B. Engineered Surfaces for Diesel Engine Components

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Objectives

- Develop coating processes to apply amorphous steels and quasicrystal materials to engine pistons and cylinder heads for use as thermal barrier coatings in homogenous charged combustion ignition (HCCI) engine designs.
- Quantify the diffusion stability of new quasicrystalline material at engine operating temperatures.

Approach

- Use high-velocity oxygen fueled (HVOF) processes to apply amorphous and quasicrystalline materials to engine piston and cylinder head.
- Use microprobe analysis of diffusion couples to determine the stability of quasicrystalline and bond coating couples at engine operation temperatures.

Accomplishments

- Coated HCCI pistons with amorphous steel for single cylinder engine testing.
- Measured diffusion profiles for the quasicrystalline material and three different bond coating materials.

Future Direction

- Modify the thickness and uniformity of the amorphous steel coating if needed after initial engine testing.
- Develop graded coating structures for the quasicrystalline material based upon the diffusion profiles developed.

Introduction

Two new materials, amorphous steels and quasi-crystalline materials, are investigated as thermal barrier coatings. Both materials are capable of being sprayed using high-velocity oxygen fuel (HVOF) processes that produce denser coatings with higher strengths than plasma spraying. The denser coating structure of HVOF coatings eliminates the need for sealing of the coating porosity and the higher strength enhances the coating durability. Amorphous steel coatings are reported to have low thermal conductivity as well as high hardness and toughness, making them attractive as thermal barrier coatings.[1,2]

The quasicrystal being studied, $Al_{71}Co_{13}Cr_8Fe_8$, has been shown to be capable of 1100°C operation in a turbine engine.[3] Application of thermal barrier coatings (TBCs) to new homogeneous charged combustion ignition (HCCI) engine components can result in lower fuel consumption and lower engine component temperatures similar to that shown in standard diesel engine configurations (Figure 1).

Approach

Amorphous Steel Coatings

The SHS717 amorphous steel produced by The NanoSteel Company, Maitland, Florida, was selected for use as a TBC. Thermal diffusivity of HVOF sprayed SHS717 shows that the amorphous structure is retained up to approximately 700ºC (Figure 2). New HCCI engine designs have surface temperatures below this range allowing the use of the amorphous coatings. New piston designs were procured, and coating processes were developed to apply up to 3.5-mm coating to the piston bowl.

The piston components were coated using a kerosene-fueled HVOF torch manufactured by Praxair TAFA. The geometry of the part is shown in Figure 3. Because the geometry of the pistons consists of surfaces that are up to 60° from normal, they represent a challenge to coat uniformly. It is also necessary to maintain the torch orientation as close to 90° to the surface to obtain the highest coating density.

		Water-Cooled Baseline	Unsealed TTBC	Sealed TTBC
Recip. BMEP	KPa	1427	1411	1406
Air Flow	kg/h	274	288	249
Vol. Efficiency	%	85.5	81.3	80.3
Air/Fuel Ratio		30.4	30.3	29.5
Peak Cyl. Pressure	MPa	16.0	16.0	16.0
Recip. SFC	G/kW·h	217.1	231.7 (+6.7%)	206.5 (-4.9%)
Recip. SHR	kW/kW	0.479	0.499	0.399

