Effect of Different Molding Process on Mechanical Properties of 316L Stainless Steel

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Abstract—The effects of laser selective melting (SLM) and rolling on the mechanical properties of 316L stainless steel were studied. The morphology and fracture characteristics after impact were characterized by means of an optical microscope (OM) and scanning electron microscope (SEM). Meanwhile, tensile strength, hardness, and impact toughness are characterized. The results show that compared with the roll forming, the 316L stainless steel group formed by laser selective melting has surface holes, cracks and spheroidization, and the grains are smaller, the dimples are smaller and shallower, and the strength and hardness are higher than the roll forming. Plastic toughness is much lower than that of rolling.

1. INTRODUCTION

316L stainless steel has characteristics of strong corrosion resistance, good biocompatibility and high oxidation resistance. It is widely applied in nuclear industry, biomedicine and aerospace[1-3]. It is well known that 316L stainless steel pipe is the main material of nuclear power plant pipeline. The field operation data of nuclear power plants for decades show that stress corrosion cracking is the main cause of corrosion failure of stainless steel pipeline[4-5]. The preparation of nuclear industry 316L stainless steel parts by laser selective melting technology is the current research focus. Compared with traditional manufacturing techniques, the manufacturing cost is low and the development cycle is short[6-7]. At present, a lot of research have been done on the powder properties, process parameters optimization, mechanical properties and heat treatment of SLM shaped stainless steel, superalloy and titanium alloy[8]. In the past few years, Wang et al.[9] found the influence of parameters and process parameters of 316L stainless steel on the forming properties of selective laser melting (SLM). The powder with smaller average particle size had better formability than the powder with larger average particle size. Nodular phenomena was obvious when the particle size has a wide range of particle size distribution. Amir Mahyar Khorasani et al. [10] studied the effects of SLM process parameters on the density, hardness, tensile strength and surface quality of Ti-6Al-4V. Huang Wenpu et al.[11] studied the SLM forming process, morphology and heat treatment microstructure and mechanical properties of K4202 nickel-based cast superalloy. Gao Piao et al.[12] discovered that the effect of layer thickness on
the microstructure and properties of selected laser melting and forming Ti-5Al-2.5Sn alloy. The results show that the thickness of the layer increases with the laser power and scanning spacing. The reduction of the scan rate of the large sum, the cooling rate during the SLM forming process is gradually reduced, and the microstructure is gradually changed from the acicular martensite \(a'\) to the island shape \(a\). Wang et al.\[13\] produced austenitic 316L stainless steel by SLM technology and found that the combination of yield strength and tensile ductility was higher than that of conventional forged 316L stainless steel. Snehashis Pal et al. \[14\] found that the effects of molding direction and energy density on the tensile properties of Ti-6Al-4V. Gray et al.\[15\] studied the dynamic compression properties and spalling properties of 316L stainless steel materials prepared by SLM, discussed the effects of heat treatment, and compared the mechanical properties of forged 316L stainless steel. Fergani O et al. \[16\] studied the effect of heat treatment on the fatigue crack growth behavior of selective laser melting 316L stainless steel. It was concluded that Heat treatment above recrystallization temperature, followed by quenching to produce compressive residual stress, which could significantly improve the crack propagation resistance. Salman O O et al.\[17\] studied the effects of different annealing temperatures on the phase stability, ingredient stability and structure stability of 316L stainless steel prepared by SLM, and used the changes caused by heat treatment to understand the corresponding changes. In this study, compared with the traditional rolled 316L stainless steel, the difference between SLM forming technology and traditionally manufactured 316L stainless steel is analyzed.

2. EXPERIMENTAL DETAILS
The experimental materials used water atomized 316L stainless steel powder. The chemical composition and specific content of the powder were shown in Table 1. Adopting 316L stainless steel powder belonged to the approximate regular spherical shape, the particle size range was 20–63μm, the fluidity was less than 18s/50g, the oxygen content was less than 500 ppm, and the substrate material was 316L steel, which guaranteed the same material.

| Paramter  | Value | Unit |
|-----------|-------|------|
| Laser power | 170 | W |
| Sanning speed | 800 | mm·s\(^{-1}\) |
| Scanning spacing | 0.06 | mm |
| Layer thickness | 50 | μm |
| Phase angle | 73 | ° |

Mechanical samples (tensile specimens, impact specimens, hardness specimens) with different laser scanning speeds were prepared. The experiment was carried out under the conditions of room temperature using a universal tensile testing machine, HB-3000B microhardness and ZBC2000 series metal pendulum tester. Then, the ECLIPSE MA200 Nikon inverted metallographic microscope was used to observe the morphology of the samples after impact fracture and the corrosion metallographic experiment. Before the observation, the samples were inlaid, ground, polished, and etched, and then
etched with aqua regia for 15 s. At the same time, the scanning electron microscopy S-3000N was used to analyze the fracture morphology under the shape.

