Study on typical defects and cracking characteristics of tool steel fabricated by laser 3D printing

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Abstract. Porosity and crack are the two most common types of metallurgical defects induced by SLM. It is of great significance to study the porosity and crack defects of H13 tool steel fabricated by SLM for promoting the practical application of this technology in the tool and die manufacturing industry. In this paper, the SLM experiments of H13 tool steel powder were carried out, and H13 tool steel samples were prepared. The microstructure of the as-fabricated samples was characterized by scanning electron microscope (SEM) and optical microscope (OM) to explore the characteristics and formation mechanism of porosity and crack defects in SLM process of H13 tool steel. It can be concluded that there are some metallurgical defects in as-fabricated H13 tool steel samples, such as lack of fusion or poor fusion, pores, and cracks. Most of the cracks are originated from the side edge of the sample, and some branched secondary cracks are induced near the coarse main cracks during the process of cracking along the formed layer to the inside of the sample. And the secondary cracks with small size could prevent the main cracks from continuing to propagate. Furthermore, due to the local stress concentration, some micro-cracks with smaller size are induced near the internal porosity defects.

1. Introduction

Additive manufacturing (AM) is a material rapid prototyping technology which manufactures parts by the method of gradual accumulation of materials. This technology is a new development direction of manufacturing industry and would promote the rapid innovation and upgrading of traditional manufacturing industry, which has become one of the key technologies in the long-term development strategy of manufacturing industry in many countries around the world. The core position and value of AM technology in the future manufacturing industry are clearly emphasized in “German Industry 4.0” strategy and “Made in China 2025” plan. As an important branch of Laser Additive Manufacturing (LAM), based on the principle of layered manufacturing, Selective Laser Melting (SLM) technology takes high-energy laser beam as its heat source, and can directly and rapidly manufacture any complex metal parts. With a high degree of freedom, this technology is almost not limited by the structure shape and material type, and it is particularly suitable for manufacturing metal tools and dies with complex structure [1-3]. However, the SLM process is prone to induce large stress and metallurgical defects such as pore, warpage and crack, which could significantly affect the surface accuracy,
densification level, internal quality, mechanical properties and finally the service life of the formed parts.

Otani et al. [4] added Si to 7075 aluminum alloy powder, and studied the effect of Si content on the micro defects of 7075 aluminum alloy fabricated by SLM. The results showed that the addition of Si was conducive to improving the densification level of the formed parts and effectively inhibiting the formation of cracks in SLM process. With the increase of Si content, the pores and cracks in the formed parts gradually decreased, and the cracks could be eliminated when 5% Si was added to as-used 7075 aluminum alloy powder. Zhu et al. [5] prepared 316L stainless steel using SLM technology under different laser exposure time to explore the effect of laser exposure time on porosity defects in the formed parts. It was found that the number of pores induced by SLM decreased and the density of the samples increased with the increase of laser exposure time. Almangour et al. [6] studied the evolution of metallurgical defects of as-fabricated TiC/316L stainless steel nanocomposites by SLM under different laser energy densities. The results showed that there were some obvious spheroidization and porosity defects under lower laser energy density. Under higher laser energy density, the densification level significantly increased due to the increase of the liquid lifetime, but some smaller spherical pores and micro-cracks were induced. Hu et al. [2] prepared TiB2/S136 composite using SLM technology under different laser energy densities to study the influence of laser energy density on the densification behavior of as-fabricated samples. The results indicated that low energy density could lead to poor fusion of powder, and high energy density could lead to crack defects. When the applied energy density was 66.7 J/mm3, there were so less defects that the density of as-fabricated sample was as high as 97.3%.

However, there are few studies on the internal defects and cracking behavior of H13 tool steel fabricated by SLM. Therefore, in this paper, the typical metallurgical defects of H13 tool steel fabricated by SLM are studied, the formation and propagation behavior of cracks in SLM process are analyzed to explore the distribution, morphology, and formation mechanism of cracks induced by SLM. This study aims at providing reference for the control of porosity and crack defects in SLM process of H13 tool steel.

