Cavitation erosion resistance of 316L stainless steel fabricated using selective laser melting

Hongqin DING^{1,†}, Qing TANG^{1,†}, Yi ZHU^{1,2,*}, Chao ZHANG¹, Huayong YANG¹

¹ State Key Laboratory of Fluid Power and Mechatronic Systems, Zhejiang University, Hangzhou 310027, China

² Ningbo Research Institute, Zhejiang University, Ningbo 315100, China

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Abstract: Cavitation erosion degrades the performance and reliability of hydraulic machinery. Selective laser melting (SLM) is a type of metal additive manufacturing technology that can fabricate metal parts directly and provide lightweight design in various industrial applications. However, the cavitation erosion behaviors of SLM-fabricated parts have rarely been studied. In this study, SLM 316L stainless steel samples were fabricated via SLM technology considering the scanning strategy, scanning speed, laser power, and build orientation. The effect of the process parameters on the cavitation erosion resistance of the SLM-fabricated 316L stainless steel samples was illustrated using an ultrasonic vibratory cavitation system. The mass loss and surface topography were employed to evaluate the surface cavitation damage of the SLM-fabricated 316L stainless steel samples after the cavitation test. The cavitation damage mechanism of the SLM-fabricated samples was discussed. The results show that the degree of cavitation damage of the sample fabricated via SLM with a few defects, anisotropic build direction, and columnar microstructure is significantly decreased. Defects such as pores, which are attributed to low laser power and high scanning speed, may severely aggravate the cavitation damage of the SLM-fabricated samples. The sample fabricated via SLM with a low laser power and exposure time exhibited the highest porosity and poor cavitation erosion resistance. The cellular structures are more prone to cavitation damage compared with the columnar structures. A sample with a high density of grain boundaries will severely suffer cavitation damage.

Keywords: selective laser melting; stainless steel; cavitation erosion; process parameters; microstructure

1 Introduction

Cavitation is a common phenomenon initiated by local pressure fluctuations in aqueous environments [1–4]. The formation of cavitation bubbles and their sudden implosion generate a high micro jet and shock wave, leading to a significant mass loss, erosion damage, and premature failure of the material [5–9]. The cavitation erosion phenomenon often occurs in machine components in aqueous media, especially in hydraulic systems, such as

pumps and valves. Furthermore, it will seriously affect the surface performance and shorten the service life due to cavitation damage. Several studies have been conducted on the various aspects of cavitation and cavitation erosion resistance.

Recently, metal additive manufacturing technology has been applied to produce hydraulic components having a low weight and small size [10, 11]. Selective laser melting (SLM) technology is a type of metal additive manufacturing technology that uses a laser to melt a pre-spread layer of powder selectively

[†] These authors contributed equally to this work.

* Corresponding author: Yi ZHU, E-mail: yiz@zju.edu.cn

according to the sliced computer-aided design model and builds a part in a layer-by-layer manner [12–14]. Stainless steel has been widely used in hydraulic systems because of its good mechanical properties and corrosion resistance, and 316L stainless steel is commonly used as a commercial SLM material. Owing to the temperature gradient in the SLM process, the material microstructure of the SLM-fabricated 316L stainless steel is different from that of conventional castings and forgings [15–17]. Therefore, the mechanical properties of the SLM-fabricated 316L stainless steel are different from those of the traditional parts because of their unique microstructure [18–20]. Several researchers have investigated the microstructure and performance of SLM-fabricated 316L stainless steel, including the effect of process parameters on its porosity [21], hardness [22], strength [16], fatigue [23], residual stress [24], and wear resistance [25]. This study aims to obtain high and satisfactory mechanical properties of SLM-fabricated 316L stainless steels. However, the cavitation erosion resistance of SLM-fabricated 316L stainless steel has been rarely reported. Only a few studies have investigated the cavitation erosion resistance of metallic materials formed via additive manufacturing technology. Zou et al. [26] studied the cavitation erosion behavior of SLM-fabricated AlSi10Mg material. The results showed that the cavitation erosion damage process of the SLM-fabricated material was significantly different from that of the wrought AlSi10Mg material. Furthermore, the mass loss of the SLM-fabricated samples increased significantly in the initial stage owing to the unmelted powder particles and the spalling of samples during the cavitation exposure. Tocci et al. [27] studied the cavitation erosion resistance of aluminum alloy materials fabricated via direct metal laser sintering using an ultrasonic vibration cavitation test system. The test results showed that, owing to the strengthening effect of the Mg_2Si phase and the strength improvement, the AlSi10Mg alloy exhibited an outstanding cavitation erosion resistance in terms of both the incubation period and maximum erosion rate. Hardes et al. [28] compared the cavitation erosion resistance of SLM-fabricated 316L stainless steel with that of the traditional 316L stainless steel using an ultrasonic

vibration cavitation erosion system. The test results showed that the cavitation erosion resistance of the SLM-fabricated stainless steel was not evidently improved. The hardness and yield strength of the SLM-fabricated stainless steel were improved, resulting in a longer incubation period for the material. The increase in the dislocation density of the SLM-fabricated samples may result in a smaller grain size.

