Mechanical Properties and Constitutive Model of Selective Laser Melting 316L Stainless Steel at Different Scanning Speeds

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1. Introduction

Selective laser melting (SLM), also commonly known as laser powder bed fusion (L-PBF), is an additive manufacturing (AM) technique [1, 2]. This technology can not only realize the rapid preparation of complex structural parts but also have the advantages of shorter forming cycle and higher material utilization rate [3–5]. Therefore, it has a broad application prospect in the field of metal parts manufacturing [6–8], such as aerospace, automotive industry, and other fields. 316L stainless steel (316L SS) is a common metal material used in SLM technology. The formed SLM 316L SS is often used in compressive structures due to its high strength and impact resistance [9, 10]. However, its mechanical properties vary greatly under different SLM process parameters. Therefore, it is important to study the mechanical properties of SLM 316L SS prepared by different processes to ensure their service safety and to expand their applications.

In recent years, many researchers have made extensive studies on the mechanical properties of SLM 316L SS around different process parameters, such as laser power, scanning speed, and powder feeding rate. For example, optimizing the laser energy density can enhance the intensity of SUS316L material [11], and choosing a reasonable scanning speed can improve the surface quality and increase the hardness of 316L material [12]. Otherwise, the forming angle and scanning strategy also significantly affect the microstructure and tensile strength of SLM 316L material [13, 14]. Some scholars have optimized the Johnson-Cook (J-C) model to predict the dynamic mechanical behavior of materials at high strain rates more accurately. Zhou et al. [15] analyzed the stress-strain curve obtained from the SHPB experiment and modified the J-C model of Ti6Al4V based on dislocation stacking theory. Zhu et al. [16] modified the strain rate hardening coefficient in the J-C model by studying the adiabatic heating of the specimen in the SHPB experiment.
Seo et al. [17] carried out a wide strain rate tensile test on 304/316 SS. They improved the J-C model by combining the relationship between plastic strain and strain rate to reduce the error between the model and experimental data at different strain levels.

In view of the existing literature, the studies on the mechanical properties of SLM 316L SS mainly focus at low strain rates, and the mechanical properties of SLM 316L SS at high strain rates are still unclear. Therefore, this study prepared four kinds of SLM 316L SS samples at different scanning speeds and tested their quasistatic and dynamic mechanical properties. And the microstructures of the four SLM 316L SS were analyzed to clarify the mechanism of the mechanical property differences. In addition, the J-C models were further modified to describe their mechanical behavior. This study can provide an experimental basis for the process improvement of SLM 316L stainless steel and promote the production and application of this AM material.

2. Preparation of Experimental Materials and Samples

The TB-SLM100 selective laser melting equipment was adopted as the forming device. The device is equipped with IPG500W, a single-mode fiber laser with a wavelength of 1064 nm, whose spot output is in circular mode with a diameter of 70 μm. The process parameters of the equipment can be adjusted. The adjustable range of laser power is 100 to 340 W, and the adjustment ranges of scanning speed and hatch spacing are 350 to 1250 mm/s and 0.07 to 0.11 mm, respectively. The spherical 316L SS powder was prepared by aerosol polarization method. Figure 1 shows that the micromorphology of the powder has a good spherical shape, in which most particles are spherical and a few particles are irregular. The particle size of the powder was in the range of 15–53 μm, and its chemical composition was shown in Table 1.

The conventional preparation method of SLM process is as follows. Firstly, a layer of powder material from the powder feeding apparatus is spread on the built platform by the recoater blade. Then, a moving laser beam generated by the laser beam source and the moving mirror is applied to selectively fuse the powder material to create a layer of the part. Finally, a new layer of powder material from the powder feeding apparatus is spread over its previous layer by the recoater blade. The entire sample preparation is completed by cycling the above steps [18, 19]. In addition, the alternating stripes scanning strategy was used for the forming process (Figure 2). Each layer was scanned using simple alternating scan vectors, and the scanning direction rotated 90° after each layer.

The TB-SLM100 additive manufacturing equipment used in this paper was provided by Anhui Topper Additive Manufacturing Co. According to the research of the company [20, 21], SLM 316L stainless steel sample has the best density and the lowest defect density when the laser power is 180 W, the scanning speed is 650 mm/s, and the scanning spacing is 0.1 mm. The scanning speed of this manufacturing equipment can be adjusted between 350 and 1250 mm/s. In order to investigate the effect of a single scanning speed factor on the mechanical properties of the sample, the parameters of laser power and scanning spacing were kept unchanged to avoid the influence of other process parameters on the experimental results. Therefore, the laser power (180 W), hatch spacing (0.1 mm), and powder thickness (50 μm) were kept consistent during the experiment. Two types of specimens with different scanning speeds (350 mm/s, 650 mm/s, 950 mm/s, and 1250 mm/s) were fabricated, one was a cylindrical specimen of Φ 12×5 mm for quasistatic mechanical tests, and the other was a cylindrical specimen of Φ 12×15 mm for dynamic mechanical tests, as shown in Figure 3.

