Microstructure evolution and mechanical property response via 3D printing parameter development of Al–Sc alloy

Kuo, C. N.; Chua, Chee Kai; Peng, P. C.; Chen, Y. W.; Sing, Swee Leong; Huang, Sheng; Su, Y. L.

2020

Kuo, C. N., Chua, C. K., Peng, P. C., Chen, Y. W., Sing, S. L., Huang, S., & Su, Y. L. (2020). Microstructure evolution and mechanical property response via 3D printing parameter development of Al–Sc alloy. *Virtual and Physical Prototyping*, 15(1), 120-129.
doi:10.1080/17452759.2019.1698967

<https://hdl.handle.net/10356/145906>

<https://doi.org/10.1080/17452759.2019.1698967>

This is an Accepted Manuscript of an article published by Informa UK Limited, trading as Taylor and Francis in *Virtual and Physical Prototyping* on 3 Dec 2019, available online:
<http://www.tandfonline.com/10.1080/17452759.2019.1698967>

Downloaded on 26 Apr 2023 17:45:58 SGT

Microstructure Evolution and Mechanical Property Response via 3D Printing Parameter Development of Al-Sc Alloy

Abstract

3D printed Sc-modified Al alloy by Powder Bed Fusion (PBF) performs significant strength and ductility without hot tearing during process. This kind of 3D-printable high specific strength material exhibits great potential in lightweight applications. Due to the less design limitation through 3D printing process, the degree of lightweight is greatly affected by the specific strength of the materials. Hence, to further improve the mechanical properties of the material through process optimization or post treatment is of great importance. Microstructure feature variations due to different processing parameters are well known for traditional process and materials. This study explores the parameter microstructure performance relationship of 3D printed Sc-modified Al alloys from the perspective of melting pool interactions. According to stress concentration effect and Hall-Petch effect, the mechanical properties of the 3D printed materials vary greatly depending on the differences in defect size, shape, and grain size.

Keywords: powder bed fusion; selective laser melting; additive manufacturing; Al-Sc alloy; mechanical property

1. Introduction

Generally, there are two ways to fabricate lightweight products, one is to introduce the materials exhibit high specific strength and the other one is to introduce the design with lightweight structure. However, it is very hard to achieve these two approaches at the same time by traditional processes. With the development of the additive manufacturing technology, materials that are difficult to be manufactured by traditional processes are re-emerging and playing a pivotal role in lightweight issues (Chua, Leong, and Lim 2010; Gibson, Rosen, and Stucker 2010; Liu et al. 2016; Zhao et al. 2016; N. Sudarmadji 2011; Murr 2017; S.Y. Chen 2018). Additive manufacturing technology, also known as rapid prototyping technology, is mainly divided into Rapid Prototyping (RP) technology and Rapid Manufacturing (RM) technology. The most well-known characteristics of additive manufacturing technology are the customized production and small amount of diverse production (Chua, Leong, and Lim 2010; Gibson, Rosen, and Stucker 2010; Liu et al. 2016; Zhao et al. 2016; N. Sudarmadji 2011; Murr 2017; S.Y. Chen 2018). The most widely used method for fabricating metal products is powder bed fusion (PBF) method. And there are two powder bed fusion method which are laser powder bed fusion (LPBF) and electron beam powder bed fusion (EBPBF) (Chua, Leong, and Lim 2010; Gibson, Rosen, and Stucker 2010; Liu et al. 2016; Zhao et al.

2016; N. Sudarmadji 2011; Murr 2017; S.Y. Chen 2018).

Thanks to the maturity of 3D printing technology, porous materials of metal porous structure could be well controlled and realized. The metal porous structure is a very common special structural material (Yang et al. 2015; Murr et al. 2012; Yan et al. 2015; Liu et al. 2016; Weißmann et al. 2016), which simultaneously exhibits high strength, light weight characteristics, and good thermal resistance (Nakajima 2007; Evans et al. 2001; Li et al. 2014; Tan et al. 2017). The metal porous structure could be divided into stochastic porous structures and periodic cellular lattice structures, in which the periodic cell lattice structure could exhibit better material properties at the same volume fraction (Evans et al. 2001; Cansizoglu et al. 2008). Moreover, the porous materials fabricated by 3D printing technology are widely used in high-end engineering products such as vehicles parts, aerospace parts and medical implants (Zhou, Shrotriya, and Soboyejo 2004; W.Y. Yeong 2004; X. Wang 2016; S.A. Khairallah 2016; D. Herzog 2016)

