Effect of phase transition temperature and particle size on residual stresses and properties of laser cladding layer

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Abstract. Laser cladding is one of the main technologies for material surface strengthening technologies. Residual tensile stress on the surface of the cladding layer reducing the fatigue and wear performances, is difficult to control. The phase transition dilation during the cooling process with the laser cladding technique is proposed to counteract the volume shrink and then reduce the residual tensile stress and partially replace the post cladding treatment. The influence of low temperature phase change alloy on the residual stress of the cladding layer was investigated by comparing with that of the 17-4PH stainless steel powder cladding layer. The micro hardness and friction and wear properties of the cladding layer with different particle size were also analyzed. The result shows that the volume expansion caused by phase change counter-acts the heat shrinkage produced during the cooling of the cladding layer, and the hardness and abrasion resistance of the cladding layer are improved.

1. Introduction

As a new surface repairing and manufacturing technology, laser cladding with high energy density, metallurgical bonding cladding and substrate, high melting efficiency, has been widely used in molds, tools and mechanical parts repair, antiwear and corrosion-resistant coating processing and so on [1,2]. Laser cladding process is a rapid state transition process. The certain difference in thermal properties between the substrate and cladding power results in its solidification process of crystallization imbalance which tends to produce uneven tensile stress in the cladding surface [3,4]. The presence of residual tensile stress increases the cracking sensitivity of the cladding layer and reduces its fatigue, wear resistance and other properties [5,6]. The post-treatment method such as local heating method, impact method and shot peening method can reduce the residual stress to improve fatigue and wear resistance, but these methods increase the production cost and reduce the production efficiency.

Iron and steel materials in the cooling process will be organized into the transformation, accompanied by different volume expansion, when the volume expansion in the constraints of the conditions, can produce compressive stress [7]. The low temperature phase material reduce the phase transition temperature of the martensite by controlling the alloying element content so that the volume expansion produced by martensitic transformation can counteract some or all of the tensile stress caused by the heat shrinkage and achieve the goal of improving or eliminating harmful residual tensile stress [8]. In this paper, aiming at the problem that the mechanical properties of the parts are reduced due to the residual stress on the surface of the laser cladding layer, the method of laser cladding low
temperature phase transformation alloy powder is proposed to improve the residual stress on the cladding surface in order to improve the mechanical strength of the cladding layer.

2. Experimental materials and methods

2.1. Experimental materials

In order to investigate the effect of martensitic transformation on the residual stress and mechanical properties of the cladding layer after the fusion of the low transformation temperature alloy material, the cladding layer formed by conventional 17-4PH stainless steel powder was used as the comparative sample. The effect of particle size on the residual stress and mechanical properties of the cladding layer was analyzed by the different particle sizes of the low transformation temperature alloy powder. The low temperature phase change alloy powders with the meshes of 200 (LTT1) and 500 (LTT2) and the 17-4PH stainless steel powders with the mesh of 200 were adopted. The basic chemical compositions of the three kinds of depossited alloy powders are shown in table 1.

| Powder  | C  | Si  | Mn  | Cr   | Ni  | Mo  | V  | Cu  | Ti  | B  | Nb  | Fe   |
|---------|----|-----|-----|------|-----|-----|----|-----|-----|----|-----|------|
| 17-4PH  | 0.01 | 0.72 | 0.097 | 16.95 | 4.06 | --  | -- | 4.05 | --  | 0.2 | --  | Bal. |
| LTT1    | 0.1 | 0.2 | 0.5 | 5 | 3 | 0.3 | 0.2 | 0.5 | 0.2 | 0.002 | 0.01 | Bal. |
| LTT2    | 0.1 | 0.2 | 0.5 | 5 | 3 | 0.3 | 0.2 | 0.5 | 0.2 | 0.002 | 0.01 | Bal. |

2.2. Text methods and equipment

Germany ROFIN FL-060 type 6kW fiber laser with small laser spot (5mm × 5mm), combined with ABB IRE4600 robot processing system, was used in the experiment. The laser cladding experiment was carried out on Q235 steel with the sizes of 100mm × 100mm × 10mm and the preparation parameters are shown as follows: the laser power is 2800kW, the laser scanning speed is 28mm/min, the focus is 3mm and the Ar flux is 5L/min. The cladding process is protected by high-purity argon. The GTV PF2 / 2 laser cladding powder feeder ensures the uniformity and continuity of the powder in the cladding process. Powder delivery method is coaxial argon powder, as shown in figure 1.

