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An Improved Specimen Geometry for ASTM C633-79 to Estimate Bond Strengths of Thermal Spray Coatings

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ASTM Standard C633-79, "Standard Test Method for Adhesion or Cohesive Strength of Flame-Sprayed Coatings," is widely used in industry and research for evaluating bond strengths of thermal spray coatings. Tests are conducted by applying the coating to the end of a cylindrical test specimen 25.4 mm (1 in.) in diameter by 25.4 mm (1 in.) long. The coating surface is bonded to an uncoated cylinder of the same material and geometry. The force required to pull the cylinders apart is recorded. The bond strength is calculated by dividing the maximum force by the area of the 1-in. diameter cylinder assuming that the stress is uniform over the area where the debonding occurs.

A combination of finite-element stress analysis and experimental stress analysis using strain gages was used to evaluate the stresses at the interface between the coating and substrate. Finite-element analysis of the standard specimen geometry shows that the maximum stress at the coating interface can be 25% higher than the average stress. An elongated specimen was selected, constructed, and evaluated to produce the uniform stress distribution assumed by ASTM C633-79. Strain gage measurements and epoxy tensile tests have verified that the bond strengths measured with the elongated specimen provide better estimates of bond strengths than tests with the standard specimen.

1. Introduction

BOND strength is an important property of thermal spray coatings. High bond strength of a coating is associated with higher erosion, corrosion, and abrasion resistance. There are many testing standards to evaluate the bond strength of thermal spray coatings. Currently, four major standards are used in industry and research. These are ASTM Standard C633-79 (USA), DIN 50 160-A (Germany), AFNOR NF A91-202-79 (France), and JIS H8666-80 (Japan).[1-3] Although each standard uses a different specimen geometry, test method, and analysis procedure, the primary goal of each standard is to determine the degree of adhesive or cohesive strength between the coating and the substrate. ASTM Standard C633-79, "Standard Test Method for Adhesion or Cohesive Strength of Flame-Sprayed Coatings," is widely used in the United States for evaluating bond strengths of thermal spray coatings. The application of ASTM Standard C633-79 can be traced to 1959.[4] This standard is currently used to test thermal spray coatings, thin films, epoxies, and adhesives in the aerospace industry, automobile industry, oil and gas industry, chemical industry, medical industry, and food processing industry.[5-9] Meanwhile, much research has been done on the test method, data analysis, failure mode, and debond mechanisms. Research results indicate that ASTM C633-79, as well as the other standards mentioned above, will continue to be used to characterize the bond strength of thermal spray coatings, although more research is needed on specimen preparation, test procedure, data repeatability, failure mode, and debond mechanisms.[2,10-14]

Following ASTM C633-79, tests are performed by applying the coating to the end of a cylindrical test specimen 25.4 mm (1 in.) in diameter by 25.4 mm (1 in.) long. The coated surface is bonded to another cylinder of the same geometry. The force required to pull the cylinders apart is recorded. As shown in Fig. 1, bonded specimens are mounted in a self-aligning device. The geometry of the ASTM C633-79 standard specimen is shown in Fig. 2. The bond strength or ultimate bond stress is calculated by dividing the ultimate force by the cross-sectional area of the 1-in. diameter cylinder. This procedure inherently assumes that the stress is uniform over the cross-sectional area where the coating is bonded. Although this assumption is convenient, there are several characteristics of the specimen design, including the geometry of the specimen and the mismatch of material stress-strain constants between the coating and substrate, that can lead to a nonuniform stress distribution at the bonding interface. A nonuniform stress distribution infers that there is a place on the coating where the stress is higher than the average stress calculated by the applied force divided by the area. To better interpret the results of ASTM C633-79, it is important to have an estimate of the stress distribution applied to the coating during the test. The objective of this study is to examine the ASTM C633-79 test procedure for accuracy and develop improvements in the procedure to increase the accuracy.

