Research Article

Sun Zhonggang*, Ji Shuwei, Guo Yanhua, Lu Yichen, Chang Lili, and Xing Fei

**Microstructure evolution and mechanical properties of Hastelloy X alloy produced by Selective Laser Melting**

https://doi.org/10.1515/htmp-2020-0032
Received Apr 28, 2019; accepted Aug 16, 2019

**Abstract:** Selective laser melting (SLM) is considered as an important additive manufacturing (AM) technology which can fabricate parts with complex geometry. However, it is difficult to predict the optimal SLM-parameters of metallic materials. In this study, orthogonal experiments were designed to study the influence of SLM-process parameters on the density and fabricated quality of Hastelloy X superalloy. Moreover, the relationship between microstructure evolution and performance of deposited microstructure was studied after heat treatment. The laser power, scanning speed and energy density have a significant effect on the density of the fabricated parts. The optimal parameters for determining Hastelloy X are 250 W laser power, 500 mm/s scanning speed, 100 µm hatch space, and 30 µm layer thickness. The deposited microstructure is a lamellar microstructure in the horizontal direction and a columnar crystal in the longitudinal direction, and the microstructure is mainly martensite. After solid-solution and aging treatment, grain grows up. Martensite decomposes and the carbide M6C was precipitated during the aging process. The strength of the microstructure decreases slightly due to the growth of grain size.

**Keywords:** Hastelloy X alloy, laser selective melting, microstructure, heat treatment, mechanical properties

---

**1 Introduction**

Laser Selective Melting (SLM) is an additive manufacturing technology based on powder bed fusion. It is also a three-dimensional printing technology which directly processes from metal powder to solid objects. The theory is that the 3D objects can be processed with layered manufacturing. During this section, the digital part models are divided into space matrix. With 3D-CAD software producing data, the laser is controlled to scan and melt powder [1, 2]. Traditional casting process has some problems, such as slow cooling, some elements and second phase segregating, poor thermal processing, uneven organizations, unstable properties. In comparison with the traditional casting process, SLM is a promising manufacturing technology because it can manufacture complex structural metal parts with stable properties during production time. Nowadays it has already played an important role in various fields, such as aerospace, automobile, weaponry and healthcare industry.

Hastelloy X is a Nickel based super-alloy with 17%~20% high iron content. It mainly uses Cr and Mo to strengthen the alloy. Therefore, it has good hot and cold processing properties, oxidation and corrosion resistance. When under a high temperature range between 700–900°C, Hastelloy X alloy stays in a long creep strength and its density is 8.28 g/cm³ [3]. Compared to other similar types of super-alloys, Hastelloy X has higher specific strength and ductility. It has been mainly used to manufacture aeroengine combustor and others components. In traditional ways, components are manufactured by casting and forging. But these processes are excessively time consuming and complex components are difficult to manufacture. So it is meaningful to combine use SLM and for manufacture of super-alloy because laser melting can decrease cost and term time [4, 5].

Wang [6] first studied the SLM process of Hastelloy X, and the manufactured specimens with dense microstructure. However, during SLM, large temperature gradients would lead to serious residual thermal stress. Therefore, by
hot isostatic pressing treatment, good mechanical properties and quality are obtained.

Tomus et al. [7] investigated that the mechanism of crack formation with SLM of Hastelloy X, which is relative to hot tearing. Based on the thermodynamic calculations, Si and C element influenced the hot tearing seriously. Only thermal cycling was not enough to cause the formation of crack. Because of the thermal cycling stress, manufactured parts involved microcracks. Therefore, after SLM-process, the crack was caused by hot tearing and thermal cycling.

Tian et al. [8] compared different SLM-process parameters which influence on specimen’s surface roughness, such as different laser powers, scanning speeds, sloping angles, hatch spaces, layer thicknesses and scan contours. Therefore, the optimum combine of process parameters for up-skin and down-skin have been obtained.

Clark et al. [9] studied mechanical properties, number of cracks and dimensional accuracy of Hastelloy specimen which was manufactured by SLM. They have already found that the density of laser energy was the main influencing factor and obtain specimens whose density are more than 99.5% by improving process parameters. In china, the research direction of Hastelloy X is mainly about the properties of casting and welds.

