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Technical Note: Plasma-Sprayed Ceramic Thermal Barrier Coatings for Smooth Intermetallic Alloys

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A durable ceramic thermal barrier coating is applied directly to a smooth, highly oxidation resistant intermetallic alloy in two layers. The first layer of ceramic is applied by low pressure plasma spraying and the second layer is applied by conventional atmospheric pressure plasma spraying. This approach would allow the use of plasma sprayed ceramic coatings in applications where a metallic bond coat is not desirable.

1. Introduction

TRADITIONAL thermal barrier coatings (TBC) for aircraft gas turbine engines typically consist of an outer layer of a thermally insulating ceramic, such as zirconia-yttria, and an inner layer of an oxidation-resistant metallic bond coat, such as an MCrAlY alloy (where "M" may represent Ni, Co, Fe, NiCo, etc.). However, in certain cases, the bond coat layer may be undesirable. For example, the substrate may be highly oxidation-resistant or the application may involve rotating turbomachinery where weight is a concern. Currently, ceramic thermal barrier coatings can only be applied to smooth surfaces by the electron beam/physical vapor deposition (EB-PVD) process[1] and not by the plasma spray process. This communication describes a new approach for plasma spray deposition of ceramic thermal barrier coatings directly to smooth substrates. This process was initially used to apply ceramic thermal barrier coatings to substrates that had been coated with low-pressure plasma-sprayed NiCrAlY bond coats and then centerless ground to simulate a smooth oxidation-resistant substrate.[2] In this article, the substrates are cast 1.3 cm (0.5 in.) diameter, large grain (1 to 3 cm) NiAl + Zr (nominally 50 at.% Al and 0.1 at.% Zr) intermetallic alloys that had been ground to a smooth surface finish. The high-temperature oxidation behavior of NiAl + Zr is typically superior to that of conventional MCrAlY alloy.[3-5] Therefore, the bond coat is not required for oxidation resistance.

2. Experimental Methods

The approach used was to apply a ZrO_2-8 wt.% Y_2O_3 ceramic thermal barrier coating to the substrate in two layers. The first layer was deposited onto the preheated substrate by low-pressure plasma spraying at 52 kW (1050 A) using an Ar-2.5% H_2 arc gas; and the second was deposited by conventional atmospheric pressure plasma spraying at 35 kW (900 A) using an Ar-40% He arc gas. The inner ceramic thermal barrier coating layer bonds to the substrate and has a surface roughness that is sufficiently rough to allow attachment of the outer layer. This approach eliminates the need for a conventional metallic bond coat because the low-pressure plasma-sprayed ceramic adheres well, even when the substrate is smooth.

In this study, one substrate was ground to a surface roughness, Ra, of 0.06 μm (2.5 μin.), as measured by a prolifometer[6] using a 0.08-cm (0.03-in. cut off), and another was ground to an Ra of 0.25 μm (10 μin.). These values for the substrate surface roughness are far lower than typical bond coat roughnesses, which usually are at least 4 μm (150 μin.),[7] and they probably represent the lower limit of roughness for any future application. The substrates were 8.9 cm (3.5 in.) long for the 0.06-μm rough specimen and 7.5 cm (3 in.) long for the other. The initial layer was applied to a thickness of 0.0020 cm (0.0008 in.) in the first case and 0.0018 cm (0.0007 in.) in the second case. The first specimen required ten spray passes, which was typical of specimens that had been sprayed previously. The second specimen experienced a serious drop in deposition efficiency, in that 48 passes were required. The reason for this fall-off in efficiency is not known, but it may have been due to mis-aiming. The low deposition efficiency may also have affected the roughness of the low-pressure plasma-sprayed ceramic layer. Its Ra value was only about 2.5 μm (100 μin.), whereas the roughness of this layer typically had exceeded 4 μm (150 μin.).

The burner rig used for this study was similar to those described in Ref 8. The rig burns JP5 jet fuel and 260 °C preheated air at a combustor pressure of 0.007 MPa (1 psi, or 6.9 kPa). The combustion gases exit the combustor through a nozzle at Mach 0.3 and impinge on the single rotating specimen. Each cycle consisted of 6 min in the flame and 4 min of forced air cooling. The 0.06-μm specimen was tested at 1150 °C, as measured using a disappearing filament pyrometer that had previously been calibrated against a thermocoupled specimen. It survived 159 cycles before the thermal barrier coating spalled toward the top but not at the edge of the specimen. Metallographic examination of the top of the test specimen revealed about 4 μm of thermally grown oxide, which was a relatively thick oxide even though the specimen was cooler in this region. Although this specimen has not yet been analyzed in detail, the excessive scale thickness could possibly have been due to the presence of a lower temperature θAl_2O_3 phase rather than the equilibrium αAl_2O_3.[9-11]