3. Quasistatic and Dynamic Mechanical Properties Test

3.1. Quasistatic Mechanical Property Test. Quasistatic compression experiments were performed on the MTS Landmark® 370.5 electrohydraulic servo experimental system according to the national standard of GB/T 7314–2017 Metallic materials compression test method at room temperature. The specimen measuring Φ 12 × 15 mm was fixed in the center of the base, and lubricant was applied to the contact surfaces at both ends to reduce the friction. In order to ensure the uni-axial loading, the axis of the cylindrical specimen should coincide with the axis of the indenter, and the working surface of the upper and lower indenters of the testing machine should be parallel, with a parallelism of less than 1 : 0.0002 mm/mm. Depending on the height of the specimen, the loading speed was set to 0.015 mm/sec, and the strain rate was controlled at 0.001 s⁻¹. To ensure the accuracy of the experimental results, external extensometer was equipped to record the deformation of the specimen. The experiment was conducted at room temperature within the range of 10°C–35°C. All tests in this work were carried out three times to ensure the reliability of the test and the results were found to be reproducible.

3.2. Dynamic Mechanical Property Test. The high strain rate compression testing was carried out on SHPB experimental device. The apparatus consists of a loading device (air gun), a pressure bar device (impact bar, incident bar, transmission bar, and absorption bar), a data acquisition system, and a damping absorption device, as shown in Figure 4.
The loading conditions of the dynamic experiment are determined through the blank test before the experiment. The blank test was conducted without adding specimens to determine the axial alignment of the compression bar system by detecting the amplitude of the reflected wave [22–24]. As shown in Figure 5, the amplitude of the reflected wave was much smaller than that of the incident wave, which indicated that the compression bars on the experimental platform had achieved axial alignment and could be used for dynamic mechanical test.
The specimen with size of φ12×5 mm was clamped between the incidence bar and the transmission bar, keeping the specimen aligned with the center axis of the compression bars. During experiment, the strike bar was loaded at different speeds by adjusting the air pressure. The impact process generates elastic strains $\varepsilon_i$, $\varepsilon_r$, and $\varepsilon_t$ in the incident and transmission bars, and the signals are obtained through a data acquisition system. According to wave propagation theory in solids, the strain rate $\dot{\varepsilon}(t)$, strain $\varepsilon(t)$, and stress $\sigma(t)$ of the 20 material were obtained by the following equation [25, 26]:

$$
\begin{align*}
\varepsilon(t) &= \frac{c_0}{L_0} \int_0^t (\varepsilon_i - \varepsilon_r - \varepsilon_t) dt \\
\dot{\varepsilon}(t) &= \frac{c_0}{L_0} (\varepsilon_i - \varepsilon_r - \varepsilon_t), \\
\sigma(t) &= \frac{AE}{A_0} (\varepsilon_i + \varepsilon_r + \varepsilon_t).
\end{align*}
$$

In formula (1), $c_0$, $E$, and $A$ are the elastic wave velocity, elastic modulus, and cross-sectional area of the pressure bar; $L_0$ and $A_0$ are the original length and cross-sectional area of the specimen, respectively.

4. Analysis of Static and Dynamic Mechanical Properties

Figure 6 displays the stress-strain curves obtained in quasistatic and dynamic mechanical tests on SLM 316L SS samples prepared at four scanning speeds. The quasistatic and dynamic stress-strain curves are generally similar, which can be roughly divided into elastic and plastic stages, showing the common elastic-plastic characteristics with general metal materials. In the quasistatic curve, when the sample strain is less than 0.02, the stress increases linearly with the strain, and the elastic modulus remains constant, which is the elastic stage. After entering the plastic phase, due to the combined effect of strain strengthening when the material yields, no obvious yielding phenomenon is observed in the figure. After the yield stage, the specimen enters the stable strain strengthening stage, and the stress value increases gradually with the increase of plastic strain. It indicates that the material surface has obvious strain strengthening characteristics. In the dynamic stress-strain curve of a high strain rate, its mechanical response is basically the same as that of a quasistatic state. The linear elastic characteristics and strain hardening phenomenon of the material are apparent. However, the upper yield point and lower yield point can be observed in the dynamic mechanical curve. This phenomenon is more evident with the increase of strain rate.