Based on the necessity of manufacturing super-alloy complex components, it is necessary to develop the additive manufacturing of Hastelloy X systematically. In this paper, the effects of different SLM-process parameters on the density and mechanical property of the specimen are comprehensively studied. An optimum combination of SLM-process parameters of Hastelloy X is obtained. Afterwards, by appropriate heat treatment, the microstructure and mechanical property are improved.

2 Material and experimental procedures

In this experiment, Hastelloy X alloy powder whose particle size ranges from 15 to 53 µm was prepared by gas atomization. The average particle size is 42.4 µm. Figure 1 depicts the scanning electron microscope (SEM) image of powder. The powder’s degree of sphericity is high, which keeps above 90%. Most powder surfaces almost have no impurities to adhere, without satellite powder and elliptical powder [10]. It is suitable to be processed by SLM. Table 1 shows the chemical composition of Hastelloy X.

Renishaw SLM 3D printer (AM250) whose maximum fabricating size is 250 mm×250 mm×326 mm and maximum laser power is 400 W was used in the experiment.

![Image of SEM micrographs of Hastelloy X alloy powders.](image)

**Table 1:** The chemical composition of Hastelloy X powder.

| Element | Cr  | Fe  | Mo  | Co  | Si  | Mn  | C   | Ni  |
|---------|-----|-----|-----|-----|-----|-----|-----|-----|
| Wt (%)  | 21.0| 18.8| 9.2 | 1.03| 0.88| 0.9 | 0.09| Bal.|

It also has a room controlling gas and automatic powder delivering system. In order to relieve the heat stress during the printing process, Figure 2 depicts scanning strategy: part model was firstly layered sliced to certain thickness. Each layer was continued to be divided to several 5 mm×5 mm square area and printed respectively. Hatch space was 100 µm. Laser continuously scanned powder bed in at a 30% overlap rate. After one layer being processed, powder bed’s height dropped for a layer’s thickness. The laser scanned in a zigzag route with 67° rotation between layers to minimize residual thermal stress which was produced by repeating scanning the same area. During SLM process, the number of layers have a numerical relationship with hatch angle, which can be calculated by formula (1) [11]:

\[
N = \frac{360°}{\text{gcd}(a, 360°)}, \quad 0° < a < 360°
\]

Where \(a\) is hatch angle, \(\text{gcd}(a, 360°)\) is the minimum common divisor of \(a\) and 360°. For example, when \(a\) is 120°, it takes 3 layers when the laser scanning direction becomes the same as the initial layer’s direction. When \(a\) is 67°, \(N\) is 360. In this way, it takes 360 layers, which makes the overlapping times of laser scanning the least. Therefore, the relative density can be improved and residual thermal stress can be minimized.

During SLM process, the amount of oxygen was controlled under 0.1%. When SLM finished, the surface was under laser exposure solution so that the surface roughness and SLM-quality can be improved.
In this study, the substrate used is a standard carbon steel substrate whose size is 250 mm × 250 mm × 25 mm. Before used, the substrates’ surface were polished, sand-blasted and cleaned with ethanol. 10 mm × 10 mm × 10 mm test specimen were used for orthogonal experiment of different parameters.

After SLM, the SLM-alloy specimens’ density can be measured by Archimedes for three times in deionized water. Then the highest-density specimens were under heat treatment which included solid-solution and aging treatment. The SLM specimens were sealed into evacuated and argon-back-flushed quartz capsules, and were subjected to solid-solution and aging treatment. Three of the SLM specimens were only solid-solution treated at 1273 K (1000 °C), 1373 K (1100 °C) and 1473 K (1200 °C) respectively. During the solid-solution, specimens were heated from 873 K (600 °C) to the temperatures above. Afterwards, specimens were held at 1000 °C, 1100 °C and 1200 °C, respectively for 0.5 h followed by air cooling (AC). Another specimen was under 1200 °C-solid-solution and 850 °C-aging treatment. After held at 1473 K for 0.5 h, the specimen was air cooled(AC) to 1123 K (850 °C) followed by being held for 2 h. Afterwards, it was air cooled again.