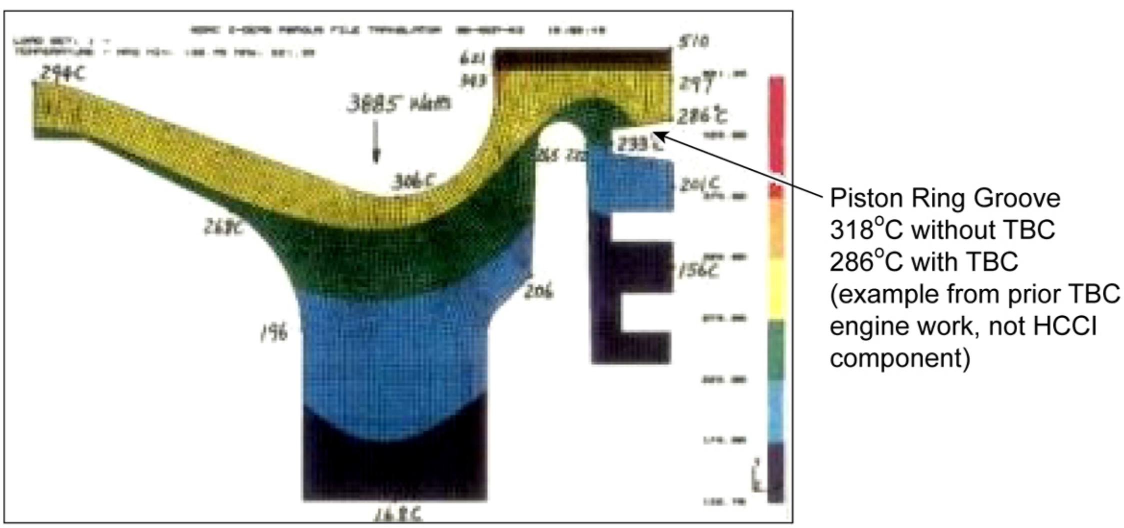

Figure 1. High-density (sealed) TBCs can reduce fuel consumption and provide temperature reduction needed for HCCI engine components.

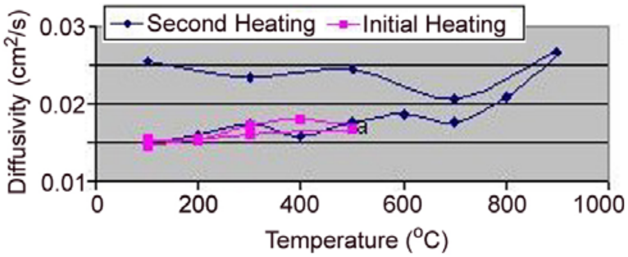

Figure 2. Exposure to temperatures above glass transition temperature (700°C) causes an increase in thermal diffusivity of amorphous steel.

Figure 3. Coated piston geometry.

Two types of robotic motion were investigated for coating deposition: (1) single radial [Figure 4(a)], and (2) raster combined with a short radial motion to cover the 60° angled part [Figure 4(b)]. The raster type motion is the easiest to program to achieve a uniform coating thickness but results in a high wastage of coating material due to the torch traversing off the part for much of the cycle. The radial motion is more efficient in material usage (lower cost) but difficult to program as the speed control of the robot is uncertain due to the high acceleration/deceleration rates required. As the circumference of the spray footprint depends on the position with respect to the center, the robot speed was adjusted accordingly to achieve a uniform deposition rate. Initially, practice piston geometries were used to develop the coating. The pistons were rotated in a lathe for either robotic motion with the rotation speed at 1700 rpm.

The raster type motion provides an easier method to control the deposition rate because each pass over the part is done at a constant speed. However, the raster type motion results in a part of the surface being sprayed under 30° angle rather than 90°. Also, the stand-off distance is not held constant and varies by half of the bowl depth. In total, 20 practice pistons were coated using the radial type motion and 2 using the raster type motion. Final two pistons coated for engine testing used the raster type motion as this provides the most uniform coating. Further work to achieve coating uniformity with the radial motion is required and will be pursued if the initial engine testing is successful.

Quasicrystalline Materials

Microprobe analysis of diffusion couples is being used to assess the thermal stability of the quasicrystalline coatings for use as thermal barrier coatings. HVOF coatings of the $Al_{71}Co_{13}Cr_8Fe_8$ material were previously produced for diffusion couple testing: (1) the quasicrystal and steel substrate, (2) the quasicrystal, a Ni-17Cr-6Al-0.5Y bond coat, and steel substrate, (3) the quasicrystal, a Ni-31Cr-11Al-0.6Y bond coat, and steel substrate, and (4) the quasicrystal, a Fe-26Cr-8Al-0.4Y bond coat, and steel substrate. The diffusion couples were produced by spraying a steel sample, 12.5 mm diameter by 19 mm, with 0.5-mm-thick layers of the bond coatings and quasicrystal. These samples were then sealed in evacuated quartz tubes and held at temperatures of 500, 700, and 900°C for 25, 100, and 500 h. The samples were water quenched after annealing, and samples were prepared for examination by optical microscopy, scanning electron microscopy (SEM), and microprobe analysis.