Comparing the peak yield stress in the high strain rate ($10^2–10^4$ s$^{-1}$) and quasistatic (0.001 s$^{-1}$) stress-strain curves, the specimens show obvious strain rate sensitivity under dynamic loading. When the strain rate increases from 0.001 to $10^2$ s$^{-1}$, the peak yield strength of 350, 650, 950, and 1250 mm/s specimens increases by 18.9%, 19.1%, 15.5%, and 24.3%, respectively, and the maximum yield strength increases by 19.45% on average. It can be seen that the strain rate sensitivity is very obvious when the sample is loaded from quasistatic state to dynamic state. However, when the loading strain rate increases from $10^2$ to $10^4$ s$^{-1}$, the peak yield stress does not change much. When the process parameters are 350, 650, 950, and 1250 mm/s, the dynamic yield strength increases by 4.0%, 4.8%, 6.4%, and 9.9%, respectively. It indicates that the strain rate hardening effect is relatively weak when the compressive strain rate is in the same order of magnitude. Furthermore, it can be obviously found in the figure that the yield strength of the sample formed at 1250 mm/s is significantly lower than that of the sample formed at 350–950 mm/s. Figure 7 shows the peak yield strength of four scanning speed specimens under different loading strain rates.

5. Defect and Microstructure Analysis

The different process samples were ground with sandpaper along the laser scanning plane until the observation surface was flat and then polished mechanically to obtain a bright mirror. The metallographic specimens were etched in aqua regia (3 ml HNO3 + 1 ml HCl) for 10 s. The microstructure of the specimens was observed by Zeiss evo180 scanning electron microscope.

The following are internal defect figures of different process specimens. It can be clearly observed that when the scanning speed is 350 mm/s or 1250 mm/s, dense defects are produced inside the specimen. However, when the scanning speed is gradually increased to 950 mm/s, the defects inside the specimen are significantly reduced, as shown in Figure 8.

The method of measuring the specimen densities by Archimedes is calculated by the following equation: $\rho_s = \rho_1 m_2 / \rho_0 (m_0 - m_1)$, where $m_0$ is the dry weight of the specimen; $m_1$ is the floating weight of the specimen in water; $\rho_1$ is the density of distilled water at standard atmospheric.
pressure, which is taken as 0.9982 g/cm$^3$ and $\rho_0$ is the theoretical density of the specimen. As shown in Figure 9, the densities of the specimens improved with the increase of the scanning speed and then decreased to reach the peak at 950 mm/s.

According to the above analysis, it can be found that there is a strong correlation between the defect density of the sample and the scanning speed. This is because the volume energy density plays a crucial role in the process of forming the specimen by SLM technology [27, 28]. The corresponding volume energy density $E$ (J/mm$^3$) is calculated in formula: $E = p/vdL$, where $p$ is the laser power, $W$; $v$ is the scanning speed, mm/s; $d$ is the scanning distance, mm; $L$ is the slice layer thickness. Therefore, when the scanning speed increases, the volume energy density decreases, which reduces the amount of radiation per unit volume of powder. In addition, the metal powder cannot be completely melted due to the insufficient energy of the laser beam during the manufacturing process of the sample, resulting in the failure to form bonding between the powders and poor liquid phase flow in the metal layer and holes in the metal material. On the contrary, when the scanning speed decreases gradually, the material holes will be reduced, which is conducive to the solidification and formation of the contact surface between metal particles, reduce the material holes, and significantly improve the density. However, when the scanning speed is too low or the volume energy density is too high, the excessive melting of metal powder will lead to the relative instability of liquid metal, which will also lead to the generation of tissue defects and the reduction of density. Therefore, the evaporation defects caused by extreme temperatures and the unmelted powder defects caused by
insufficient temperatures observed in this paper have been consistent with the results of Ansari et al. [29].

Figure 10 shows the molten pool morphology of samples with different process parameters, as they are perpendicular to the laser scanning. Given the Gaussian distribution of laser energy, the highest energy is concentrated in the beam center, and the powder on both sides of the fusion line will be absorbed during scanning [30, 31]. The morphology of the molten pool of the samples with various parameters in the figure is fish scale shape distribution. This is because the laser melted metal powder sinters, solidifies, and is superimposed into a semicircular molten pool, layer by layer, making it has cascade characteristics. By measuring, the size of molten pool is different with different process parameters. The width of the molten pool is approximately 138.00 μm at 350 mm/s. With the increase of scanning speed, the width of the molten pool decreases gradually (107.86 and 98.95 μm at 650 and 950 mm/s). When the scanning speed reaches 1250 mm/s, no obvious cascade characteristics of molten pool are observed. Cracks and inclusions appear locally.