![Figure 1. The schematic diagram of laser cladding.](image)

Secondly, the three kinds of cladding layers were tested on the MFT-5000 friction and wear tester. The wear specimen was 20mm × 10mm × 10mm. Before the experiment, the surface of the test was polished smooth and flat with sandpaper. The friction pair is a 440C stainless steel ball with the diameter of 9.524mm. The load is 100N and the friction slip speed is 8mm/s, with the accuracy of 0.1mg electronic balance to measure the wear and tear weight of the situation.
The residual stress of the different kinds of cladding layers was measured by the Canadian Proto LXR D X-ray diffraction stress analyzer. Before the test, the instrument was calibrated with stress-free iron powder. To the end of the cladding 5 mm as a starting point, the residual stress was measured by the points in increments of 0.5 mm in the 0° direction, a total of 11 points. The test was shown in figure 2.

![Figure 2. Sketch map of residual stress test.](image)

Finally, after cutting, grinding, and polishing, the cladding layer produced in the experiment was corroded using picric acid solution (1g picric acid + 4% nitric acid + 96% alcohol). The microstructure of cladding layer is observed under an optical microscope. The phase of the cladding layer was analyzed by X-ray diffractometer, and the micro-hardness of the cladding layer, the heat affected zone and the base metal was measured using an HV-1000 micro-hardness tester, as shown in figure 3.

3. Results and discussion

3.1. Macroscopic morphology and microstructure analysis of cladding layer

Figure 4 shows the cladding of low temperature phase change alloy powder and 17-4PH ordinary stain-less steel powder under the same laser welding process conditions. It is clearly seen from Figure 4 that the cladding of the three powders is well formed and the droplets on both sides are less, and the surface of the 17-4PH cladding layer is brightest. In the case of flatness, compared with figure 4 (a), (b) and (c), it was found that the surface of the LTT2 cladding layer with finer powder size was more wrinkled.

![Figure 4. The macroscopic morphology of cladding layer: a) Cladding layer of LTT1; b) Cladding layer of LTT2; c) Cladding layer of 17-4PH.](image)

The analysis shows that the total surface area is large with the fine powder. The contact between the fine particles is more, producing a larger internal friction, resulting in poor fluidity of deposited metal which affecting the ability to produce powder during the cladding process [9]. When the particle
size of the powder is fine, the uniformity of the delivery of the powder alloy is poor and the deposited metal is intermittently sprayed into the laser irradiation area. The formation of the bridging effect makes the cladding layer easy to form wrinkles affecting the final shape. It is further explained that when the particle size of the LTT alloy powder is small, it is not conducive to obtain the cladding layer with better forming effect.

Figure 5 (a) and (b) show the microstructures of LTT1 and LTT2 cladding layers, respectively. It can be seen from figure 5 that the two powder cladding layers are composed of lath martensite (black) and the retained austenite (white) between them. After reaching room temperature, a small amount of austenite that cannot completely transform to the martensite was remained and formed as the residual austenite. Small amount of retained austenite structure are formed to enhance the toughness of the cladding layer. Comparing figure 5 (a) and (b), it can be seen that the density in LTT2 cladding layer structure was higher. The analysis considers that the powder with small particle size has fine structure with more grain boundaries distributed with a lot dislocation defects. The powder is rapidly crystallized after melting and the finer grains are formed into dense structures.

Figure 5. The microstructure of cladding layer: a) LTT1 cladding microstructure; b) LTT2 cladding microstructure.

The XRD diffraction pattern of LTT2 powder cladding is shown in figure 6. Microstructure shows that the cladding layer is mainly martensite and retained austenite. According to the analysis of jade software, the diffraction peak mainly contains Fe element and Cr element. It is judged that the C and Cr elements are sol-id-dissolved into the Fe element to form a solid solution structure of martensite and austenite. Through com-paring the PDF card, indices relationship of crystal face can be inferred that the (110) peak and (211) peak rep-rezent the martensite, and the (200) peak represents the austenite. It is found that the main structure of the clad-ding layer is martensite and a small amount of retained austenite after laser cladding the LTT alloy.

