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Effects of Coating Thickness and Residual Stresses on the Bond Strength of ASTM C633-79 Thermal Spray Coating Test Specimens

D.J. Greving, J.R. Shadley, and E.F. Rybicki

Wire-arc-sprayed nickel-aluminum is widely used in the aircraft industry for dimensional restoration of worn parts and as a bond coat for thermal barrier coatings and other top coats. Some repair applications require thick coatings, which often result in lower bond strength. A mechanism being investigated to explain this decrease in bond strength is the free edge effect, which includes both coating residual stresses and coating thickness. The layer-removal method was used to determine experimentally the residual stresses in wire-arc-sprayed nickel-aluminum coatings of different thicknesses. Bond strength evaluations were performed using an improved ASTM C 633-79 test specimen. Finite-element analysis and fracture mechanics were used to investigate the effects of coating thickness and residual stress state on coating bond strength.

1. Introduction

THERMAL spray coatings are often used to provide thermal barriers in turbine engines and internal combustion engines, and to repair expensive worn machine and engine parts. These applications require that the coating remain bonded to the component. Although thick coatings would appear to provide longer service life, certain problems are unique to thick coatings. Specifically, early debonding of thick coatings can reduce service life and preclude any advantages. Bond strength tests and in-service applications of coatings with different thicknesses have shown that bond strength and service life decrease with increasing coating thickness (Ref 1-3). Howell (Ref 2), in a study concerned with metal coatings applied to concrete, reports that increased coating thickness results in decreased bond strength. Results given by Unger and Grossklaus (Ref 1) show that for some coatings the bond strength of a thick coating applied to stainless steel or titanium can be as low as one-third of the bond strength of a thin coating. Woods (Ref 3) presents data for coatings on internal combustion engines that indicate a trend of decreasing bond strength and decreasing number of cycles to failure with increasing coating thickness.

One credible hypothesis to explain this behavior is that residual stresses contribute to the reduced bond strength for thicker coatings. Residual stresses are inherent in thermal spray coatings; furthermore, such stresses are often tensile because thermal spray coatings are applied at a high temperature to a cooler substrate. Upon cooling, the coating will contract more than the substrate. Because the substrate constrains the coating from contracting, the coating has tensile residual stresses after cooling (Ref 4).

The literature indicates that tensile residual stresses are a factor in fracture. For example, Rybicki and Stonesifer (Ref 5) have shown that tensile residual stresses clearly have an effect on reducing the fracture strength of a pressure vessel for linear elastic conditions. Another finding, related to the contribution of residual stresses to coating debonding, is that in-plane tensile stresses, acting in the same direction as the residual stresses in the thermal spray coatings, cause free-edge debonding of laminated plates (Ref 6). The in-plane tensile stresses in the laminate create a peel-back mechanism that can lead to debonding at the edge of coated test specimens. However, little work has been performed to show that residual stresses have an effect on the bond strength of thermal spray coatings.

The mechanism concerning how residual stresses interact with coating thickness to contribute to reduced bond strength is of interest. This behavior is called the "free-edge effect" and occurs in the debonding of laminated composite materials (Ref 7). The Appendix to this paper describes the free edge effect.

In previous work (Ref 8), a fracture mechanics approach was used to predict the bond strengths of different coatings using an improved ASTM C 633-79 test specimen. This approach was applied to an aluminum oxide coating, a tungsten carbide coating, and an adhesive. The goal of the present work is to investigate the effects of coating thickness and residual stresses on bond strengths of thermal spray coatings. The approach is to select a commonly used coating system and to characterize the residual stresses and bond strengths for a range of coating thicknesses. The fracture mechanics analysis is extended to include residual stresses and is applied to the bond strength data to examine possible mechanisms linking residual stresses and coating thickness to the observed decreased bond strength behavior. Results are compared with bond strength data available in the literature. The long-range goal of this work is to increase the service life and operational efficiency of thick thermal spray coatings by improving the residual stress state in the coatings.

Keywords ASTM C 633-79, coating thickness, finite-element analysis, mechanical properties, residual stress

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2. Experimental Program

The coating material selected for this study was 95% Ni and 5% Al by weight. This coating and variations of it are frequently

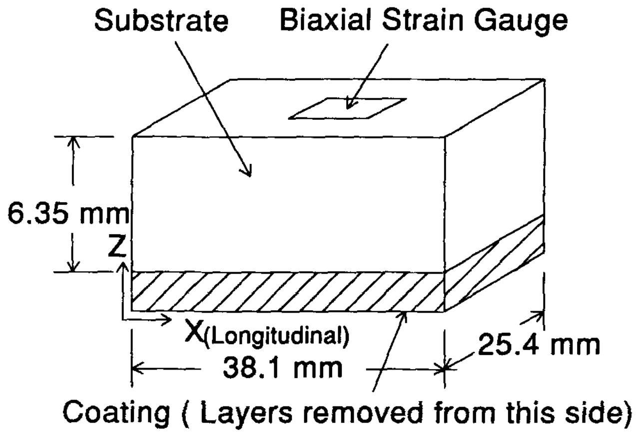

Fig. 1 Residual stress specimens

used as a repair material and as a bond coat. The substrate material was AISI 1018 steel. All substrate specimens were stress relieved by heat treating in accordance with ASM stress-relieving recommendations for steel (Ref 9) and then grit blasted prior to coating. Coating thicknesses of approximately 0.254, 0.762, 1.143, and 1.524 mm (0.010, 0.030, 0.045, and 0.060 in.) were applied to specimens prepared for residual stress, bond strength, and metallographic evaluations. The equipment used for all spraying was a Hobart Tafa (Hobart Tafa Technologies, Inc., Concord, NH) model 9000 arc spray system. The wire used was TAFA Bondarc 75B (Hobart Tafa Technologies, Inc., Concord, NH) nickel-5 aluminum. The propellant gas was air, with a spray distance of 75 mm (3 in.) and spray angle of 90°. A robot manipulator controlled the motion of the spray gun, which applied a coating thickness of approximately 0.0686 mm (0.0027 in.) per pass. All coated specimens were prepared at the same time for each thickness.