In this study, 316L stainless steel samples with different process parameters are fabricated using SLM technology. The cavitation erosion behavior of the SLM-fabricated stainless steel samples is evaluated using an ultrasonic vibratory cavitation experimental facility. The mass loss and erosion morphology are employed to illustrate the cavitation erosion behavior of the SLM-fabricated 316L stainless steel samples. The cavitation damage mechanism of the SLM-fabricated 316L stainless steel samples is discussed.

2 Experimental

2.1 Sample preparation

An SLM system (Renishaw AM250), which comprised automatic powder layering, gas protective, laser scanning, and computer numerical control systems, was used to prepare the additively manufactured samples. A schematic of the SLM system is shown in Fig. 1.

The chemical composition of the 316L stainless steel powder used to fabricate the samples in this study is listed in Table 1. The dimensions of the SLM-fabricated sample were 10 mm × 8 mm × 5 mm. Table 2 lists the process parameters adopted in this work to produce the SLM-fabricated 316L stainless steel samples. The laser power, exposure time, scanning strategy, and build orientation were the key parameters used to produce different SLM-fabricated samples for the same layer thickness and point distance. The SLM-fabricated samples were named 200 W–80 μs –M, 200 W–80 μs –C, 160 W–60 μs –M, and 200 W–80 μs –M–B according to the laser power, exposure time, scanning strategy, and build orientation as indicated in Table 2. Figure 2 shows a schematic of the scanning strategies, namely,

Fig. 1 Schematic of the SLM system.

Fig. 2 Schematic of scanning strategies: (a) meander and (b) chessboard.

Table 1 Chemical composition of the stainless steel powder.

Chemical composition (wt%)	C	Ni	Mn	S	P	Cr	Cu	Mo	Fe
316L stainless steel	0.01	11.3154	1.5155	0.01	0.01	15.0441	0.1570	3.4454	Bal.

Table 2 Sample notations according to different process parameters.

Sample	Scanning strategy	Laser power (W)	Exposure time (μ s)	Layer thickness (μ m)	Point distance (μ m)	Build orientation (mm, Z-axis)
200 W–80 μ s–M	Meander	200	80	50	60	5
200 W–80 μ s–C	Chessboard	200	80	50	60	5
160 W–60 μ s–M	Meander	160	60	50	60	5
200 W–80 μ s–M–B	Meander	200	80	50	60	10

the meander and chessboard strategies. Figure 3 shows a schematic of the process parameters. Figure 4 shows the different build orientations and test surfaces used in this study. The top surface is used to perform the cavitation tests for the 200 W–80 μ s–M, 200 W–80 μ s–C, and 160 W–60 μ s–M samples, whereas the side surface is used to perform the cavitation test for the 200 W–80 μ s–M–B sample.

2.2 Mechanical properties test

The density of the samples was measured according

Fig. 3 Schematic of the process parameters.

Fig. 4 Build orientation of the SLM-fabricated samples.

to Archimedes' principle using an electronic balance (Sartorius BSA124S) with an accuracy of 0.1 mg. Each measurement was repeated three times and characterized by the mean value. The hardness was measured using a Vickers hardness tester (NDT-TIMETMVS-1) with an applied load of 50 g. The hardness measurements of each sample were performed on the surfaces of the cuboid parts. The tensile strength was tested using a microcomputer-controlled electronic universal tester (CMT5305) according to the Chinese Standard (GB/T 228e2002). Each tensile strength test was repeated three times.

2.3 Microstructure characterization

The crystallographic structure of the SLM-fabricated 316L stainless steel sample was characterized using X-ray diffraction (XRD). An X-ray diffractometer with Cu K α radiation was used to conduct the XRD test. The samples were previously subjected to conventional inlaying, polishing, and etching with glyceric acid etchant (10 mL glycerin + 15 mL HCl + 5 mL HNO₃) for microscopic observation. The porosity and surface topography were observed using confocal laser scanning microscopy (CLSM; VK-150 Keyence Corp). The surface microstructures of the non-eroded and eroded samples were observed using scanning electron microscopy (SEM). The crystal morphology was revealed using electron backscatter diffraction (EBSD).