Keywords: ASTM C633-79, bond strength, debond stress, finite element stress analysis, mechanical properties, strain gauge measurements, stress distributions, test specimen geometry, thermal spray coating, ultimate bond stress

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2. Goals and Approach

The goals of this work are to (1) evaluate the stress distribution in a test specimen at the interface between the coating and

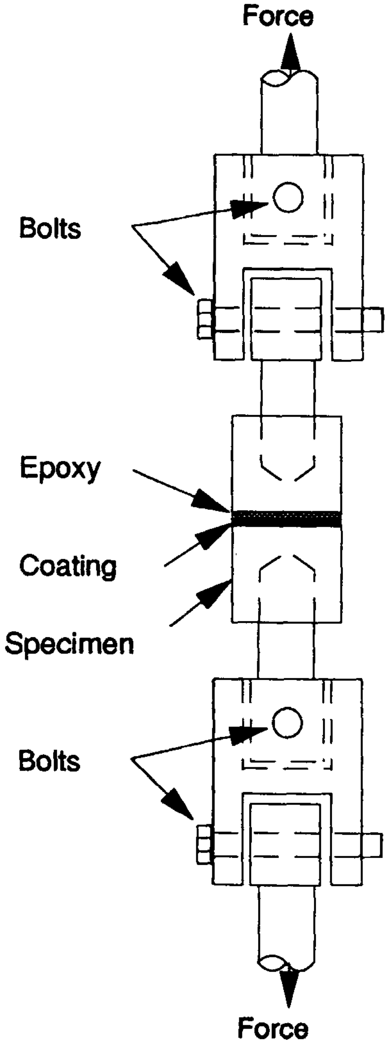


Fig. 1 ASTM C633-79 self-aligning test fixture.

the substrate and (2) design a new specimen to have a uniform stress distribution at the interface, as assumed by ASTM C633-79. The approach to achieving these goals is defined by the following steps:

1. Develop a finite-element model for the standard specimen
2. Apply a tensile load and evaluate the stress distribution at the interface between the coating and substrate
3. Verify the finite-element model by experimental stress analysis
4. Compare the finite-element analysis predictions of the stress distribution at the debonding region with the uniform stress distribution assumed by ASTM C633-79
5. Develop a finite-element model for an elongated specimen that provides a uniform stress distribution at the interfacial debonding region; verify the model with experimental stress analysis
6. Conduct debond tests for both the standard and elongated specimens and compare the debond strengths obtained

Step 4 of the approach is important because a nonuniform interface stress distribution can lead to misinterpretation of the test results.

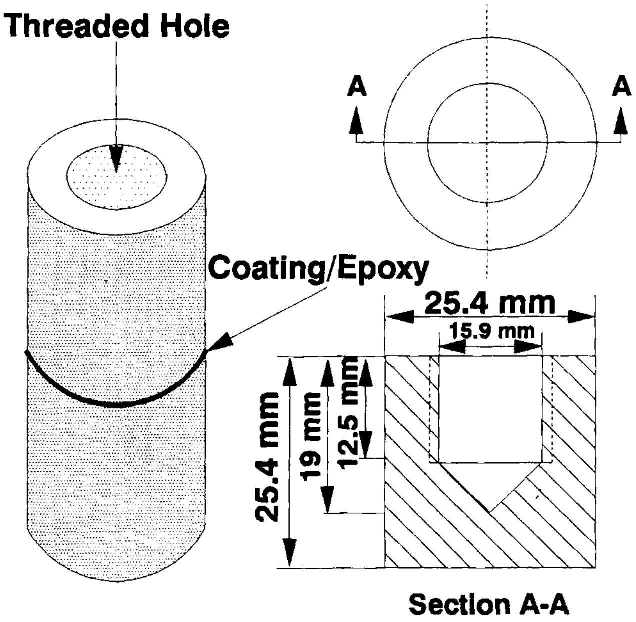


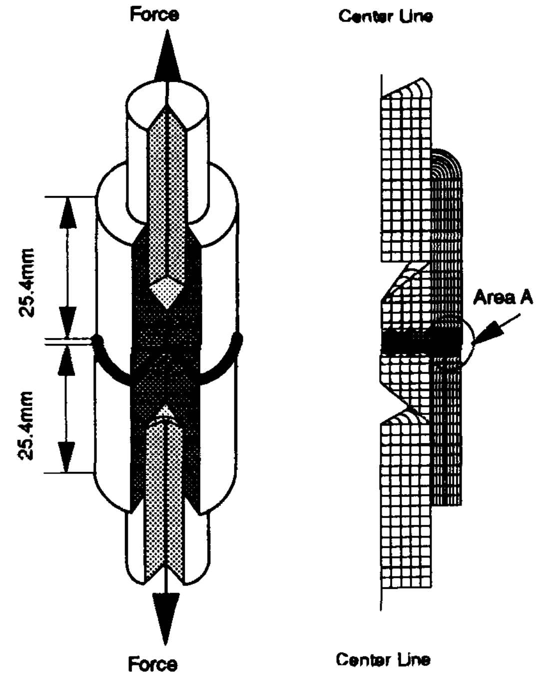
Fig. 2 ASTM C633-79 standard specimen geometry.

