Study on Pores and Crack Sensitivity of Ni-based Composite Coating by Laser Cladding

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Abstract: This study aims to explore the types and mechanism of pores and crack on Ni-based composite coating of laser cladding. The results show that pores are generally found on the surface and bottom of cladding layer, and the gas comes from the cladding or the interaction between composites during the cladding process. There are two major categories of cracks, vertical crack and horizontal ones, which is mainly related to the low melting eutectic in the cladding area, and also relevant to coating composition, contents of inclusion and laser specific energy.

1. Introduction
Laser cladding technique is a new surface modification technology. Surface coating material and the substrate material melt quickly and solid to form metallurgical bond cladding layer, thereby improving the wear resistance, corrosion resistance and high temperature oxidation resistance, and has broad application prospects [1-4]. But presence of pores and cracks on the cladding layer affects the quality and performance of the layer. Therefore, further study of laser cladding should focus on the types and mechanism and influencing factors, so that the promotion of industrial technology has practical significance.

This paper analyzes the form and mechanism of pores and cracks on Ti alloy laser cladding Ni-based MoS2 of Ni package and investigates the effects of laser specific energy and the ratio of the coating material on the cladding layer crack sensitivity. We have determined the main factors affecting its formation, thus we can effectively control and eliminate the cladding defects, and ensure the quality of laser cladding process.

2. Materials and methods
TC4 alloy substrate materials was used in the study, and its chemical composition as shown in table 1, with the sample size of 60 mm x 30 mm x 10 mm. Samples were cut and grinded on the surface before cladding to each mayonnaise roughness of 0.2 um, its surface oxide layer was removed with metallurgical sandpaper, and then cleaned with acetone. Ni60 self-fluxing alloy powder and MoS2 of
Ni package powder were used as cladding material, and their chemical composition and physical properties are shown in table 1. 0% to 80% of MoS2 of Ni package powder was added to Ni-based self-fluxing alloys, then fully ground and mixed. Cladding material was pre-set on the surface of the substrate sample using bonding method, and the preset coating had a thickness of 1.0 mm.

YLS-4000 fiber laser was used to perform cladding, with laser beam spot diameter of 4 mm, the protective gas N\textsubscript{2} was 5 MPa. Laser power was 1.5 ~ 2.5 kW, and scanning speed was 6 ~ 12 mm/ s.

The samples were cut along the direction perpendicular to the scanning direction. The cross-section of cladding layer was made into a metallurgical samples, and then etched with a mixed solution of hydrofluoric acid, nitric acid and water with the composition ratio of 7 ml: 3 ml: 50 ml, etching time 10 ~ 30 s. OLYMPUSGX-51 optical microscope was used to observe pore morphology and distribution on cross-sectional area of the cladding layer, SZ660 stereo microscope was used to observe and measure the number of cracks, S-3400N scanning electron microscopy (SEM) and energy dispersive spectroscopy XFlash5030 (EDS) was used to analyze cladding cracks and tissues.

| Experimental materials | Composition (quality fraction %) | Powder density/μm | Melting point/°C | Coefficient of thermal expansion/10\textsuperscript{−6}°C |
|------------------------|---------------------------------|-------------------|-----------------|--------------------------------------------------|
| TC4 alloy              | 6.01Al,3.84V,0.1C,0.3Fe, Allowance for Ti | -                 | 1660            | 7.89                                             |
| Ni60                  | 16Cr,3.3B,4.5Si,0.9C,≤8.0 Fe, Allowance for Ni | 140~250          | 1027            | 13.4                                             |
| Ni-MoS2               | 14.6Mo,9.7S, Allowance for Ni       | 200              | 1185            | 10.7                                             |

3. Results and discussion

3.1. Pore types and mechanism

Pores are caused the gas that fails to escape during solidification and remains in the liquid metal [5]. The size, number and distribution of pores are important to characterize the quality of the macro-cladding layer. It not only affects the density of the cladding layer, but also affects the corrosion protection coating capabilities, in addition, there are parts of the cladding holes could easily lead to stress concentration, can easily lead to microcracks. Therefore, controlling the pore rate is one of the important measures to improve the density and mechanical properties of corrosion resistance.