2.4 Cavitation test

The cavitation erosion behavior of the SLM-fabricated 316L stainless steel samples was assessed using an ultrasonic vibration system in accordance with the

ASTM standard (G32-16) [29]. Figure 5 shows the schematic of the cavitation erosion facility. This test facility had an ultrasonic vibratory frequency and amplitude of 20 kHz and 6 μ m, respectively. The separation distance between the ultrasonic horn tip and the sample was 0.5 mm. The distance between the liquid level and the horn tip was 15 mm. The counterpart material in the cavitation test was stainless steel. The cavitation medium in the beaker was 3.5% NaCl water. The used NaCl water was replaced with fresh 3.5% NaCl water at regular intervals of 30 min while maintaining the temperature at 20 ± 5 °C. The samples were ultrasonically cleaned and dried in an oven and subsequently weighed in a balance with an accuracy of 0.1 mg before and after each cavitation experiment test.

3 Results

3.1 Material properties

3.1.1 Density

Figure 6 shows the relative densities of the SLM-

Fig. 5 Schematic of the ultrasonic vibration system.

Fig. 6 Relative densities of the SLM-fabricated 316L stainless steel samples.

fabricated 316L stainless steel samples with different process parameters. The relative densities of the 200 W-80 μ s-M and 200 W-80 μ s-M-B samples are 99.4% and 99.0%, respectively. On the other hand, the 160 W-60 μ s-M sample fabricated under a low energy density exhibits the lowest relative density (93.3%) among all the samples. The relative density of the 200 W-80 μ s-C sample is 97.9%, which is lower than that of the 200W-80 μ s-M and 200 W-80 μ s-M-B samples, but higher than that of the 160 W-60 μ s-M sample.

3.1.2 Porosity

Figure 7 shows the polished top surfaces of the SLM-fabricated 316L stainless steel samples. The porosity is in accordance with the density measurement results. It is observed in Figs. 7(a) and 7(d) that the porosities of the 200 W-80 μ s-M and 200 W-80 μ s-M-B samples are 0.082% and 0.083%, respectively. Some sporadic holes can be observed on the surfaces of the 200 W-80 μ s-C sample in Fig. 7(b). However, the pores of the 160 W-60 μ s-M sample are considerably increased compared with those of the 200 W-80 μ s-M sample (average pore area: 11.78 μ m²) and 200 W-80 μ s-M-B sample (average pore area: 6.99 μ m²), as shown in Fig. 7(c). The pores on the 160 W-60 μ s-M sample are irregular and more than 100 μ m in size. As reported in previous studies, these shrinkage porosities are due to the incomplete flow of metal into the melt region [30]. The formation of porosity is closely related to the hydrogen absorption, melting splashing, Marangoni flow, or other phenomena [31, 32]. The low laser power of 160 W and short exposure time of 60 μ s cause insufficient laser energy and accordingly enhance the balling phenomenon, resulting in an increase in the number of unmelted powder particles [26, 28, 31], as shown in Fig. 7(c). Figures 8(a) and 8(b) show the morphologies of the 200 W-80 μ s-M

Fig. 7 CLSM topographies of the SLM-fabricated samples before the cavitation test: (a) 200 W-80 μ s-M, (b) 200 W-80 μ s-C, (c) 160 W-60 μ s-M, and (d) 200 W-80 μ s-M-B.

Fig. 8 SEM observation topographies: (a) unpolished topography of the 200 W-80 $\mu\text{s-M}$ sample, (b) unpolished topography of the 200 W-80 $\mu\text{s-C}$ sample.

and 200 W-80 $\mu\text{s-C}$ samples, respectively. The visible laser scanning tracks of the 200 W-80 $\mu\text{s-M}$ sample are approximately 1 mm wide, which are narrower than those of the 200 W-80 $\mu\text{s-C}$ sample due to its longer raster path. In addition, longer raster paths might obstruct heat accumulation, leading to a lower thermal gradient and lesser local deformation [33]. The melted tracks of the 200 W-80 $\mu\text{s-C}$ sample fabricated via the chessboard strategy shown in Fig. 2(b) are not successive, and some unmelted powder particles are observed in the gap and crisscross region, which contribute to the porosity due to the lack of fusion [30]. Therefore, the porosity of the 200 W-80 $\mu\text{s-C}$ sample is higher than that of the 200 W-80 $\mu\text{s-M}$ sample.