The results show that the slower the scanning speed when the metal powder melts, the larger the heat conduction and radiation range per unit time, and the stronger the fluidity of the solution. As a result, the size of the molten pool increases, and the accumulation of the molten pool on the sample section becomes more obvious. When the scanning speed is too high, the metal powder cannot melt completely, and the liquid phase fluidity is poor [32]. This will lead to poor interlayer fusion, unfused powder inclusions, and molten pool defects.

Through microstructure analysis of the mechanical properties of SLM 316L SS samples with four parameters, it can be found that the defect characteristics are the key factors affecting the quasistatic and dynamic compressive mechanical properties of materials [33]. The tissue defects caused by poor process parameters can lead to a large number of pores, holes, and unmelted powder particles in the formed specimen and eventually lead to large gaps between the molten layers. This is closely related to the residual stress within the specimen. A nonuniform rapid cooling rate can leave thermal stresses in the form of residual stress between tissues. Large residual stress will lead to the delamination of stress layer and the formation of molten powder gap or crack [34]. The defective part of the material will generally become the starting point of the plastic deformation of the macroobject. When the sample is subjected to impact load, the stress will focus on the location of defects due to the uneven material structure, resulting in the deformation of the holes first along the direction of the applied load. Therefore, the mechanical properties of the SLM samples are closely related to their tissue defects. As shown in Figure 10(d), when the scanning speed is excessively fast, the fusion between layers is poor, which eventually leads to the quasistatic and dynamic yield strength lower than that of other forming process samples.

6. J-C Constitutive Model and Dynamic Mechanical Characterization

The constitutive relation of the metal material mainly reflects the stress-strain change rule under certain deformation conditions. The J-C constitutive model [35, 36] is an elastic-plastic constitutive model, which has been applied in many cases of finite element analysis to predict the thermal deformation behavior of the alloy for its simple multiplicative form in the previous works [37, 38]. Owing to the limited prediction accuracy of the original J-C model, the model was revised several times to better predict the rheological stress of the material considering the effect of strain rate on the rheological behavior of the material during deformation [39–41]. Therefore, the J-C model was adopted and then revised to exactly predict the rheological stress of the SLM 316L in this work.

The general formula is as follows:

\[
\sigma = (A + Be^n) \left[ 1 + C \ln \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \right] \left[ 1 - \left( \frac{T - T_0}{T_M - T_0} \right)^m \right], \tag{2}
\]

In the formula: \( \sigma \) is the equivalent plastic stress; \( \dot{\varepsilon} \) is the equivalent plastic strain; \( A, B, \) and \( n \) are the initial yield stress, hardening modulus, and hardening index at the reference strain rate and temperature; \( \dot{\varepsilon}_0 \) and \( \dot{\varepsilon}_0 \) are the quasistatic experimental strain rate and the equivalent plastic strain rate, respectively; \( C \) is the strain rate sensitivity coefficient; \( T, T_0, \) and \( T_M \) are the ambient temperature of the sample, room temperature (25°C), and melting point of the material, respectively, and \( m \) is the temperature sensitivity coefficient.

This experiment’s quasistatic and dynamic compression mechanical properties were tested at room temperature \( (t = t_0 = 25°C) \). Thus, formula (2) can be simplified as follows:

\[
\sigma = (A + Be^n) \left[ 1 + C \ln \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \right]. \tag{3}
\]
The parameters $A$, $B$, and $n$ in formula (3) are calibrated, and the stress-strain curve obtained from quasistatic compression experiment at room temperature ($t = t_0 = 25^\circ C$) is used as reference data. Thus, formula (3) can be reduced as follows:

$$\sigma = (A + Be^n). \quad (4)$$

Given the adiabatic temperature rise in dynamic compression, the yield strength $A$ is obtained from the stress value at the plastic strain of 0.012 according to the quasistatic compression test of different process samples. The hardening coefficient $B$ and hardening index $n$ are obtained by fitting the data points in the strengthening stage of the static curve by formula (4). Table 2 shows the parameters obtained by fitting.

The strain rate sensitivity coefficient $C$ in formula (4) is calibrated. The plastic strain is 0 when the dynamic loading reaches yield. In this case, formula (5) can be simplified as follows:

$$\sigma = A \left[ 1 + C \ln \left( \frac{\dot{e}}{\dot{e}_0} \right) \right]. \quad (5)$$
Using formula (5) to fit the yield strength of the material under different strain rates, the strain rate sensitivity coefficient $C$ is obtained. Figure 11 shows the fitting curve. The fitting parameter $C$ is listed in Table 2.