3. Stress Distribution at the Interface Between the Coating and Substrate

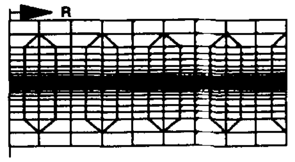
A finite-element model was developed to examine the stress distribution at the interface between the coating and the substrate. Figure 3 shows the two standard specimen halves bonded together with epoxy according to the test procedure and the axisymmetric finite-element model of this structure. The focus of this work is on the interface between the epoxy and the substrate. To provide accurate information on how the stress changes in the epoxy and in the substrate nearest the interface,the finite-element grid in these regions is more refined than in other regions of the finite-element model. Accordingly, the 0.508-mm (0.02-in.) thick layer of the epoxy was divided into four finite-element layers of thickness 0.127 mm (0.005 in.). A tensile load of 13.34 kN (3000 lb) was applied to the model, as shown in Fig. 3.

To verify the finite-element model, eight strain rosettes were installed on the surface of a standard specimen. Four strain rosettes were located on the surface near the bonding interface. The other four strain rosettes were placed at locations where the finite-element analysis indicated that high stresses occur (see Fig. 4). Strains then were measured when a tensile load of 13.34 kN (3000 lb) was applied to the standard specimen using a tensile tester. Comparisons of surface stresses on the specimen, obtained from the strain gages, with the finite-element analysis surface stresses are shown in Fig. 4. As shown, the stresses calculated from the gage measurements are in good agreement with the finite-element analysis stresses. This provides confidence that the finite-element model is valid and that stress distributions predicted by the model are accurate.

The axial stress distribution predicted by the model at the interface of the "standard" specimen is shown in Fig. 5. The stress distribution at the interface of the standard specimen was found



(a) Specimen Assembly (b) Axisymmetric Grid



(c) Grid For Area A

Fig. 3 Finite-element model for standard specimen.

to be nonuniform. The peak stress is almost 34.47 MPa (5000 psi), which is 25% higher than the average stress of 26.2 MPa (3800 psi) assumed by the ASTM C633-79 analysis procedure. This implies that bond strengths determined using the standard specimen and procedure could be significantly underrated due to the existence of the peak stress at the outer edge of the specimen that is higher than the value assumed by the ASTM standard.

4. Modification to the Standard Specimen Geometry

As shown in Fig. 2, there is a cavity in the standard specimen where the specimen is drilled for tapping. The distance from the tip of the cavity to the surface where the epoxy is applied is only 6.35 mm (0.25 in.). The cavity makes the specimen less stiff at the center near the cavity than it is at the outer edge. Tensile stresses are unable to distribute evenly across the interface. Thus, because of the close proximity of the cavity to the interface, stresses are not as high near the center of the specimen as they are at the outer edge.

To alter the stress distribution at the interface, the geometry of the specimen was changed. The specimen was elongated to provide stiffness to the bonded interface area near the cavity. A finite-element model of the elongated specimen was developed. The elongated specimen was identical to the standard specimen in all aspects, except that the length was increased from 25.4 to 38.1 mm (1 to 1.5 in.). Again, a tensile load of 13.34 kN (3000 lb) was applied to the finite-element model. To validate the finite-element model for the elongated specimen, eight strain rosettes were installed on the elongated specimen surface. Strains were measured when a tensile load of 13.34 kN (3000 lb) was applied. Comparisons were made between the surface stresses on the specimen and the surface stresses predicted by the finite-element model. As shown in Fig. 6, the stresses calculated from strain gage measurements agreed with the finite-element model predictions.

The stress distribution at the interface, computed from the finite-element model, is shown in Fig. 5 by the line corresponding to the "elongated" specimen. This figure shows that the axial stress distribution at the interface of the elongated specimen is nearly uniform and almost identical to the average stress of 26.2 MPa (3800 psi) assumed by the standard analysis procedure. This is an improvement over the standard specimen, for which a nonuniform stress distribution was found.

5. Experimental Bond Strength Comparisons of Standard and Elongated Specimens Using Epoxy

Three standard specimens and three elongated specimens made of 1018 carbon steel were bonded together using a 3M epoxy designated EC-1386. Following the procedure given in ASTM C633-79, alignment was provided by the double swivel self-aligning fixture. Verification of the alignment for the self-aligning fixture was conducted using three axial strain gages that were equally spaced around the specimen circumference. A load was applied using the fixture and a material testing system MTS 810. Each gage reading was within 1.5% of the average value of the three gages.