2. Experiment

2.1. Materials and fabrication

In this study, H13 tool steel powder with a spherical shape was used as the starting material, their morphology was illustrated in Figure 1. SLM processing were carried out on an SLM machine EOS M280 with a continuous wavelength of 1064 nm Yb-fibre laser. The maximum processed dimensions of this SLM machine were 250 mm×250 mm×325 mm. In SLM process of H13 tool steel, the building chamber was under the protection of the Ar atmosphere with a high purity to prevent oxidation. The as-used laser scanning strategy was illustrated in Figure 2. And the dimensions of the as-fabricated cubic samples were about 10 mm×10 mm×10 mm.

![Figure 1. Morphology of as-used H13 powder.](image1)

![Figure 2. As-used laser scanning strategy of SLM](image2)
2.2. Characterization method
The bulk H13 tool steel samples fabricated by SLM were cut into cross-section samples perpendicular to the laser scanning direction by wire cutting. After inlaying, grinding and polishing, the cross-section morphology of the as-fabricated samples was characterized by optical microscope (OM, Leica DM1750M, Germany) and scanning electron microscope (SEM, JEOL JSM-IT300, Japan).

3. Results and discussion
Figure 3 shows the SEM images of typical poor fusion and pore defects on the cross-section of H13 tool steel sample fabricated by SLM. It can be observed that there are some porosity defects with different shapes due to the lack of fusion or poor fusion of the powder, which are closely related to the laser energy input. Under the lower laser energy input, a molten pool is obtained with lower temperature, smaller size, less liquid metal and shorter lifetime, which means that the liquid metal obtained in the molten pool has high viscosity and poor fluidity. At this time, the liquid metal in the molten pool cannot be fully spread and wetted so that H13 tool steel powder cannot be completely melted, thereby resulting in the lack of fusion or poor fusion phenomenon. The porosity defects caused by the lack of fusion or poor fusion are generally large in size, which greatly reduce the density and mechanical properties of the as-fabricated parts. In addition, some pores can be observed, which may relate to the residual gas mixed in the original H13 tool steel powder or the gas produced by the material vaporization at high temperature in SLM process. These gases do not have enough time to escape from the molten liquid metal during the solidification process of the molten pool, thereby inducing the residual pores which are difficult to be completely eliminated. These pores are generally spherical, and they are small in size.

![Figure 3. SEM images showing the porosity defects on the cross-section of SLM-processed samples.](image-url)
In SLM process of H13 tool steel, the pores produced and the porosity defects caused by the lack of fusion or poor fusion phenomenon would reduce the effective bearing area of as-fabricated H13 tool steel parts, resulting in the decrease of strength. The internal porosity defects are prone to become crack sources, which can be ascribed to the local high stress concentration [3]. On the one hand, the inherent porosity defects induced by SLM may induce the formation of crack defects in the subsequent manufacturing process, affecting the forming of parts. On the other hand, under the action of the mechanical load, especially under the fatigue load, the inherent porosity defects would become the starting point of the failure and damage [7,8], thereby accelerating the failure of SLM-processed part and reducing their service life, which is also one of the main factors restricting the engineering application of SLM-processed load-bearing components. Obviously, a large number of metallurgical defects with large size would significantly reduce the formability and mechanical properties of the SLM-processed part. If they were not properly controlled, these metallurgical defects may even directly cause the SLM processing to fail. At the same time, metallurgical defects would also affect the thermal conductivity and other properties of the material. Of course, according to the demand of practical applications, porous parts would also be fabricated to obtain certain specific properties and functions.

