Chapter 28
Effect of Residual Stress on Spallation of NiCrBSi Coating

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Abstract The impact induced spallation characteristics of two specimens with NiCrBSi coating developed by different treatments are investigated. Two typical spallation patterns corresponding to the two kinds of specimens are observed. Theoretical analysis indicates that the difference in spallation characteristics is due to the residual stress. The initial stress states for the two kinds of specimens are investigated. The outcomes verify that the compressive residual stress within the coating will lead to large buckling region of the coating upon impact.

Keywords Coating • Impact • Residual stress • Spallation • Buckling

28.1 Introduction

Hard alloy coatings are widely used on the surface of the parts to improve its resistance to wear, impact and thermal degradation. The adhesion of the coating to the substrate is crucial for the integrity of the component. Wu et al [1, 2] developed an impact testing method to evaluate the interface adhesion of coating to substrate. In such method, a front-end-coated light bullet is accelerated by powder gun or gas gun and impinged at the substrate side of the coated specimen. The input compressive stress pulse would be reflected into tensile stress pulse at the test interface and ultimately makes the coating to separate from the substrate. Moreover, their recent work also showed that the residual stress would influence the impact responses of the coatings [3]. After the interface debonding, the off-plane displacement of the test coating will introduce large in-plane tensile stress within the coating. Such in-plane stress will be influenced by the residual stress of the test coating. Furthermore, the residual stress in the coating may also influence the propagation of the interface cracking. Generally speaking, the interface debonding and coating stress should be mutually dependent. This may be the principle mechanism why residual stress would affect the impact response of the coatings.

In the present work, the method of Bullet Impact is applied to study the dynamic fracture behavior of the NiCrBSi coating on superalloy substrate. It has been shown that the residual stress within the NiCrBSi coatings can be different with different processing conditions [4, 5]. In particular, the large residual stress can be reduced or even reversed by remelting after spraying. As mentioned, the residual stress would greatly influence the fracture behaviors of the coating upon impact. Therefore, this research focuses on relating the spallation pattern of the coating with its residual stress state.

First, experiments were conducted to investigate the spallation behaviors of the coating. The results reveal that two distinct spallation patterns could be obtained for the coatings with different processing conditions, by which different interface adhesion and different residual stress state were developed. Then, the residual stresses of the two kinds of specimen were measured by XRD and related to the spallation patterns. Finally, the cause of the different spallation patterns is discussed by considering the effect of residual stress. It is demonstrated that the residual stress can significantly influence the cracking pattern of the coating when subjected to impact by a front-end coated bullet.

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28.2 Experimental Description and Results

28.2.1 Description of the Test

According to the bullet impact method, experiments are carried out as depicted in Fig. 28.1a, b. Two types of NiCrBSi coatings are tested, of which one is as-sprayed coating and the other coating is subjected to re-melting after spraying. The thickness of the superalloy substrate and coating is 5 and 0.3 mm, respectively. The planar dimension of the specimen is about 150 × 100 mm. The cylindrical nylon bullet is used with its front end coated with nickel foil. The bullet diameter is 12.7 mm and the bullet coating, nickel foil thickness is about 20 μm. And the length of the bullet body is approximately 50 mm, which is enough to avoid the disturbance from the secondary pulse reflected from the bullet rear of the bullet [1]. After the impact test, the specimen is observed and optical images are taken to investigate its spallation morphology.

28.2.2 Test Results

The coated bullet accelerates to about v = 100 m/s and impinges at the specimen substrate. The typical spallation morphology is shown in Fig. 28.2a, b, of which the bullets after test have also been provided. Obviously, the nylon bullets front-end exaggeratedly cracked and expanded into mushroom geometry due to the severe impact.

The magnified central impacted region is shown in Fig. 28.3a, b. One can see that the clear separation is developed in the impact region for the remelted specimen (Fig. 28.3a), comparing to interface debonding and radial cracking of the as-sprayed specimen (Fig. 28.3b). Comparing to the re-melted coating, a larger spallation area on the as-sprayed specimen was observed.

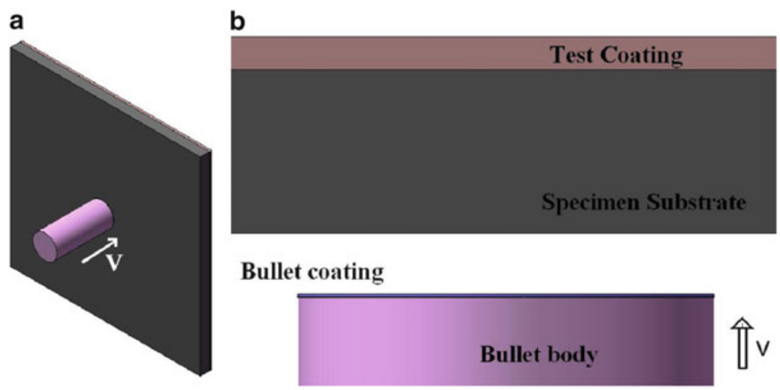

Fig. 28.1 (**a**) Sketch of the impact test and (**b**) magnified part of the specimen and bullet