Figure 6. The XRD diffraction pattern of LTT2 cladding layer.
3.2. Micro-hardness analysis of section of cladding
The micro-hardness distribution of the three cladding layers is shown in figure 7. It is seen from figure 7 that the micro-hardness of the three kinds of powder cladding layers is a gradient distribution. Along the normal direction of the cladding layer, the micro-hardness value increases first and then decreases gently. The analysis considers that in the laser cladding coaxial argon power feeding was used (shown in figure 1). During the cladding process, the powder leaves the fritted nozzle into the air and some of the powder is not able to move into the laser beam due to air resistance, but is free fall. This led to that part of the powder can only accept the west heat melting of the cladding layer and, cladding surface density decreased, hardness decreases. This led to the part of the powder can only melt by accepting the formation of cladding layer of waste heat, followed by a decrease in the surface density of the cladding layer and a decrease in hardness. The sub-surface powder melts fully and the state transforms rapidly, which result in density cladding layer and increasing hardness. Due to the rapid melting and cooling, the cladding layer has a small grain size, a dense structure, and thus a higher hardness than the substrate. With the increase of the depth of the cladding layer, reaching the fusing area, the hardness value decreases due to the dilution of the matrix, and the slow drop zone corresponding to the heat affected zone. The hardness value drops to the lowest after reaching the substrate.

Compared with the micro-hardness distribution of the two kinds of composition powders, it was found that the low temperature phase change powder cladding layer had better hardness enhancement effect than stainless steel powder. The micro-hardness of LTT2 powder cladding layer is as high as 431.7HV, which is much higher than that of substrate about 160HV, and the micro-hardness is increased by about 2.7 times. The maximum hardness of the stainless steel powder cladding layer is 367.3HV and the micro-hardness is improved by about 2.3 times. The residual compressive stress in the cladding layer of the low temperature phase change powder reduces the shear stress of the indentation pressed by the micro-hardness gauge and improves the micro-hardness of the cladding layer. The maximum hardness of LTT1 powder cladding is 419HV. This is mainly because the LTT2 powder cladding layer of the structure is more compact, making its micro-hardness value slightly higher. The high micro-hardness value is beneficial for the improvement of the wear resistance of the cladding layer.

Figure 7. The micro-hardness of the cladding layer.

3.3. Analysis of residual stress on cladding surface
Figure 8 shows the residual stress distribution on the surface of the three powder laser cladding layers. It can be seen from figure 8, compared with the low temperature phase change alloy powder cladding layer, the surface residual stress of 17-4PH cladding layer is higher and the maximum value is about 236MPa. The surface residual stress of the low temperature phase change alloy powder laser cladding layer is negative, that is, the surface stress state is compressive stress. It is concluded that the
martensitic transformation occurs during the solidification of the three alloy powders, and the martensitic transformation will produce volume expansion [10,11]. When the martensitic transformation occurs at a lower temperature, the deposited metal is constrained, and the volume expansion resulting from the martensitic transformation counteracts the heat shrinkage produced during the cooling of the cladding layer. If the phase transition pressure produced by the phase change expansion is greater than the tensile stress generated during the heat shrinkage, the cladding layer would exhibit a residual compressive stress. The martensitic transformation of the 17-4PH cladding layer occurs at a higher temperature, where the deposited metal is in a plastic state and the volumetric expansion of the martensitic transformation is released without being restricted. No compressive stress is produced, and finally the residual tensile stress is expressed.

Comparing LTT1 and LTT2 powder cladding surface residual stress, it can be seen that LTT1 exhibits a larger residual compressive stress and the maximum compressive stress is 288.4MPa. The residual stress distribution of LTT2 cladding layer is gentle and the maximum compressive stress is 135.1MPa. There are two reasons for the low compressive stress of LTT2 cladding. On the one hand, the grain size of the austenite is small when the original size is small, so the grain boundary migration is small in the process of martensitic transformation. The formation of the grain size is small and the volume expansion is reduced accordingly. On the other hand, due to small particle size of LTT2 powder, the burning of the LTT2 powder is more serious. Some of the martensitic transformation point (Ms) reduction element content reduces resulting in that the final martensitic transformation expansion do not achieve the best effect.

Figure 8. The residual stress distribution of laser cladding layer.

3.4. Cladding layer friction and wear properties
According to the change of friction coefficient and wear weight, the wear resistance of the three cladding layers was analyzed. Figure 9(a) shows the weight loss of the three powders at different wear periods. As can be seen from the figure, with time increases, the wear amount of the cladding layer of the three powders increase gradually, but the wear per unit time is gradually reduced. In 15 minutes of the wear time, the wear rate is large, in which the wear rate of LTT2 powder is minimum, 4.5mg. Analysis shows that at the beginning of the wear time, there are many particulate on the surface of the layer, which are contact with the friction side first, and produce large stress [12,13]. The presence of these stresses leads to the destruction of the microburst giving a rise to the initial mass wear.