A modified layer-removal method for thermal spray coatings was used to determine the residual stresses in four replicate samples for each of the four coating thicknesses. In this method, layers are removed from the coated side of the specimen (Fig. 1) and the changes in strain on the substrate side are monitored. Strain-change data and thickness information are used as input to a program for calculating residual stresses. The modified layer-removal method has been used for a variety of thermal spray coatings and has been verified as an appropriate technique (Ref 10).

The original residual stress specimens used a substrate twice as thick as that shown in Fig. 1. The substrate was reduced in thickness to increase the strain-gage sensitivity for the layer-removal procedure. Strain gages recorded the change in strain caused by reducing the substrate thickness. These strain changes were converted to stress changes and were combined with the stresses obtained from the layer-removal method to evaluate the stress distribution that existed in the specimen prior to cutting.

Bond strength evaluations were conducted using ASTM Standard C 633-79 as a guideline and employing elongated test specimens with a 25.4 mm (1.0 in.) diameter and an overall length of 38.1 mm (1.5 in.) (Ref 11). Figure 2 illustrates an elongated bond strength specimen and the self-aligning fixture. The 3M (3M, St. Paul, MN) adhesive EC-1386 was used for bonding the test specimens. A test was deemed successful if the coating failed at or near the coating/substrate interface. Alignment and load cell calibration were checked prior to testing.

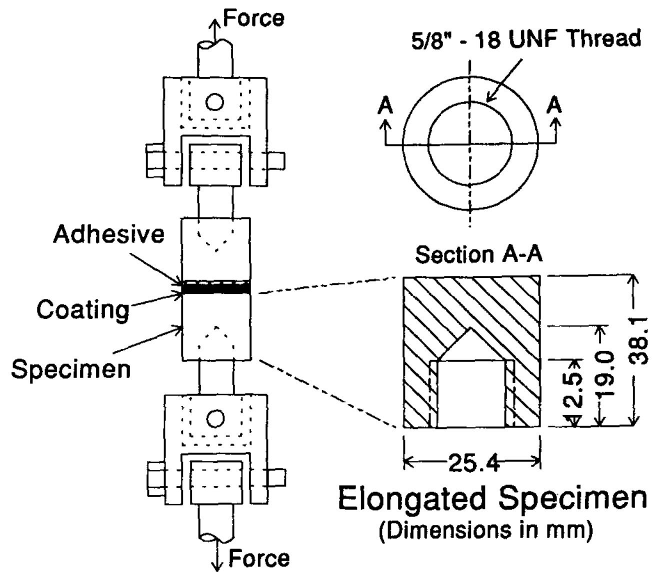

Fig. 2 Bond strength specimens and ASTM C 633-79 self-aligning test fixture

3. Effects of Coating Thickness on Residual Stresses

Figures 3 to 6 show the through-thickness residual stress distributions for the different thickness nickel-5 aluminum coatings (four separate specimens for each). The horizontal axis shows distance into the specimen as measured from the surface of the coating. The vertical axis shows the residual stress, σ_x, in the longitudinal direction of the specimen. A coating modulus, E_c, of 68.9 GPa (10.0×10^6 psi) and a coating Poisson's ratio, ν_c, of 0.3 were used for calculating the residual stresses. The coating modulus was found by conducting a cantilevered beam test of a coated specimen. A modulus of 200.0 GPa (29.0×10^6 psi) and a Poisson's ratio of 0.3 were used for the substrate in the residual stress analysis.

Note that all results indicate tensile stresses of about 90 MPa (13 ksi) through the thickness of the coating. Results also show that a zone of compressive stress exists in the substrate near the interface. Figure 7 shows the average tensile residual stress, σ_x, through the coating for each coating thickness with a 95% confidence interval. Average tensile residual stress in the coating was calculated by using the residual stress data to compute the force on the coating cross section and then dividing the force by the coating cross-sectional area. Figure 7 shows that the average residual stress in the coating is almost independent of coating thickness.

4. Effects of Coating Thickness on Bond Strength

Figure 8 shows bond strength data for the four coating thicknesses evaluated in this study and from Ref 1. Maximum and