Corroded with aqua regia (HNO₃ : HCl=1:3), the specimens can be observed under different amplification factor with Axiocam 105 color optical microscope (OM). scanning electron microscope (SEM) equipped with energy dispersive spectroscopy (EDS) detector was used to study the morphology and chemical composition of SLM-specimen. Then the microstructure transformation between different parameters and heat treatments was analyzed. The micro-hardness test was carried out on the cross section with a HVS-1000A microhardness tester under a load of 500 g for 10 s. The phrase composition’s transformation which was in deposited and heat-treated condition was analyzed after using a Smart Lab TM 3KW X-ray diffractometer. Then, the test specimen was designed, as shown in Figure 3, according to China GB/T228.1-2010 standard. The tensile properties of the deposited and heat-treated Hastelloy X tensile specimens at the room temperature were measured using an MTS E45-205 universal tensile tester. After fracture, the fracture morphology was observed by a JSM-6510 scanning electron microscope (SEM).

## 3 Results and discussions

### 3.1 The influence of SLM process parameters on Hastelloy X’s density

Using orthogonal experiment, the SLM process parameters are optimized. The influence extents and trends of different parameters on laser power and exposure time are studied. Layer thickness, hatch space and point distance are kept constant which are 30 µm, 100 µm and 65 µm respectively. 25 cube specimens with dimension of 10 × 10 × 10 mm³ are produced. Meanwhile, laser power is 200~400 W and power interval is 50 W. Exposure time is 70 µs~150 µs and time interval is 20 µs. After obtaining specimens, according to GB 3850-83 ISO 3369-1975(density sintered metal and cemented carbide density test method), density can be measured by Archimedes method. Quality M (in air) is measured firstly and then quality m (in water). Density ρ can be measured by formula (2):

\[
\rho = \frac{M - m}{m} \times \rho_1
\]

Figure 4(a) depicts that under different exposure time, the specimens’ density is relative to different laser power. From Figure 4(a), when the power is 200 W and 250 W, if the exposure time changes, the change of density is stable so that a high-density specimen can be obtained. When the power is more than 300 W, as the exposure time increases, the density mainly tends to keep falling (except 70 µs-exposure time). The density of specimen which is under the largest power (400 W/150 µs) is lowest. When the exposure time is very short, there are a large number of unmelted particles and holes, which influence the surface.
roughness and fabricating quality. When the laser power is enough, the powder can be entirely melted and form homogeneous surface. After powder being entirely melted, increasing the exposure time will magnify the dynamic viscosity of the melting pool, produce a balling phenomenon, and then affect the laser energy deposition of the latter layers [12–14].

Scan speed can be calculated by exposure time and point distance:

$$v = \frac{d}{t}$$  \hspace{1cm} (3)

where $v$ is the scanning speed (mm/s), $d$ is the point distance, and $t$ is the exposure time. Figure 4(b) depicts the relationship between scanning speed and density for different laser powers. When the scanning speed is low, the linear energy density is high. Moreover, when forming melting pool, the melting temperature is also high. However, the cooling time is long. As the effective laser power input increases, and the melting pool volume magnifies. It aggravates the evaporation of the material in the melting pool, which will affect the stability of the laser power scanning to the powder matrix and reduce the density of the specimen. When the scanning speed increases, the evaporation phenomenon weakens. As a result, the stability of the melting pool improves and the density of the obtained specimen also increases. As the scanning speed further increases, the linear energy input density and temperature of melting pool continuously decreases. Some alloy particles are not melted or in a semi-molten condition. Therefore, surface tension and melt viscosity increase with temperature decreasing, resulting in some defects such as pores. The fabricating quality of the specimens deteriorates. When the laser power is less than 300 W, a higher density can be obtained at a scanning speed of about 500 mm/s. On the contrary, when the laser power is larger than 350 W, a high-density specimen can be obtained at a scanning speed of about 900 mm/s. The curves where laser power is 200 W and 250 W are both relatively flat and the density is stable.

Energy density formula is:

$$E = \frac{pt}{hd}$$ \hspace{1cm} (4)

where $E$ is the energy density (J/cm$^2$), $p$ is the laser power, $t$ is the exposure time, $h$ is the hatch distance, and Figure 4(c) can be obtained. When the energy density ranges from 350 to 550 J/cm$^2$, the densities are generally higher than others. When the energy density is greater than 600 J/cm$^2$, the density tends to decrease obviously. It is mainly attributed to the phenomenon that the energy density ranging from 350 to 550 J/cm$^2$ is high enough to melt
the powder entirely. Further increasing the energy density leads to burning loss and corrugated surface, which hindered the powder recoating [15].