3.1.3 Hardness

The hardness results of the SLM-fabricated 316L stainless steel samples are shown in Fig. 9. Considering the statistical variation, the hardness values of the SLM-fabricated samples are not evidently different. The hardness value of the 200 W-80 $\mu\text{s-M}$ sample (285 HV) is higher than that of the 160 W-60 $\mu\text{s-M}$ sample (250 HV) mainly due to the porosity. The measured hardness value of the 200 W-80 $\mu\text{s-C}$ sample is 262 HV, which is close to that of the 200 W-80 $\mu\text{s-M-B}$ sample (260 HV). It is well known that grain refinement and dislocation will improve the hardness value [34]. The grains of the 200 W-80 $\mu\text{s-M}$ sample are fine, and the density of the grain boundary is high, which hinders the dislocation motion effectively, leading to the strengthening of the grain boundary [31].

Fig. 9 Hardness values of the SLM-fabricated 316L stainless steel samples.

3.1.4 Tensile strength

As with the hardness measurement results, the tensile strength results of the SLM-fabricated 316L stainless steel samples exhibit similar trends. The tensile strength results are shown in Fig. 10. The values for the 200 W-80 $\mu\text{s-M}$, 200 W-80 $\mu\text{s-C}$, 160 W-60 $\mu\text{s-M}$, and 200 W-80 $\mu\text{s-M-B}$ samples are 603, 580, 485, and 578 MPa, respectively.

3.2 Microstructure characterization

3.2.1 Phase analysis

Figure 11 shows the XRD patterns of the SLM-fabricated 316L stainless steel samples and raw powders. The SLM-fabricated 316L stainless steel samples and raw powders presented two phases: the γ austenite phase and the δ ferrite phase. From

Fig. 10 Tensile strengths of the SLM-fabricated 316L stainless steel samples.

Fig. 11 XRD patterns of the SLM-fabricated 316L stainless steel samples.

the diffractogram peaks, it is evident that the diffraction peaks of the SLM-fabricated 316L stainless steel samples with different process parameters are not aligned. This is because the cooling and solidification rates are different, which further influences the nucleation and thermal stress [35].

3.2.2 Microstructure

Figures 12 and 13 show the microstructures of all the SLM-fabricated 316L stainless steel samples. There are two typical crystal structures, namely, cellular and columnar structures. The same results were also obtained in previous studies [25]. Owing to the high temperature gradient and different cooling and solidification rates, the microstructures of the SLM-fabricated 316L stainless samples are not uniform. There is no remarkable difference in the microstructures of the SLM-fabricated samples, except the 160 W-60 μ s-M sample. This sample shows a different microstructure owing to its low energy density. The micropores result in non-continuous cellular and columnar structures. In addition, the enlarged images show that the cellular structures of the 200 W-80 μ s-C and 160 W-60 μ s-M samples are finer than those of the 200 W-80 μ s-M sample. In Fig. 14(a), some oblong melted pools marked with black dotted lines on the 200 W-80 μ s-M, 200 W-80 μ s-C, and 160 W-60 μ s-M samples

Fig. 12 Microstructures of the SLM-fabricated 316L stainless steel samples: (a) 200 W-80 μ s-M, (b) 200 W-80 μ s-C, (c) 160 W-60 μ s-M, and (d) 200 W-80 μ s-M-B.

Fig. 13 Enlarged cellular structures of the SLM-fabricated 316L stainless steel samples: (a) 200 W-80 μ s-M, (b) 200 W-80 μ s-C, (c) 160 W-60 μ s-M, and (d) 200 W-80 μ s-M-B.

Fig. 14 SEM observations of the SLM-fabricated 316L stainless steel samples: (a) microstructure of the 200 W-80 μ s-M sample, (b) microstructure of the 200 W-80 μ s-M-B sample, (c) cellular structure, and (d) columnar structure.

can be observed, whereas crescent pools marked with black dotted lines in Fig. 14(b) can be observed on the 200 W-80 μ s-M-B sample. Moreover, the 200 W-80 μ s-M-B sample is characterized by several columnar structures, and the cells continuously grow toward the center of the molten pool. However,

the etched surface of the 200 W-80 μ s-M sample is composed of massive cellular structures. The enlarged images of the cellular and columnar structures are shown in Figs. 14(c) and 14(d), respectively. This is because the heat generated by the laser is loaded on the top surface, and it flows to the substrate,

causing a high thermal gradient on the surface of the 200 W–80 μs –M–B sample [36, 37]. The difference in the crystallographic microstructures is more prominent with the variation in laser power, exposure time, scanning strategy, and build orientation. The typical characteristics can be represented in terms of surface pores and microstructures in this study.