At the mean time, advanced lightweight materials 3D printing process/parameter R&D is also received attention by global researchers. One of the advanced lightweight materials that global researchers are focusing on is Al-Sc alloy, or so called Scalmalloy. In the Al alloy system with the alloying elements (Cu, Mg, Zn, Si), hot tearing usually happened during solidification due to the large solidification ranges that promoted by these elements. By adding small amount of Sc, the Al_3Sc phase nucleated at high temperature and provide lots of nucleation sites and thus limited the formation of columnar grain and hot tearing during cooling as well (Schmidtke et al. 2011; Jäggle et al. 2016). Due to the fine grain size and precipitation strengthening effect, Al-Sc alloy exhibit high strength and high ductility (Schmidtke et al. 2011).

Since the high strength of Al-Sc alloy is contributed by the fine grain size and precipitation strengthening effect, the strength could be further improved if the initial grain size can be finer via the 3D printing parameter optimization by exploring the relationship between parameter-microstructure-performance. To explore the relationship between the parameter, defect, microstructure, and mechanical properties of the 3D printed materials, three selected parameter were selected to fabricate advanced lightweight Al-Sc alloy by laser powder bed fusion (LPBF) technology. The defect/microstructure evolution and relative mechanical response via the change of 3D printing parameter of such materials was examined and discussed carefully.

2. Experimental Procedure

2.1 Materials

Pre-alloyed Al-Sc (Scalmalloy) powder was provided by Heraeus Group and Circle Metal Powder Co., Ltd. The powder size ranges mainly from 20 to 63 μm , and the powder shape is spherical. The chemical composition is shown as [Table 1](#).

2.2 Laser Powder Bed Fusion

All of the samples of this study were manufactured by laser powder bed fusion method using a Renishaw AM400 system. Before the process, the vacuum is drawn to about 1×10^{-2} torr, and the Ar protective atmosphere is backfilled to about one atmosphere. The maximum power of the laser can reach about 400 W, and the scanning rate can reach up to about 2 m/s, spot size is about 70 μm , the thickness of each layer of metal powder is about 30 μm , and the maximum manufacturing size is about $25 \times 25 \times 30 \text{ cm}^3$. Taking Al-Sc alloys as an example, the building rate is about 5-20 cm^3/hour . In this study, no post heat treatment has been conducted on the as-built Al-Sc sample.

2.3 Microstructure Analysis

To observe the micro-sized defects and the microstructure carefully, the scanning electron microscopy (SEM, JEOL JSM-6330) and electron backscattered diffraction (EBSD, Zeiss Supra 55) were introduced. Before the SEM observation, all of the samples were grinded and polished carefully. For the EBSD examination, the samples were electro-polished after mechanical grinding and polishing.

2.4 Tensile Test

The 3D printed Al-Sc alloy samples by LPBF were prepared for the tensile testing, which was performed by an Instron 5582 universal testing machine at room temperature under a strain rate of $1 \times 10^{-4} \text{ s}^{-1}$. Before tensile test, all of the samples were grinded and polished carefully. The tensile testing of 3D printed Al-Sc alloy samples have been carried out for at least 3 times, and all the mechanical properties are measured with tensile stress-strain curve.

3. Results and Discussion

3.1 Parameter Development

In this study, the main objective of parameter development is to decrease the size and

volume fraction of micron-sized defect and decrease the average grain size of 3D printed Al-Sc alloy. To determine the microstructure feature and related mechanical properties, cubic samples with 1*1*1 cm³ for parameter study (Fig. 1) and tensile test samples refer to ASTM E8 standard were fabricated. The tensile test samples were wire cut and grinded carefully to remove the uneven surface due to powder attachment during 3D printing process(Fig. 2).

