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Study of laser cladding thermal damage: A quantified microhardness method

Chao Zeng [a], Wei Tian [a,*], Wen-He Liao [a,b], Liang Hua [a,c]

[a] *College of Mechanical and Electrical Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China*
[b] *Nanjing University of Science and Technology, Nanjing 210094, China*
[c] *Nanjing Institute of Railway Technology, Nanjing 210031, China*

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ABSTRACT

A quantitative thermal damage model was suggested as a function of microhardness, residual stress and material discontinuity. This study reports a method to quantify the microhardness component. Laser cladding was used to repair a V-groove. The tensile properties of static and fatigue of the repaired specimens were investigated. Resulted from the phase transition and differences in the material properties, the laser-based process was shown to cause damage to the treated workpiece due to the formation of a large hardness gradient and a soft band. Thus, the strength of the treated specimen was deteriorated, and the fracture generally occurred in the region of a large hardness gradient or in the softened area. A quantified hardness damage model is developed which contains the hardness gradient and the softening effect. According to this model, the gradient damage and softening damage can be calculated via the microhardness profile of the treated piece. Since the hardness of a material corresponds to its strength, a comprehensive hardness damage model is expected to be drawn in future work.

1. Introduction

Laser cladding is a high-energy and high-productivity technology in which the cladding material is deposited by some method on the surface of the specimen or component and melted by high-power laser radiation [1,2]. This technique is usually used to directly form a component or to recondition a condemned product [1–4]. However, since the factors that affect the usage performance are highly complicated, this technology is not yet widely used. Many studies have been carried out on the application of laser cladding. Through an investigation of the mechanical properties of Inconel 718 components built by laser cladding, it was found that the laser-cladding strategy has a significant influence on the stress–strain curves, and a high directionality of mechanical properties can be resulted [5]. For thermally induced residual stress, it has been demonstrated that the influence of phase transformation plasticity cannot be ignored [6]. Through a three-dimensional finite element model, it is feasible to draw a set of optimised processing parameters to reduce the stress [1]. While the thermally induced stress directly causes microcracks [7], the different thermally induced microstructures may have different fatigue properties [8]. With regard to thermal damage in a martensitic steel substrate consequent to the laser cladding process, Valsecchi et al. studied the hardness characteristics in association with the temperature profile [9]. Since there have not got any common accepted standards for the assessment of thermal damage, researchers studied thermal damage from different perspectives, and most of the previous studies are limited to qualitative approaches [10–13]. According to the authors' previous work, a scalar model was proposed to determine the extent of thermal damage [14]. This model contains damage components related to material discontinuity, microhardness and residual stress. In this paper, the static and fatigue tensile properties will be studied for specimens produced by different laser-based processes. The damage, which is characterised by strength degradation, will be discussed from the perspective of the change in microhardness. A quantitative method relating to the damage is raised to analyse the microhardness profile.

2. Experiment procedure

2.1. Materials

The substrate material used in this research is Q235A steel (E235A in ISO 630-1995). Its chemical composition is listed in Table 1. This steel has good properties of strength and plasticity, as well as good surface cladding properties. Ni60 metal powder was chosen as the cladding material, and the particle size was between 38–48 μm. This powder is a type of Ni–Cr–B–Si self-fluxing alloyed powder which allows for the cladding layer to achieve high hardness, good wear- and corrosion-resistance. It is named according to its hardness value which is approximately HRC60 (HV700). Its chemical composition is given in Table 2.

2.2. Experiment method

The substrate plates (212 × 170 mm) used for the experiment were cut down from a rolled plate with a thickness of 6 mm and machined

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* Corresponding author. Tel.: +86 25 84891836.
E-mail address: tw_nj@nuaa.edu.cn (W. Tian).

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Table 1
Chemical composition of the substrate (wt.%).

Material no.	C	Si	Mn	S	P	Fe
Q235A	≤0.22	≤0.35	≤1.40	≤0.050	≤0.045	Bal.

to a thickness of 5 mm by grinding. In total, 6 plates were machined, among which 4 plates had a transverse V-groove at the middle line (symmetric line). The V-grooves were then repaired by the laser cladding process with laser powers of 1.2 kW, 1.4 kW, 1.6 kW and 1.8 kW, respectively. The cladding process was conducted at the same scanning speed (300 mm/min), the same powder feed rate (12 g/min) and the same laser spot diameter (3.5 mm) for all the plates. One of the rest two plates with no V-groove was burned by a laser beam of 1.2 kW at a scanning speed of 300 mm/min. Lastly, 6 tensile specimens were cut from each plate transversely to the cladding track. Of the 6 tensile specimens from each plate, 3 specimens were subjected to a static tensile test, and the rest were used for the fatigue test. Fatigue tests for all the specimens were carried out under the same load conditions with a loading frequency of 2 Hz, an average load of 18 kN and a load amplitude of 14 kN. Fig. 1 is a schematic drawing of the tensile specimen with a repaired V-groove.

In the experiment, the coaxial powder-feeding laser cladding process was employed. During the process, the laser beam, metal powder and shielding gas were injected simultaneously from the nozzle.