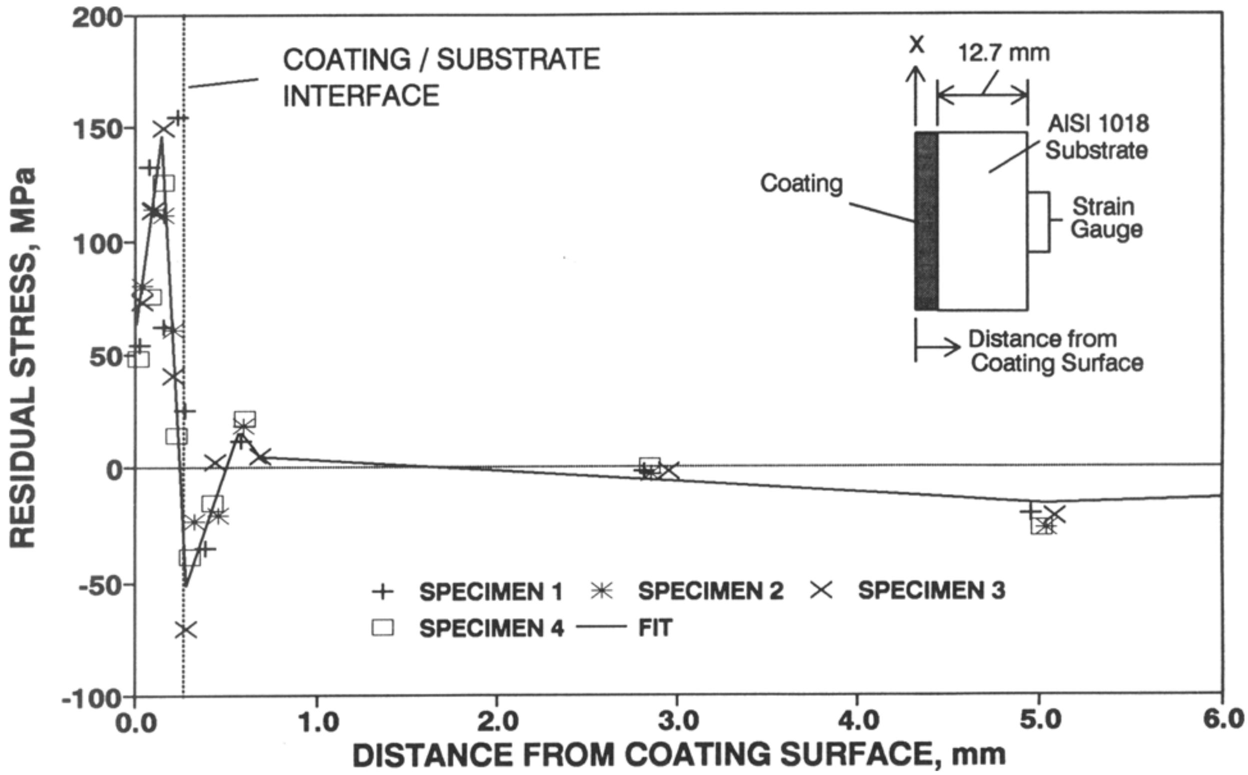

Fig. 3 Through-thickness residual stress distribution for 0.254 mm (0.010 in.) thick coating of nickel-5 aluminum on AISI 1018 steel

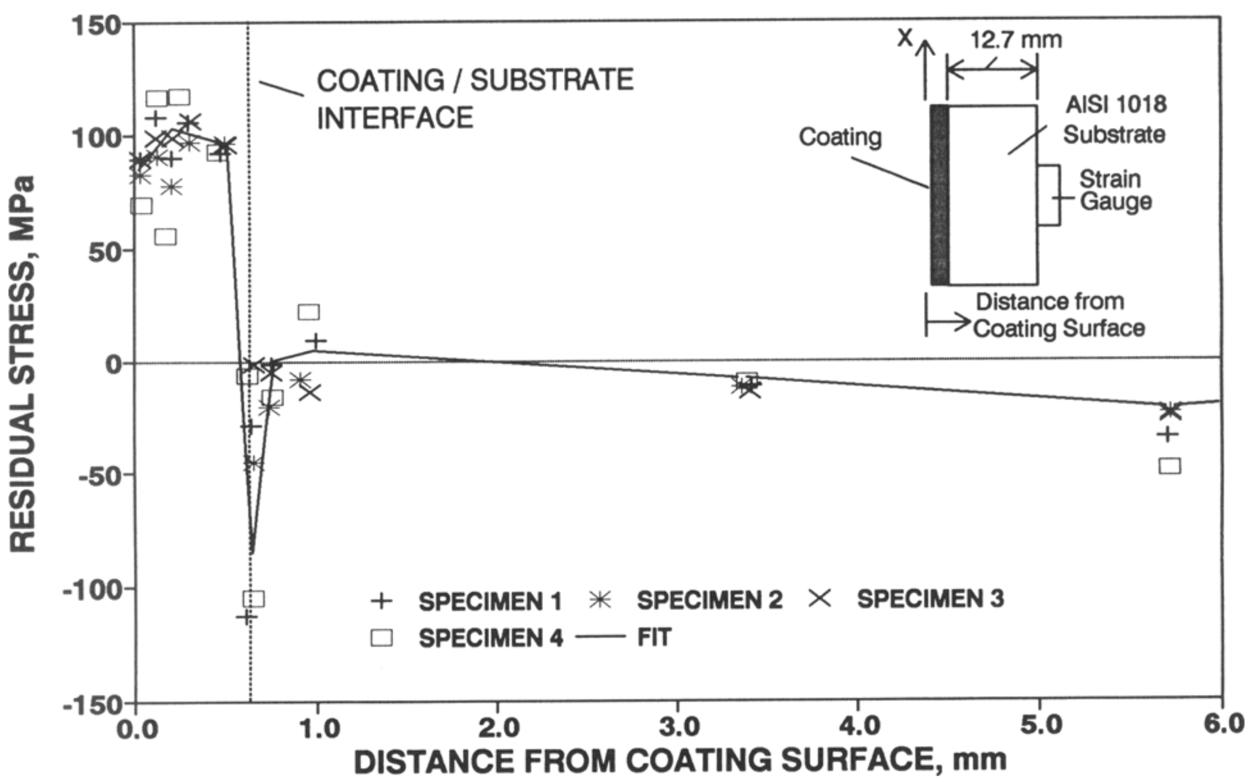

Fig. 4 Through-thickness residual stress distribution for 0.762 mm (0.030 in.) thick coating of nickel-5 aluminum on AISI 1018 steel