According to the parameters of the constitutive model, the basic models of 316L SS samples under quasistatic and dynamic compression tests can be obtained. Based on the basic model, the quasistatic and dynamic compression experimental data of four process parameters SLM 316L SS are fitted, and the fitting results are shown in Figure 12.

The fitting diagram shows that the original J-C model can fit the stress-strain curve of SLM 316L SS obtained from

**Table 2: Parameters of the J-C constitutive model.**

| Parameter                | Process parameter (mm/s) |
|--------------------------|--------------------------|
|                          | 350 | 650 | 950 | 1250 |
| Yield strength $A$ (MPa) | 583 | 584 | 573 | 492  |
| Hardening modulus $B$ (MPa) | 5086 | 4336 | 4554 | 4818 |
| Hardening index $n$     | 1.37 | 1.26 | 1.28 | 1.31 |
| Strain rate sensitivity coefficient $C$ | 0.01805 | 0.01861 | 0.01896 | 0.01812 |
| Material parameter $C_1$ | 7.23e-4 | 1.37e-3 | 3.3e-3 | 1.16e-3 |
| Material parameter $m$  | 0.77 | 0.69 | 0.60 | 0.75 |

**Figure 10:** Morphology of the molten pool perpendicular to the laser scanning plane. (a) 350 mm/s, (b) 650 mm/s, (c) 950 mm/s, (d) 1250 mm/s.

**Figure 11:** Yield strength and its fitting curve under different strain rates.
quasistatic (0.001 s\(^{-1}\)) compression test, but apparent differences are found between the fitting curve and the experimental stress-strain curve under high strain rate (10\(^2\)–10\(^4\) s\(^{-1}\)) dynamic loading. It shows that the parameters A, B, and n in the J-C model are correct. However, the strain rate sensitivity coefficient C cannot accurately measure the strain rate sensitivity of materials.

In order to better reflect the difference of material strain rate effect in different strain rate range, this paper uses the CS model \([42–44]\) to obtain a relationship between the dynamic stress and strain rate of the material, which is expressed as

\[
\sigma = A \left(1 + C_1 \varepsilon^M\right),
\]  

where C and M are material constants that describe the strain rate strengthening properties of the material.

Using formula (6) to fit the yield strength of the material at different strain rates, the parameters C, m were obtained. The fitted curves are shown in Figure 13. The fitted parameters are listed in Table 2.

According to the modified J-C constitutive model, the quasistatic and dynamic stress-strain curves of SLM 316L SS samples with four process parameters are refitted. Figure 14 shows the fitting results.
Figure 13: The modified fitting curve of parameter C, m.

Figure 14: Continued.
His study compares the fitting curve with the experimental curve. It can be concluded that the modified J-C constitutive model could better describe the mechanical behavior of SLM 316L SS under quasistatic and dynamic compression tests. Therefore, the modified J-C model has good applicability for predicting the quasistatic and high strain dynamic mechanical properties of SLM 316L SS.

7. Discussion

By analyzing the mechanical property curves of slm316lss samples with different scanning speeds, combined with the characterization of internal defects and micromorphology of the samples, it is found that the densification and molten pool characteristics of the above samples will show obvious regular changes with the increase of scanning speed. The change of microstructure is bound to be accompanied by the difference of mechanical properties.

In the process of plastic deformation, the macrodefects and microstructure of the sample are the necessary factors affecting the change of its mechanical properties. As we all know, the bonding mode between layers in SLM metal forming process is similar to metallurgical welding. Through the research of this paper, it can be found that when the scanning speed is slow, the difference of mechanical properties of the macrodefects of the sample is small without affecting the superimposed morphological characteristics of the micromolten pool. Only when the scanning speed is too fast and the macrodefects significantly affect the metallurgical bonding characteristics between layers, the mechanical properties of the sample will be significantly reduced. The microstructure difference of samples with different process parameters is not a single factor, but a variety of factors affect the mechanical properties of samples.

In this paper, the internal defects and molten pool characteristics of samples with different processes are characterized, the relationship between microstructure and mechanical properties is described, and the micro-mechanism of the difference of mechanical properties of samples with different processes is preliminarily analyzed. This can help the mechanical regulation of slm316lss material.

