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Finite-Element Evaluation and Improvement of a Test Procedure for Coating Shear Bond Strength Determination

Y.L. Zhu, S.N. Ma, and B.S. Xu

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In the research and development of thermal spraying coating systems for wear-resistance applications, it is essential to determine coating/substrate bond strength with a proper test procedure. This article describes mechanical evaluations of a widely adopted coating shear bond strength test procedure conducted via the finite-element method. Analyses of the stress distributions on the coating/substrate interface indicate that significant errors will be introduced if the standard test procedure is used to determine coating shear bond strength. A new test procedure with modified specimen geometry is proposed and then verified for effectiveness.

Keywords coating, finite-element method, shear bond strength

1. Introduction

Thermal sprayed coating systems for wear-resistance applications require good bond strength between the coating and substrate. As in any coating application, the minimum requirement for acceptable performance of a coated component must be a sufficient level of coating/substrate adhesion (Ref 1). This makes it essential to quantitatively, or at least qualitatively, estimate the bond strength of a coating system before any practical application. Presently, due to the lack of detailed knowledge of the vast array of parameters involved, there has been no such theoretical model that can be used to derive the bond strength of a coating system directly from the coating deposition process parameters. The only practical and reliable way of determining bond strength is by experimentation. A coupon is prepared with specific coating deposition parameters, which is then tested with an appropriate test procedure, and the acquired data is evaluated with a sound computational model to give an estimation of the coating/substrate bond strength. In order for the estimation to be more reliable, the test model and procedure should be designed such that it represents the practical situation as closely as possible. In addition, simplifications and assumptions should be carefully introduced in computational modeling or interpretation of the test model and procedure. However, these requirements are not always very easy to satisfy. The reason lies in the fact that either the test model may be irrational and therefore cannot represent the real problem in a proper manner, or the underlying mechanical responses of the test model are not fully understood, which leads to the adoption of an improper computational model. For example, Han et al. (Ref 2, 3) have recently conducted a computational and experimental stress analysis on the ASTM Standard C 633-79, "Standard Test Method for Adhesion or Cohesive Strength of Flame-Sprayed Coating," to evaluate the effectiveness of the test method, and they found that the maximum stress at the coating interface can be 25% higher than the average stress due to an improper specimen dimension specified by the standard. To improve the reliability of the tensile adhesion test, Han et al. used an elongated specimen, which they showed provides better estimates of bond strength than tests performed with the standard specimen. In fact, many test standards and procedures for coating properties evaluation are rather unsophisticated (Ref 1) and need to be verified strictly to find whether they will bring any errors to the results, and/or need to have further improvements made on them.

In this study, DIN 50161-1967 (Ref 4) and GB/T 13222-91 (Ref 5) standards determining the adhesion strength in shear mode is evaluated via finite-element analysis method. Analyses of the stress distributions on the coating/substrate interface indicate that, due to improper modeling, significant errors will be introduced if the test procedure is used to measure coating shear bond strength. A new test procedure with a modified specimen geometry is proposed and then verified for effectiveness.

2. Description of the Test Procedure and Finite-Element Modeling

The current adhesion shear strength standards (Ref 4, 5) require a mild steel cylindrical specimen of 36 mm diameter, d, which is coated to a thickness t on its outer surface and machined to form a flange of width w. The coating/substrate system is placed onto a rigid die to form a stable and axisymmetrical support between the lower surface of the coating and the upper surface of the die. An axial pressure, P, is quasi-statically applied on the top end of the cylinder to shear the coating from the substrate (Fig. 1). With the maximum load P_0 recorded, the shear bond strength of the coating is calculated using (Ref 5):

$$\tau_s = \frac{P_0}{\pi d w} \qquad \text{(Eq 1)}$$

At first sight, the test and evaluation procedure seems to be very simple, and it is obvious from Eq 1 that a rather intuitive as-

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sumption of uniform shear stress distribution over the coating/substrate interface is introduced. In fact, if the friction forces between the lower surface of the coating and the upper surface of the die are ignored, the interfacial shear stress values at the top and bottom hoops of the coating/substrate interface must be zero according to the equality of cross shears (Ref 6). Thus, it is impossible for the shear stress to distribute uniformly across the coating/substrate interface, as will be demonstrated later in this article. In addition, normal stress will inevitably arise on the coating/substrate interface owing to the effect of bending moment, which contributes to coating/substrate detachment. This latter phenomenon also indicates that the test and evaluation procedure will underrate the shear bond strength of the coating system due to the existence of interfacial tensile stress that will