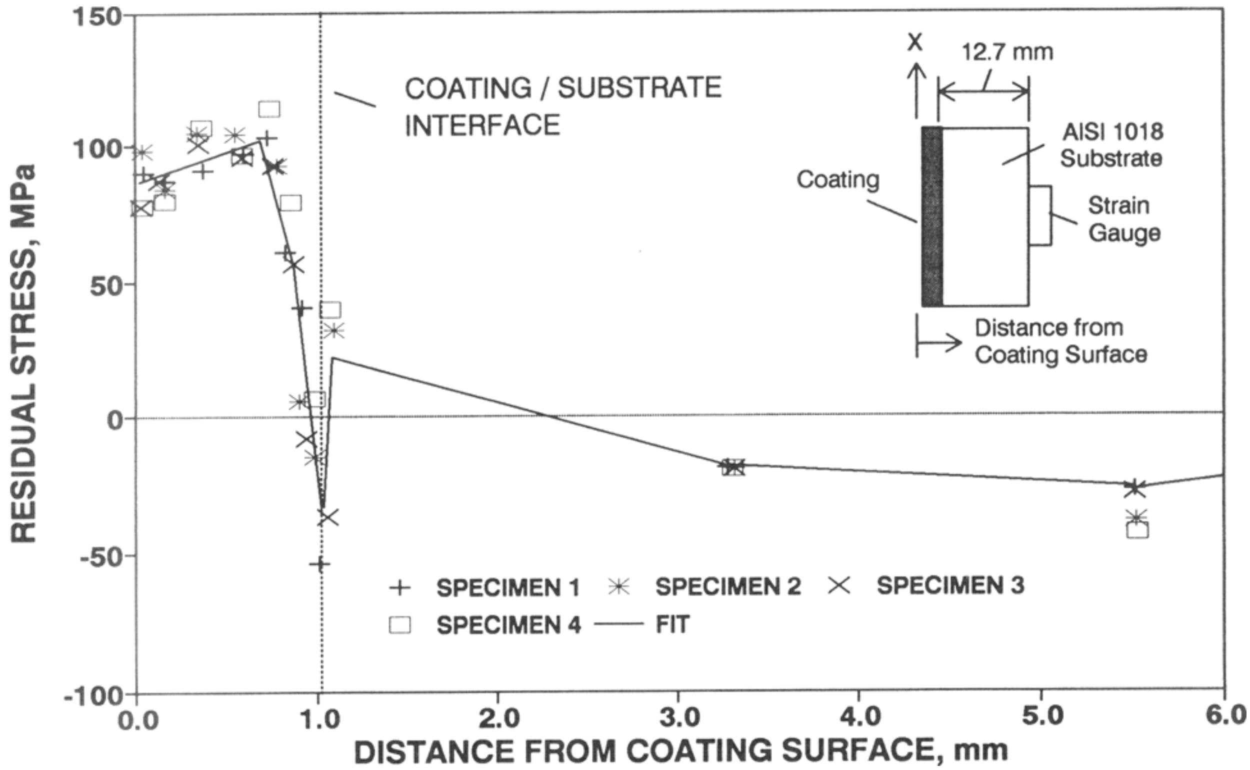

Fig. 5 Through-thickness residual stress distribution for 1.143 mm (0.045 in.) thick coating of nickel-5 aluminum on AISI 1018 steel

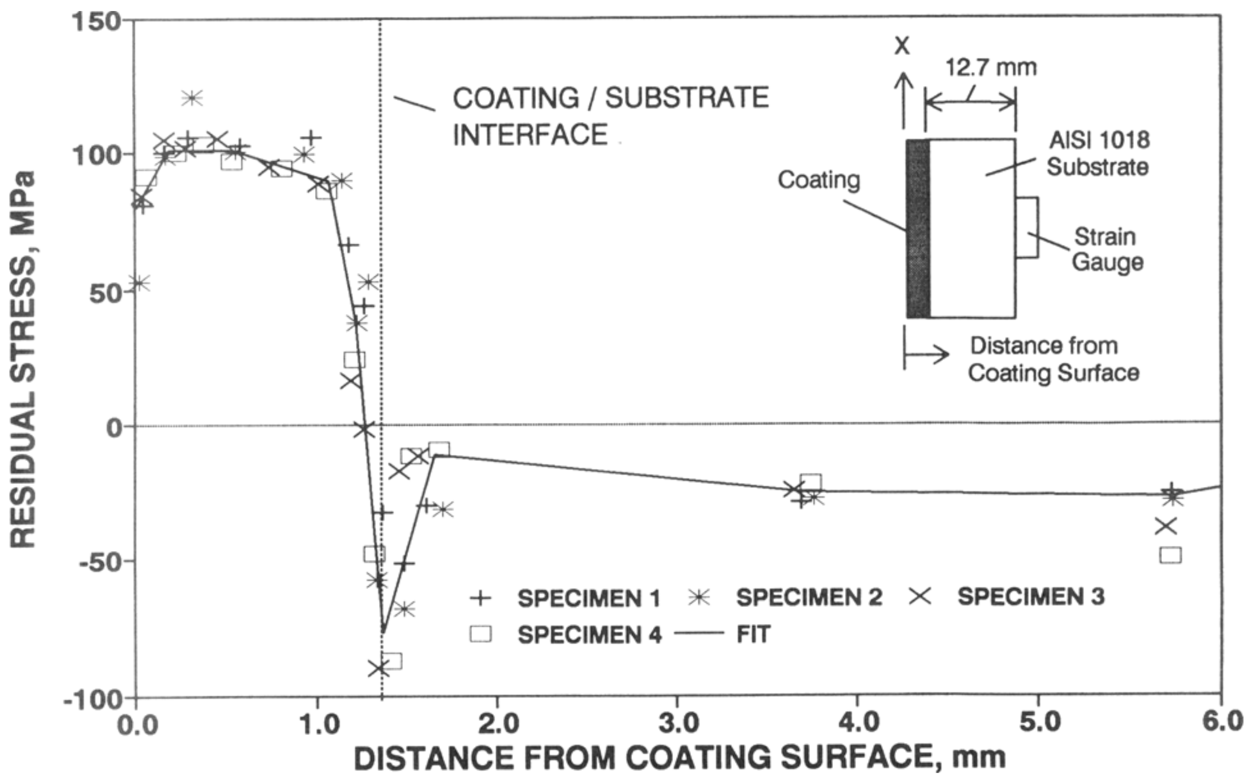

Fig. 6 Through-thickness residual stress distribution for 1.524 mm (0.060 in.) thick coating of nickel-5 aluminum on AISI 1018 steel