3.3 Cavitation erosion behavior

The cavitation erosion behavior of the SLM-fabricated 316L stainless steel samples was evaluated using an ultrasonic vibration system over 6 h of exposure. Figure 15 shows the mass loss curve of the SLM-fabricated samples as a function of the cavitation exposure time. The mass loss of all the SLM-fabricated samples increases significantly during the test time of 1 h. After a total exposure of 6 h, the mass loss of the 200 W–80 μs –M–B sample is 1.87 mg. This value is approximately 30% that of the 160 W–60 μs –M sample (6.16 mg), 60% that of the 200W–80 μs –M sample (3.13 mg), and 51% that of the 200 W–80 μs –C sample (3.66 mg). The cavitation erosion resistance of the 200 W–80 μs –M–B sample is higher than those of the 200 W–80 μs –M, 160 W–60 μs –M, and 200 W–80 μs –C samples. Similar results were obtained in a previous study [26]. However, these results differ from those of a published study [28]. The cumulative mass loss versus time for the SLM-fabricated samples and cast samples with hot-rolling and subsequent solution annealing is consistent with the corresponding description of the different stages of cavitation erosion according to the ASTM standard (G32-10). The mass rate is lower in the incubation stage and rises rapidly as a function of test time, which is due to the generation of stacking faults and strain hardening to accommodate the impact of shock waves in the incubation stage [28]. A possible explanation for this variation is that unmelted powder particles inside the pores of the SLM samples were removed initially [26], which can be verified in Figs. 7 and 8. In addition, the special microstructure of the SLM-fabricated samples may shift the different stages of cavitation erosion in this study.

Figure 16 shows the roughness values of the SLM-fabricated 316L stainless steel samples before

and after 3 and 6 h of the cavitation experiments. Figure 15 shows that the roughness values of all the SLM-fabricated 316L stainless steel samples gradually increase with the increase in cavitation test time, and the variation of the different samples is evident. All the SLM-fabricated 316L stainless steel samples were polished before the cavitation erosion test. The 160 W–60 μs –M sample is not smooth owing to high porosity. The roughness value of the 160 W–60 μs –M sample after 6 h of the cavitation erosion test is approximately 17 μm , which is the highest value among all the SLM-fabricated 316L stainless steel samples. This indicates that the cavitation erosion resistance of the 160 W–60 μs –M sample is the lowest among the SLM-fabricated 316L stainless steel samples.

Fig. 15 Mass loss curves of the SLM-fabricated 316L stainless steel samples as a function of the exposure time.

Fig. 16 Roughness values of the SLM-fabricated 316L stainless steel samples before and after 3 and 6 h of the cavitation tests.

The CLSM topographies of the SLM-fabricated 316L stainless steel samples are shown in Fig. 17. The topographies of all the SLM-fabricated 316L stainless steel samples become coarse after the cavitation erosion test. With the cavitation test time, shallow gullies are formed on the surface of all the SLM-fabricated 316L stainless steel samples. Figure 18 shows that the degree of cavitation damage of the samples is not uniform. The pores of the 160 W-60 $\mu\text{s-M}$ and 200 W-80 $\mu\text{s-C}$ samples are connected, and they expand after the cavitation test. Defects such as pores are extremely vulnerable to the impact of cavitation bubbles. The eroded surface of the 200 W-80 $\mu\text{s-M}$ sample is characterized by a few crisscrossing patterns, whereas the non-eroded area is divided into several regular blocks. However, the eroded surface of the 200W-80 $\mu\text{s-M-B}$ sample is represented as a long strip pattern. In addition, the three-dimensional topographies of all the SLM-fabricated samples are shown in Fig. 18 before and

after the cavitation erosion test.

The SEM observations of all the SLM-fabricated samples are shown in Fig. 19 before and after the cavitation erosion test to illustrate the cavitation erosion mechanism further. As shown in Fig. 19, the surfaces of all the SLM-fabricated samples are heterogeneous. In addition, some irregular pits and slip lines are clustered severely in the local areas of the 200 W-80 $\mu\text{s-M}$, 200 W-80 $\mu\text{s-C}$, 160 W-60 $\mu\text{s-M}$ samples. The material is easily removed from the sample surface. Serious plastic deformation and material abscission are observed in certain regions, which are typical eroded cavitation damage mechanisms. With the cavitation test time, most of the original surfaces are striped, and they become rough. These damaged surfaces are characterized by deep corrugations. As mentioned earlier, the morphologies of all the eroded surfaces are the same as those of a ductile fracture. The erosion damage of the 160 W-60 $\mu\text{s-M}$ sample is the most

Fig. 17 CLSM topographies of the SLM-fabricated samples before and after 3 and 6 h of the cavitation test: (a) 200 W-80 $\mu\text{s-M}$, (b) 200 W-80 $\mu\text{s-C}$, (c) 160 W-60 $\mu\text{s-M}$, and (d) 200 W-80 $\mu\text{s-M-B}$.