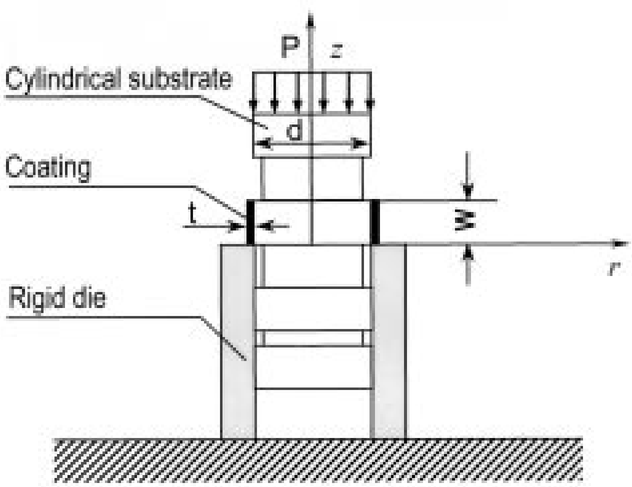

Fig. 1 Standard shear bond strength test system

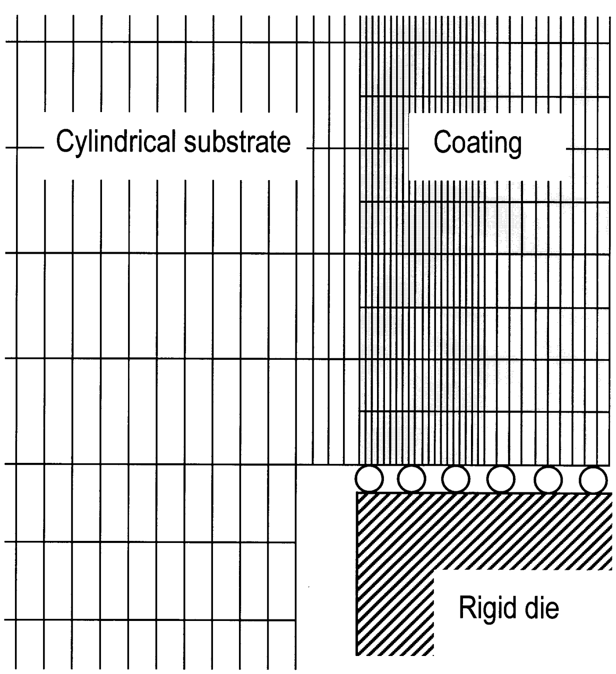

Fig. 2 Refined mesh near the coating/substrate interface

accelerate the failure process of the coating system. These preliminary considerations gave impetus to careful investigation of the test procedure. As experimental verification of the stress distributions on the interface is difficult to implement, the finite-element method was used in this study.

Considering the axial symmetry property of the structure and loading conditions, only half of the coating/substrate system is discretized for analyses. A total of 4000 four-noded isoparametric elements are used to conduct the simulation. To understand the details of the high gradient stress distribution and to increase accuracy of the calculation, meshes near the coating/substrate interface are refined, as shown in Fig. 2. Bearing in mind that friction between the die and the specimen is neglected, the boundary conditions are specified as follows: roller boundary conditions are applied on the outer surface of the cylinder and the bottom surface of the coating in contact with the inner and upper surfaces of the die, respectively. All nodes along the z-axis are constrained from motion in the r-direction. As here the reader is concerned only with interfacial stress distributions prior to coating detachment, elastic material responses and permanent bonding between the coating and substrate are assumed.

3. Results and Discussion

3.1 Nonuniform Interfacial Stress Distributions

Figure 3 shows the normal and shear stress distributions over the coating/substrate interface for a coating 2 mm thick and 15 mm wide when the axial load, *P*, reaches 81 kN. The shear stress distribution is very uneven, with a maximum value of 106 MPa at z = 0.6 mm, which is 4.35 times of the average value τ_{av} (47.7 MPa, according to Eq 1); from z = 5.0 to 12.5 mm on the interface, shear stress value is only about 25 (±10) MPa, which is nearly half of the average value. In addition, normal stress possesses nonzero values at the lower and upper end of the interface, with a drastic change from compressive to tensile stress at z = 0.6 mm. Maximum tensile stress is as high as 75 MPa. The above observations imply that it is the combined effect of the maximum shear and tensile stresses that result in coating detachment. When adhesive failure occurs at the interface where the interfacial stresses attain their maximum value, stress values at other parts of the interface are still far lower than the actual shear bond strength of the coating system. This means that shear bond strength evaluated with this method could be significantly underrated.

