Effect of Powder Feeding Rate on the Forming Quality of Alloy by Laser Melting Deposition

Chenghong Duan, Yinzhou Zhang and Xiangpeng Luo*
Beijing University of Chemical Technology, Beijing, China

*Corresponding author: xpluo@mail.buct.edu.cn

Abstract. 12CrNi2 alloy steel was prepared by Laser Melting Deposition (LMD) technology, and the effect of powder feeding rate on surface quality, internal defects, microstructure, and microhardness of the single track and manufactured part were investigated. The results show that the metallurgical bonding of the single track deteriorates, the surface quality of the manufactured part is improved, the average microhardness of the manufactured part increases, and the number of pores first decreases and then increases with the increase of powder feeding rate. At the lower powder feeding rate, the manufactured parts have larger pore defects, while at the higher powder feeding rate, the manufactured parts have poor fusion defects. The main phase composition of the manufactured parts is ferrite(F), granular bainite (GB), and pearlite(P), and the manufactured part has finer grains at the higher powder feeding rate.

Keywords: laser melting deposition, forming quality, process parameter, alloy steel.

1. Introduction

Laser Melting Deposition (LMD) technology is one of the main metal additive manufacturing technologies. 12CrNi2 is an alloy steel which is used in many applications, such as shafts and structural components. At present, LMD technology has been successfully applied in fighter wings, rocket nozzles, aircraft load-bearing components, engine blades, etc. According to the ASTM standard F3187-16(2016), the material is generally spherical powder with a diameter of 45 to 150μm or wire with a diameter of 0.8 to 3mm [1]. The material in LMD forming process melts and solidifies in a very short time and the part material will go through this process for multiple times, which leads to high thermal stress and poor uniformity of microstructure of manufactured part. Besides, the manufactured part is prone to have deformation, cracking, and surface void, as well as internal defects such as pore, inclusion, and microcrack [2, 3, 4].

At present, the methods of improving the forming quality mainly focus on three aspects: improving powder quality, forming process and post-treatment. Zhong et al. [5] investigated the effect of Inconel 718 alloy powder quality on the quality of LMD formed specimens. It was found that the use of smaller powder could reduce the pore of the single track, and the use of powder with fewer satellites could similarly reduce pore. Campanelli et al. [6] evaluated the performance of 18 Ni (300) part formed by LMD. It showed that high density of manufactured part with few pore defects can be achieved by varying laser power, scanning speed, powder flow rate and lap rate. Tang et al. [7] investigated the microstructure evolution and frictional properties of a LMD 12CrNi2V steel heat-treated in four
different conditions. The heat treatments adopted in their work can remarkably modify the laser-induced microstructural inhomogeneity, thereby promoting the tribological characteristic of the steel.

In this paper, the single track and manufactured part of 12CrNi2 alloy steel were prepared by LMD with different powder feeding rate, and the forming quality was systemically studied. Ultimately, the study would provide an experimental reference for good quality of manufactured part.

2. Experimental process and methods

2.1. Experimental process

| Table 1. Composition of 12CrNi2 alloy powder (wt%). |
|-----------------|---|---|---|---|---|---|---|---|---|---|
|                | C  | Cr | Si  | Ni | Mn | Mo | B  | S  | P  | Fe |
| Composition    | 0.12 | 1.5 | 1.0~1.2 | 2.0 | <0.5 | 0.5~1.0 | 0.5 | 0.035 | 0.035 | Bal. |

12CrNi2 alloy steel powder prepared by inert gas atomization was used in the experiment. The powder size is 50-150μm and the chemical composition and content are shown in Table 1. The surface morphology of 12CrNi2 powder was observed by scanning electron microscope, as shown in Fig.1. As can be seen from Fig.1, the powder has good sphericity and less hollow spheres or satellites (small particles adhere on the surface of larger ones).