Results

Amorphous Steel Coatings

The microstructure of the coatings was evaluated using optical microscopy. The microstructure of the sample deposited using the raster motion

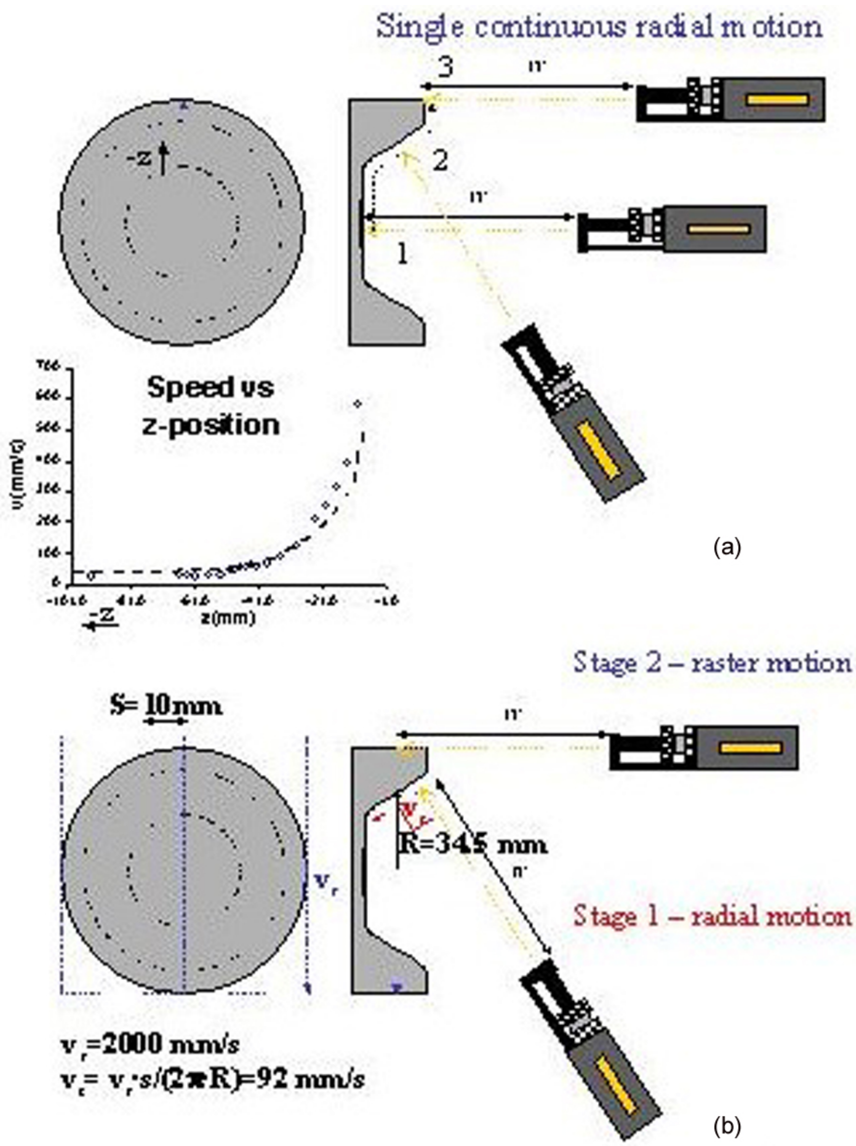

Figure 4. Coating motions used (a) continuous radial motion (top) and (b) two-stage raster motion (bottom).

(Figure 5) was compared to the microstructure produced using the radial motion (Figure 6). The coating deposited using the raster motion exhibits higher porosity in the radius area at the bottom of the bowl. This is caused by the turbulence created by the bowl geometry. The coating deposited using the radial motion exhibits higher density that is more uniform along the radius of the piston. However, thickness uniformity in coatings formed using a radial motion remains a challenge. Pistons coated using the raster motion were supplied for engine testing but have not yet been tested.