3. RESULTS AND ANALYSIS

Comprehensive analysis of tensile, hardness, impact toughness and other mechanical properties is known. The optimal process is laser power of 170 W, sweeping distance of 0.06 mm, layer height of 50 μm, scanning speed of 800 mm·s$^{-1}$, it is comprehensive properties such as strength, plasticity and impact toughness are relatively stable. According to Table 3, under the research process the SLM forming is compared with the roll forming 316L, yield strength, tensile strength and microhardness are higher than roll forming, but elongation and impact toughness are lower than roll forming. This result in higher thermal gradient and faster cooling rate characteristics of SLM forming, resulting in grain boundary strengthening, short grain growth time, grain refinement, and material yield stress related to grain size. According to the Hall-Petch relationship,

$$\sigma_s = \sigma_0 + Kd^{\frac{1}{2}}$$ (1)

Where $\sigma_s$ is the yield strength, $\sigma_0$ and $K$ represent the material correlation coefficient, $K$ represents the degree coefficient of the influence of the grain boundary on the strength, and $d$ is the grain size.

Table 3: Mechanical properties of SLM and roll forming 316L

| Processing method      | Yieldstrength Mpa | Tensile strength Mpa | Elongation % | Impact toughness J·cm$^{-2}$ |
|------------------------|-------------------|----------------------|--------------|---------------------------|
| SLM 316L               | 545–566           | 628–652              | 33–36        | 58.6–60                   |
| Traditional rolling    | 301.10            | 627.73               | 53.49        | 280–290                   |
| 316L$^{[18-19]}$       |                   |                      |              |                           |

According to the dislocation theory, the grain boundary is a dislocation motion, and the stress concentrates on the grain boundary. Due to the formation of dislocation accumulation, when the stress is large enough to cause the slip to spread from one grain to another, yielding occurs$^{[20]}$. SLM molded specimens have smaller grain diameters than conventional hot rolling$^{[21]}$. Therefore, SLM formed samples have large grain boundaries and dislocation densities, hindering dislocation motion, resulting in material strengthening, but plasticity and toughness decreased.

In addition, the tensile fracture from 316L stainless steel is plastic dimple-like, and the larger the dimple size, the larger the average diameter and the deeper the depth, the better the plastic properties of the material$^{[22]}$. Fig.1 shows the SLM forming and the traditional rolling tensile fracture morphology$^{[23]}$. From the fracture morphology of the SLM tensile specimen in Fig.1 (a), the dimple is small and shallow, and the dimple width is 1 μm. Below, there are micropores, which are ductile fractures; Fig1. (b) shows the tensile fracture morphology of conventional rolled profiles, the dimples are large and deep, and the dimple width is 4–10 μm. The tearing edges are fine and also belong to ductile fracture. Therefore, compared with conventional hot rolling, SLM has smaller and shallow dimples and poor plastic toughness.

Fig.1: Tensile fracture morphology: (a) SLM (b) conventional rolling$^{[23]}$
Fig. 2 shows the formation mechanism of holes in SLM forming. The forming process is extremely complicated under the action of thermal capillary convection, pulse laser recoil, gas-liquid interface shear force, surface roughness and randomly distributed powder particles. It is difficult to control the influence of interference factors on the forming performance, and it is easy to occasionally lap gaps, voids, micropores, and spheroidization to form defects. Surface tension, pressure, and unsolidified powder result in the keyholes. These defects lead to the generation of cracks. When subjected to the impact force, aggregation occurs and grows. The size of the microcracks reaches a critical value, expansion occurs, resulting in material fracture. However, the hot-rolled 316L stainless steel is prepared by the smelting-hot rolling process technology, the alloy elements are fully dissolved, the density of the material is high, the microstructure defects are completely eliminated, and the ductility is good. Therefore, the presence of micropores and spheroidization in the SLM molding has a great influence on the impact plastic toughness, but has little effect on the strength and hardness. Compared with the conventional rolling, the toughness is low and the strength and hardness are high.

4. CONCLUSIONS
The laser power is 170W, the scanning distance is 0.06 mm, and the layer height is 50μm. When the scanning speed is 800mm·s⁻¹, the comprehensive performance of strength, plasticity and impact toughness is the most stable. Compared with rolling, the grains are small, the dimples are small and shallow, the strength and hardness are higher than that of rolling, and the plastic toughness is much lower than that of rolling.