3. Result and discussion

3.1. Static and fatigue property

Static tensile test and fatigue tensile test were designed to investigate the change of static strength and fatigue strength of the repaired specimen. Actually, the force in a working component is usually very complicated consisting of different shear stresses and normal stresses. Using the current repaired specimens for tensile test, it cannot only ensure both the cladding layer and substrate carry the testing load, but also enable the transmission of testing load from one material to another in the form of shear stress and normal stress at the V-groove interface.

The static tensile test was carried out at room temperature using an electronic universal testing machine. During the experiment, the test load and elongation data were transferred to a computer through a force sensor and a displacement sensor. Consequently, the test force–displacement curves can be obtained through the software. Fig. 2 shows the typical force–displacement curves of the tested specimens. Curve P0 shows the situation for a normal smooth specimen (no laser, no cladding). Compared to P0, the force–displacement curve follows the same trend, although the elongation rate decreases slightly when the specimen was treated by laser surface scanning, as demonstrated by Pn. The decrease in elongation for the Pn specimen may be resulted from the phase transition, during which hard phases like martensite and bainite may be introduced, caused by laser burn. It was found that the maximum test load occurs when the test displacement reaches approximately 20 mm. According to the load at this point, the tensile strength can be calculated. Before it reaches this point, curves of P0 and Pn almost agree with each other completely. As a result, the key static strength parameters, such as yield strength (YS) and tensile strength (TS), may be very close for the two groups of specimens.

In Fig. 2, curves P1, P2, P3 and P4 show the situation for the repaired specimens by laser powers of 1.2 kW, 1.4 kW, 1.6 kW and 1.8 kW, respectively. Compared to the smooth specimens, the repaired V-groove specimens showed a completely different shape of force–displacement curves. As can be seen in Fig. 2, the load showed a sudden decrease long before the peak value point of the normal specimen. The sudden steep decrease occurred because the cladding layer broke firstly before the load reached the original maximum value. Therefore, a sudden decrease in the efficient load-bearing area of the specimens resulted. As the cross-sectional area was suddenly reduced, the load capacity of the specimens dropped abruptly. Consequently, there is no doubt that the TS values of the repaired specimens decreased. Moreover, it was found that early during the load decrease, the curves were not monotonous for most specimens. During the drop, a second peak value was observed, except for P4. Through a further observation for the fracture morphology, it was found that there were many small pores at the bottom of the V-groove between the two materials for the specimens from groups of P1, P2 and P3. Thus, it may be the material discontinuity that causes the non-monotonic fall of the test load. Fig. 2 also reveals that the repaired specimens had a decreased load capacity when the specimen was about to break.

Table 2
Chemical composition of Ni60 alloy powder (wt.%).

Material No.	C	B	Si	Cr	Fe	Ni
Ni60	0.6–1.0	2.0–3.0	2.0–3.5	11–15	≤5	Bal.

However, Fig. 2 only shows the results for one specimen in each group, and there were actually three specimens in each test group. Analysis of the force–displacement curves from the specimens in the same group reveals that differences exist among the specimens even if they were produced by the same cladding process. The main difference is that the force decreased at different elongation values. Therefore, different TS values were also observed.

Based on the tensile test curves, YS and TS were calculated, as listed in Table 3. According to Table 3, when a laser process is employed, either surface treatment or cladding, both the YS and TS of the specimen will decrease. For the YS, the maximum degradation was 95 MPa, and the maximum degradation was 104 MPa for TS. Both of these situations happened in the cases of cladding-repaired specimens. Generally speaking, it appears that the strength parameters of the cladding specimens decreased more obviously than those treated by laser surface burn. Hence, the results may suggest that the addition of a new material is also a factor that contributes to the damage.

In addition, Table 3 shows that for laser cladding, the YS first decreased and then increased with the increasing laser power, while the TS changed in the opposite trend. As a result, changing laser power cannot obtain the maximum value of the yield strength and tensile strength at the same time. As bad clad quality, e.g., pores and microcracks, may affect the test results, the changes in the trends of YS and TS may need to be proved by some more experimental trials in which the clad quality of the specimen must be strictly controlled. Besides, the decreased YS and TS were observed in the experiment with the given configuration and materials. Although it is found that the strength is degraded both for laser surface burning and surface cladding, the decreased value of YS and TS may change if the specimen configuration or the material changes.

The fatigue test is designed to study the influence of the laser and the new material on the fatigue life of the specimen. To ensure that the results would be comparable, the experimental conditions were absolutely the same for all the test pieces.

Fatigue lives of the tested specimens are listed in Table 4. As it is very difficult to predict the fatigue life of a workpiece precisely, the experimental result of fatigue life also greatly varies, even though the specimens are created by the same process, as shown in Table 4. For the normal specimens (P0), the minimum life value may be even less than 50% of the maximum value. This diversity may be caused by some initial damage in the microscale of the material that cannot be easily detected. From Table 4, it is found that after the laser-based process, the fatigue strength will decline, especially for the cladded specimens. Like the static tensile test results, the decrease was notable, especially for the cladding repaired specimens, indicating that the damage after cladding is serious and the quality of the repaired components needs further improvement to guarantee the usage performance. Moreover, the