Besides produced by laser cladding process, gas can also be produced by interaction of components. Crystal water contained in the cladding material itself to stomatal formation can not be ignored. Wherein the gas generated in the reaction bath, to go through bubble nucleation growth and escape three processes. In the molten pool, there is a bubble and a stable existence. After the gas around the yuan will spread to the bubble in the bubble to grow away when the bubble grows to a certain critical size in molten pool under the action of buoyancy. Gradually rise and escape away. But not all of the gas can escape completely, when the pool of solidification rate is greater than the escape velocity of the bubble, bubbles left in the formation of pores in the cladding layer.

Figure 1 is low times in different parts of the cladding layer morphology. As can be seen, the distribution of pores of different cladding, mostly located in the binding region. Surface porosity is close to the large pore surface of the cladding layer of a single distribution, which is due to the protection of N\textsubscript{2} gas flow rate is too large, severe turbulence is involved in the bath, the solubility of N\textsubscript{2} in the phase transition of a sudden drop in the surface layer remaining in the cladding layer. Such
pore size is usually greater than 30 AIDS m, when the protective gas is involved in too much mayonnaise diameter of 1 to 5 m, and with micro-crack initiation. Its causes may be decomposed to form MoS$_2$ Ni package of free sulfur when more than 400$^\circ$C, and oxygen combine to generate SO$_2$ tiny air mass, $2\text{MoS}_2 + 7\text{O}_2 \rightarrow 2\text{MoO}_3 + 4\text{SO}_2$, can not be discharged in the pool said the rapid solidification process may also be a cladding powder material moisture in the air, the powder in the water under the laser beam vaporization, residue in the cladding layer.

Figure 1. Morphology at different parts of the cladding layer.

3.2. Crack morphology and mechanism
Crack is a serious flaw in laser cladding process due to the combined effect of plastic reserve, stress, gas content and gas in the coating. It directly affects the quality of the cladding layer, shortens product life. To improve the quality of the cladding layer, to reduce and eliminate the crack is the key to improve the laser cladding technology, so the cladding crack research has been important in laser cladding technique subject.

Depending on the shape, cracks can be divided into the inner longitudinal and transverse, shown in figure 2. Longitudinal cracks were seen on both sides of the cladding layer, starting from the top downwards, discontinuous distribution, and sometimes there is a small crack on both sides of microcracks cloud. Transverse cracks straight smooth, continuous distribution, mostly originated in the combined area of 10 to 60 AIDS bottom cladding layer and the substrate m away from the junction.

In order to understand the distribution of the elements in and around the cracks, energy spectrum analysis was performed and results are shown in figure 3. The data in table 2 show that Si, S C content at the crack were higher than normal value, indicating that segregation Si, S, C and other elements, resulting in increased cracking susceptibility. In the cladding layer crystallization process, the first solidified metal pure, secondary crystallization containing Si, C, S push slag and other low melting point to hard phase grain boundaries, constituting a discontinuous film, reduced hard bonding strength of the matrix phase. Then cracks are formed because the stresses generated in the cooling. The above analysis shows that cracks are closely relevant to internal cladding eutectic.
Figure 2. Crack shape of cladding layer.

Figure 3. Crack morphology and its energy spectrum analysis.

Table 2. Comparison of element contents of crack elements and alloy (except oxygen and fluorine elements).

| Element     | Ti  | Al  | Ni  | Cr  | Si  | C   | S   |
|-------------|-----|-----|-----|-----|-----|-----|-----|
| Crack place | 47.68 | 2.11 | 15.27 | 1.02 | 0.34 | 30.44 | 3.14 |
| Alloy A     | 52.96 | 4.39 | 22.97 | 0.95 | 0.26 | 11.15 | 2.58 |
| Alloy B     | 55.97 | 3.59 | 20.64 | 1.18 | 0.13 | 12.23 | 1.58 |

3.3. Cracking susceptibility factors

Cracks on the cross-section of the cladding layer were colored to examine the number of cracks in a certain length, so that cracking rate can be obtained. Factors affecting Cracking susceptibility was obtained through exploring the relationship between laser specific energy, coating composition and the crack rate, and results are shown in figure 4. The results show that with the increase of MoS2 of Ni package, crack rate showed an increasing trend after the initial fall, when MoS2 content increased to 20%, the rate tends to a minimum. With increase of the laser energy, which prolongs the existence bath time, the internal organization of the cladding layer has a relatively long time to nucleation and growth, forming a thick dendrites and granular tissue, increased sensitivity to crack, the crack rate increases.