Fig. 18 Three-dimensional topographies of the SLM-fabricated samples before and after the cavitation test.

serious among all the SLM-fabricated samples. In contrast, the erosion damage of the 200 W-80 μs -M-B sample is significantly mitigated compared with that of the other SLM-fabricated samples. The surface of the 200 W-80 μs -M-B sample is almost intact in most regions, except for some clusters. Figure 20 shows the enlarged images of the SLM-fabricated samples after 6 h of the cavitation test. Figure 20 shows the fracture surfaces of all the samples. Plastic deformation is observed in Fig. 20. The material is deformed as a mountain-like undulation, without being peeled off from the surface. In addition, the deformation does not appear uniformly on the surfaces of the samples. It is well known that the initial cavitation damage is plastic deformation. Under repetitive actions of the collapsing bubbles, fatigue-like striations are observed in all the SLM-fabricated samples. The rim of the pores may be easily attacked, resulting in material removal, as shown in Fig. 20(c). Figure 21 shows the typical SEM images of the cavitation erosion damage for

the 200 W-80 μs -M sample including cracks (arrow), craters (dot line frame), and plastic deformation (arc) after 6 h of the cavitation test.

To analyze the mechanism of cavitation damage, all the SLM-fabricated samples after 6 h of the cavitation test were cut and polished along the cross-section. These cross-sections were observed using SEM, as shown in Fig. 22. After 6 h of the cavitation erosion test, micro-cracks and irregular craters were observed on the cross-section for almost all the SLM-fabricated samples. These craters have a depth of 1–10 μm . The crater is perpendicular to the surfaces of the 200 W-80 μs -M, 200 W-80 μs -C, and 200 W-80 μs -M-B samples. However, some deep craters are observed on the surface of the 160 W-60 μs -M sample (as shown in Fig. 22(c)) with the depth of 10–50 μm . This is mainly because the 160 W-60 μs -M sample has high porosity and large pores, which may lead to serious cavitation damage. As shown in Fig. 22(a), several cracks are formed at the bottom of the pits, and they propagate

Fig. 19 SEM images of the SLM-fabricated samples before and after 3 and 6 h of the cavitation test: (a) 200 W–80 μs –M, (b) 200 W–80 μs –C, (c) 160 W–60 μs –M, and (d) 200 W–80 μs –M–B.

Fig. 20 Enlarged SEM images of the SLM-fabricated samples after 6 h of the cavitation test: (a) 200 W–80 μs –M, (b) 200 W–80 μs –C, (c) 160 W–60 μs –M, and (d) 200 W–80 μs –M–B.

Fig. 21 Typical SEM images of cavitation damage for the 200 W-80 μs -M sample containing cracks (arrow), craters (dot line frame), and plastic deformation (arc) after 6 h of the cavitation test.

toward the interface without preferential orientation. A series of long cracks (as shown in Fig. 22(b)) are formed under the pits and become connected with a large pore, which accelerates the cavitation damage to the interface of the sample. The profiles of the transverse section of the 200 W-80 μs -M-B sample (as shown in Fig. 22(d)) are smooth compared with those of the other SLM-fabricated samples. In addition, there are fewer defects, such as pores, cracks, pits, and craters, observed in Fig. 22(d). Therefore, with increasing cavitation test time, the 200 W-80 μs -M-

B sample exhibits a higher cavitation erosion resistance in comparison with those of the 200 W-80 μs -M, 200 W-80 μs -C, and 160 W-60 μs -M samples.

4 Discussion

4.1 Effect of material properties on cavitation erosion resistance

4.1.1 Effect of porosity on cavitation erosion resistance

Pores have a detrimental influence on the performance of the SLM-fabricated parts, as they may induce stress concentration and provide a preferential path for crack generation and propagation [26, 31, 38]. Notably, the macro defects (pores and cracks) may have a considerable influence on the cavitation erosion resistance of the SLM-fabricated samples. Similar results were obtained in a previous study [28]. Joint defects of an irregular shape result in relatively loose material fragments that are torn apart by cavitation-induced impacts, leading to a sudden mass loss. The mass loss rate is higher during the first hour of the cavitation test. The fracture of pores and the removal of unmelted powder are prone to occur in the initial cavitation

Fig. 22 Cross-section images of the SLM-fabricated samples after 6 h of the cavitation erosion test: 200 W-80 μs -M, (b) 200 W-80 μs -C, (c) 160 W-60 μs -M, and (d) 200 W-80 μs -M-B.