REFERENCES
[1] Elmesalamy A S, Francis J A, Li L. A comparison of residual stresses in multi pass narrow gap laser welds and gas-tungsten arc welds in AISI 316L stainless steel. International Journal of Pressure Vessels and Piping, 2014, 113: 49-59.
[2] Shang Y, Yuan Y, Li D, et al. Effects of scanning speed on in vitro biocompatibility of 316L stainless steel parts elaborated by selective laser melting. The International Journal of Advanced Manufacturing Technology, 2017, 92(9): 4379-4285.
[3] Yap C Y, Chua C K, Dong Z L, et al. Review of selective laser melting: Materials and applications. Applied Physics Reviews, 2015, 2(4): 041101.
[4] Zhang L T, Wang J Q. Stress Corrosion crack propagation behavior of doviestic forged nuclear 316L stainless steel in high temperature and high pressure water. Acta Metallurgica Sinica, 2013, 49(08): 911-916. (In Chinese)
[5] Rannar L E, Koptyug A, Olsen J, et al. Hierarchical structures of stainless steel 316L manufactured by Electron Beam Melting. Additive Manufacturing, 2017, 17: 106-112.
[6] Santos E C, Shiomi M, Osaka K, et al. Rapid manufacturing of metal components by laser forming. International Journal of Machine Tools & Manufacture, 2006, 46(12): 1459-1468.
[7] Shi W T, Wang P, Liu Y D, et al. Experimental Study on Surface Quality and Process of Selective Laser Melting Forming 316L. Surface Technology, 2019(3): 257-267. (In Chinese)
[8] Zong X W, Gao Q, Zhou H Z, et al. Effects of bulk laser energy density on anisotropy of selective laser sintered 316L stainless steel. Chinese Journal of Lasers, 2019, 5:344-350. (In Chinese)

[9] Wang L, Wei Q S, He W T, et al. Influence of powder characteristic and process parameters on SLM formability. Journal of Huazhong University of Science and Technology (Natural Science Edition), 2012, 6:20-23. (In Chinese)

[10] Khorasani, Amir Mahyar Gibson, Ian Awan, Umar Shafique. The effect of SLM process parameters on density, hardness, tensile strength and surface quality of Ti-6Al-4V. Additive Manufacturing, 2019, 25:176-186.

[11] Huang W J, Yu X C, Yin J, et al. Microstructure and mechanical properties of K4202 cast nickel base superlloy fabricated by fabricated by selective laser melting. Acta Metallurgica Sinica, 2016, 52(9):1089-1095. (In Chinese)

[12] Gao P, Wei K W, Yu X C, et al. Influence of layer thickness on microstructure and mechanical properties of selective laser melted Ti-5Al-2.5Sn alloy. Acta Metallurgica Sinica, 2018, 54(7):999-1009. (In Chinese)

[13] Wang Y M, Voisin T, Mckeown J T, et al. Additively manufactured hierarchical stainless steels with high strength and ductility. Nature Materials, 2017, 17(1):63-70.

[14] Snehashis Pal, Nenad Gubeljak, Radovan Hudak, et al. Tensile properties of selective laser melting products affected by building orientation and energy density. Materials Science & Engineering A, 2019, 743:637-647.

[15] Gray G T, Livescu V, Rigg P A, et al. Structure/property (constitutive and spallation response) of additively manufactured 316L stainless steel. Acta Materialia, 2017, 138:140-149.

[16] Fergani O, Bratli Wold A, Berto F, et al. Study of the effect of heat treatment on fatigue crack growth behaviour of 316L stainless steel produced by selective laser melting. Fatigue & Fracture of Engineering Materials & Structures, 2018, 5:1102-1119.

[17] Salman O O, Gammer C, Chauvey A K, et al. Effect of heat treatment on microstructure and mechanical properties of 316L steel synthesized by selective laser melting. Materials Science & Engineering A, 2017, 748:205-212.

[18] Tan F L, Jang B W, Wang L, et al. Microstructure and mechanical properties of SLM formed and hot-rolled 316L stainless steel. Foundry Technology, 2018, 39(12):2694-2697. (In Chinese)

[19] Gao B, Li J, S, Li Y S. Preparation and mechanical properties of 316L stainless steel with heterogeneous lamella structure. Acta Metallurgica Sinica, 2018, 43(3):20-25. (In Chinese)

[20] Niels Hansen. Hall–Petch relation and boundary strengthening. Scripta Materialia, 2004, 51(10):801-806.

[21] F Bartolomeu, M Buciumeanu, E Pinto, et al. 316L stainless steel mechanical and tribological behavior: A comparison between selective laser melting, hot pressing and conventional casting. Additive Manufacturing, 2017, 16:81-89.

[22] Tang Yangyang, Yuan Shouqian, Wei Chenhao, et al. Effect of heat treatment on microstructure and mechanical properties of different nitrogen levels in 316L stainless steel. Hot working technology, 2014, 43(12): 212-215. (In Chinese)

[23] Jiang Kejing, Wang Liang, Zhang Qunli, et al. Laser annealing and softening process of 316L stainless steel. Surface Technology, 2019, 48(2):10-16. (In Chinese)

[24] Tan F L, Jang B W, Wang L, et al. Microstructure and mechanical properties of SLM formed and hot-rolled 316L stainless Steel. Foundry Technology, 2018, 39(12):2694-2697. (In Chinese)