To explore the relationship between parameter-microstructure-performance, three parameters were choose for further research after the 3D printing parameter R&D, which are:

1. Al-Sc-O: the optimized parameter which exhibit highest densification and finer average grain size.
2. Al-Sc-L: the parameter with less overlap between nearby melting pool due to same scan speed and 200% hatch distance compared to optimized parameter.
3. Al-Sc-S: the parameter with smaller melting pool size due to 200% scan speed and same hatch distance compared to optimized parameter.

The three choose parameters in detail were shown in Table 2.

3.2 Observation of Micron-Sized Defects

To investigate the inference of parameter on micron sized defects, all of the samples built by the three parameters (3 samples for each parameter) were examined by SEM, the SEM images were shown in Fig.3 and Fig. 4. According to the observation of Fig. 3(a) and Fig. 4(a), there were only few micron sized defects in the Al-Sc-O sample. And the largest observed defect size was about 31.4 μm. Meanwhile, the shape of the micron sized pore was approximately spherical. In comparison, numinous micron sized defects were found in the samples of Al-Sc-L and Al-Sc-S, as shown in Fig. 3(b-c) and Fig. 4(b-c). The largest observed defect size in Al-Sc-L and Al-Sc-S were about 71.9 μm and 305.1 μm, respectively. Moreover, there were approximately spherical and irregular shape micron sized pore in Al-Sc-L sample and there were only irregular shape micron sized pore in Al-Sc-S sample. All of the micron sized defect feature are summarized in Table 3.

The density of all samples were measure by Archimedes method to explore the relationship between the parameter and densification of the 3D printed alloy. The densification of the 3D printed samples was calculated according to the following formula:

$$\varepsilon = (\rho/\rho_s) \times 100 , \quad (1)$$

where ρ and ρ_s are the density of the 3D printed sample and the theoretical density. The theoretical density of Al-Sc alloy is 2.67 g/cm³. The measured density and calculated densification of the samples built by the three parameter are summarized in Table 3.

According to the observation of micron-sized defects and the density measurement results, the pore size, pore shape, density and calculated densification of each samples are quite different. The difference in pore size and density came from the different interaction between the nearby melting pool, as shown in Fig. 5. In the sample built by optimized parameter (Al-Sc-O), there existed perfect combination between the melting pool size and distance, as shown in Fig. 5(a). And thus almost no defects were observed in the Al-Sc-O samples. In comparison with the optimized parameter, the Al-Sc-L parameter exhibits same energy input (same scan speed and power), and thus the melting pool size should be almost the same with the optimized sample. However, since the hatch distance is larger than the optimized one and thus the overlapping between the nearby melting pool is less than that in optimized sample and thus there existed pore/unmelted region between melting pools nearby, as shown in Fig. 5(b). On the other hand, Al-Sc-S parameter exhibits less energy input (same power but lower scan speed). Hence, the energy density and melting pool size are smaller than that in optimized sample. Therefore, even the hatch distance in Al-Sc-S parameter is the same as that in Al-Sc-O parameter, there existed more and larger pores/unmelted regions between melting pools nearby, as shown in Fig. 5(c).

Due to the difference in the melting pool size and interaction between the melting pool nearby, the pore size and densification of these three samples are quite different and it may affect the mechanical properties following the concept of Gibson and Ashby model and stress concentration. In general, the densification would affect the Young's modulus and yield stress following Gibson and Ashby model(Gibson and Ashby 1982) which shown below:

$$E/E_s = C_1(\rho/\rho_s)^2 \quad (2)$$

$$\sigma_{pl}/\sigma_s = C_2(\rho/\rho_s)^{1.5}, \quad (3)$$

where E is the elastic modulus of the porous structure, E_s is the elastic modulus of the open-cell edge (ligament) material, σ_{pl} is the plateau stress of the porous material, σ_s is the yield strength of the ligament material, ρ is the density of the fabricated materials, ρ_s is the theoretical density, and C_1 and C_2 are the constant varied with different materials and porous structure.

On the other hand, the pore size and shape would affect the elongation following the stress concentration effect. The stress concentration factor (K_t) is used to quantify how concentrated the stress is in a material, and it is calculated by the formula below (W.D. Pilkey 2008):

$$K_t = 1 + 2 \sqrt{\frac{d}{\rho}} \quad (4)$$

where d is the depth of the notch and ρ is the radius of the notch. And the elongation of tested materials usually decreases with the increasing of K_t . The effect of Gibson and Ashby model and stress concentration on mechanical properties will be discussed in section 3.4.