Analysis shows that factors contributing to reduced residual tensile stress will reduce cracking tendency, and factors contributing to increased stress will raise cracking tendency. From table 1, the linear expansion coefficient of the cladding material is significantly higher than that of the linear expansion coefficient of the base material, while the temperature decrease is much larger than the base of the cladding layer, resulting a bigger contraction than the base of the cladding layer. When the
tensile stress is greater than the ultimate strength of the cladding material, the cracks will form in the cladding. Therefore, physical properties of the material itself cracking are fundamental to susceptibility of the cladding layer.

Factors contributing to reduce the inclusion within the cladding holes and other defects can suppress the crack formation and expansion. Results from previous studies [6] shows that the low melting point inclusions at grain boundaries coarse hard phase will form a liquid film, the liquid film to form pores in the shrinking process or rupture, becomes a source of cracks. Weld pool solidification process, because no time left in the bottom of the cladding layer inclusions floating particles and holes and other factors, led to the cladding surface crack initiation expansion. Therefore, the number of inclusions and porosity content directly affect the cladding cracking susceptibility. Those who help to increase the toughness of plastic cladding factors will reduce the tendency to crack. Kwok Wing-keung, etc. [7] studied the microstructure and properties of Ni-based composite coating by laser cladding, noting that strengthening mechanisms of laser cladding particulate reinforced metal matrix composite coating is mainly fine grain strengthening hard phase dispersion strengthening and dislocation - Ni solid solution strengthening. When the hard phase when TiC precipitates in the petaloid large grain, greatly increases the brittleness of the material and with said diamond fine particulate dispersed in solid solution, not only significantly improves the strength of the alloy, and toughness of the alloy can be substantially maintained. Laser than can determine the status and distribution of the coating microstructure and, therefore, the laser process parameters have an impact on the cladding cracking susceptibility. From the above results and analysis, the formation of cracks in laser cladding layer is the result of many factors, the influence of laser cladding cracking susceptibility

The above results and analysis show that cracks on laser cladding layer is the interaction of many factors, which are coating composites, pores and laser specific energy. There are many ways to reduce crack sensitivity. One is to optimize powdered ingredients, control the number of reinforcing phase, and try to make them evenly distributed in the liquid and solid; the other is to lengthen cooling time to reduce stress and therefore reduce cracks through pre-heating and post-cladding processing [8] We can also use additives with suitable additives linear expansion coefficient as the transition layer to reduce internal stress in the coating, so that cladding cracking susceptibility is minimized [9].

![Figure 4. Relation between crack rate and composition of coating and the laser energy.](image)

4. Conclusions

- Pores on laser cladding Ni-based composite coating are mainly on the surface and the bottom. Pores on the surface are produced by protective gas N₂ gas involved, but pores on the bottom are produced when cladding layer is oxidized to SO₂ and vaporized crystal water fails to escape.
- Cracks can be divided into vertical and horizontal ones. Horizontal cracks are found on both sides, extending from the top to bottom, and the source is the conjunction of cladding layer and the substrate, extending parallel to the binding region. Crack is closely related to low melting eutectic cladding. Segregation of Si, S, C and other elements can reduce the combined strength of the coating, results in crack susceptibility, and produces cracks under cooling shrinkage stress.
Coating composition, pores and laser specific energy can have a certain effect on the crack sensitivity ratio, wherein the coating composition has the greatest impact. There are several ways to reduce cladding crack susceptibility: one is to optimize allocation of powdered ingredients, and the other is to eliminate residual stress through pre-heating and post-cladding processing. In addition, gradient cladding can also be used.

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