Quality Control Factors during Laser Forming Repair of Complex Surface Part

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ABSTRACT

The Laser Forming Repair (LFR) is a state-of-the-art technology combining the Rapid Prototyping (RP) with the Laser Cladding (LC), which is the further application and development in the field of part repair and laser cladding. The metal powder was served as the raw material in LFR technology. LRF overcomes the shortcoming of conventional repair techniques, such as the weak bonding force and the repair position difficult to precisely control. In addition, the parts repaired by LRF possess the superior microstructure and properties. Besides, LRF removes the restriction of laser cladding technology on the shape, construct and thickness of cladding layer of parts. The factors influencing the quality of laser cladding layer are various, and there still exists many uncertain factors in the fabrication process. Therefore, the accomplishment of the best quality of cladding layer need accumulate abundant processing experience. Accordingly, it is necessary to find out the universal law between the processing parameters and the quality of laser cladding layer, build the quality prediction model suitable for the process control, and realize the control and prediction of the quality of laser cladding layer. As a result, the comprehensive investigation of quality control factors can achieve the intelligent control of laser machining process and the forecast of processing quality, reduce the technical requirements for operators, improve processing efficiency, and provide the basis for practical application.

INTRODUCTION

The Laser Forming Repair (LFR) is a state-of-the-art technology combining the Rapid Prototyping (RP) with the Laser Cladding (LC), which is the further application and development in the field of part repair and laser cladding. The metal powder was served as the raw material in LFR technology. With the support of CAD/CAM software, NC controls the laser, powder spray nozzle and workbench to move in terms of the specified space trajectory. Based on the defect geometry, the powder is sprayed into the position of part remaining to be repaired, and the forming process is carried out layer by layer. Finally, the 3D entity with near-net shaped defect position is generated, which completes the recovery for the geometric and mechanical properties of damaged parts, as shown in Figure 1. LRF overcomes the
shortcoming of conventional repair techniques, such as the weak bonding force and the repair position difficult to precisely control. In addition, the parts repaired by LRF possess the superior microstructure and properties. Besides, LRF removes the restriction of laser cladding technology on the shape, construct and thickness of cladding layer of parts [1-3].

The quality of cladding layer of repaired part is divided into two aspects: the macroscopic quality and the microscopic quality. The macroscopic quality of cladding layer includes the geometry sizes of cladding layer, namely height (H), width (W), surface roughness and surface defects, such as cracks and pores. The microscopic quality of cladding layer includes the chemical composition, dilution rate and interface bonding status, microstructure, stress distribution, etc. The factors influencing the quality of laser cladding layer are various, and there still exists many uncertain factors in the fabrication process. These factors involves the stability of powder feeding system, the focus of laser nozzle, laser power, spot diameter, scanning speed, etc. Therefore, the accomplishment of the best quality of cladding layer need accumulate a large number of processing experience, because this method possesses the high test cost and heavy workload, and tend to cause a certain degree of waste [4-5].

Although there are many factors affecting the quality of laser cladding layer, the influences of processing parameters on the quality of cladding parts were comprehensively investigated by international scholars. In practice, the laser processing parameters can be adjusted is insufficient. The main reason is that once the laser is selected, the characteristics of the laser system is decided. Consequently, in concrete operation, the processing parameters of laser can be adjusted are very limited. Therefore, the influence of processing parameters on the quality of the laser cladding layer can be analyzed from the following several aspects.

**INFLUENCE OF LASER POWER ON THE QUALITY OF THE CLADDING LAYER**

The laser power is proportional to the molten amount of alloy. With the increase of laser power, the alloy molten quantity augment, so the occurrence probability of porosity will go up. Then, the depth of the coating also increase, and the adjacent liquid metal continuously flows into the pores. The pores are reduced or eliminated, and the cracks are decreased. After the depth of coating reaches the limit depth, with
the increase of power, the plasma is proportional to increase. As a result, the surface temperature of substrate rise rapidly, so the deformation and cracks of cladding layers are inevitable. The influences of laser power on the quality of cladding layer are very significant, so it is important to choose suitable laser power value to avoid porosity and cracking phenomenon.

The laser power determines the molten temperature of powder in the process of laser cladding forming. Figure 2 shows that in the case of the constant powder feeding speed (F), the cladding track widths (W) are different in terms of the different laser powers (P) and scanning speeds (S).