3.3 Observation of Microstructure Feature

The EBSD images of the samples built by the three parameters were shown in Fig. 6. The trace of melting pools can be obviously observed in the EBSD results. According to the EBSD results, there were micron-sized and submicron-sized grains due to the temperature gradient and cooling rate difference from the surface to inside of the melting pools. The submicron-sized grains showed up in darker regions and the micron-sized grains showed up in the regions with colors. To clearly observe the grain size change due to the parameter change, the enlarged EBSD images had been taken, as shown in Fig. 7. The grain size and volume fraction of the micron-sized grains and submicron-sized grains were measured by line intercept method (over 30 lines of each samples), and the results were summarized in Table 4. In the Al-Sc-O samples, the grain size and volume fraction of micron-sized grains was about 2.16 μm and 51.04 % while the grain size and volume fraction of submicron-sized grains was 0.40 μm and 48.96 %. In the Al-Sc-L samples, the grain size and volume fraction of micron-sized grains was about 2.40 μm and 65.00 % while the grain size and volume fraction of submicron-sized grains was 0.40 μm and 35.00 %. In the Al-Sc-S samples, the grain size and volume fraction of micron-sized grains was about 3.72 μm and 78.89 % while the grain size and volume fraction of submicron-sized grains was 0.44 μm and 21.11 %. The average grain size of the three samples was calculated by the grain size and volume fraction of micron-sized grains and submicron-sized grains, which were 1.30 μm (Al-Sc-O sample), 1.70 μm (Al-Sc-L sample), and 3.03 μm (Al-Sc-S sample), respectively.

In the EBSD and grain size measurement results, the grain size of micron-sized grains of Al-Sc-O sample was much smaller than the other two samples. Meanwhile, the volume fraction of submicron-sized grains of Al-Sc-O sample was much higher than the other two samples. The smaller grain size of micron-sized grains and higher volume fraction of submicron-sized grains were caused by the higher cooling rate during the process according to

the remelting zone size and spacing affected by 3D printing parameter. The Schematic illustration of the relationship between the parameters, remelting zone size and spacing of the three samples is shown in Fig. 8. In Fig. 8(a), there existed larger remelting zone size and thus wider the area around the surface of melting pool where contacted the lateral and vertical printed solid parts with higher thermal conductivity and reduced the contacted area with the powders with lower thermal conductivity.

In Fig. 8(b), there exists smaller lateral remelting zone due to the 200% hatch distance in Al-Sc-L sample, and thus the contact area with the higher thermal conductivity solid parts is reduced compared to the Al-Sc-O sample. Hence, cooling rate in Al-Sc-L sample was lower than the Al-Sc-O sample and thus the grain size of the micron-size grains was larger in Al-Sc-L sample. Moreover, the spacing of the remelting zone is much higher in Al-Sc-L sample than in Al-Sc-O sample, since the submicron-sized grains showed up on the cooled surface of melting pool, higher spacing of the remelting zone or larger hatch distance means that the repeat-occurrence number within a fixed distance of the submicron-sized region in Al-Sc-L sample is less than that in Al-Sc-O sample. Therefore, the volume fraction of the submicron-sized grains in Al-Sc-L sample is less than that in Al-Sc-O sample.

In Fig. 8(c), there exists smallest lateral and vertical remelting zone due to the smaller melting pool in Al-Sc-S sample. Hence, the contact area with the higher thermal conductivity solid parts in Al-Sc-S sample is smallest compared the other two samples. Therefore, the cooling rate of Al-Sc-S sample was lowest and thus the grain size of the micron-size grains was largest. Meanwhile, the repeat-occurrence number within a fixed distance of the submicron-sized region in Al-Sc-S sample is less than that in Al-Sc-O sample as well. And it means that the fraction of the submicron-sized grains in Al-Sc-S sample is less than that in Al-Sc-O sample. Due to the Al-Sc-S sample exhibits smallest contact area with solid parts and less repeat-occurrence number of the submicron-sized region, the average grain size was higher than the other two samples.