Quasicrystalline Materials

Microprobe analysis of the diffusion couple samples shows high mobility of aluminum into both the nickel- and iron-based bond coatings in only 25 h at 700ºC (Figures 7 and 8). Cobalt shows higher mobility into the iron based bond coating than the nickel. Further analysis of the diffusion zones at various temperatures and times is under way to provide a better understanding of the diffusion behavior of various species.

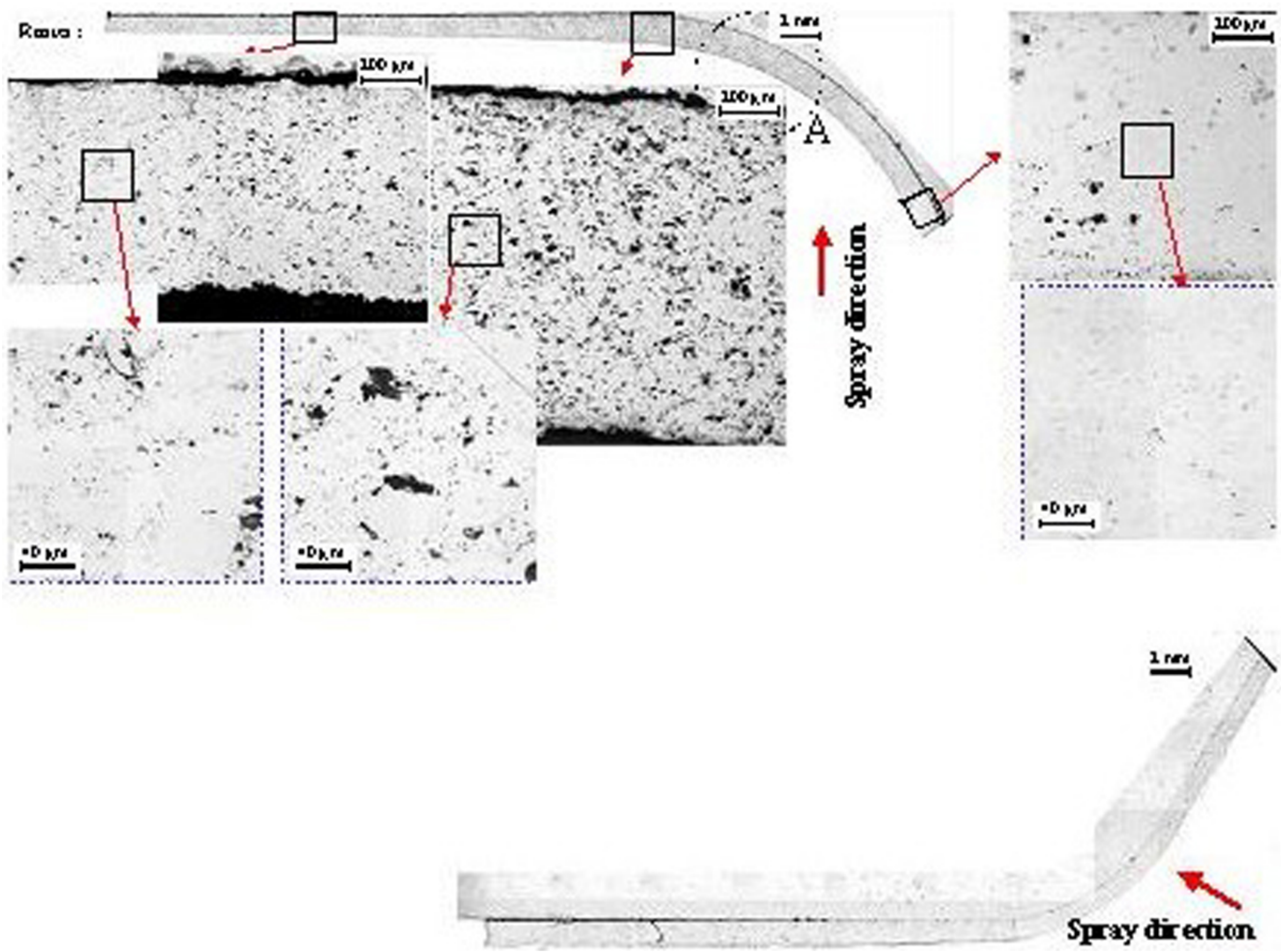

Figure 5. Microstructure of the practice piston 9 sprayed using a raster type motion showing higher porosity in the radius area of the bowl.