To determine bond strengths, tensile loads were applied to the specimens until debonding occurred and ultimate loads were recorded. The tensile bond strength of the epoxy to the substrate was calculated using the ultimate force divided by the cross-sectional area. Bond strengths of the epoxy, as determined by this procedure for both the standard and elongated specimens, are shown in Fig. 7. For the same epoxy and the same test procedure, the bond strengths using the elongated specimen are higher than the bond strengths of the standard specimen. This result implies that bond strengths measured using the standard specimen can be significantly lower than bond strengths determined using the elongated specimen.

6. Discussion and Conclusions

Finite-element analysis has been found to be a useful tool for evaluating the stress distribution at the interface between coatings and substrates. Strain gages mounted on the surface of

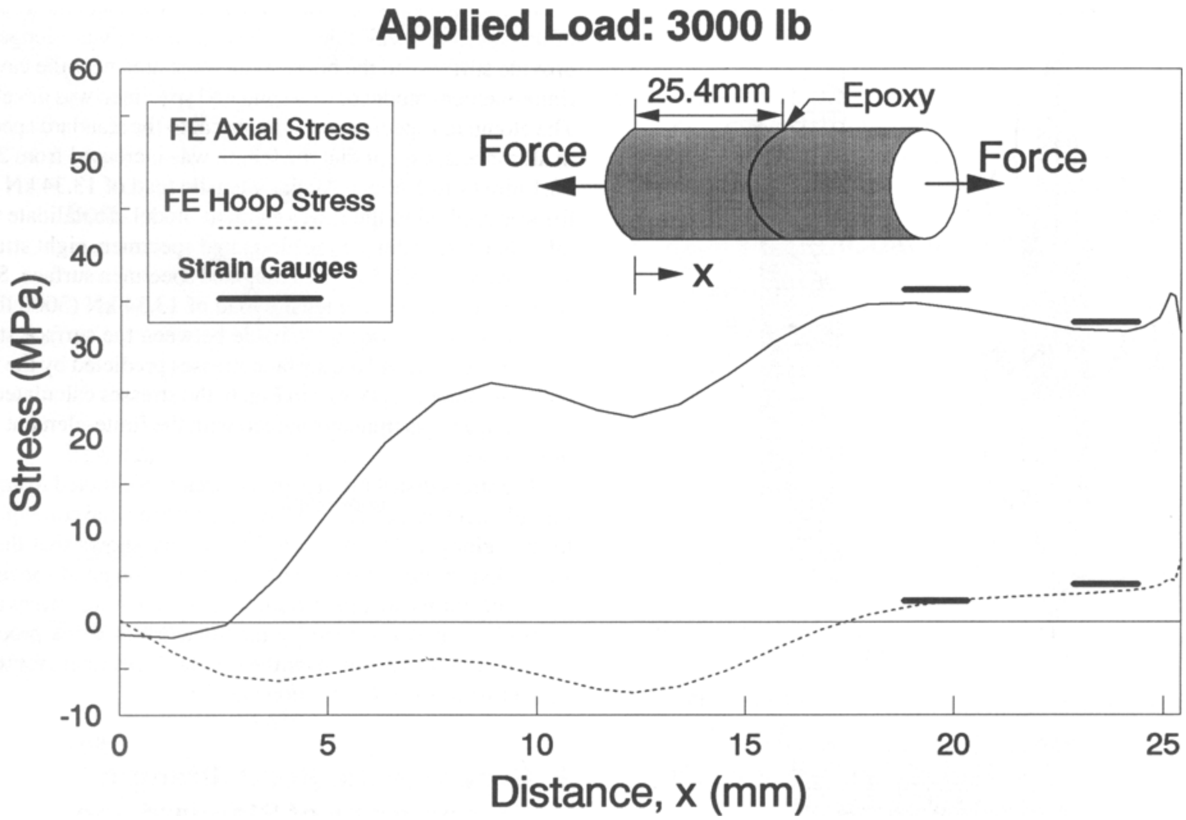


Fig. 4 Surface stresses on standard specimen.