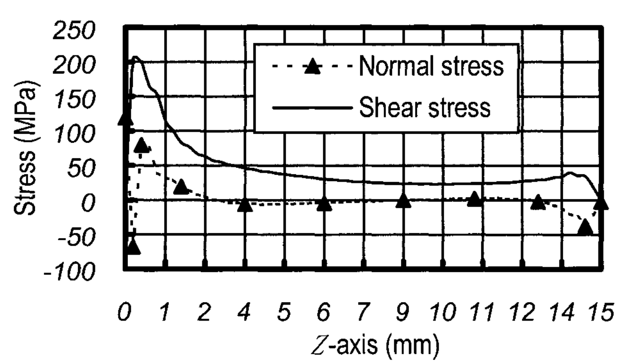

Fig. 3 Interfacial stress distributions

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3.2 Effects of Coating Dimensions on Interfacial Stress Distributions

Coating dimensional parameters, such as thickness and width, can affect interfacial stress distribution to a certain degree. In order to assess this effect, coatings of different thickness and width are evaluated in the finite-element simulations.

To begin with, the effect of coating thickness variation is studied. The interfacial shear and normal stress distributions for three coatings of different thickness (1.0, 1.5, and 2.0 mm) at 81 kN axial pressure are shown in Fig. 4 and 5, respectively. The figures show a shear stress peak and a normal stress transition for all the three coatings, implying that coating thickness variations have little effect on the interfacial stress distribution patterns. However, the maximum stress values are quite different. For the three coatings of 1.0, 1.5, and 2.0 mm thickness, the corresponding maximum shear stress values are 286, 236, and 206 MPa, respectively, and the corresponding maximum tensile stress values are 191, 144, and 119 MPa, respectively. This shows that thick coatings tend to reduce the maximum stress values and, hence, improve the reliability of the estimated shear bond strength.

To evaluate the effects of coating width variations, coatings of 2 mm in thickness and of three different widths (7.5, 15.0, and 22.5 mm) are examined. Figures 6 and 7 show the interfacial shear and normal stress distributions, respectively, for the three coatings under equivalent loading conditions. "Equivalent loading" infers that when the load-bearing area is changed due to coating width variation, the axial pressure, *P*, should be applied in a manner that will keep the average interfacial shear stress, τ_{av}, unchanged. The equivalent loads for the three coatings are 40.5, 81.0, and 121.5 kN, respectively. It can be found from the figures that, for the three coatings of 7.5, 15.0, and 22.5 mm width, the corresponding maximum shear stress are 138, 202, and 312 MPa, respectively, and the corresponding maximum tensile stress values are 54, 119, and 190 MPa, respectively. This shows that a smaller sample width tends to reduce the maximum stress values. In addition, it also can be found from Fig. 6 that decreased sample width will lead to less variation of interfacial shear stress distribution. These observations indicate that samples of smaller width will give more reliable shear bond strength evaluation results.

From the above analyses, it can be concluded that, in evaluating coating shear bond strength with this test method, a thicker coating and smaller sample width better satisfies the assumption of uniform shear stress distribution over the coating/substrate interface. One should also be aware that with the standard test procedure, perfectly uniform shear stress distribution with no tensile stress on the interface is impossible. As shown in Fig. 6 and 7, even for the coating 2 mm thick and 7.5 mm wide, a maximum interfacial shear stress of 138 MPa is developed, which is nearly three times the average shear stress value, and the maximum interfacial tensile stress value for this coating is 54 MPa. In fact, for most of the frequently used thermal spraying techniques, it is a nontrivial task to deposit coatings with thickness greater than 3 mm due to interfacial stress accumulation. An understanding of the underlying stress/strain response and mate-

