the decrease in hardness to solid solution treatment applied to the alloy. They explained that the ‘fine cellular dendritic’ microstructure formed by SLM was dissolved during solid solution treatment leading to deterioration in the mechanical properties. It was concluded that the solid solution treatment of Al7075 alloy should not be employed for the purpose of increasing the hardness except for stress relief. Instead, aging treatment be employed since it shows increase hardness.

Dayo et al (2013) [43] in agreement with Sistiaga et al [40] reported that age-hardened cast 7075 alloy yields higher hardness due to MgZn2 phases that are coherent and finely dispersed. It was stated that the precipitates obstruct dislocation movements and are formed when aged artificially.

3.8. Effects of scan speed on the hardness

Artificial aging to room temperature yields higher hardness since it is a gradual process of cooling, unlike solution treatment that is cooled quickly by quenching [43]. It has been reported for SLM of steel that at higher scan speeds, the cooling rate is high and micro hardness decreases at a fixed laser power [44]. Table 5 shows hardness results at selected scan speed for the laser power of 150 W and the values are plotted in figure 14 to further illustrate the relationship between scan speed and hardness for the densest sample and to study the effect of solidification rate on hardness. The result in figure 14 indicates that as scan speed increases, hardness

![Figure 13. Showing the relationship between hardness and relative density.](image1)

![Figure 14. Relationship between hardness and scan speed.](image2)
decreases and the highest value of hardness can be achieved at lower scan speeds i.e. 100 mm s\(^{-1}\). This trend is also similar to that of the relative density because at higher scan speeds, porosities increase leading to low relative densities and consequently lower hardness. At the highest scan speed of 500 mm s\(^{-1}\), hardness could not be successfully performed due to high porosities. This is similar to observation on mar-aging steel reported by Kempen [8]. It was observed that at higher scan speeds, there were a very high number of pores which led to the inability to perform correct hardness measurements. The high rate of cooling due to high scan speed decreases the strengthening phase of precipitation resulting in a decrease in hardness [44].

4. Conclusion

The 7075 aluminum alloy composed of Al, Zn, Mg, Ag, Cu, and O was used in this research to build parts by SLM technology. The effect of process parameters such as laser power, scan speed and hatch distance on densification behavior, microstructural properties, and hardness of the SLM made parts have been investigated. The effect of heat treatment on SLM made samples was also studied after the samples were subjected to T6 heat treatment. The result shows that the highest relative density can be achieved with higher laser power and lower laser scan speed and hatch distance due to a significant reduction in the number of pores. Two major types of pores including metallurgical and keyhole pores have been identified with the keyhole pores dominating the samples processed by low laser power of 100 W. The keyhole pores increase in size at a high scan speed and hatch distances. By using higher laser power of 150 W, the keyhole pores reduced significantly while metallurgical pores appear. The hardness test conducted on the densest sample of the as-built 7075 alloys using the Vickers hardness testing machine yielded an average value of 93.5 HV. The hardness value decreased to a value of 90.7 HV when the sample was subjected to T6 heat treatment which is an indication that it is not a perfect option for increasing hardness but may be employed for stress relief. The result of an investigation carried out on the effect of scan speed on the hardness of the as-built samples shows that hardness decreases as scan speed increases and the highest value of hardness can be achieved at lower scan speeds i.e. 100 mm s\(^{-1}\).

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