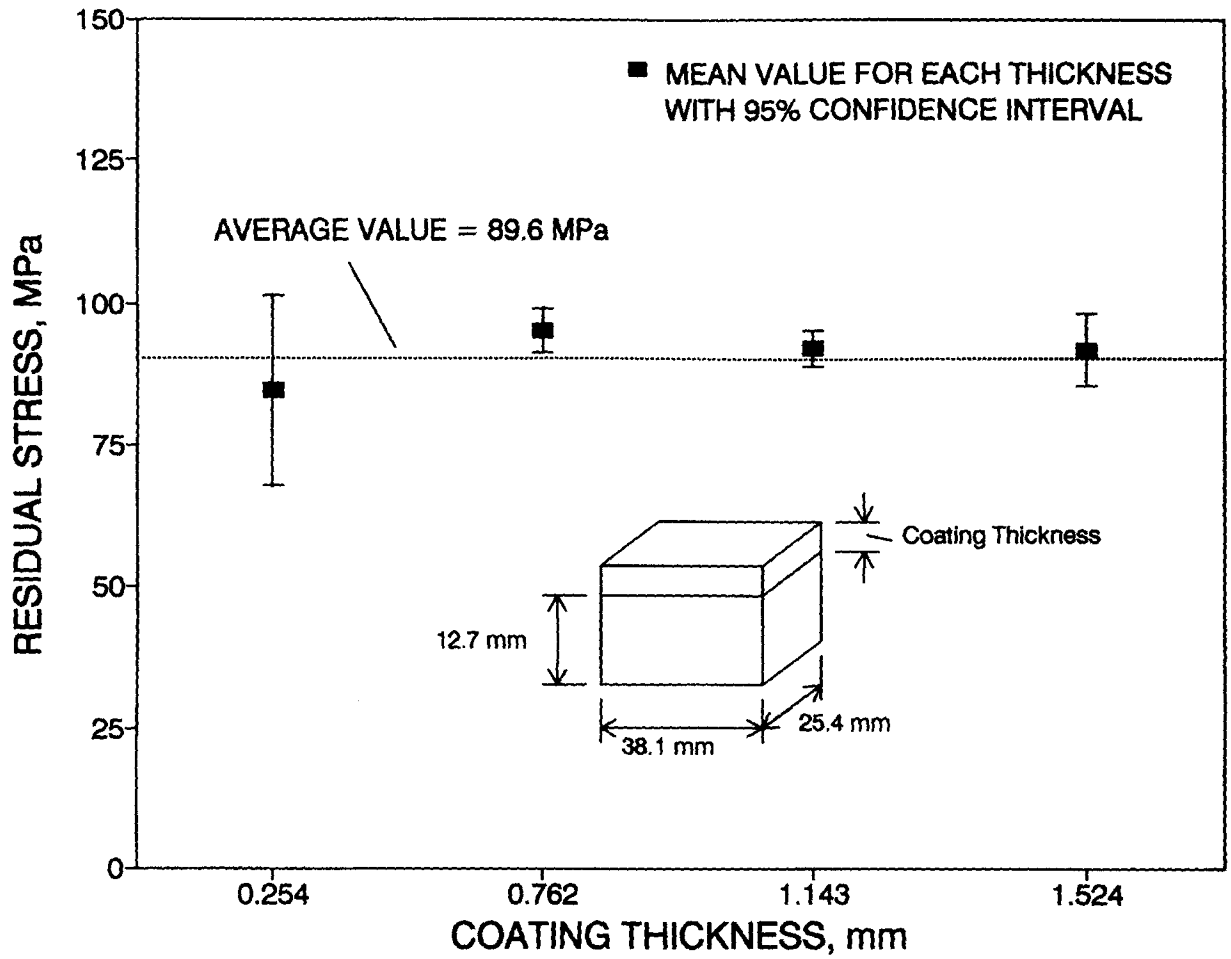

Fig. 7 Average residual stresses, σ_x, in coatings of varying thickness

minimum values for four to five separate specimens for each coating thickness are presented. Values from Ref 1 include bond strength data for a nickel-5 aluminum coating applied with a standard wire-arc gun on a substrate of 410 stainless steel and a nickel-5 aluminum coating applied by the ArcJet process on a substrate of Inconel 718. As shown, bond strength decreases with increasing coating thickness. Reference 1 also reported similar decreasing bond strength behavior for a plasma spray process using the same coating and a substrate of Inconel 718. These findings illustrate the tendency for bond strength to decrease as coating thickness increases.

5. Fracture Mechanics Analysis

A finite-element model of the specimen was developed using the approach described in Ref 8. The substrate is modeled with the properties of steel. The coating has a Young's modulus of 68.9 GPa (10.0×10^6 psi) and a Poisson's ratio of 0.2. An axisymmetric model was constructed with a debonding flaw on the outside edge of the specimen between the substrate and the coating. An adhesive layer, used in the ASTM C 633-79 test, was included in the model. The adhesive had a Young's modulus of 3.45 GPa (0.50×10^6 psi) and a Poisson's ratio of 0.35. The model represents the steps involved in fabricating and testing the debond specimens. First, the coating is applied to one of the two test specimen halves of the finite-element model. Residual stresses in the coating of the finite-element model were simulated by thermal stresses. Next, the coated half of the ASTM C 633-79 test specimen and the uncoated half were joined by the adhesive layer. A tensile force was applied to the specimen as is done in the ASTM C 633-79 test procedure.

The fracture mechanics approach was based on the energy-release-rate criterion for debonding. A description of the energy release rate can be found in Ref 12. The energy release rate is the amount of energy released per unit area of crack surface created if the crack (or debond region) were to grow. When the energy release rate reaches a critical value, G_{Icr}, crack extension or further debonding occurs. An application of the energy release rate to thermal spray coatings is described in Ref 8. The energy-release-rate criterion has also been applied to predict fracture and debonding (Ref 4, 5, 13).