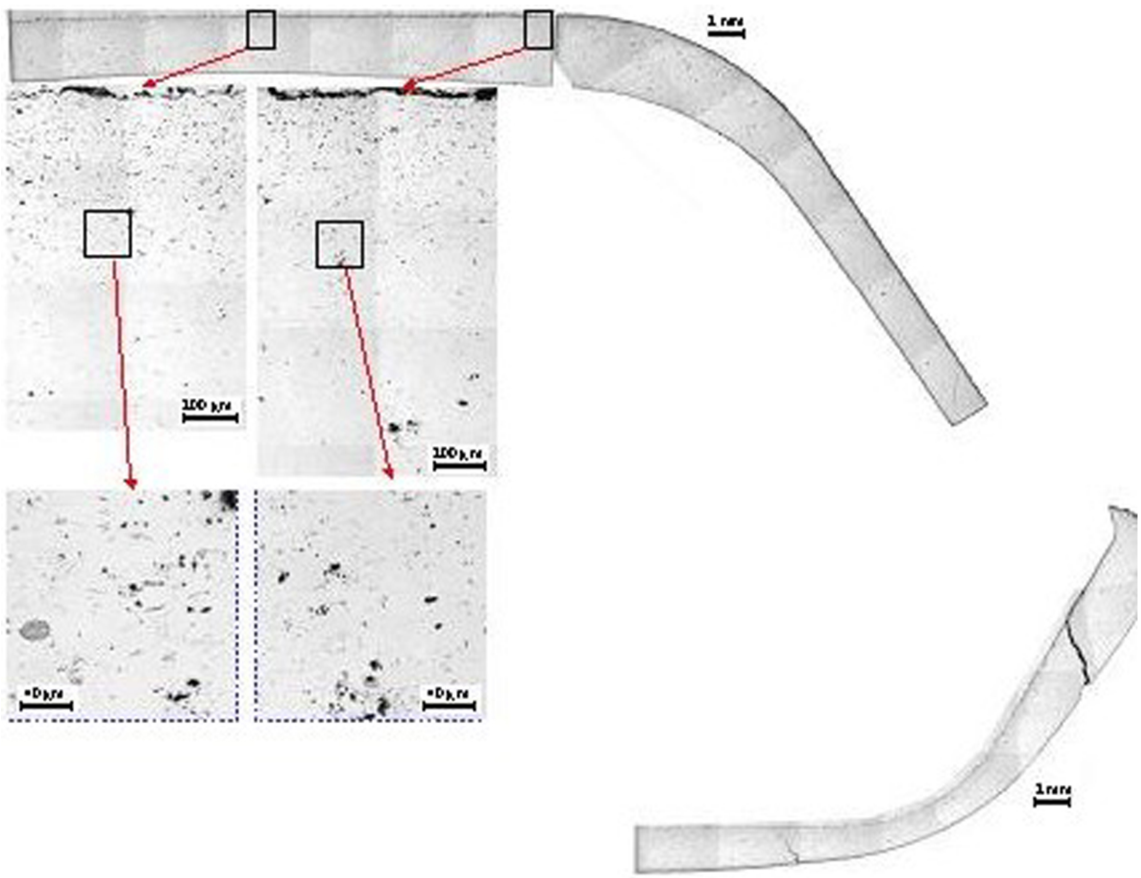

Figure 6. Microstructure of the practice piston 20 sprayed using a radial type motion showing lower porosity in the radius area of the bowl.