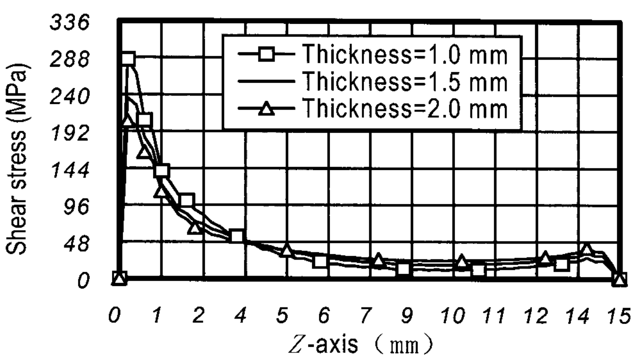

Fig. 4 Interfacial shear stress distributions for coatings of different thickness

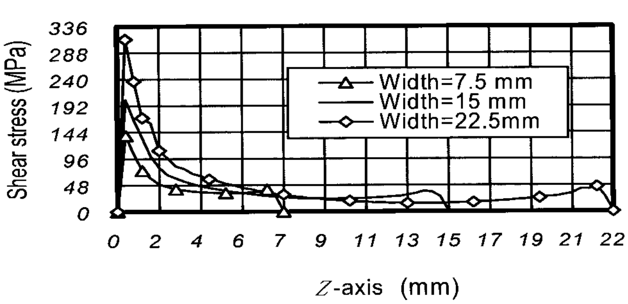

Fig. 6 Interfacial shear stress distributions for coatings of different width

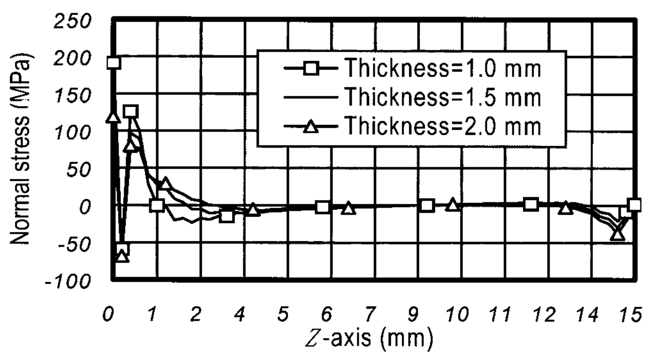

Fig. 5 Interfacial normal stress distributions for coatings of different thickness

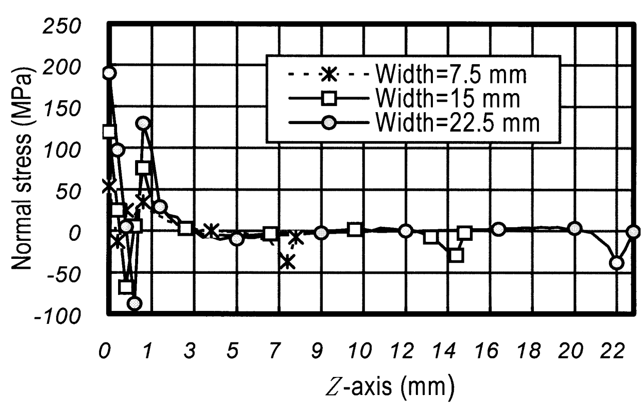

Fig. 7 Interfacial normal stress distributions for coatings of different width

rial failure modes are often of great help in interpreting the test result.

3.3 Improved Test Procedure

In order to improve the interfacial stress distribution and to reduce the maximum value of the interfacial shear and normal stress, a new test procedure with modified specimen geometry is proposed. As shown in Fig. 8, the coating is machined to form a cone-shaped outer surface, with a half-cone angle $\alpha = 3.8°$. A conical die of equal conical angle with the cone surface of the coating is used to support the specimen. To evaluate the influence of the coefficient of friction between the coating and the die, the "penalty method" (Ref 7) is used in the finite-element program to model unilateral contact with friction. Three different frictional conditions are considered, with the coefficients of friction $f = 0.1$ and 1.0 and a condition of permanent bonding between the coating and the die. In the case of $P = 81$ kN and $w = 15$ mm, Fig. 9 and 10 show the interfacial shear and normal stress distributions, respectively. For the three frictional conditions, $f = 0.1$ and 1.0 and permanent bonding between the coating and the die, the corresponding maximum shear stress values are 85, 72, and 70 MPa, respectively, and the corresponding maximum compressive stress values are 162, 100, and 71 MPa, respectively. Compared with the standard specimen, the modified specimen produces relatively uniform stress distribution over the interface (refer to Fig. 4 and 9). For the worst case of $f = 0.1$, its maximum interfacial shear stress value (85 MPa) is only 1.78 times the average value (47.7 MPa) and the minimum interfacial shear stress value (at the middle range of the interface) reaches 40 MPa, which is 84% of the average value. Moreover, there are no tensile stresses on the interface. As for the compressive stresses on the interface, they do not contribute to coating detachment. Besides, in most tribological applications, shear and compression is usually the dominant stress state on coating/substrate interface. These results show that the modified specimen can give more reliable coating/substrate shear bond strength evaluation than the standard specimen.