test. The 160 W–60 μs –M and 200 W–80 μs –C samples experience severe cavitation damage due to low density and high porosity. Pre-existing pores are a critical issue in the parts fabricated via SLM technology. Owing to the presence of pores, mechanical erosion and electrochemical corrosion may synergistically influence the mechanical action of bubble implosion. This will result in passive film thickness reduction and surface damage acceleration, thereby exposing the underlying fresh surface. The cavitation erosion resistances of the 200W–80 μs –M and 200 W–80 μs –M–B samples are excellent due to high density and low porosity, whereas those of the 160 W–60 μs –M and 200 W–80 μs –C samples are poor due to low density and high porosity. However, pores are difficult to avoid, and appropriate process parameters should be chosen. As shown in this study, the process parameters of 200 W–80 μs –M and 200 W–80 μs –M–B samples are recommended to reduce the porosity and enhance the cavitation erosion resistance of SLM-fabricated 316L stainless steel.

4.1.2 Effect of microstructure on cavitation erosion resistance

As shown in Fig. 23, the 200 W–80 μs –M sample exhibits a cellular grain structure with a fine and equi-axed grain of average size approximately 25 μm . However, the 200 W–80 μs –M–B sample exhibits a columnar grain structure with coarse grains. These columnar grains are above hundreds of micrometers in length but only several or a dozen micrometers in width. Owing to the thermal diffusion of the substrate in the SLM process, a high cooling gradient is generated with a rapid solidification rate. Thus, columnar grains grow parallel to the Z-direction [25, 39]. Under a low thermal gradient, the crystals are more likely to be equi-axed and fine. In contrast, the growth of the crystals tends to be coarse under a high thermal gradient, which is in accordance with the results obtained above. The density of the grain boundary of the 200 W–80 μs –M sample is higher than that of the 200 W–80 μs –M–B sample. A high density of grain boundaries is beneficial for improving the mechanical properties, such as hardness and tensile strength. However, dislocations tend to be piled up along the grain

boundaries, and the cracks initiate and expand under repeated impacts [31, 40]. Local topographical differences on the investigated surfaces resulting from a protrusion of SLM specific grain boundaries increase the probability of subsequent cavitation bubble impacts, which is detrimental to the cavitation erosion resistance of the SLM-fabricated samples [28]. Cavitation damage is more likely to occur at the grain boundaries, which is attributed to the fatigue process under cavitation erosion. Owing to the presence of numerous grain boundaries, the electrochemical corrosion process may lead to the acceleration of surface cavitation damage. Therefore, the cavitation erosion resistance of the 200 W–80 μs –M sample is significantly affected by the damage aggravation under the corrosion liquid environment. The grain boundaries of the SLM-fabricated sample undergo preferential plastic deformation and become dissolved [41]. As shown in Figs. 23(c) and 23(d), several extrusions and ravines can be observed along the grain boundaries. This cavitation damage area along the grain boundaries may lead to not only stress concentration but also cavitation bubble nucleation and collapse near the grain boundaries [40]. After 6 h of the cavitation erosion test, plastic deformation is observed in Fig. 24, with a depth of approximately 10–20 μm . In addition, the surface profile is irregular and craters are visible. Columnar and cellular structures are observed in the etched transverse section. The cavitation damage phenomena of the columnar and cellular structures are considerably different. Under the effect of cavitation bubbles, the cellular structures near the surface reveal an oblong shape, whereas the cellular structures far from the surface reveal a circular shape. This indicates that these structures are more likely to be condensed and collapsed. In contrast, the columnar structures are prone to bending, as depicted by the black dotted line in Fig. 24. Therefore, the ability of the columnar structure to resist the cavitation damage is superior to that of the cellular structure. This may result in the improvement of the cavitation erosion resistance of the SLM-fabricated samples with columnar structures in comparison with that of the SLM-fabricated samples with cellular structures. This phenomenon may be attributed to

Fig. 23 EBSD and CLSM images of the SLM-fabricated samples: (a, c) 200 W-80 μ s-M sample, (b, d) 200 W-80 μ s-M-B sample.

Fig. 24 Cross-section image of the SLM-fabricated 200 W-80 μ s-M-B sample after 6 h of the cavitation test.

the lower yield strength of cellular structures than that of columnar structures. This issue requires further study. The 200 W-80 μ s-M-B sample is characterized by columnar structures. Hence, the cavitation erosion behavior of the 200 W-80 μ s-M-B sample is better than those of the 200 W-80 μ s-M, 200 W-80 μ s-C, and 160 W-60 μ s-M samples.