As depicted in Figure 2, under the same scanning speed, the width of the cladding track increases with the growth of laser power. Under the same laser power, the width of the cladding track decreases with the increase of scanning speed. However, the excessively high or low laser power is disadvantageous to the quality of cladding parts. When the laser power is very low, the metal powder cannot be thoroughly molten, so the powder and substrate cannot form the superior metallurgical combination and achieve the cladding effect. While the laser power is too high, the substrate is molten excessively, which improves the dilution rate and reduces the quality of the cladding layer. In addition, when the laser cladding is performed with the high power, the thermal stress of cladding layer is substantially enhanced, so the cladding layer surface is easy to crack. Consequently, it is important to control the laser power in the process of laser cladding.

**INFLUENCE OF SCANNING SPEED ON THE QUALITY OF CLADDING LAYER**

The limit speed is the scanning speed with which the laser beam can only melt alloy powders, and hardly melt substrate. To form the cladding layer successfully, the laser scanning speed must be smaller than the limit speed. The materials of coating and substrate are different, so the limit speed of them are also different. The related studies show that under the condition that other parameters keep constant, in the process of laser scanning, if the scanning speed is slower, the surface of coating material is easy to generate burning loss, which makes the surface roughness
augment. If the scanning speed is faster, laser energy is in short supply, so the coating material cannot be molten in a short period of time. As a result, it is difficult to form cladding layer, so the control of scanning speed is a very key factor.

Based on the single-pass cladding experiment, while the laser power $P=700\,\text{W}$, spot diameter $D=3\,\text{mm}$, and powder feeding rate $F=107.2\,\text{mg/s}$, the influences of scanning velocity on the height and width of single cladding pass are shown in Figure 3. The results indicate that as the other parameters keep constant, the scanning speed is in inverse proportion to the height and width of single cladding pass. The reason is that with the increase of scanning speed, the laser energy enters into the molten pool in unit time decrease, so the laser energy is not enough to melt more metal powder.

![Figure 3](image)

**Figure 3.** Influences of scanning velocity on the height (a) and width (b) of single cladding pass.

**INFLUENCE OF POWDER FEEDING RATE ON THE QUALITY OF CLADDING LAYER**

The powder feeding rate refers to the powder feeding amount per unit time. On the condition that other processing parameters keep constant, with the increase of powder feeding rate, the width of cladding layer decreases. In addition, the molten depth of substrate decreases, while the molten thickness and surface roughness increase. Then, the light transmittance decreases, so the heating degree of cladding material decreases, which causes the microstructure tend to be more fine in cladding layer. Furthermore, when the powder feeding rate is low, the dilution rate is great. The optimal powder feeding rate is proportional to the laser power, but is inversely proportional to the spot diameter. It is also related to the shape of laser beam.

Figure 4 shows the change rule of cladding track height $H$ in relation to the processing parameters. As shown in Figure 4, when the laser power is constant, for different scanning speeds, the height of cladding track tend to rise straightly along with the increase of powder feeding rate. However, for the given laser power, whether the powder feeding rate is too big or small is disadvantageous to improve the quality of cladding parts. When the powder feeding rate is too large, the powder is molten incompletely. Then, the gas in the gap of powder is uneasy to discharge, and is easy to produce pores in the cladding layer. Probably, the pores will turn into the cracks during multilayer cladding. When the powder feeding rate is too small, the substrate is molten excessively, which improves the dilution rate and reduces the quality of cladding parts. Accordingly, the suitable powder feeding rate should be chosen in the cladding process, so as to guarantee the quality of cladding parts.
INFLUENCE OF SPOT DIAMETER ON THE QUALITY OF CLADDING LAYER

The spot diameter mainly influences the width of cladding layer. The relations among the spot diameter $D$, the cladding layer width $W$, and the scanning speed $V_b$ can be determined by the equation:

$$W = D \times (1 - \alpha V_b)$$

In this formula, $\alpha$ is the empirical constant and process characteristics, which is related to the material properties. When the laser power, scanning speed and powder feeding rate are constant, with the increase of spot diameter, the powder particles molten by the laser beam increases, and the powder particles absorbing the laser energy increases. At the same laser power, the width of laser cladding layer increases, while the thickness of cladding layer decreases. In addition, the laser spot diameter and the laser molten pool increase, and surface tension of molten pool decrease. As a result, the surface quality of cladding layer is improved. For different models and types of laser, with different laser power irradiation, they all influence the size and shape of the laser spot. The relationship between the laser power, scanning speed and laser spot diameter is studied through experiments. The results prove that when the laser power and scanning speed keep constant, the cladding thickness is inversely proportional to the laser spot diameter, while the cladding width is proportional to the spot diameter, as exhibited in Figure 5.