3.4 Mechanical Properties

To explore the relationship between parameter-microstructure-performance, all of the samples were tested by universal testing machine under tensile mode under a slow strain rate of $1 \times 10^{-4} \text{ s}^{-1}$. The strain-stress curves of the samples with three different parameter are shown in Fig. 9. All the 3D printed Al-Sc samples were tested for at least 3 times until mechanical fracture occurred. The mechanical properties with yield stress (0.2% offset), Young's modulus and elongation are listed in Table 5.

From Fig. 9 and Table 5, it can be seen that all of the samples exhibit similar Young's modulus but different in yield stress and elongation. The Young's modulus only scatters marginally from 72.07 to 72.11 GPa. According to Gibson and Ashby model, Young's modulus can be affected by the variation of densification. In Table 3, the densification of these high dense samples only scatters marginally from 98.16% to 99.85%, it means the difference in densification is only 1.69% and thus the Young's modulus variation followed Gibson and Ashby model is very limited.

The yield stress increases from 269.04, 282.56, to 286.94 MPa (an increment of 5.0% and 6.7%) with 3D printing parameter variation from Al-Sc-S, Al-Sc-L, to Al-Sc-O, respectively. Following the Gibson and Ashby model, yield stress can be affected by the variation of densification as well. However, the yield stress affected by densification should be very limited since the densification difference is only 1.69%. On the other hand, the yield stress can also be affected by grain size followed the empirical relationship of Hall-Petch effect which shown below (Kim et al. 2013; Sanaty-Zadeh 2012):

$$\sigma_{GR} = \sigma_0 + \frac{k_y}{\sqrt{d}} \quad (5)$$

where σ_{GR} is the strength of materials, σ_0 is the yield strength of a single crystal in absence of any strengthening mechanisms except the solid solution effect, d the average grain size and k_y is a constant depending on the materials. Meanwhile, in Table 4, the grain size decreases from 3.03 μm , 1.70 μm , to 1.30 μm with 3D printing parameter variation from Al-Sc-S, Al-Sc-L, to Al-Sc-O. The grain size change is obvious and thus it should be the key factor that affects the variation of yield stress of the 3D printed Al-Sc alloys in this study.

The elongation of these samples built by different parameter increases from 11.59%, 14.44%, to 18.39% (an increment of 24.6% and 58.7%) with 3D printing parameter variation from Al-Sc-S, Al-Sc-L, to Al-Sc-O, respectively. The obviously variation in elongation should be contributed by the pore size and shape followed the stress concentration factor. In Table 3, the max pore size decreases from 305.1, 71.9, to 31.4 μm (size differences are about 424.3% and 971.7%) with 3D printing parameter variation from Al-Sc-S, Al-Sc-L, to Al-Sc-O, respectively. The serious difference in pore size would serious affect the deformation stability during the plastic deformation. Meanwhile, the pore shape changes from irregular, spherical and irregular, to near spherical with 3D printing parameter variation from Al-Sc-S, Al-Sc-L, to Al-Sc-O, respectively. According to the concept of stress concentration effect, the radius of the notch would greatly affect the stress concentrated at the tip of notch. And thus the stress concentration factor of Al-Sc-S sample is much larger than that of Al-Sc-O sample on the

basis of great difference in pore size (971.7% in difference) and shape (irregular to near spherical).

4. Conclusion

The Al-Sc alloy were successfully fabricated by 3D printing via the laser powder bed fusion (LPBF) technology. Meanwhile, the relationship between parameter-microstructure-performance was explored. The following conclusions can be drawn.

1. The defect and microstructure evolution related to the interaction of melting pool can be predicted and controlled by change the process parameter.
2. The pore size (31.4 to 305.1 μm), shape (near spherical to irregular), and densification (98.16 to 99.85%) can be varied by changing the melting pool size and overlapping between melting pools nearby. According to stress concentration effect, such difference would affect the ductility of printed materials serious (18.39 to 11.59%).
3. The grain size difference of as built samples can be large as 233.1% (1.30 to 3.03 μm) via change the remelting zone size and spacing. According to Hall-Petch effect, the yield stress of printed materials would be affected (286.96 to 269.04 MPa).