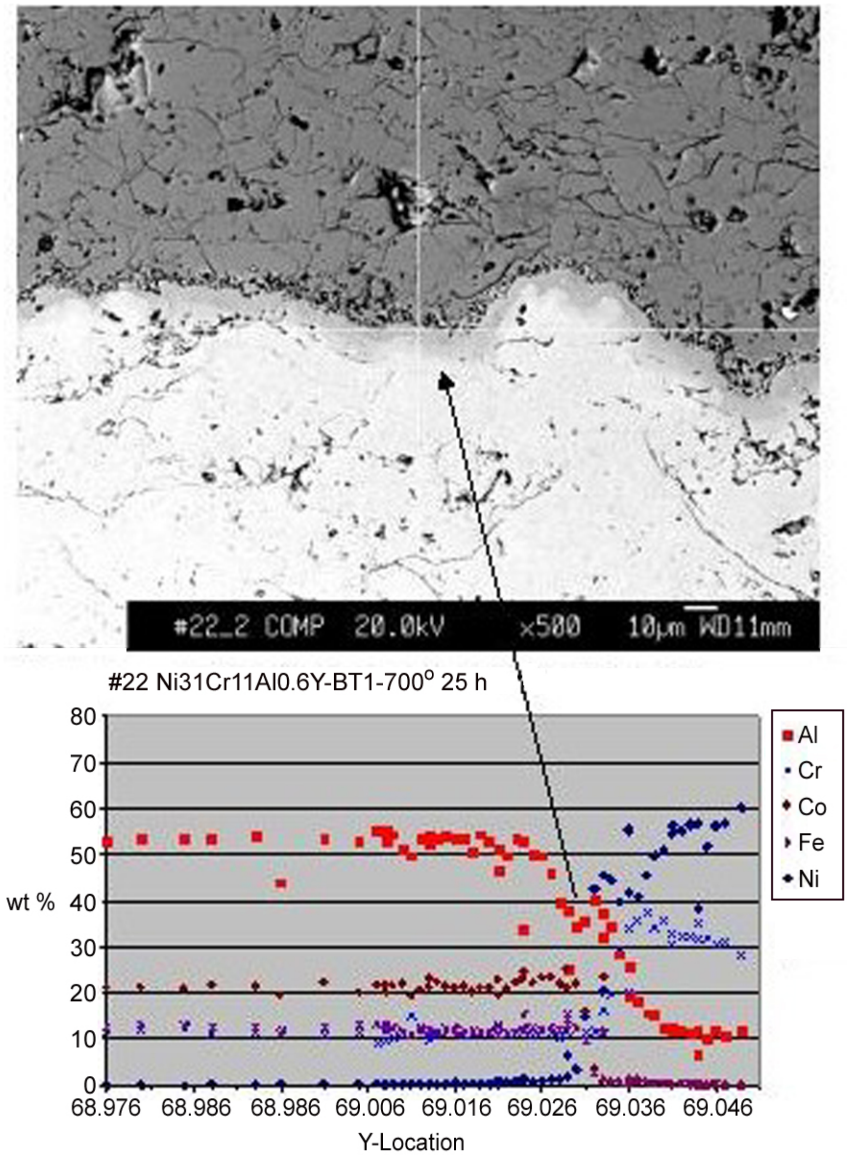

Figure 7. Microprobe results for the quasicrystal and nickel-based bond coating showing high mobility of the aluminum into the bond coating.