The energy-release-rate criterion is applicable to cases of brittle fracture where there is little plasticity. Debonding of the nickel-5 aluminum coating appears to behave in a brittle fashion, and thus the energy release rate is an appropriate criterion. Values of the energy release rate were calculated using the modified crack closure integral described in Ref 14. In the calcula-

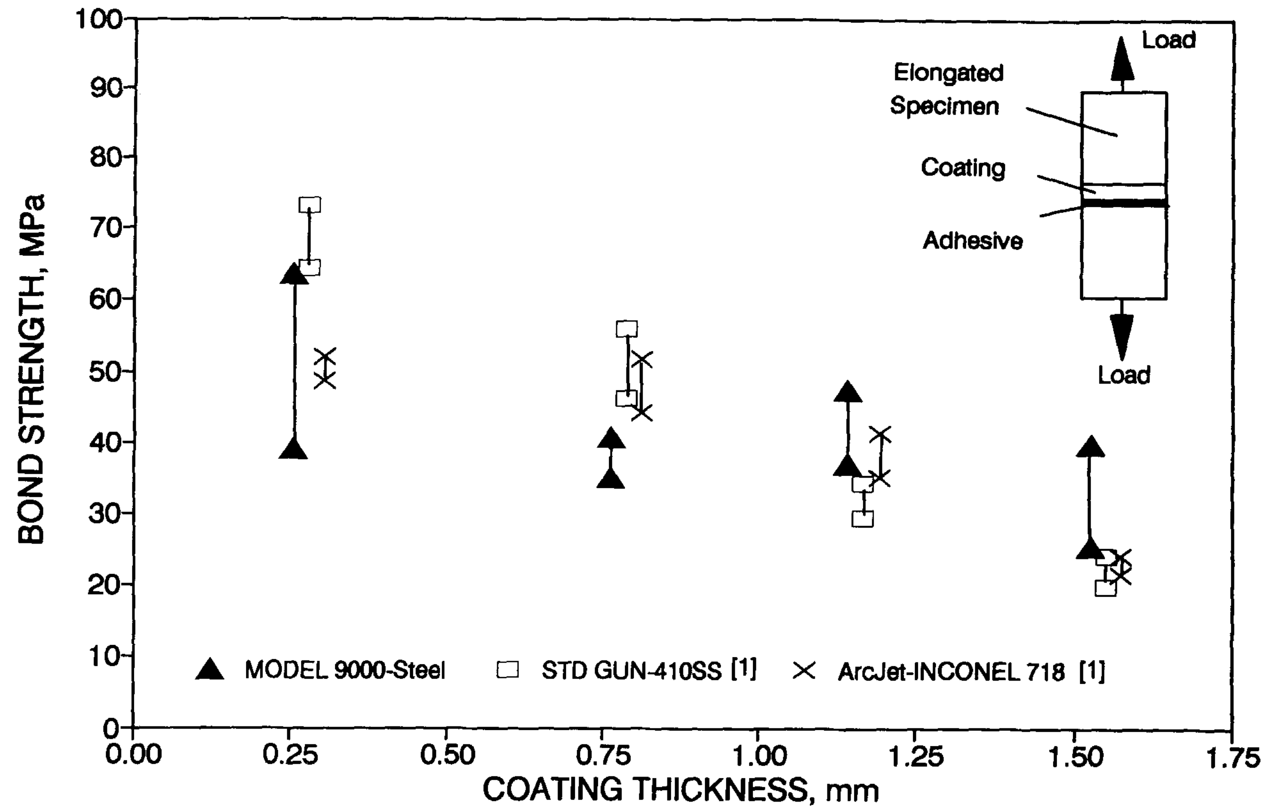

Fig. 8 Maximum and minimum ultimate bond stress values for coatings of varying thickness

tions, the stress state consisted of the coating residual stresses superimposed on the stresses from the applied loading.

Seven sets of debonding data from Ref 1 and this study were analyzed. Each analysis contained the effects of residual stresses on debonding behavior. The procedure for analyzing each of the seven data sets consisted of first determining the critical value of the energy release rate from one data point for one thickness. A coating thickness of 0.254 mm (0.01 in.) was selected, along with a crack length of 0.127mm (0.005 in.). Next, the bond strengths for the other thicknesses were predicted based on the condition that debonding occurs when the energy release rate reaches the critical value. The results for a nickel-5 aluminum coating sprayed with a standard wire arc gun on a substrate of 410 stainless steel are shown in Fig. 9, which presents the bond strength data of Ref 1 versus coating thickness. The two data points included for each thickness indicate the range of maximum and minimum values of the experimental data. The solid curve shows the predicted bond strengths for a coating residual stress of 89.6 MPa (13.0 ksi). Residual stress values determined from this study were used for predicting bond strength because residual stress values were not available for Ref 1 specimens. The predicted curve is close to the experimental data points and also displays the decreasing bond strength behavior of the coating for increasing coating thickness. The value of 89.6 MPa (13.0 ksi) was determined from the experimental residual stress evaluations and is the average residual stress in the coating for all thicknesses (see Fig. 7).

To demonstrate the influence of the residual stress on bond strength behavior, the case of zero residual stress in the coating was also considered (represented by the dashed curve in Fig. 9). Notice that when residual stress is excluded, bond strength is nearly independent of coating thickness. However, when residual stress is included in the model, good agreement results with the experimental data—that is, bond strength decreases with increasing coating thickness.