The experiment was conducted by the LMD manufacturing system developed by Nanjing Huirui photoelectric technology Co., LTD. In the experiment, the 45-steel substrate of 100mm ×66mm ×16mm was selected and dried after grinding with sand paper and cleaning the surface stains with alcohol. Samples L1, L2, L3, L4, and L5 were printed in argon-protected chamber using powder feeding rate of 7.6, 9.6, 11.6, 13.6 and 15.6 g/min, respectively. For all the samples, the scanning speed and laser power are constant with values of 8 mm/s and 2200 W, respectively. Overlap ratio was 50% between deposited tracks. Laser scanning strategy of LMD is shown in Fig.2.

| Table 2. Process parameters of LMD samples. |
|-----------------|---|---|---|---|
| Sample          | P(W) | V(mm/s) | Powder feeding rate(g/min) | Overlap ratio |
| L1              | 2200 | 8        | 7.6                          | 50           |
| L2              | 2200 | 8        | 9.6                          | 50           |
| L3              | 2200 | 8        | 11.6                         | 50           |
| L4              | 2200 | 8        | 13.6                         | 50           |
| L5              | 2200 | 8        | 15.6                         | 50           |
2.2. Experimental methods
The single track and manufactured part were prepared by wire cutting, inserted, grinded with sandpaper to 2000 mesh and polished. The geometry of the single track and metallurgical defects of the manufactured parts were observed by the MX4R metallographic microscope and TP114000A imaging system. And the density of manufactured parts was measured based on the Archimedes' principle. Then the manufactured parts were put in nitric acid and alcohol corrosion at a concentration of 4% for 8-10s for the observation of microstructure with the DM 4M metallographic microscope and its imaging system. Microhardness test was carried out by using digital display auto turret microhardness tester EM1500L with a load of 0.98N and 15s dwell time. Location of microhardness test points were the bottom, middle, and top of manufactured parts.

3. Results and discussion

3.1. Geometry of single track

![Figure 3. The single track of different powder feeding rate.](image)

![Figure 4. The sketch of cross section of the single track.](image)
Figure 5. Effect of powder feeding rate on the geometry of the single track.

The single track of different powder feeding rate is shown in Fig.3. The height(h), width(b), and tangent chord angle(θ) of the single track are shown in Fig.4. As can be seen from Fig.5, with the increase of powder feeding rate, the width of the single track is almost unchanged, the height of the single track increases slightly, and the left and right tangent chord angle both tend to become larger. The molten pool temperature is an important characteristic parameter of LMD, which not only affects the shape of the molten pool and the geometry of the single track, but also has a great influence on the metallurgical quality of manufactured part. The main process parameters affecting the molten pool temperature are laser power, powder feeding rate, scanning speed and spot diameter. In order to comprehensively consider the influence of the above process parameters, a dimensionless parameter LED is introduced [8], which is defined as:

\[
LED = \frac{P}{dVM}
\]  

(1)

Where P is laser power; V is scanning speed; d is spot diameter; M is the weight of powder.

As can be seen from Eq (1), the molten pool temperature is lower when powder feeding rate is higher. Because of the Gaussian distribution of laser energy, the temperature in the center of the molten pool is higher than that at the edge of the molten pool. Therefore, when the powder feeding rate is higher, the temperature gradient on the surface of the molten pool is smaller, resulting in smaller surface tension. This phenomenon is not conducive to the spreading of the molten pool and leads to tangent chord angle of the single track.
3.2. Surface quality

![Surface quality images](image1)

Figure 6. Surface quality of the manufactured parts with different powder feeding rates.

Fig.6 shows the surface morphology of manufactured parts with different powder feeding rates. When the powder feeding rate is lower (Fig.6a, b), the surface of manufactured parts are very rough and uneven. Besides, there are voids appearing on surface of manufactured parts (Fig.7a, b). However, the increase of powder feeding rate can improve the surface of manufactured part. When the powder feeding rate is lower, the temperature of the molten pool is higher, which results in an unstable molten pool. The unstable molten pool leads to splashing of the molten metal. And the next track or layer will become worse due to the poor surface quality of the previous one.

![Surface porosity images](image2)

Figure 7. Surface porosity of 7.6g/min and 9.6g/min samples.