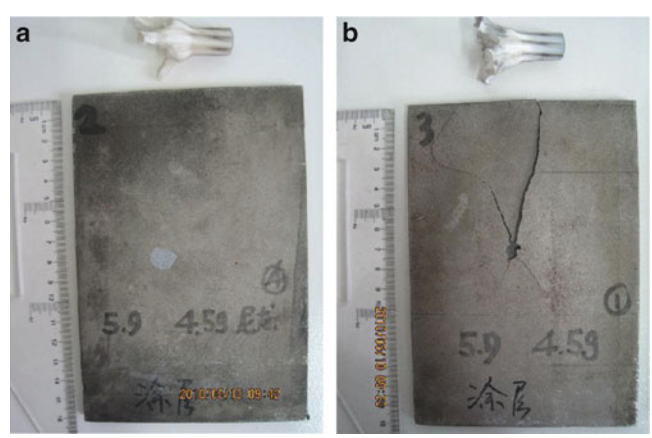

Fig. 28.2 Photo after test for (**a**) re-melted coating and (**b**) as-sprayed coating

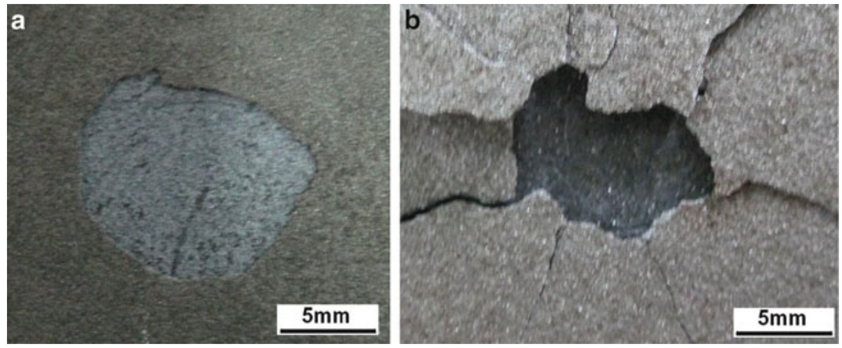

Fig. 28.3 Surface morphology for (**a**) re-melted coating and (**b**) as-sprayed coating

As for the difference in the material states of the two kind of specimen, the remelting process would change the properties of the coating, the interface bonding condition as well as the residual stress state. Strictly speaking, such factors may all contribute to the dynamic fracture behaviors of the coatings. Considering the fact that there is not enough evidence at present for the change of coating properties and interface bonding condition, only the effect of the residual stress state on the impact failure of the coatings is taken into account.

28.3 Residual Stresses and Its Effect

The XRD method [6] was used to measure the surface residual stress in the coating as shown in Fig. 28.4a and a typical test result is shown in Fig. 28.4b. The residual stresses were tested at the locations at different distances from the adjacent free edge of the specimens. Two orthogonal surface stress components are measured for each test point considering the rectangle geometry characteristic of the specimen. The tested orthogonal stress components are parallel to the orthogonal free edges of the specimen.

The measured results reveal that the tested points are almost of equiaxial residual stress states. The algebraic average residual stresses are obtained from the two stress components. The residual stresses versus the distance from the adjacent free edge are graphed in Fig. 28.5a, b. Figure 28.5a, b represent the residual stresses of remelted coating and as-sprayed coating, respectively. Considering the uncertainty of the measurement, about 20 % of the measured value should be regarded as test error. It is indicated that the absolute value of the residual stresses for both coating decrease from the center to the free edge of the specimen, for which it is conceivable that the residual stress should be gradually released by the free edge.

Basically, even considering the test uncertainty, the measurement results still indicate that large compressive residual stress exists in the as-sprayed NiCrBSi coatings. However, this residual stress will be reduced greatly or even changed into small tensile stress by the remelting treatment.

Such difference in residual stress may lead to the difference in the spallation patterns as shown in Figs. 28.2 and 28.3, with which the theoretical descriptions on the spallation process are sketched as in Fig. 28.6a, b. In Fig. 28.6a, b, the last picture of each case is shown in half plane view while the others are shown in cross section view. The off-plane displacement of the coating under bullet impact will result in large tensile stress in the coating, especially around the edge of the impact region. Such tensile stress will lead to fracture of the coating as shown in Fig. 28.6a. As for the clear interface separation between coating and substrate, there is not much deflection in the coating relative to the substrate. Thus the impact induced interface normal stress would not be significantly influenced by the in-plane residual stress [3]. Therefore the interface debonding will arise once the reflected stress pulse arrive or exceed the interface strength σ_{inter} [2],

$$2v(\rho c)_1(\rho c)_2(\rho c)_3/\left(\left((\rho c)_1+(\rho c)_2\right)\left((\rho c)_2+(\rho c)_3\right)\right) \geq \sigma_{inter} \quad (28.1)$$

where, v is the initial impinged velocity of the bullet, ρ and c represents density and elastic wave velocity of the medium, respectively. The subscripts 1, 2 and 3 are representing bullet coating, specimen substrate, and specimen coating.