Six other cases were considered for predicting experimental bond strength data. All cases involved either a plasma or wire-arc spray process to apply a nickel-5 aluminum coating onto different substrates. The results were similar to those shown in Fig. 9. Three important observations can be made. First, all cases analyzed show that including residual stress in the coating explains the decreasing bond strength behavior with increasing coating thickness as displayed by the data of Ref 1 and this study. Second, for zero residual stress in the coating, bond strength is almost independent of thickness. Third, the magnitude of the residual stresses found from the residual stress measurements of the nickel-5 aluminum coatings is the magnitude needed in the debond analysis to predict the decreasing bond strength data observed for increasing coating thickness. This result helps provide a degree of confidence in the model and the results of the analyses.

6. Summary and Conclusions

Bond strength test data show that the bond strength of thermal spray coatings decreases with increasing coating thickness. The effect of coating residual stress on decreasing bond strength

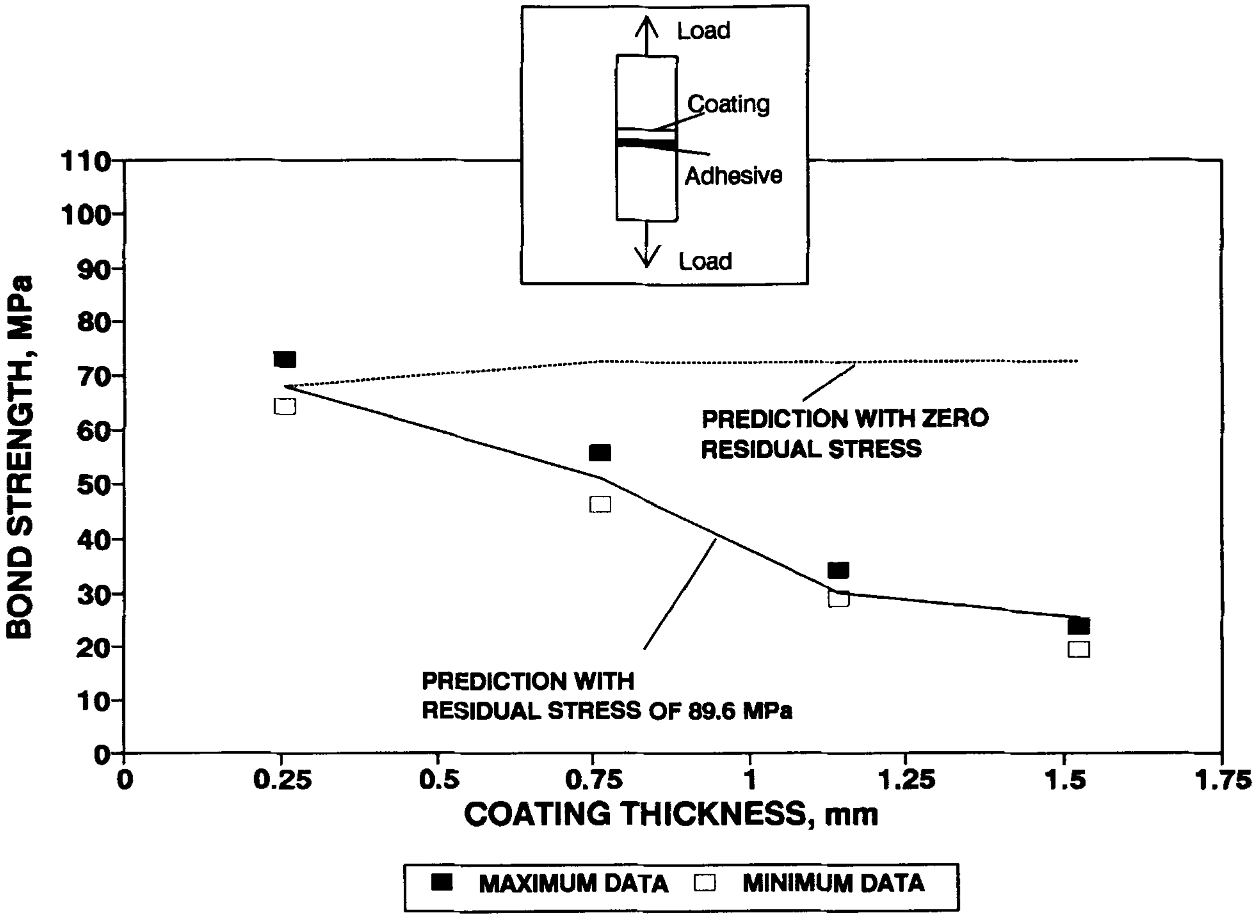

Fig. 9 Comparison of predicted ultimate bond stress values with experimental data for a standard wire-arc sprayed nickel-5 aluminum coating on a 410 stainless steel substrate. *Source:* Ref 1

was investigated. Residual stresses were determined experimentally for four coating thicknesses using a modified layer-removal method. Residual stress measurements indicate that residual stresses are minimally influenced by coating thickness for wire-arc sprayed nickel-5 aluminum coatings on AISI 1018 steel. It appears that tensile residual stresses in the coating cause the degradation of bond strength with increasing coating thickness. A possible mechanism for this effect is described in the Appendix to this paper.

Debonding was simulated using a fracture mechanics approach. It was shown that the effects of residual stress on bond strength for different coating thicknesses could be predicted using a fracture mechanics analysis that included the measured residual stresses in the coatings. Based on the fracture mechanics results, the decreasing bond strength behavior of the coatings can be explained without assuming an increase in residual stresses as the coating thickness increases. The fracture mechanics results also suggest that by changing residual stresses from tension to compression, or to lower levels of tensile stresses, bond strengths of thicker coatings can be improved.