At present, the laser cladding is mainly applied with rectangular or circular multimode laser spot. The distribution of temperature field of the surface of molten pool during laser cladding is not uniform, and the temperature near the center of molten pool is the highest. The farther distance from the center, the lower the temperature of cladding material. Due to the effect of surface tension gradient of the inclined steep, the strong convection is generated within the molten pool of alloy, so that the solidification surface of cladding layer is a bumpy. The solution is a change in the beam pattern, which makes the energy distribution of laser beam section uniform. The laser cladding applied with oscillation beam and rotating mirror broadband can obtain satisfactory results.

Figure 4. Relationship between the powder feeding rate (F) and the height of laser cladding layer (W).
INFLUENCE OF OVERLAPPING RATE ON THE QUALITY OF CLADDING LAYER

The suitable overlapping rate is the key to get the large-area laser cladding layer. Since the spot size of laser beam is small, the area of cladding layer could be expanded only by the overlap between the scanning passes. In addition, the influence of overlapping rate on the surface roughness of multi-pass laser cladding layer is very significant. With the increase of overlapping rate, the surface roughness of the laser cladding layer would reduce, but it is difficult to guarantee the uniformity of the surface of overlapping part.

The overlapping rate is an important factor resulting in the defect of bad fusion. The overlapping rate in the rapid prototyping technology directly affects the surface finish of the cladding layer. The excessively small overlapping rate can generate depressions between adjacent cladding beads. In contrast, the relatively large overlapping rate can make the surface of cladding layer smooth, but the very high overlapping rate may produce the pores and cracks. Therefore, the appropriate overlapping rate is the key to cause the adjacent cladding beads to obtain the same height, and achieve the forming parts with smooth surface. As illustrated in Figure 6, 6(b) represents the appropriate overlapping rate, while 6(a) and 6(c) depict the too small and large overlapping rate respectively.

Figure 6. Three kinds of cross-sectional states of the contiguous cladding passes. (a) Overlapping percentage is too small. (b) Overlapping percentage is proper. (c) Overlapping percentage is too large.
INFLUENCE OF DILUTION RATE ON THE QUALITY OF CLADDING LAYER

The dilution rate is used to measure the element dilution degree of cladding layer caused by the mixture of elements substrate material with cladding layer, which is signified by the percentage of alloy of substrate materials in the cladding layer. It is the main indicator to evaluate the microscopic quality of cladding layer, which is usually denoted by the geometric dilution rate and the measured values of composition of cladding layer. The dilution rate in the laser cladding process depends on the laser parameters, material properties, processing technology and environmental conditions, etc. As shown in Figure 7(a), the low dilution rate could cause the cladding layer to solidify into a sphere and form the poor combination with the substrate. In contrast, as exhibited in Figure 7(b), the high dilution rate can improve the bonding strength between the cladding layer and the substrate, but reduce the mechanical properties of cladding layer at the same time. It is generally believed that the dilution rate remains below 10%, and had better be around 5%.

\[ \eta = \frac{h}{(H+h)} \quad (2) \]

As the laser spot diameter keeps constant, the width of the cladding layer shows no obvious change with the variation of processing parameters. Therefore, the changes of cross-sectional area \( A_1 \) and \( A_2 \) mainly reflect in the cladding layer height \( H \) and substrate penetration \( h \). Then, the dilution rate can be calculated by the following formula:

When the powder-bed depth is constant, the dilution rate will decrease with the increase of scanning speed. As the laser power and spot diameter keep constant, with the increase of laser power, the dilution rate increase. The laser power has less effect on the depth of cladding layer, so the impact of laser power on the dilution rate is not significant.

SUMMARY

The Laser Forming Repair (LFR) is a state-of-the-art technology combining the Rapid Prototyping (RP) with the Laser Cladding (LC), which is the further application and development in the field of part repair and laser cladding. The metal powder was served as the raw material in LFR technology. LFR overcomes the shortcoming of conventional repair techniques, such as the weak bonding force and the repair position difficult to precisely control. In addition, the parts repaired by LFR possess the superior microstructure and properties. Besides, LFR removes the restriction of laser cladding technology on the shape, construct and thickness of cladding layer of parts. The factors influencing the quality of laser cladding layer are various, and there still exists many uncertain factors in the fabrication process. Therefore, the accomplishment of the best quality of cladding layer need accumulate
abundant processing experience. Accordingly, it is necessary to find out the universal law between the processing parameters and the quality of laser cladding layer, build the quality prediction model suitable for the process control, and realize the control and prediction of the quality of laser cladding layer. As a result, the comprehensive investigation of quality control factors can achieve the intelligent control of laser machining process and the forecast of processing quality, reduce the technical requirements for operators, improve processing efficiency, and provide the basis for practical application.

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