Figure 9(b) shows the variation trend of friction coefficient of cladding layer with time in three kinds of powders under the same cladding process. The average coefficient of friction of 17-4PH is about 0.67. The friction coefficient of LTT1 is close to that of 17-4PH powder, and the average friction coefficient is about 0.6. The smallest friction coefficient appears in the LTT2 powder coating.
with an average value of about 0.4. The friction coefficient fluctuates greatly at the initial stage of friction, and the friction coefficient tends to be stable with the increase of time.

![Graph showing weightlessness and friction coefficient over time](image)

**Figure 9.** (a) The weightlessness of the cladding layer. (b) The Variation of friction coefficient of different powder cladding layer with time.

Compared with the wear and friction coefficient of the three kinds of powders, the wear amount of LTT2 powder cladding layer is the lowest and the friction coefficient is the lowest, which shows the best wear resistance. As the LTT2 alloy powder particle size is smaller, after the absorption of laser energy, the powder particles quickly melt and curd resulting in smaller grains. In the case where the cladding layer is the same as the martensite structure, the wear resistance of the cladding layer is higher than that of the powder having a larger particle size. Compared with the weight loss of 17-4PH powder cladding, the weight loss of LTT1 powder cladding showed a tendency to increase first and then decrease. The friction coefficients of the two coating also present a small difference, showing a similar wear resistance. The wear resistance of the LTT1 cladding layer is slightly higher because the residual compressive stress in the cladding layer relaxes the stress concentration and the shear stress caused by the friction pair on the surface is reduced, thereby improving the wear resistance. Due to the higher hardness of the LTT1 powder cladding layer, the abrasion resistance is slightly higher than that of the stainless steel powder cladding layer. Moreover, the residual compressive stress in the cladding layer relaxes the stress concentration and then the shear stress caused by the friction pair on the surface was reduced. This improves its wear resistance to a certain extent.

4. Conclusions

In this paper, 17-4PH stainless steel alloy powder and two kinds of low temperature phase change alloy powders with different particle sizes were adopted for comparison. The residual stress and microstructure of cladding layer were analyzed:

1. During the laser cladding of the low temperature phase change alloy powder, the volumetric expansion of martensitic transformation counteracts the heat shrinkage stress of the cladding layer, and the surface of the cladding layer shows residual compressive stress of -228.4MPa improving the wear resistance of the cladding layer.

2. The microstructure of the low temperature phase change cladding layer is mainly martensite and a small amount of retained austenite. The martensitic transformation starts at a lower temperature. A small amount of retained austenites distributed between the lath martensites improve the toughness of the cladding layer.

3. Due to its dense structure, the micro-hardness of the LTT alloy power cladding layer was improved significantly. The cladding layer with high density has better wear resistance, and the increase of micro-hardness also has a beneficial effect on the wear resistance of the cladding layer.
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References
[1] Zhang J, Wu W and Zhao L 2013 *Hot Working Technology* **42** 131–4
[2] Li Y L, Jin H X, Bai X B, et al 2009 *Heat Treatment Technology and Equipment* **30** 1–5
[3] Fang Y Y 2016 *Residual Stress and Corrosion Performance of Pipeline Steel with Dissimilar Welding Wire* Jiangsu University
[4] Alam M K, Edrisy A, Urbanic J, et al 2017 *J. Mater. Eng. Perform.* **26** 1–9
[5] Wang D Z, Hu Q W and Zeng X Y 2015 *Surf. Coat. Technol* **274** 51–9
[6] Shiozaki T, Tamai Y and Urabe T 2015 *Int. J. Fatigue* **80** 324–31
[7] Wang W X, Huo L X and Zhang Y S 2003 *China Mechanical Engineering* **756** 5–20
[8] Kromm A, Dixneit J and Kannengiesser T 2014 *Welding in the World* **58** 729–41
[9] Li H S 2004 *Theoretical and Experimental Study on the Interaction of Laser and Metal Powder Flow in the Laser Remanufacturing* Tianjing Polytechnic University
[10] Chen X Z, Fang Y Y, Li P et al 2015 *Mater. Des.* **65** 1214–21
[11] Kannengiesser T and Kromm A 2009 *Soldagem & Inspeção* **14** 74–81
[12] Chen X Z, Hu K and Yuan Q B 2016 *China Surface Engineering* **29** 118–24
[13] Song J, Zhang Q M, Lin X C and Liao J H 2008 *Chinese Journal of Lasers* **35** 776–81