8. Conclusion

This study obtained SLM 316L SS samples with four scanning speeds (350, 650, 950, and 1250 mm/s) by changing the laser scanning speed. The surface quality, static, and dynamic mechanical properties of samples with four parameters were studied. The density and surface roughness were also measured. In addition, the quasistatic (0.001 s\(^{-1}\)) and dynamic (10\(^2\) to 10\(^4\) s\(^{-1}\)) compression experiments were carried out. The microstructure was observed, and the elastoplastic constitutive model was established. The analysis of the experimental results revealed the following:

1. The quasistatic and dynamic mechanical behaviors of SLM 316L SS samples with four scanning speeds show typical elastic-plastic characteristics. The material displays an apparent strain rate strengthening phenomenon at a high strain rate. Furthermore, through the microstructure analysis of the four samples, the sample’s stacking feature is the primary factor affecting its mechanical properties. Thus, when the scanning speed reaches 1250 mm/s, the yield strength of the sample is lower than that of the other parameter samples because of the stacking feature’s disappearance.
(2) The J-C constitutive model established in this study can accurately describe the mechanical behavior of SLM 316L SS under dynamic load. This study fitted the quasi-static and dynamic stress-strain curves of SLM 316L SS samples with different process parameters to illustrate further constitutive model’s applicability for describing the dynamic mechanical properties of SLM elastoplastic materials.

This study can provide methodological support for the design and development of SLM mechanical parts. Therefore, the study of the relationship between temperature and dynamic mechanical properties of SLM 316L SS and the analysis of the J-C model with temperature terms are important to improve the design and development of the product.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Disclosure

A preprint has previously been published [45].

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

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References

[1] S. Luo, Y. Su, and Z. Wang, "Tailored microstructures and strengthening mechanisms in an additively manufactured dual-phase high-entropy alloy via selective laser melting," Science China Materials, vol. 63, no. 7, pp. 1279–1290, 2020.
[2] D. Wang, Y. Yang, R. Liu, D. Xiao, and J. Sun, "Study on the designing rules and processability of porous structure based on selective laser melting (SLM)," Journal of Materials Processing Technology, vol. 213, no. 10, pp. 1734–1742, 2013.
[3] T. Long, X. Zhang, Q. Huang et al., “Novel Mg-based alloys by selective laser melting for biomedical applications: microstructure evolution, microhardness and in vitro degradation behaviour,” Virtual and Physical Prototyping, vol. 13, no. 2, pp. 71–81, 2018.
[4] Y. Yin, Q. Huang, and L. Liang, "In vitro degradation behavior and cytocompatibility of ZK30/bioactive glass composites fabricated by selective laser melting for biomedical applications," Journal of Alloys and Compounds, vol. 785, pp. 38–45, 2019.
[5] H. Wu, L. Liang, H. Zeng et al., “Microstructure and nano-mechanical properties of Zr-based bulk metallic glass composites fabricated by laser rapid prototyping," Materials Science and Engineering A, vol. 765, Article ID 138306, 2019.
[6] Y. Zhang, A. Majeed, M. Muzamil, J. Lv, T. Peng, and V. Patel, “Investigation for macro mechanical behavior explicitly for thin-walled parts of AlSi10Mg alloy using selective laser melting technique,” Journal of Manufacturing Processes, vol. 66, pp. 269–280, 2021.
[7] J. Q. Xue, Z. Feng, J. G. Tang, C. Tang, and Z. Zhao, "Selective laser melting additive manufacturing of tungsten with niobium alloying: microstructure and suppression mechanism of microcracks," Journal of Alloys and Compounds, vol. 874, Article ID 159879, 2021.
[8] J. W. Chen, C. H. Zhang, F. Q. Zhou, S. Zhang, H. T. Chen, and Q. Wang, "Microstructural, electrochemical and wear-corrosion characterization of TC4-5Cu alloy fabricated by selective laser melting," Journal of Alloys and Compounds, vol. 874, Article ID 159953, 2021.
[9] C. Wang, X. Lin, L. Wang, S. Zhang, and W. Huang, "Cryogenic mechanical properties of 316L stainless steel fabricated by selective laser melting," Materials Science and Engineering A, vol. 815, Article ID 141317, 2021.
[10] D. Wang, C. Song, and Y. Yang, "Investigation of crystal growth mechanism during selective laser melting and mechanical property characterization of 316L stainless steel parts," Materials & Design, vol. 100, pp. 291–299, 2016.
[11] G. B. Bang, W. R. Kim, H. K. Kim et al., “Effect of process parameters for selective laser melting with SUS316L on mechanical and microstructural properties with variation in chemical composition," Materials & Design, vol. 197, 2021.
[12] J. A. Cherry, H. M. Davies, S. Mehmoood, N. P. Lavery, S. G. R. Brown, and J. Sienz, “Investigation into the effect of process parameters on microstructural and physical properties of 316L stainless steel parts by selective laser melting," International Journal of Advanced Manufacturing Technology, vol. 76, no. 5-8, pp. 2117–2131, 2019.
[13] M. J. Huang, Z. X. Zhang, and P. Chen, "Effect of selective laser melting process parameters on microstructure and mechanical properties of 316L stainless steel helical micro-diameter spring," International Journal of Advanced Manufacturing Technology, vol. 104, no. 5-8, pp. 2117–2131, 2019.
[14] K. Tomasz, G. Konrad, S. Wojciech, B. Kuźnicka, and E. Chlebus, "Correlation between process parameters, microstructure and properties of 316 L stainless steel processed by selective laser melting," Materials Science and Engineering A, vol. 718, pp. 64–73, 2018.
[15] T. Zhou, J. Wu, Z. Liang, J. Che, Y. Zhang, and X. Wang, "A novel constitutive model for Ti-6Al-4V alloy based on dislocation pile-up theory," Materials Science and Technology, vol. 33, no. 11, pp. 1379–1387, 2017.
[16] S. Zhu, J. Liu, and X. Deng, "Modification of strain rate strengthening coefficient for Johnson–Cook constitutive model of Ti6Al4V alloy," Materials Today Communications, vol. 26, no. 26, Article ID 102016, 2021.
[17] J. M. Seo, S. S. Jeong, Y. J. Kim et al., "Modification of the johnson-cook model for the strain rate effect on tensile properties of 304/316 austenitic stainless steels," Journal of Pressure Vessel Technology, vol. 144, no. 04, 04, 2021.
[18] Y. Qin, Q. Qi, P. Shi, P. J. Scott, and X. Jiang, “Automatic determination of part build orientation for laser powder bed fusion," Virtual and Physical Prototyping, vol. 16, no. 1, pp. 29–49, 2020.
[19] S. L. Sing, S. Huang, G. D. Goh et al., “Emerging metallic systems for additive manufacturing: in-situ alloying and multi-metal processing in laser powder bed fusion,” Progress in Materials Science, vol. 119, Article ID 100795, 2021.