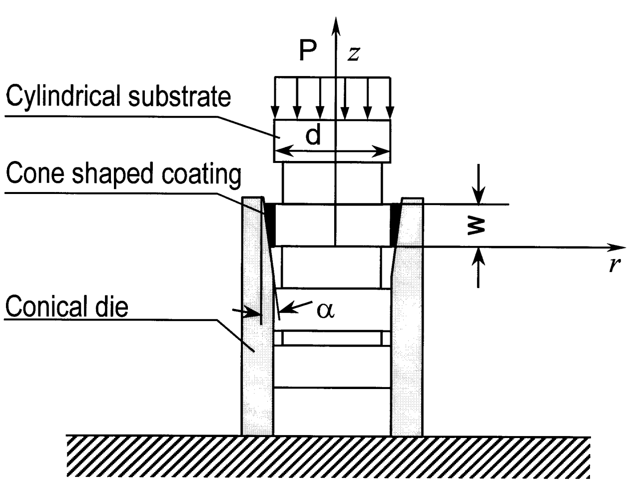

Fig. 8 Modified test system, where the coating is machined to form a cone-shaped outer surface

4. Conclusions

By using the finite-element method, the interfacial stress distributions and the effects of coating geometrical parameters in a standard coating/substrate shear bond strength test are obtained. Some major conclusions are as follows:

- In evaluating the coating/substrate shear bond strength with the standard specimen geometry, the interfacial stress distribution is very uneven. When the interfacial shear stresses attain a maximum value of nearly 4 times the average value, the stresses at other parts of the interface are far lower than the average value. Moreover, the interfacial stress state is by no means pure shear. The large tensile stress present on the interface will contribute to coating detachment. Therefore, the shear bond strength evaluated with this method could be significantly underrated.
- Thicker coatings with a smaller sample width tend to lower the maximum shear and tensile stress values and therefore give a relatively better estimation of the shear bond strength.
- With the modified geometry of the specimen, interfacial stress distribution is largely improved with no tensile stresses on the interface, which suggests that the modified specimen can give more reliable coating/substrate shear bond strength evaluation than the standard specimen.

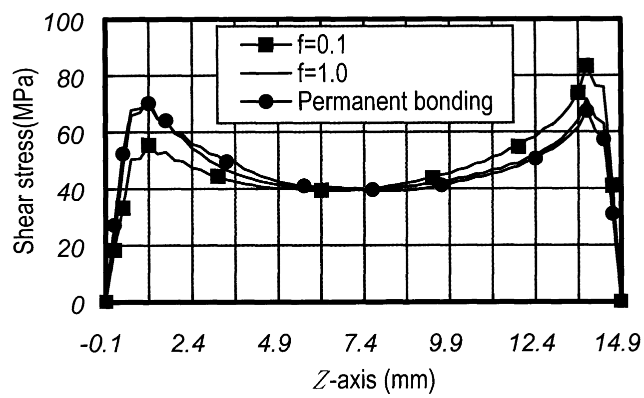

Fig. 9 Interfacial shear stress distributions at different frictional conditions

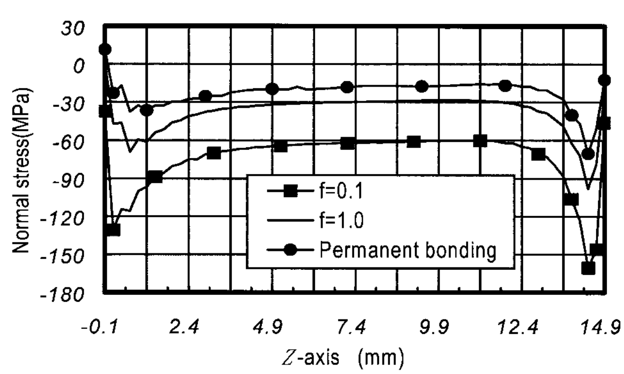

Fig. 10 Interfacial normal stress distributions at different frictional conditions

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