4.2 Cavitation erosion mechanism

During the cavitation erosion test, the collapse of

nucleated bubbles generates repeated impact shock waves and micro-jets, which may result in cavitation damage to the sample surface. A few slight impacts lead to local stress concentration and induce dislocation movements along the grain boundaries. With the cavitation test time, plastic deformation, pits, and craters may gradually form. Some violent shocks with high energy will result in material removal [27]. In Fig. 25, a schematic of the SLM-fabricated 316L stainless steel samples under a cavitation bubble impact is shown. The cavitation erosion behavior of pores and different microstructures is illustrated. The 200 W-80 μ s-M sample with low porosity exhibits a favorable cavitation erosion behavior; however, the high density of grain boundary and the surface dominated by cellular structures are detrimental to the cavitation erosion resistance. The 200 W-80 μ s-C sample with several pores and grain boundaries suffers from a severe cavitation damage acceleration due to the effect of the electrochemical process under the corrosion liquid condition. The porosity of the 160W-60 μ s-M sample is the highest among all the SLM-fabricated samples; consequently, this sample shows the worst

Fig. 25 Schematic of the SLM-fabricated 316L stainless steel samples under cavitation bubble impact.

cavitation erosion behavior. In contrast, owing to low porosity, low density of grain boundary, and dominant columnar structures on the surface, the 200 W–80 μs –M–B sample is slightly eroded and exhibits a superior cavitation erosion resistance in comparison with those of the 200 W–80 μs –M, 200 W–80 μs –C, and 160 W–60 μs –M samples.

5 Conclusions

In this study, 316L stainless steel samples were fabricated via SLM technology with various process parameters (scanning strategy, scanning speed, laser power, and build orientation). The effect of the process parameters on the cavitation erosion resistance of the SLM-fabricated 316L stainless steel samples was evaluated using an ultrasonic vibratory cavitation system. Various test methods were adopted to illustrate the surface cavitation damage of the SLM-fabricated 316L stainless steel samples after 6 h of cavitation test. The cavitation damage mechanism of the SLM-fabricated 316L stainless steel samples was discussed. Based on the discussion, the main conclusions are as follows:

- 1) The cavitation damage of the 200 W–80 μs –M–B sample was significantly decreased in comparison with those of the 200 W–80 μs –M, 200 W–80 μs –C, and 160 W–60 μs –M samples.
- 2) Low laser power and high scanning speed resulted in insufficient laser energy density to generate the balling phenomenon, and pores and unmelted powder particles increased. These defects severely aggravated the cavitation damage of the SLM-fabricated samples. The 160 W–60 μs –M sample

with the highest porosity exhibited a poor cavitation erosion resistance.

3) The ability of the columnar structure to resist cavitation damage was superior to that of the cellular structure, which may result in the improvement of the cavitation erosion resistance of the SLM-fabricated samples.

4) By varying the build orientation, the microstructures of the SLM-fabricated sample were observed to be significantly different. A sample with a high density of grain boundaries will suffer severe cavitation damage.

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Hongqin DING. He received his Ph.D. degree (2019) in mechanical engineering from Southeast university in China. He is currently an assistant research fellow in the State Key

Laboratory of Fluid Power and Mechatronic Systems in Zhejiang University. His research interests include surface design of additive manufacturing machine elements and application in hydraulic component, tribology, and cavitation erosion.

Qing TANG. He received his B.S. degree (2019) in mechanical design and manufacturing and its automation from Hunan University of Technology in China. He is currently

a master student studying mechanical electronics in Zhejiang University. His research interests include selective laser melting, tribology, and cavitation erosion.

Yi ZHU. He received his Ph.D. degree (2013) in mechanical engineering from KTH Royal Institute of Technology in Sweden. He is currently an associate professor in the State Key Laboratory of

Fluid Power and Mechatronic Systems in Zhejiang University in China. His research interests include surface design of additive manufacturing fabricated machine elements and the application of selective laser melting in hydraulic components.

Chao ZHANG. He received his Ph.D. degree (2019) in mechanical engineering from University of Lyon in France. He joined Zhejiang University as an associate professor

in 2019. His current research focuses on the field of fluid power, including optimal design and 3D printing of fluid power components, fluid power measurement and intelligent control, and fluid-powered robotics and machines.

Huayong YANG. He received his Ph.D. degree (1988) in mechanical engineering from University of Bath in United Kingdom. He is currently a professor in the State Key Laboratory of Fluid Power

and Mechatronic Systems in Zhejiang University in China. He is an academican of Chinese Academy of Engineering. His research interests include immersion lithography, double feedback principle load control valve, and shield tunnelling boring machine.