In summary, as shown in Fig. 28.6a, the remelted coating subjected to impact test would mainly experience three conditions in stages: interface debonding, coating fracture and coating fragment flying away.

If large compressive residual stress exists within the coating, the compressive residual stress may offset the tensile stress resulted from impact. On the other hand, the large compressive residual stress will lead to buckling of the coating after the interface debonding. The buckling will lead to propagation of interface crack, as shown in Fig. 28.6b. Once the interface

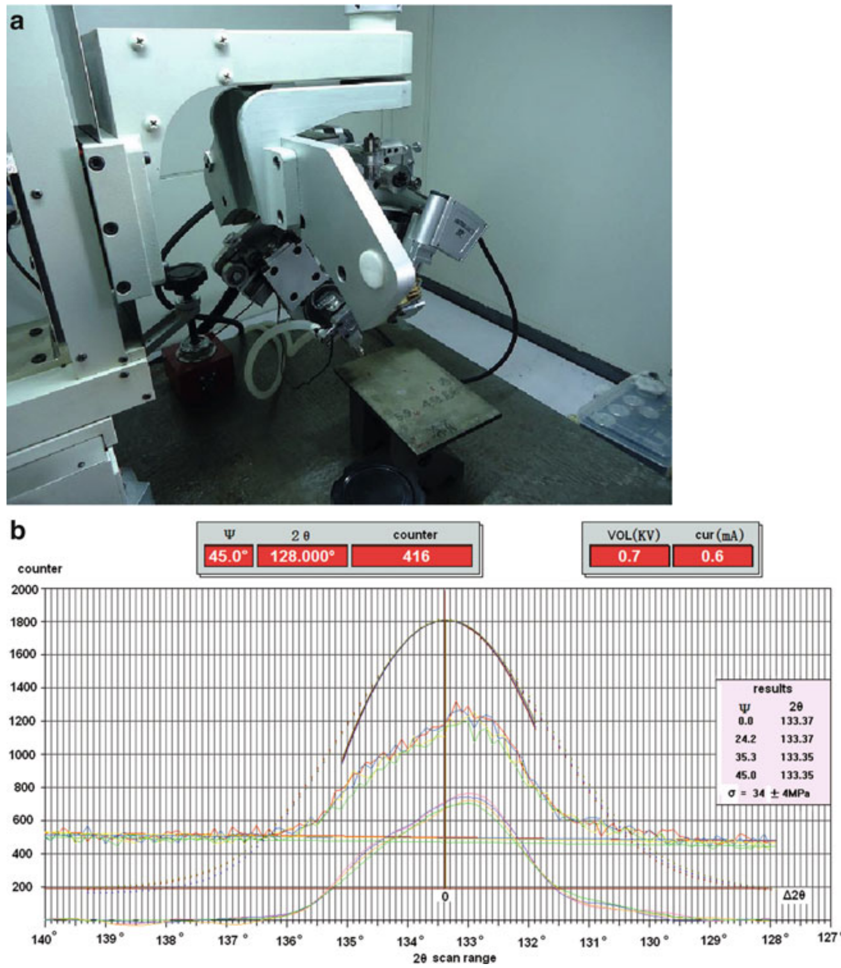

Fig. 28.4 (**a**) Photo of residual stress measurement and (**b**) typical test result

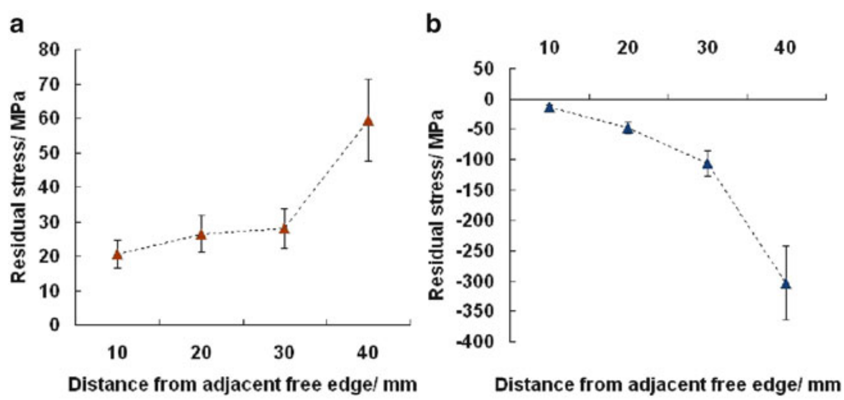

Fig. 28.5 Residual stresses of (**a**) re-melted coating and (**b**) as-sprayed coating