ASTM C633-79 standard specimens and elongated specimens were found to provide estimates of stresses in these specimens that were in very good agreement with stresses predicted by finite-element models of these specimens. Through the use of finite-element models, it has been shown that the ASTM C633-79 specimen inherently has a nonuniform stress distribution at the interface. The peak stress at the interface can be 25% higher than the average stress assumed by ASTM C633-79. Coating bond strengths determined according to this standard could be significantly lower than actual bond strengths. The elongated specimen, designed in this study, has a stress distribution that is uniform to within 0.6% of the average stress assumed by ASTM C633-79. Laboratory tests using the procedure defined in ASTM C633-79 to determine the tensile strength of an epoxy showed that the variation in tensile strength can exist from specimen to specimen. However, epoxy tensile strengths using elongated specimens were found to be consistently and significantly higher than tensile strengths using ASTM C633-79 standard specimens. The mean tensile strength using the elongated specimen was 21% higher than the mean tensile strength using the ASTM C633-79 standard specimen. Based on findings from the finite-element analyses and from the epoxy tensile tests, it is concluded that elongated specimens provide more accurate estimates of bond strength than ASTM C633-79 standard specimens.

Acknowledgments

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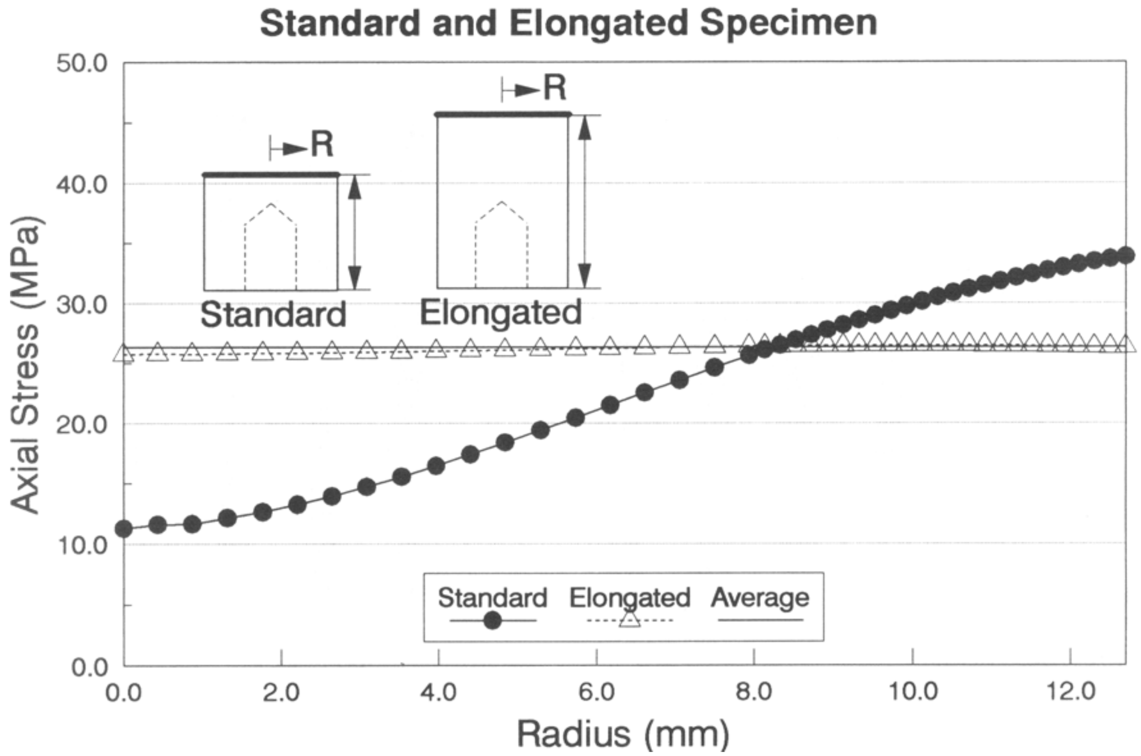

Fig. 5 Comparison of axial stresses.