Acknowledgments

The authors gratefully acknowledge the support from sponsorship from Ministry of Science and Technology of Taiwan, ROC, under the project No. MOST 108-2218-E-468-001 and MOST 107-2218-E-468-002. Meanwhile, the authors are thankful for the support from Heraeus Group and Circle Metal Powder Co., Ltd..

References

- Cansizoglu, O, O Harrysson, D Cormier, H West, and T Mahale. 2008. "Properties of Ti–6Al–4V non-stochastic lattice structures fabricated via electron beam melting." *Materials Science and Engineering: A* 492 (1-2):468-74.
- Chua, Chee Kai, Kah Fai Leong, and Chu Sing Lim. 2010. *Rapid prototyping: principles and applications*: World Scientific.
- D. Herzog, V. Seyda, E. Wycisk, C. Emmelmann. 2016. "Additive manufacturing of metals." *Acta Mater.* 117:371-92.
- Evans, Anthony G, John W Hutchinson, Norman A Fleck, MF Ashby, and HNG Wadley. 2001. "The topological design of multifunctional cellular metals." *Progress in Materials Science* 46 (3-4):309-27.
- Gibson, Ian, David W Rosen, and Brent Stucker. 2010. *Additive manufacturing technologies*: Springer.
- Gibson, L. J., and M. F. Ashby. 1982. "The Mechanics of Three-Dimensional Cellular

- Materials." *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences* 382 (1782):43-59.
- Jäggle, Eric. A., L. Lu, L. Wu, and D. Raabe. 2016. "Alloy design for Additive Manufacturing." In, 1-43.
- Kim, Chang-Soo, Il Sohn, Marjan Nezafati, J. B. Ferguson, Benjamin F. Schultz, Zahra Bajestani-Gohari, Pradeep K. Rohatgi, and Kyu Cho. 2013. "Prediction models for the yield strength of particle-reinforced unimodal pure magnesium (Mg) metal matrix nanocomposites (MMNCs)." *Journal of Materials Science* 48 (12):4191-204. doi: 10.1007/s10853-013-7232-x.
- Li, S. J., Q. S. Xu, Z. Wang, W. T. Hou, Y. L. Hao, R. Yang, and L. E. Murr. 2014. "Influence of cell shape on mechanical properties of Ti-6Al-4V meshes fabricated by electron beam melting method." *Acta Biomaterialia* 10 (10):4537-47.
- Liu, Y. J., S. J. Li, H. L. Wang, W. T. Hou, Y. L. Hao, R. Yang, T. B. Sercombe, and L. C. Zhang. 2016. "Microstructure, defects and mechanical behavior of beta-type titanium porous structures manufactured by electron beam melting and selective laser melting." *Acta Materialia* 113:56-67. doi: <http://dx.doi.org/10.1016/j.actamat.2016.04.029>.
- Murr, L.E. 2017. "Open-cellular metal implant design and fabrication for biomechanical compatibility with bone using electron beam melting." *J. Mech. Behav. Biomed. Mater.* 76:164-77.
- Murr, Lawrence E., Sara M. Gaytan, Diana A. Ramirez, Edwin Martinez, Jennifer Hernandez, Krista N. Amato, Patrick W. Shindo, Francisco R. Medina, and Ryan B. Wicker. 2012. "Metal Fabrication by Additive Manufacturing Using Laser and Electron Beam Melting Technologies." *Journal of Materials Science & Technology* 28 (1):1-14. doi: [http://dx.doi.org/10.1016/S1005-0302\(12\)60016-4](http://dx.doi.org/10.1016/S1005-0302(12)60016-4).
- N. Sudarmadji, J.Y. Tan, K.F. Leong, C.K. Chua, Y.T. Loh. 2011. "Investigation of the mechanical properties and porosity relationships in selective laser-sintered polyhedral for functionally graded scaffolds." *Acta Biomater.* 7:530-7.
- Nakajima, Hideo. 2007. "Fabrication, properties and application of porous metals with directional pores." *Progress in Materials Science* 52 (7):1091-173.
- S.A. Khairallah, A.T. Anderson, A. Rubenchik, W.E. King. 2016. "Laser powder-bed fusion additive manufacturing: physics of complex melt flow and formation mechanisms of pores, spatter, and denudation zones." *Acta Mater.* 108:36-45.
- S.Y. Chen, C.N. Kuo, Y.L. Su, J.C. Huang, , Y.C. Wu, Y.H. Lin, Y.C. Chung, C.H. Ng. 2018. "Microstructure and fracture properties of open-cell porous Ti-6Al-4V with high porosity fabricated by electron beam melting." *Mater. Charact.* 138:255-62.
- Sanaty-Zadeh, A. 2012. "Comparison between current models for the strength of particulate-reinforced metal matrix nanocomposites with emphasis on consideration of Hall–