[20] P. Lu, L. Z. Cheng, Y. L. Hui, W. Liang, and T. Liu, “A new two-step selective laser remelting of 316L stainless steel: process, density, surface roughness, mechanical properties, microstructure,” Materials Research Express, vol. 7, no. 5, Article ID 056503, 2020.

[21] L. Pan, C. Zhang, W. Liang, T. Liu, and L. X. Cheng, “Research on mechanical properties and microstructure by selective laser melting of 316L stainless steel,” Materials Research Express, vol. 6, no. 12, Article ID 126577, 2020.

[22] M. Güden, S. Enser, M. Bayhan, A. Taşdemirci, and H. Yavas, “The strain rate sensitive flow stresses and constitutive equations of a selective-laser-melt and an annealed-rolled 316L stainless steel: a comparative study,” Materials Science and Engineering A, vol. 838, Article ID 142743, 2022.

[23] X. Zhai, J. Gao, H. Liao, C. D. Kirk, Y. A. Balogun, and W. W. Chen, “Mechanical behaviors of auxetic polyurethane foam at quasi-static, intermediate and high strain rates,” International Journal of Impact Engineering, vol. 129, pp. 111–118, 2019.

[24] Y. Qiao, Y. Chen, F. H. Cao, H. Y. Wang, and L. H. Dai, “Dynamic behavior of CrMnFeCoNi high-entropy alloy in impact tension,” International Journal of Impact Engineering, vol. 158, 2021.

[25] Q. Fu, Y. Xie, G. Long, D. Niu, H. Song, and X. Liu, “Impact characterization and modelling of cement and asphalt mortar based on SHPB experiments,” International Journal of Impact Engineering, vol. 106, pp. 44–52, 2017.

[26] Y.-j. Xie, Q. Fu, K.-r. Zheng, Q. Yuan, and H. Song, “Dynamic mechanical properties of cement and asphalt mortar based on SHPB test,” Construction and Building Materials, vol. 70, pp. 217–225, 2014.

[27] B. AlMangour, D. Grzesiak, T. Borkar, and J.-M. Yang, “Densification behavior, microstructural evolution, and mechanical properties of TiC/316L stainless steel nano-composites fabricated by selective laser melting,” Materials & Design, vol. 138, pp. 119–128, 2018.

[28] B. AlMangour, D. Grzesiak, J. Cheng, and Y. Ertas, “Thermal behavior of the molten pool, microstructural evolution, and tribological performance during selective laser melting of TiC/316L stainless steel nano-composites: experimental and simulation methods,” Journal of Materials Processing Technology, vol. 257, pp. 388–301, 2018.