Figure 4 shows the typical morphologies of the crack defects on the cross-section of SLM-processed H13 tool steel samples. As illustrated in Figure 4(a), (b) and (c), most of the cracks produced in H13 tool steel samples originate from the side edge of the sample, and propagate along the formed layer to the inside of the sample, and finally terminate at the inside of the sample, which implies that the crack propagation is directional. Besides, it is clearly demonstrated that there are many notches on the rough and uneven side of the sample, which are conducive to the formation of cracks on the side due to small constraint and large degree of freedom. The side of the SLM-processed sample is the interface between solidified material after laser scanning and un-scanned powder by laser. And the semi-melted powder particles due to lack of enough laser energy absorbing would adhere to the side, resulting in the phenomenon of powder sticking on the surface, which implies that the side with low quality would be obtained. As illustrated in Figure 4(c), there are some branched secondary cracks with smaller size and shorter propagation distance near the main crack with larger size in the crack propagation process. And as illustrated in Figure 4(d), some micro-cracks are induced near the porosity defects in the formed sample, which can be ascribed to the local stress concentration. The micro-cracks induced by porosity are generally smaller in size and larger in number, which would propagate a short distance to the periphery of the porosity to release stress.

The formation and propagation of cracks are related to the material strength, residual stress and release behavior of the residual stress. At present, it is commonly accepted that the formation of crack defects can be mainly ascribed to the rapid and complex solidification process of SLM and the large residual tensile stress caused by large temperature gradient [1,9]. Cracks would preferentially occur in those regions where the material is weak or residual stress is concentrated. When the tensile stress induced by SLM exceeds the tensile strength of the material, crack defect would be produced to release the stress. With propagating the crack, the internal stress of the formed parts is gradually released and reduced. And when the stress is lower than the tensile strength of the material, the crack would stop propagating. Obviously, the secondary crack near the main crack could also make some stress be released, which is beneficial to prevent the main crack from continuing to propagate into a larger size crack, thereby reducing the damage of the main crack. It can be seen that controlling the residual stress of SLM process and improving the strength of the formed parts could effectively suppress the formation of cracks.

Crack is one of the most common and destructive metallurgical defects, which is difficult to be controlled in SLM process. On the one hand, the cracks produced in SLM process would propagate to a different extent to release the stress under the complex stress induced by the complex thermal behavior in the subsequent manufacturing process. On the other hand, the cracks would also propagate preferentially in the service time, accelerating the failure and damage of materials, which would result in the decrease of service life. No matter in the subsequent processing or service time, the cracks
would propagate preferentially toward where the material is weak, which implies that the cracks would propagate to other internal defects. And the presence of other metallurgical defects would accelerate the crack propagation, thereby accelerating the failure and damage of SLM-processed parts. Through the above analysis, the crack defects of H13 tool steel fabricated by SLM could be controlled by: (1) reducing the residual stress level of the formed parts by adjusting and optimizing laser processing parameters and other methods; (2) improving the surface formed quality and reducing the internal metallurgical defects such as porosity, lack of fusion or poor fusion by adjusting and optimizing the laser processing parameters and other methods, so as to improve the internal formed quality and mechanical properties of the formed parts. Besides, adding other elements to the metal powder could also effectively suppress cracks. In the study of Li et al. [10], they added the second phase nano particle ZrC to pure W powder to prepare W-ZrC using SLM technology. The results showed that the addition of ZrC significantly reduced the crack defects of the as-fabricated parts, implying the improvement of the crack resistance, which was attributed to the grain refinement caused by ZrC particles. And more energy was needed for crack propagation owing to the increase of grain boundaries brought by the grain refinement, thereby improving the crack resistance.

Figure 4. OM or SEM images showing the cracks on the cross-section of SLM-processed samples.

4. Conclusion
(1) There are some metallurgical defects in as-fabricated H13 tool steel samples by SLM, such as lack of fusion or poor fusion with irregular shape and larger size, pores with smaller size, and cracks.

(2) Most of the cracks produced in H13 tool steel samples fabricated by SLM originate from the side edge of the sample, and propagate along the formed layer to the inside of the sample, and finally terminate at the inside of the sample. During the process of crack propagation, some branched
secondary cracks with smaller size are induced near the coarse main cracks to prevent the main cracks from continuing to propagate.

(3) The internal porosity defects of as-fabricated H13 tool steel samples by SLM are prone to become crack sources, causing some micro-cracks with small size to be easily induced nearby, which can be ascribed to the local stress concentration.

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