- Petch effect." *Materials Science and Engineering: A* 531:112-8. doi: 10.1016/j.msea.2011.10.043.
- Schmidtke, K., F. Palm, A. Hawkins, and C. Emmelmann. 2011. "Process and Mechanical Properties - Applicability of a Scandium modified Al-alloy for Laser Additive Manufacturing." *Physics Procedia* 12:369-74.
- Tan, X. P., Y. J. Tan, C. S. L. Chow, S. B. Tor, and W. Y. Yeong. 2017. "Metallic powder-bed based 3D printing of cellular scaffolds for orthopaedic implants: A state-of-the-art review on manufacturing, topological design, mechanical properties and biocompatibility." *Materials Science and Engineering C* 76:1328-43.
- W.D. Pilkey, D.F. Pilkey. 2008. *Peterson's Stress Concentration Factors*: John Wiley & Sons.
- W.Y. Yeong, C.K. Chua, K.F. Leong, M. Chandrasekaran. 2004. "Rapid prototyping in tissue engineering: challenges and potential." *Trends Biotechnol.* 22:643-52.
- Weißmann, Volker, Rainer Bader, Harald Hansmann, and Nico Laufer. 2016. "Influence of the structural orientation on the mechanical properties of selective laser melted Ti6Al4V open-porous scaffolds." *Materials & Design* 95 (Supplement C):188-97. doi: <https://doi.org/10.1016/j.matdes.2016.01.095>.
- X. Wang, S. Xu, S. Zhou, W. Xu, M. Leary, P. Choong, M. Qian, M. Brandt, Y.M. Xie. 2016. "Topological design and additive manufacturing of porous metals for bone scaffolds and orthopaedic implants: a review." *Biomaterials* 83:127-41.
- Yan, Chun Ze, Liang Hao, Ahmed Hussein, and Philippe Young. 2015. "Ti-6Al-4V triply periodic minimal surface structures for bone implants fabricated via selective laser melting." *Journal of the Mechanical Behavior of Biomedical Materials* 51 (Supplement C):61-73. doi: <https://doi.org/10.1016/j.jmbbm.2015.06.024>.
- Yang, Li, Ola Harrysson, Denis Cormier, Harvey West, Haijun Gong, and Brent Stucker. 2015. "Additive manufacturing of metal cellular structures: design and fabrication." *JOM* 67 (3):608-15.
- Zhao, Xiao Li, Shu Jun Li, Man Zhang, Yan Dong Liu, Timothy B. Sercombe, Shao Gang Wang, Yu Lin Hao, Rui Yang, and Lawrence E. Murr. 2016. "Comparison of the microstructures and mechanical properties of Ti-6Al-4V fabricated by selective laser melting and electron beam melting." *Materials & Design* 95:21-31. doi: <http://dx.doi.org/10.1016/j.matdes.2015.12.135>.
- Zhou, J, P Shrotriya, and WO Soboyejo. 2004. "On the deformation of aluminum lattice block structures: from struts to structures." *Mechanics of Materials* 36 (8):723-37.

Table 1 Summary of chemical composition of the pre-alloyed Al-Sc powder.

Element	Al	Mg	Sc	Mn	Zr	Fe	Si	other
wt. %	balance	4.49	0.71	0.51	0.27	0.07	0.03	<0.02

Table 2. Summary of the three 3D printing parameters used in this study.