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Appendix

Figure 10(a) shows a free-body diagram of through-thickness residual stresses in a coated sample. Figure 10(b) shows tensile residual stresses, in the x direction, for a thin and a thicker coating. It is assumed in this analysis that the magnitude of the residual stresses in the two coatings is the same, although residual stresses can be altered to some degree by the selection of the thermal spray parameters. The free-edge effect is a stress distribution in the z direction with tension at the edge and compression away from the edge. The shape of the σ_z stress distribution satisfies equilibrium for the free-body diagram. Two characteristics of the σ_z stress distribution are important. First, moment equilibrium about point B of the free-body diagram in Fig. 10(b) for the thin coating requires that the σ_z stress distribution be tensile at the free edge. Second, if the coating is thicker and the residual stress does not change, the moment caused by the residual stresses in the coating, as shown in Fig. 10(b) for the thicker coating, is larger. Therefore, the σ_z stress distribution must increase to balance this larger moment. The result is a higher ten-

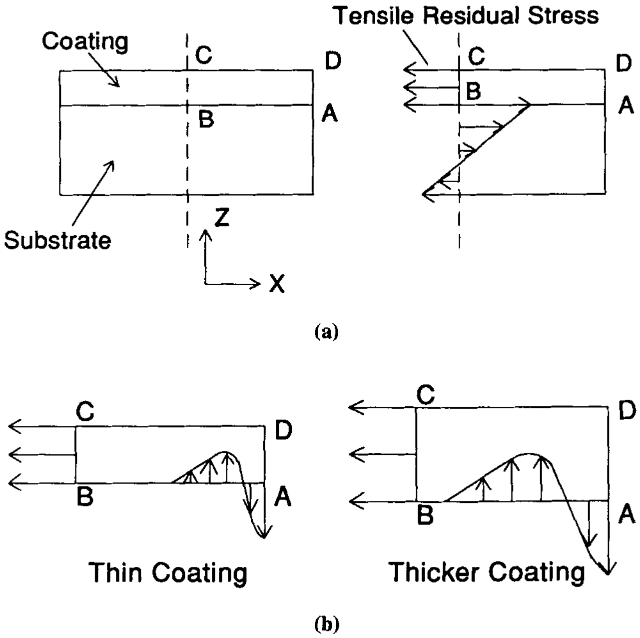

Fig. 10 Effect of coating thickness and tensile residual stresses on tensile stresses at free edge. (a) Through-thickness residual stresses in coatings. (b) Residual stresses in coating showing larger edge stress at point A for thicker coating than for thin coating

sile σ_z stress at the edge, as shown in Fig. 10(b) for the thicker coating. The conclusion is that the thicker coating causes higher tensile edge stresses and will increase the tendency for debonding and hence reduce the applied stress required to cause debonding.

This behavior occurs without an increase in coating residual stresses for the thicker coating. Therefore, a thicker coating will be more likely to have a lower bond strength than a thinner coating with the same level of residual stress.

References

1. R.H. Unger and W.D. Grossklaus, "A Comparison of the Technical Properties of Arc Sprayed Versus Plasma Sprayed Nickel-5 Aluminum," SAE Technical Paper Series, 28th Annual Aerospace/Airline Plating & Metal Finishing Forum & Exposition (San Diego), 20-23 April 1992
2. K.M. Howell, Evaluating Bond Strength of Metal Coatings over Concrete Surfaces, *Mater. Prop.*, Vol 31 (No. 7), 1992, p 29-32
3. M.E. Woods, Thermal Fatigue Rig Testing of Thermal Barrier Coatings for Internal Combustion Engines, *Thermal Spray Technology—New Ideas and Processes*, D.L. Houck, Ed., ASM International, 1988, p 245-253
4. C.W. Marynowski, F.A. Halden, and E.P. Farley, Variables in Plasma Spraying, *Electrochem. Technol.*, Vol 3, 1965, p 109-115
5. E.F. Rybicki and R.B. Stonesifer, An LEFM Analysis for the Effects of Weld Repair Induced Residual Stresses on the Fracture of the HSST ITV-8, *J. Pressure Vessel Technol.*, Vol 102, 1980, p 318-323
6. E.F. Rybicki, D.W. Schmuesser, and J. Fox, An Energy Release Rate Approach for Stable Crack Growth in the Free-Edge Delamination Problem, *J. Compos. Mater.*, Vol 11, 1977, p 470-487
7. E.F. Rybicki and D.W. Schmuesser, Effect of Stacking Sequence and Lay-Up Angle on Free Edge Stresses Around a Hole in a Laminated Plate Under Tension, *J. Compos. Mater.*, Vol 12, 1978, p 300-313
8. W. Han, E.F. Rybicki, and J.R. Shadley, Application of Fracture Mechanics to the Interpretation of Bond Strength Data from ASTM Standard C633-79, *J. Thermal Spray Technol.*, Vol 2 (No. 3), 1993, p 235-241
9. Stress-Relief Heat Treating of Steel, *ASM Handbook*, Vol 4, *Heat Treating*, ASM International, 1991, p 33-34
10. D.J. Greving, E.F. Rybicki, and J.R. Shadley, Residual Stress Evaluations of Thermal Spray Coatings by a Modified Layer Removal Method, *Proc. National Thermal Spray Conf.*, ASM International, 1994
11. W. Han, E.F. Rybicki, and J.R. Shadley, An Improved Specimen Geometry for ASTM C633-79 to Estimate Bond Strengths of Thermal Spray Coatings, *J. Thermal Spray Technol.*, Vol 2 (No. 2), 1993, p 145-150
12. G. Irwin, Fracture, *Handbuch der Physik*, Vol 6, Spinger, 1958, p 551 (in German and English)
13. E.F. Rybicki, T.D. Hernandez, Jr., J.E. Deibler, R.C. Knight, and S.S. Vinson, Mode I and Mixed Mode Energy Release Rate Values for Delamination of Graphite/Epoxy Test Specimens, *J. Compos. Mater.*, Vol 21 (No. 2), 1987, p 105-123
14. E.F. Rybicki, and M.F. Kanninen, A Finite Element Calculation of Stress Intensity Factors by a Modified Crack Closure Integral, *Eng. Frac. Mech.*, Vol 9, 1977, p 931-938