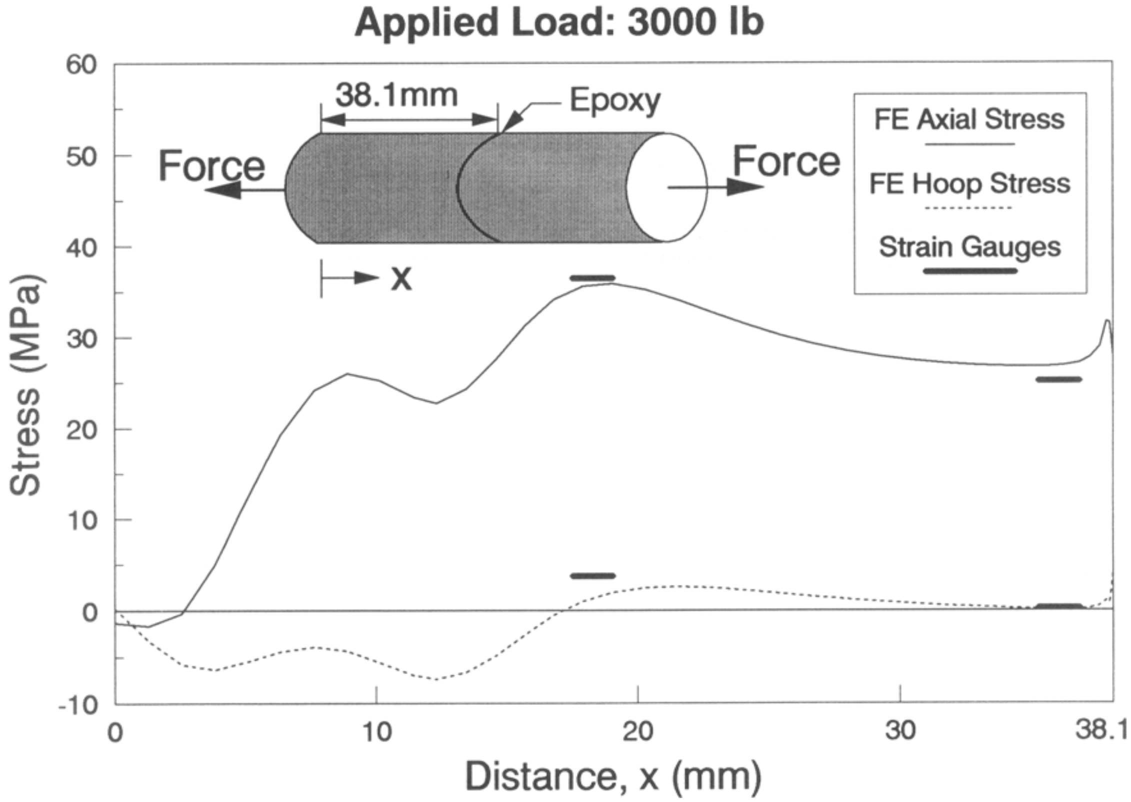

Fig. 6 Surface stresses on elongated specimen.

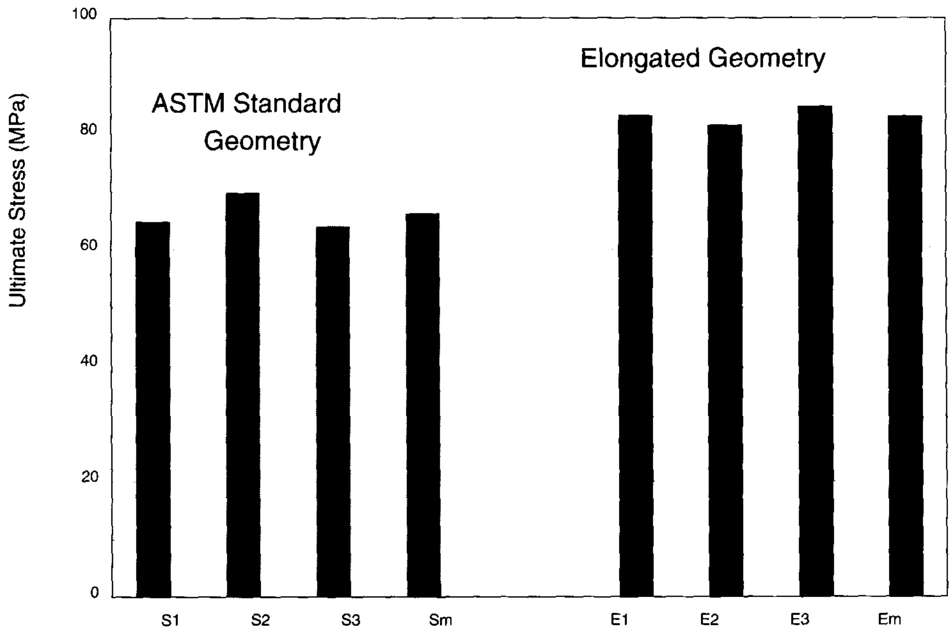

Fig. 7 Epoxy bond strength tests.

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