Figure 5 deposits the density of the specimens obtained under different laser power sweeps at different layer thicknesses at a scan speed of 500 mm/s. During the SLM process, laser scanning makes the previous layer or previous several layers to be remelted to form a melting pool. When the linear energy density is constant, the layer thickness mainly affects the remelting time and the homogeneous distribution of the melting pool. As the layer thickness decreases, the energy density for each layer increases and the remelting effect becomes more obvious. During this remelting procedure, some of the partial-melted powders are fully melted again. When melting pool solidifies, the number of pores which form in the interval of unmelted powder decrease. Therefore, the density increases as the layer thickness decreases.

### 3.2 Effect of SLM process parameters on hardness and surface quality of as-deposited Hastelloy X

Figure 6 depicts the relationship between energy density and microhardness at a layer thickness of 30 \( \mu \text{m} \). It reveals that when the energy density is 300-500 \( J/\text{cm}^2 \), the Vickers hardness is between 312 and 318 HV. When the energy density is less than 300 \( J/\text{cm}^2 \), due to limited laser energy input, a homogeneous melting pool cannot form. Therefore, the microhardness has decreased. When it is larger than 600 \( J/\text{cm}^2 \), the input energy density is too high, resulting in serious gasification inside the melting pool and a large number of small pores. Meanwhile, as the temperature of the melting pool increases during SLM, the cooling rate increases, leading to precipitation strengthening reduction [16]. With the precipitation strengthening phase decreasing, the microhardness decreases, which affects the hardness of the printed article, and the density also decreases.

Figure 7 and Figure 8 depicts the changes in surface roughness at different energy densities. When the energy density is 300 and 500 \( J/\text{cm}^2 \), due to the splashy powder on the surface and low energy density, there will be some partial unmelted powder after laser scanning. Therefore, surface roughness increases and sdr (interface expansion area ratio) becomes relatively larger. After the energy density reaching 700 \( J/\text{cm}^2 \), the energy output is too high so that the surface of melting pool is homogeneous by remelting. However, the microhardness is low.

### 3.3 Hastelloy X deposited microstructure after SLM

During SLM, laser scanning causes the previous one or several layers to be remelted to form a melting pool. As the laser power increases, the energy density increases. The influence of remelting becomes more obvious, and the melting track are more homogeneous. The microstructure of unheated Hastelloy X is like lamellar microstructure. At 1000-time magnification OM, it is found that during SLM, boundaries exist between the melt tracks. The stability of the boundary is lower than the middle area of the melt track. It is because the bonding force which is between the melting pools is weak. When under load in some certain conditions, melting pools and these boundary regions are
prone to cracks. In Figure 9(b), the laser energy output is insufficient. Therefore, a large amount of acicular martensite structure form at the edge of the laser scanning track because of partial melting of the powder and a faster cooling rate. In Figure 9(f), a regular and homogeneous particle phase is distributed on the laser scanning track. Since the energy output is too large, there is a small amount of crack in the middle of the melting track. The grain at the edge of the scanning track is subjected to heat extrusion. Due to the instability among the scanning tracks, distortion exists [17, 18]. This phenomenon depicts that the overlap rate is high enough; the microstructure of different regions is not stable enough. In Figure 9(d), it is filled with a large amount of lamellar matrix and a small amount of martensite microstructure whose morphology is more stable.

3.4 Hastelloy X heat treatment
microstructure evolution after SLM

The optimum laser selection melting process parameters for Hastelloy X were determined by a group of orthogonal experiments, as shown in Table 2.

Under the optimal parameters, the SLM-process specimen was prepared for the heat treatment experiment (solid-solution and aging treatment). Figure 10 depicts the evolution of microstructure after different heat treatments. After solid-solution at 1000°C (Figure 10(a)), the boundary line between the original melt tracks becomes vague. The equiaxed austenite grains with a size range of 5-20 µm appear. Many small-particle carbides are dispersed among the grains. Figure 10(c) depicts the microstructure after solid-solution at 1100°C. It is found that as the solid-solution temperature increases, the boundaries of grain become more obvious. Figure 10(e)(g) depicts that as the solid-solution temperature further increased, grains continue to grow to about 10-40 µm. The carbides dispersed in the original grains gradually decompose. After remelting...
Figure 9: Laser selected melted Hastelloy X sedimentary microstructure: (a) (b) 200 W sedimentary state (c) (d) 250 W sedimentary state (e) (f) 300 W sedimentary state.