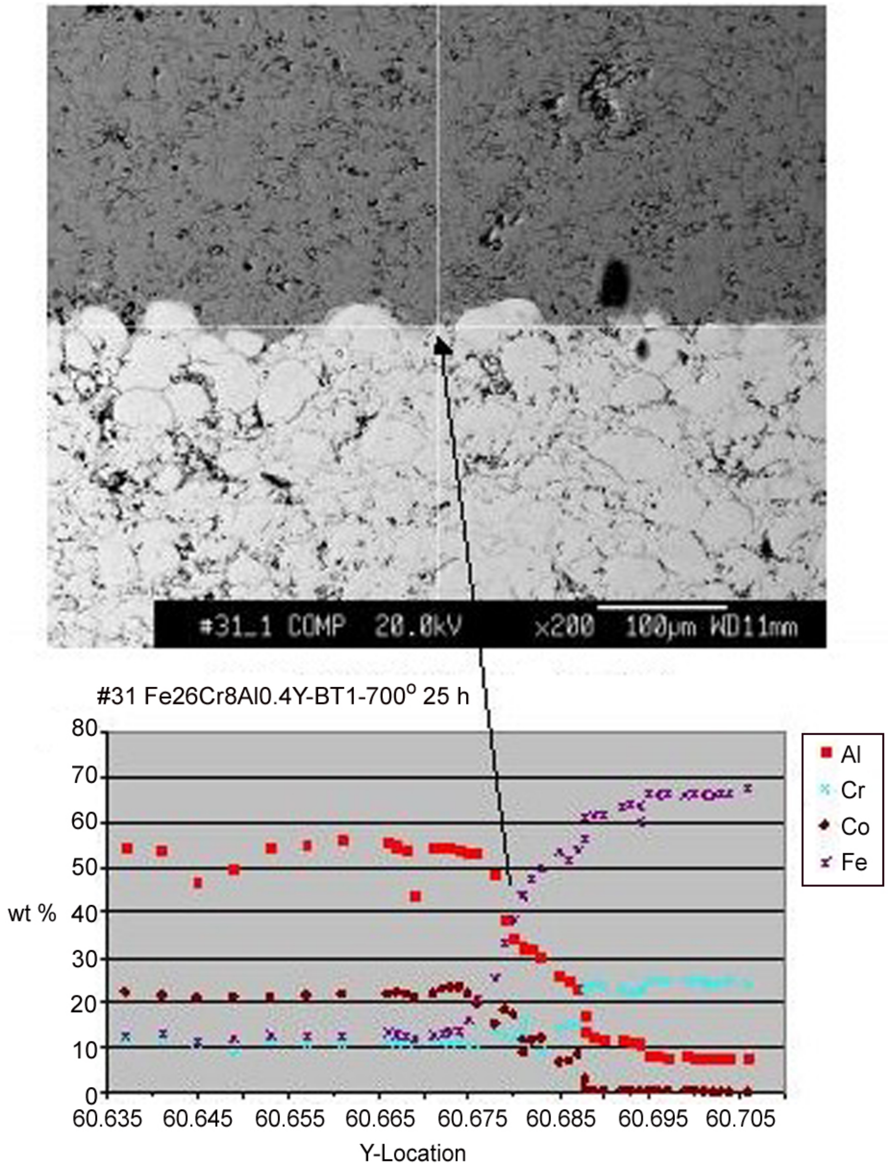

Figure 8. Microprobe results for the quasicrystal and iron-based bond coating showing mobility of the cobalt in the bond coating.

Conclusions

Amorphous Steel Coatings

The microstructures of the coatings applied to engine test pistons can be improved using the radial motion, but the coating thickness uniformity will need to be improved. Successful engine testing of the initial coated pistons will provide the emphasis to further develop these coatings.

Quasicrystalline Materials

The reaction zone between the quasicrystalline and bond coatings of iron and nickel show high mobility of the aluminum at 700ºC. Because the interface of the bond coating and quasicrystalline material will be below 500°C, this should not preclude their use as a thermal barrier coating system. Graded designs may be limited by this reactivity, and further analysis of the diffusion kinetics will be done to verify the temperatures of use for the quasicrystal and bond coatings combinations.

References

1. D. J. Branagan, W. D. Swank, D. C. Haggard, and J. R. Fincke, "Wear Resistant Amorphous and Nanocomposite Steel Coatings," *Met. & Mat. Transactions A*, **32A**, 2615–2621 (2001).
2. D. Shin, F. Gitzhofer, and C. Moreau, "Development of Metal Based Thermal Barrier Coatings (MBTBCs) for Low Heat Rejection Diesel Engines," Proceedings of the 2005 International Thermal Spray Conference, 915–919 (2005).
3. A. Sanchez, F. J. Garcia, J. M. Algaba, J. Alvarez, P. Valles, M. C. Garcia-Poggio, and A. Aguero, "Application of Quasicrystalline Materials as Thermal Barriers in Aeronautics and Future Perspectives of Use for These Materials," *Mat. Res. Soc. Symp. Proc.*, **553**, 447–458 (1999).