Key Words: burner rig test, coating adhesion, coating roughness, spray procedure, thermal barrier coating (TBC), zirconia-yttria ceramic

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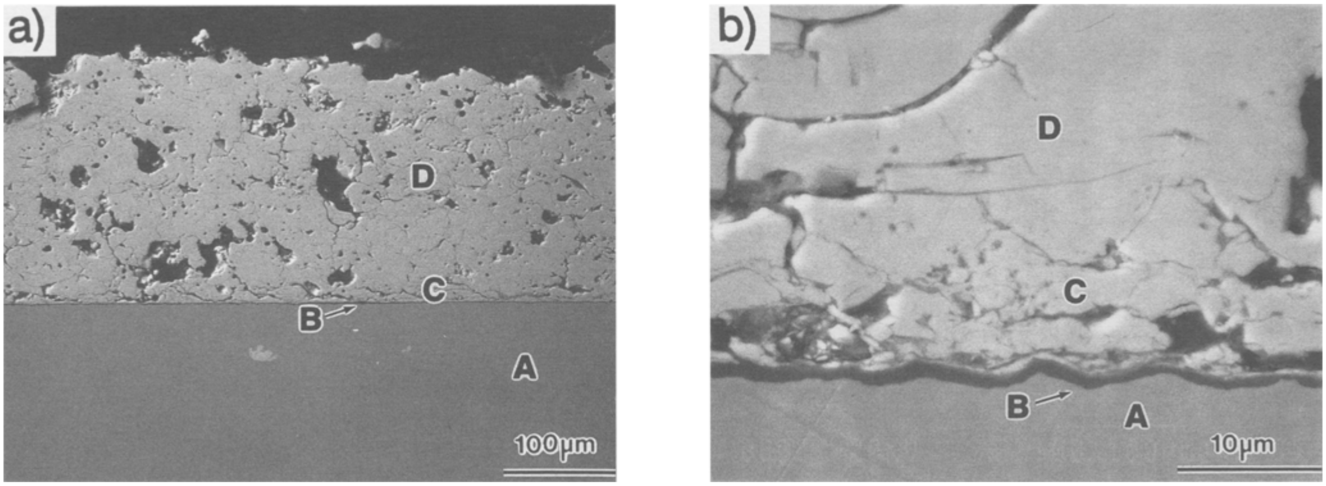
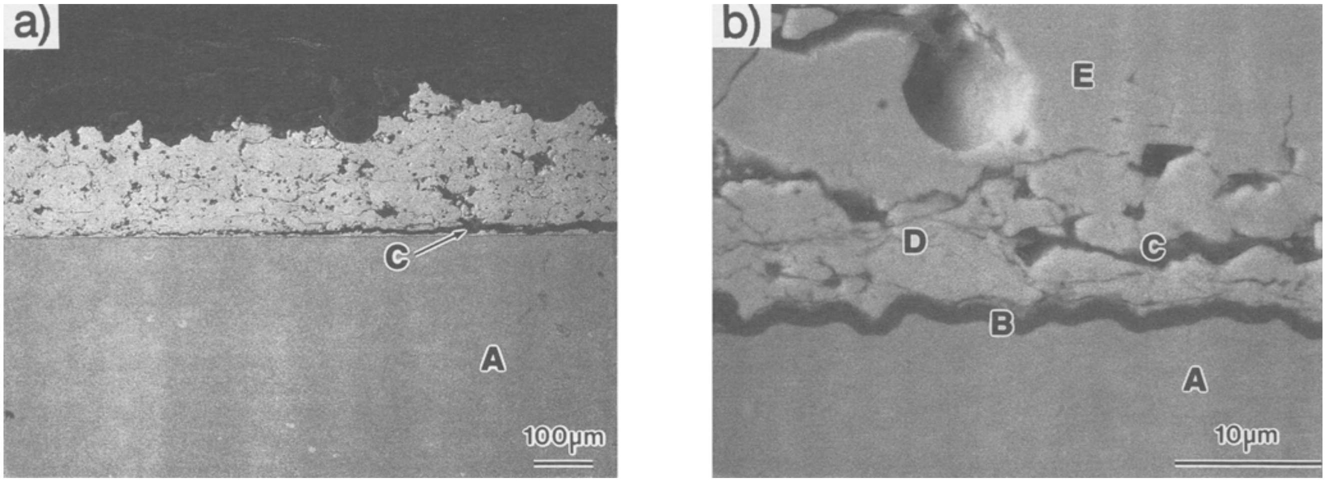


(a) (b)

Figure 1 SEM photomicrographs of cooler region of specimen (near grip end) showing **(a)** entire thickness of ceramic layer and **(b)** region near interface. Labels refer to the NiAl + Zr substrate (A), alumina scale (B), low-pressure plasma-sprayed ceramic thermal barrier coating (C), and conventional ceramic thermal barrier coating (D).