Table 3: Element content of test point.

| Element | Ni   | Cr   | Mo   | Co  | Si  | C   | Fe  |
|---------|------|------|------|-----|-----|-----|-----|
| Wt (%)  | 27.1 | 16.03| 33.36| 0.98| 5.84| 11.15| 4.84|

ing in the grain, mini precipitates of polyhedrons are dispersed at the grain boundaries [19, 20]. It is reported that the chemical potential of solute elements may change due to high temperature. After dissolving and remelting, some of the carbides re-polymerize with solute elements form carbides and precipitate at the grain boundaries. In Figure 11(a) (b), it is obvious that there are granular precipitates at the grain boundary by EDS analysis. As shown in Table 3 and Figure 12, it is found that the precipitate is $M_6C$, a carbide with a high Mo content, which plays a role of dispersion strengthening.

Figure 10(b) and Figure 10(d) depict that the growth of the tissue in the Z-axis direction is columnar crystals. The length and width of the columnar crystals are about 50 μm and 10 μm, respectively. It is because the micro-melting pool solidifies rapidly. Moreover, during the solidification process, the grain growth tends to follow the direction of the negative temperature gradient. Remelting plays a role as a micro-heat treatment on the lower part of the columnar crystal. The structure of the previous deposited layer grows, and the previously deposited layer squeeze between the grains. The result is that the columnar crystal is twisted. After several layers being remelted, when the twisting force among grains is greater than the interlayer bonding force of a certain region, new columnar crystal will form. Therefore, the length of the columnar crystals is limited. It is impossible for columnar crystals to completely penetrate the entire specimen from the bottom to top [21]. As shown in Figure 10(f)(h), as the solid-solution temperature increases, the length of the columnar crystal in the Z-axis direction decreases but the width increases. $M_6C$ is continuously precipitated at the grain boundary. After solid-solution treatment, a specimen is designed to be
Figure 10: Laser selected melted Hastelloy X heat treated state microstructure: (a) (b) 1000°C solid-solution for 0.5 h (c) (d) 1100°C solid-solution for 0.5 h (e) (f) 1140°C solid-solution for 0.5 h (g) (h) 1200°C solid-solution for 0.5 h (i) (j) 1200°C solid-solution for 0.5 h + 850°C aging for 2.5 h.
Figure 11: Laser selective fused Hastelloy X 1200°C solid-solution for 0.5 h air-cooled XY plane microstructure SEM picture: (a) 3000 times (b) 4000 times.

Figure 12: EDS spectrum for test point.

Figure 13: Engineering stress-strain curve of the specimen after heat treatment at different temperatures, at a strain rate of 1 mm/min at room temperature.

3.5 Hastelloy X Mechanical properties after SLM

Figure 13 depicts the engineering of Hastelloy X tensile specimens' stress - strain curve after heat treatment at different temperatures. The tensile strength and yield strength of the as-deposited Hastelloy X alloy specimens are both strong, but the plasticity is relatively low. It is because the formation of fine grains in the laser selective area leads to fine-grain strengthening. Furthermore, a large amount of $M_6C$ small particle carbides distributed in the crystal give rise to dispersion strengthening and the improvement of the mechanical properties. Due to the internal stress, it is easy for tensile specimen to break at the stress concentration during the stretching process, so the extension rate is lower. After the heat treatment, internal stress is eliminated. Some carbide is decomposed, so the elongation is improved and the strength decreases. The $M_6C$ carbide in the crystal will gradually decompose above 1100°C and precipitate to the grain boundary. As the solid-solution temperature increases, the grain size tends to become larger. The precipitation of $M_6C$ at the grain boundary is more obvious. The solid-solutionizing specimen has a higher elongation at 1200°C, but the yield strength is obviously reduced. After aging, some of the carbides are remelted, precipitated and evenly distributed in the grains. It slightly reduces the elongation, but the yield strength significantly increases.