debonding is fully developed by the tensile stress pulse within the impact region, the circular plate buckling theory can be approximately applied. Furthermore, the circular coating separated from the substrate is of boundary constraint more flexible than being clamped while more rigid than pinned. Therefore, we can estimate the critical buckling radial stress σ_{cr} as [7, 8],

$$\sigma_{cr} \approx 0.7875 \times \left(E/\left(1-\nu^2\right)\right) \times (h/r)^2. \tag{28.2}$$

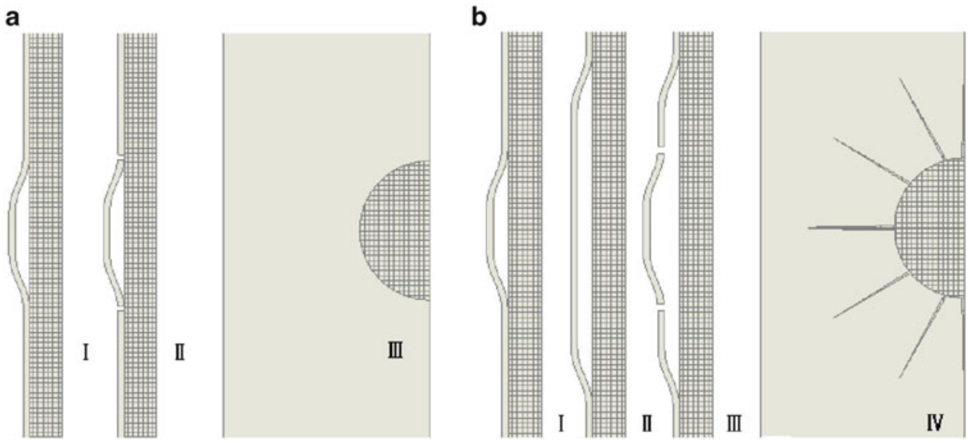

Fig. 28.6 Half size diagram for spallation of (**a**) re-melted coating and (**b**) as-sprayed coating

where E, ν is the elastic modulus and Poisson's ratio of the coating, respectively; h and r represent the thickness and the radius of the debonding region, respectively. If the elastic parameters [9] of the NiCrBSi coating of $E \approx 200$GPa, $\nu \approx 0.15$ and geometrical parameters $h \approx 0.3$ mm, $r \approx 6$ mm are substituted into Eq. 28.2, the critical buckling stress should be about 400 MPa. As shown in Fig. 28.5b, the largest stress component is about 300 MPa. After being transmitted to the polar coordinate component, the radial residual stress should be about 420 MPa. Considering the fact that a dynamic lateral loading with impact, the actual critical buckling stress should be lower than that estimated by Eq. 28.2. Thus, it is believable that the buckling would appear after interface debonding is developed within the impact region. Upon buckling of the coating, the in-plane residual stresses will influence the interface stress due to the coating inclination relative to the substrate. From the energy point of view, the off-plane deformation of coating will partially release the residual stress. Such reduction in elastic energy can increase the energy release rate of the interface crack. Generally speaking, the interface crack will propagate if the elastic energy release rate exceeds the interface fracture toughness. Therefore, the interface crack propagation will be enhanced by the residual stress. Of course, the center region of the coating will also crack along the circumferential direction as the tensile stress would increase with the further off-plane displacement of the coating segment covered by impact region.

In summary, the as-sprayed coating subjected to impact test would experience conditions in four stages: interface debonding, coating buckling with interface crack propagation, coating fracture and coating fragment flying away. The major difference in the spallation process of the two kinds of coating is the large buckling of the as-sprayed coating. This should be attributed to the contribution of the large compressive residual stress within these coating. As for the fact that the remelting treatment can reduce the residual stress, the remelted coating would not experience the large buckling stage. However, it is noteworthy that the remelting process may also increase the interface fracture toughness, which can hold back the interface crack propagation and therefore prevent the buckling of the coating.

28.4 Conclusion

Two kinds of NiCrBSi coating are subjected to bullet impact test and two corresponding distinct spallation patterns are observed. Residual stress measurements based on XRD indicate that large compressive residual stresses were developed within the as-sprayed coating while the remelting treatment reduced such residual stress to a negligible level. Due to the high compressive residual stress within the as-sprayed coating, large regime buckling of the coating will appear under impact. It is demonstrated theoretically that the distinction in the spallation of the coating could have been resulted from the difference in their residual stress states. Considering the fact that the remelting treatment can also change the interface strength, further investigation is needed to separate the contribution of the improvement in interface properties.

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