[29] P. Ansari, A. U. Rehman, F. Pitir et al., “Selective laser melting of 316L austenitic stainless steel: detailed process understanding using multiphysics simulation and experimentation,” Metals, vol. 11, no. 7, p. 1076, 2021.

[30] W.-S. Shin, B. Son, W. Song et al., “Heat treatment effect on the microstructure, mechanical properties, and wear behaviors of stainless steel 316L prepared via selective laser melting,” Materials Science and Engineering A, vol. 806, Article ID 1400805, 2021.

[31] P. F. Jiang, C. H. Zhang, S. Zhang, J. B. Zhang, J. Chen, and H. T. Chen, “Additive manufacturing of novel ferritic stainless steel by selective laser melting: role of laser scanning speed on the formability, microstructure and properties,” Optics & Laser Technology, no. 140, Article ID 107055, 2021.

[32] S. Zhao, S. J. Li, S. G. Wang et al., “Compressive and fatigue behavior of functionally graded Ti-6Al-4V meshes fabricated by electron beam melting,” Acta Materialia, vol. 150, pp. 1–15, 2018.

[33] T. Larimian, M. Kannan, D. Grzesiak, B. A. Mangour, and T. Borkar, “Effect of energy density and scanning strategy on densification, microstructure and mechanical properties of 316L stainless steel processed via selective laser melting,” Materials Science and Engineering A, vol. 770, Article ID 138455, 2019.

[34] S. Waqar, K. Guo, and J. Sun, “FEM analysis of thermal and residual stress profile in selective laser melting of 316L stainless steel,” Journal of Manufacturing Processes, vol. 66, pp. 81–100, June 2021.

[35] X. Xiao, H. Pan, Y. Bai, Y. Lou, and L. Chen, “Application of the modified Mohr-Coulomb fracture criterion in predicting the ballistic resistance of 2024-T351 aluminum alloy plates impacted by blunt projectiles,” International Journal of Impact Engineering, vol. 123, pp. 26–37, 2019.

[36] W. Gang, Z. Wie, H. Wie, Y. Nan, Y. Gao, and Y. Ni, “Effect of strength and ductility on deformation and fracture of three kinds of aluminum alloys during Taylor tests,” International Journal of Impact Engineering, vol. 73, pp. 75–90, 2014.

[37] I. Rour, H. Nahme, K. Thoma, and C. E. Anderson Jr, “Material characterisation and constitutive modelling of a tungsten-sintered alloy for a wide range of strain rates,” International Journal of Impact Engineering, vol. 35, no. 8, pp. 811–819, 2008.

[38] S. Nemat-Nasser and W.-G. Guo, “Thermomechanical response of DH-36 structural steel over a wide range of strain rates and temperatures,” Mechanics of Materials, vol. 35, no. 11, pp. 1023–1047, 2003.

[39] A. K. Gupta, V. K. Anirudh, and S. K. Singh, “Constitutive models to predict flow stress in austenitic stainless steel 316 at elevated temperatures,” Materials & Design, vol. 43, pp. 410–418, 2013.

[40] Y. Liu, M. Li, X.-w. Ren, Z.-b. Xiao, X.-y. Zhang, and Y.-c. Huang, “Flow stress prediction of Hastelloy C-276 alloy using modified Zerilli–Armstrong, Johnson–Cook and Arrhenius-type constitutive models,” Transactions of Non-Ferrous Metals Society of China, vol. 30, no. 11, pp. 3031–3042, 2020.

[41] Y. C. Lin, X.-M. Chen, and G. Liu, “A modified Johnson–Cook model for tensile behaviors of typical high-strength alloy steel,” Materials Science and Engineering A, vol. 527, no. 26, pp. 6980–6986, 2010.

[42] G. R. Coper and P. S. Symonds, Strain-hardening and Strain-Rate Effects in the Impact Loading of Cantilever Beams, Brown University, Providence, Rhode Island, 1957.

[43] W. Zhao, J. Ye, and J. Qian, “Dynamic behavior and damage mechanisms of reinforced concrete piers subjected to truck impact,” Engineering Failure Analysis, vol. 121, Article ID 105158, 2020.

[44] H. Wang, J. Huo, Y. Liu, N. Wang, and M. Elchalakani, “Experimental and numerical study on impact behavior of beam-column substructures of steel frame – Science Direct,” Structures, vol. 29, pp. 14–29, 2021.

[45] Y. Ge, J. Lei, T. Liu, and W. Bai, “Dynamic mechanical properties and constitutive model of selective laser melting 316L stainless steel at different scanning speeds,” Research Square, 25 August 2021.