(a) (b)

Figure 2 SEM photomicrographs at edge of hot zone showing **(a)** delamination macrocrack at low magnification and **(b)** delamination macrocrack end region at high magnification. Labels refer to the NiAl + Zr substrate (A), alumina scale (B), delamination crack (C), low-pressure plasma-sprayed ceramic thermal barrier coating (D), and conventional ceramic thermal barrier coating (E).

The 0.25-µm specimen was preoxidized for 1 hr at 1200 °C to ensure that a protective αAl_2O_3 scale would form. It was then burner rig tested at 1200 °C. The pyrometer reading for the uncoated end of this relatively short specimen was 1070 °C, which is the lower limit to the actual top surface temperature because the top surface was not a black body. Coating delamination and failure by spalling began at the top edge of this specimen at 231 cycles. The spalled region grew to the hot zone at cycle 294. This life, even though shortened by the edge effect failure, compared well to the performance of conventional rougher (about 7 µm or 270 µin.) NiCrAlY/ZrO_2-Y_2O_3 coated specimens that had been tested at 1200 °C in that burner rig. These specimens, tested in four specimen carousels, lasted an average of 186 cycles (the range was 164 to 207 cycles).

Post-test metallographic examination of the axially sectioned preoxidized specimen revealed that the outer layer of the ceramic thermal barrier coating was porous, whereas the inner layer was denser but microcracked throughout (Fig. 1a and b). Coating delamination and failure occurred within the microcracked region. Cracking was never observed at the alumina/substrate interface (Fig. 2a and b), and only occasionally would a crack extend into the outer region of the thermally grown alumina scale.

An additional observation was the presence of an impurity oxide scale layer along the entire length of the specimen between the alumina scale and the ceramic coatings (Fig. 3). This layer contained significant amounts of iron, chromium, and a small amount of titanium. Although the exact source of these im-

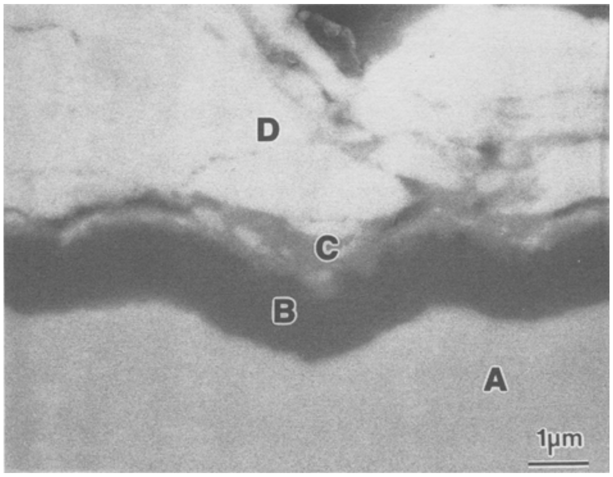


Figure 3 SEM photomicrograph showing αAl_2O_3 scale and iron-rich scale between plasma-sprayed ceramic and substrate. Labels refer to the NiAl + Zr substrate (A), alumina scale (B), iron-rich oxide scale (C), low-pressure plasma-sprayed ceramic thermal barrier coating (D). The conventional ceramic thermal barrier coating is at the top of the field of view.

purities is unknown, the burner rig combustion air contains a significant amount of iron-containing solid impurities. Most of these solids are removed by filtering, but a small fraction of this impurity passes through the filter and deposits a rust-colored layer on the cooler regions of ceramic coatings that are tested at lower temperatures. The effect on coating durability is unknown at this time.

3. Summary

This work builds on prior efforts[2] which have shown that it is feasible to plasma spray deposit a ceramic thermal barrier coating directly onto a smooth substrate. Specifically, an adherent and durable ceramic thermal barrier coating was applied directly onto a smooth NiAl + Zr substrate by a process that involved low-pressure plasma spraying of the initial layer of the ceramic thermal barrier coating onto the preoxidized substrate. This approach would allow the use of ceramic thermal barrier coatings on highly oxidation-resistant substrates and on rotating turbomachinery. Additional work is required to more fully investigate this approach. For example, the effect of the surface roughness of the substrate and the thickness and density of the inner ceramic layer must be investigated. Furthermore, it is envisioned that this process may be extended to many other ceramics and substrates.

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