Figure 14 is a SEM micrograph of the fracture surface of a tensile specimen under different conditions. During the SLM, columnar crystals are formed along the growth direction of the Z-axis. During the stretching process, dislocations accumulate at the grain boundaries, resulting...
in resistance, which hinders the generation of slip. In Figure 14(a)(b), it is found that the surface of the fracture is relatively flat and cracks exist. The laser scanning has directionality, and a heat-affected area forms among the adjacent melting channels. Grains grow in a certain direction fast and form strip-like grains. Strip-like grains are easy subjected to brittle fracture during the stretching process. Meanwhile, some small dimples exist. Therefore, the fracture mode is ductile-brittle mixed fracture. In Figure 14(c), it is found that a large amount of equiaxed dimples are unevenly distributed. These dimples increase from the surface to the bottom, accompanied by a small amount of microcracks. The main reason is that the heat affected area is eliminated after high temperature heat treatment. With columnar crystal growing, the distortion among boundaries forms, which is not conducive to the crack propagation. Carbides precipitate from the grain to the grain boundary, which reduces the reaction force generated by intragranular dislocations. Therefore, it improves the plasticity and mainly represented as ductile fracture [22]. In Figure 14, after the aging treatment, the fracture surface is flat. There are many small equiaxed dimples but almost no defects such as cracks. Some second phase precipitates on the surface, which improves the strength and represents ductile fracture.

4 Conclusion

In this paper, a systematic study on the SLM-parameter and heat treatment of Hastelloy X has been conducted. In addition, the effect of parameter and heat treatment on the density, microhardness and mechanical property of parts was studied. Based on the results above, the following conclusions are drawn:

(1) SLM-parameters has a significant effect on the density of the specimen. SLM-parameter mainly refers
to the energy density. Scanning speed has a weak effect on density when laser power is 200 W. However, under 400 W laser power, it has a strong effect. Different SLM-parameters lead to density’s changes by affecting melting pool. As the energy density increases, the relative density first increases and then decreases. When the energy density is about 500 J/cm², the density of the produced specimen is 8.236 g/cm³.

(2) The density of the specimen decreases significantly as the layer thickness increases. As the energy density increases, the microhardness increases first and then decreases, and the surface roughness decreases.

(3) The horizontal microstructure of Hastelloy X is a lamellar austenite matrix, but a columnar crystal in the longitudinal direction. There is a small amount of M₆C carbide in the grain.

(4) After the heat treatment, the grain size becomes larger and the microstructure is more stable. The intragranular carbide decomposes above 1100°C, most of which is dissolved in the matrix, but rests is precipitated at the grain boundary. The aging treatment can distribute the re-dissolved carbide in the grain.

(5) The as-deposited specimen has high yield strength, tensile strength and low elongation. After the solution treatment, the elongation of Hastelloy X can be improved. Due to the decomposition of carbides and the grain growth, the strength decreases. After the aging treatment, the second phase precipitates so that the strength increases and the plasticity decreases slightly.