Sample	Laser power (W)	Scan speed (mm/s)	Hatch Distance (mm)	Layer thickness (mm)	$E=P/vht$ (J/mm ³)
Al-Sc-O	200	500	0.05	0.03	266.7
Al-Sc-L	200	500	0.1	0.03	133.3
Al-Sc-S	200	1000	0.05	0.03	133.3

Table 3. Summary of defect size, defect feature, measure density, and calculated densification of the 3D printed Al-Sc samples with different processing parameters.

Sample	Max pore size (μm)	Pore Shape	Density (g/cm ³)	Densification (%)
Al-Sc-O	31.4	spherical	2.666	99.85
Al-Sc-L	71.9	spherical and irregular	2.658	99.55
Al-Sc-S	305.1	irregular	2.621	98.16

Table 4. The grain size and volume fraction of micron-sized grains and submicron-sized

grains of the 3D printed Al-Sc samples with different processing parameters.

Sample	Micron-sized grains		Submicron-sized grains		Average grain size (μm)
	Grain size (μm)	Volume fraction (%)	Grain size (μm)	Volume fraction (%)	
Al-Sc-O	2.16	51.04	0.40	48.96	1.30
Al-Sc-L	2.40	65.00	0.40	35.00	1.70
Al-Sc-S	3.72	78.89	0.44	21.11	3.03

Table 5. Summary of tension mechanical properties of the 3D printed Al-Sc samples with different processing parameters.

Sample	Young's modulus (GPa)	Yield stress (0.2% offset) (MPa)	Elongation (%)
Al-Sc-O	72.07 $\pm$ 0.01	286.94 $\pm$ 6.23	18.39 $\pm$ 2.76
Al-Sc-L	72.11 $\pm$ 0.06	282.56 $\pm$ 18.87	14.44 $\pm$ 2.22
Al-Sc-S	72.07 $\pm$ 0.06	269.04 $\pm$ 15.72	11.59 $\pm$ 1.72

Fig. 1. Schematic illustration of the 3D printed Al-Sc alloy specimens for parameter development.

Fig. 2. Schematic illustration of the grinded tensile specimen of the 3D printed Al-Sc alloy, the size and geometry of the sample is referred to ASTM E8 standard.

Fig. 3. SEM images of (a) Al-Sc-O sample, (b) Al-Sc-L sample with $<100\ \mu\text{m}$ sized pores, and the (c) Al-Sc-S sample with $>100\ \mu\text{m}$ sized irregular pores.

Fig. 4. SEM images of (a) Al-Sc-O with $<50\ \mu\text{m}$ sized near spherical pores, (b) Al-Sc-L sample with $<100\ \mu\text{m}$ sized irregular pores, and the (c) Al-Sc-S sample with $>100\ \mu\text{m}$ sized irregular pores and unmelted powder in the pores.

Fig. 5. Schematic illustration of the relationship between the pore formation and melting pool size and distance affected by process parameters of (a) Al-Sc-O with optimized parameter, (b) Al-Sc-L with same scan speed and 200% hatch distance compared to optimized parameter, and the (c) Al-Sc-S with 200% scan speed (smaller melting pool size) and same hatch distance compared to optimized parameter.

Fig. 6. EBSD images of (a) Al-Sc-O sample, (b) Al-Sc-L sample, and the (c) Al-Sc-S sample, and the results show that the Al-Sc-O sample exhibits highest volume fraction of submicron-sized grain.

Fig. 7. Enlarged EBSD images focused on the micron-sized grain regions of (a) Al-Sc-O sample, (b) Al-Sc-L sample, and the (c) Al-Sc-S sample, and the results show that the micron-sized grain size of Al-Sc-O sample is smaller than the other two samples.

Fig. 8. Schematic illustration of the relationship between the parameters, remelting zone size and spacing of (a) Al-Sc-O with optimized parameter, (b) Al-Sc-L with same scan speed and 200% hatch distance compared to optimized parameter which results in smaller lateral remelting zone and larger spacing between two nearby melting pool, and the (c) Al-Sc-S with 200% scan speed and same hatch distance compared to optimized parameter which might results in smallest lateral and vertical remelting zone at the same time.

Fig. 9. Tensile stress-strain curves of the 3D printed Al-Sc specimens fabricated by LPBF with different parameters.