3.3. Pore and poor fusion defects

Pore defects are mostly spherical with tens of micrometers in diameter and they are randomly distributed in the LMD forming parts. Poor fusion defects are larger and irregular in shape, and they generally appear at the interlayer or intertrack. The generation of pore defects depends on the relative speed of gas escaping from the molten pool and solidification of the molten pool. When the gas can’t escape from the molten pool before solidification in time, pore defects will be generated in manufactured parts. According to stock's law [9], uplift velocity of the gas can be calculated using the following Equation:
\[ v = \frac{2gR^2(D-d)}{9\eta} \]  

Where \( v \) is uplift velocity of the gas; \( D \) is density of metal in the molten pool; \( d \) is density of the gas; \( \eta \) is viscosity of liquid metal; \( R \) is radius of air bubble; \( g \) is gravitational acceleration.

Fig. 8 shows the distribution of pore defects in the cross-section of manufactured parts with different powder feeding rates. With the increase of powder feeding rate, the number of pore defects first decreases and then increases. The volume of the molten pool is smaller and the molten pool is unstable at lower powder feeding rate. So, the gas may not escape from the molten pool in time, which results in pore defects even if the cooling rate of the molten pool is slower. When the powder feeding rate is higher, the volume of the molten pool is bigger and the temperature is lower. The gas escaping path is longer and the flowing rate is slower, so that the gas can’t escape from the solidified molten pool in time. Therefore, there are more pore defects at lower and higher powder feeding rate.

![Image of pore distribution](image)

**Figure 8.** Pore distribution of sample with different powder feeding rates.

There are large void defects at lower powder feeding rate and poor fusion defects at higher powder feeding rate, as shown in Fig. 9. When the powder feeding rate is lower, the temperature of the molten pool is higher, which results in an unstable molten pool. Part of the powder is splashed near the molten track before it is completely melted. Therefore, it’s easy to form void defects with not completely melted
or not melted powder. When the powder feeding rate is higher, most of laser energy is used to melt the powder, so the depositing track can’t be well fused with the previous one or the previous layer, resulting in poor fusion defects.

![Figure 9. Other defects of samples with different powder feeding rates.](image)

The density of manufactured parts is also measured and the result is shown in Fig.10. The density increases significantly and then decreases with the increase of powder feeding rate. But the decrease of density is not significant.

![Figure 10. The effect of powder feeding rate on density.](image)
3.4. Microstructure

Figure 11. The microstructure of samples with different powder feeding rates.

The microstructure of manufactured parts with different powder feeding rates are shown in Fig.11. The grain becomes finer as powder feeding rate increases. Ferrite and pearlite can be observed in the
middle and bottom of sample L1, while ferrite and granular bainite can be observed in the top of sample L1. Granular bainite can be observed in the bottom of sample L2, while ferrite and pearlite can be observed in the middle and top of sample L2. The main phase composition of L3 is ferrite and pearlite. The main phase composition of L4 is granular bainite. The main phase composition of L5 is granular bainite and ferrite. The cooling rate caused by powder feeding rate and part of remelted material leads to different kinds of microstructure and grain size.

3.5. Microhardness

Figure 12. Average microhardness of samples with different powder feeding rates.

The effect of powder feeding rate on microhardness is shown in Fig. 12. As the powder feeding rate increases, the average hardness of manufactured part first increases and then smooths. When the powder feeding rate increases, the cooling rate of the molten pool increases, resulting in the generation of granular bainite, which leads to a higher microhardness.

4. Conclusion

(1) For LMD 12CrNi2 alloy steel, with the increase of powder feeding rate, the tangent chord angle of the single track becomes larger resulting in poor metallurgical bonding, which leads to poor fusion defects. At a lower feeding rate, the molten pool is unstable and the subsequent manufactured parts will form poor surface quality with pore and void defects. When the powder feeding rate is 11.6 g/min, the density of manufactured parts is highest. When receiving the paper, we assume that the corresponding authors grant us the copyright to use the paper for the book or journal in question. Should authors use tables or figures from other Publications, they must ask the corresponding publishers to grant them the right to publish this material in their paper.

(2) An increase in the powder feeding rate leads to an increase in the cooling rate of manufactured part. And the phase composition of manufactured part contains more granular bainite, which increases the average microhardness.

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