References

[1] Wang, F. Mechanical property study on rapid additive layer manufacture Hastelloy X alloy by selective laser melting technology. *International Journal of Advanced Manufacturing Technology*, Vol. 58, No. 5-8, 2012, pp. 545–551.
[2] Hong, H. U., J. S. Kim, B. G. Choi, H. W. Jeong, and C. Y. Jo. Effects of temperature and strain range on fatigue cracking behavior in Hastelloy X. *Materials Letters*, Vol. 62, No. 28, 2008, pp. 4351–4353.
[3] Wei, Z. W., C. H. Tao, Y. L. Gu, et al. *Journal of Aeronautical Materials*, Vol. 35, No. 6, 2015, pp. 41–47.
[4] Jia, C., Q. Fan, Y. Wang, et al. China Materials Conference 2012 Superalloy papers. Beijing Beiye Functional Materials Corporation, Beijing, 2012.
[5] Fayazfar, H., M. Salarian, A. Rogalsky, D. Sarker, P. Russo, V. Paserin, and E. Toyserkani. A critical review of powder-based additive manufacturing of ferrous alloys: Process parameters, microstructure and mechanical properties. *Materials & Design*, Vol. 144, 2018, pp. 98–128.
[6] Wang, F. Mechanical property study on rapid additive layer manufacture Hastelloy X alloy by selective laser melting technology. *International Journal of Advanced Manufacturing Technology*, Vol. 58, No. 5-8, 2012, pp. 545–551.
[7] Tomus, D., P. A. Rometsch, M. Heilmaster, and X. Wu. Effect of minor alloying elements on crack-formation characteristics of Hastelloy-X manufactured by selective laser melting. *Additive Manufacturing*, Vol. 16, 2017, pp. 65–72.
[8] Tian, Y., D. Tomus, P. Rometsch, and X. Wu. Influences of processing parameters on surface roughness of Hastelloy X produced by selective laser melting. *Additive Manufacturing*, Vol. 13, 2017, pp. 103–112.
[9] Wang, F., X. H. Wu, and D. Clark. On direct laser deposited Hastelloy X: Dimension, surface finish, microstructure and mechanical properties. *Materials Science and Technology*, Vol. 27, No. 1, 2014, pp. 344–356.
[10] Hu, Z., H. Zhu, H. Zhang, and X. Zeng. Experimental investigation on selective laser melting of 17-4PH stainless steel. *Optics & Laser Technology*, Vol. 87, 2017, pp. 17–25.
[11] Guan, K., Z. Wang, M. Gao, X. Li, and X. Zeng. Effects of processing parameters on tensile properties of selective laser melted 304 stainless steel. *Materials & Design*, Vol. 50, 2013, pp. 581–586.
[12] Liu, Y., Y. Yang, and D. Wang. A study on the residual stress during selective laser melting (SLM) of metallic powder. *International Journal of Advanced Manufacturing Technology*, Vol. 87, No. 1-4, 2016, pp. 647–656.
[13] Hodge, N. E., R. M. Ferencz, and R. M. Vignes. Experimental comparison of residual stresses for a thermomechanical model for the simulation of selective laser melting. *Additive Manufacturing*, Vol. 12, Part B, 2016, pp. 159–168.
[14] Kruth, J. P., G. Levy, F. Klocke, and T. H. C. Childs. Consolidation phenomena in laser and powder-bed based layered manufacturing. *Ann. Manuf. Technol.*, Vol. 56, No. 2, 2007, pp. 730–759.
[15] Kong, B., T. Li, and Q. Eri. Normal spectral emissivity of GH536 (Hastelloy X) in three surface conditions. *Applied Thermal Engineering*, Vol. 113, 2017, pp. 20–26.
[16] Tan, C., K. Zhou, W. Ma, B. Attard, P. Zhang, and T. Kuang. Selective laser melting of high-performance pure tungsten: Parameter design, densification behavior and mechanical properties. *Science and Technology of Advanced Materials*, Vol. 19, No. 1, 2018, pp. 370–380.
[17] Kong, B., T. Li, and Q. Eri. Normal spectral emissivity of GH536 (HastelloyX) in three surface conditions. *Applied Thermal Engineering*, Vol. 113, 2017, pp. 20–26.
[18] Shu, W., A. P. Dong, Y. L. Lu, et al. *Chin Shu Hsueh Pao: Acta Metallurgica Sinica*, Vol. 56, 2018, pp. 3. 3
[19] Tomus, D., Y. Tian, P. A. Rometsch, M. Heilmaster, and X. Wu. Influence of post heat treatments on anisotropy of mechanical behaviour and microstructure of Hastelloy-X parts produced by selective laser melting. *Materials Science and Engineering A*, Vol. 667, 2016, pp. 42–53.
[20] Kirchhöfer, H., F. Schubert, and H. Nickel. Precipitation Behavior of Ni–Cr–Fe–18 Mo (Hastelloy-X) and Ni-Cr-22 Co-12 Mo (Inconel-617) After Isothermal Aging. *Nuclear Technology*, Vol. 66, No. 1, 1984, pp. 139-148.
[21] Zhao, J. C., M. Larsen, and V. Ravikumar. Phase precipitation and time-temperature-transformation diagram of Hastelloy X. Materials Science & Engineering A (Structural Materials, Properties, Microstructure and Processing), Vol. 293, No. 1-2, 2000, pp. 112-119.

[22] Debroy, T., H. L. Wei, J. S. Zuback, T. Mukherjee, J. W. Elmer, J. O. Milewski, A. M. Beese, A. Wilson-Heid, A. De, and W. Zhang. Additive manufacturing of metallic components – Process, structure and properties. Progress in Materials Science, Vol. 92, 2017, pp. 112–224.

[23] Mazur, M., M. Leary, S. Sun, M. Vcelka, D. Shidid, and M. Brandt. Deformation and failure behaviour of Ti-6Al-4V lattice structures manufactured by selective laser melting (SLM). International Journal of Advanced Manufacturing Technology, Vol. 84, No. 5-8, 2016, pp. 1391–1411.