THE EFFECT OF HVOF THERMAL SPRAY ON THE ELEVATED TEMPERATURE HIGH CYCLE FATIGUE BEHAVIOR OF A MARTENSITIC STAINLESS STEEL

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Thermal spray coatings, of which HVOF is one, are an important enabling technology used to enhance the performance of materials in a diverse range of industrial applications. One area which has received relatively little attention is the effect of thermal spray coatings on the elevated temperature high cycle fatigue behavior of metallic substrates. This paper presents the results of rotating beam fatigue testing conducted on 403 stainless steel HVOF coated with three materials which have been or are being considered as candidates for blade coatings. Furthermore this paper will outline how various mechanical and physical attributes of both the coating and substrate influence this behavior.

INTRODUCTION

Surface modification processes are cost effective methods of attaining increased performance of a component where increased resistance is only required at the surface as is the case with corrosion, wear and erosion. Such processes include but are not limited to nitriding, carburizing, plating and thermal/ physical/chemical deposited coatings. A thermally sprayed coating is unique to itself and no other coating process is said to be even close in microstructural architecture. Coatings are formed as melted and partially melted particles of different size strike the substrate at perhaps a million impacts per second accumulating one upon another producing a characteristic lamellar structure.

High velocity combustion or oxyfuel spraying (HVOF) started up more than 35 years ago with the development of the detonation gun (D-gun) process by Union Carbide Corporation at its Speedway Laboratories in Indianapolis. In 1982 James Browning, a well-known inventor of plasma technologies, introduced his HVOF JetKote® process through Deloro Stellite of Goshen Indiana. Since the advent of the JetKote® system many other patented HVOF processes have followed. These processes have carved out a specialized niche in the thermal spray coatings business, particularly for the deposition of wear-resistant carbide coatings and are able to deposit very dense coatings, typically with reduced changes in the phase composition of the material, compared with plasma arc spray processes. HVOF processes also offer a number of potential advantages over, and alternatives to, competing processes including lower capital cost, portability, and ease of use in the field.

In general coating attributes, such as wear resistance and erosion resistance, have been well researched and reported whilst the basic mechanical strength characteristics and design implications have not. One area that has received relatively little attention, with the exception of diffused coatings on nickel-base superalloys [1,2], is the effect of thermal spray coatings on the elevated temperature high cycle fatigue behavior of metallic substrates. This issue is of paramount concern for stationary and rotating blading in the turbomachinery field where historically the primary failure mode is high cycle fatigue. It is therefore essential that the effect of coatings on mechanical integrity be adequately addressed prior to usage in demanding applications, such as turbomachinery blading, where the consequences of failure are significant. This study was undertaken to elucidate the high cycle fatigue behavior of a coated martensitic stainless steel utilizing coatings that have been or are serious candidates for blading applications.

EXPERIMENTAL PROCEDURE

High cycle rotating cantilever beam fatigue testing was conducted on AISI 403 stainless steel procured per DOD-F-24669/7, using modified Krouse type specimens in which gage sections, diameter 0.250", were coated with either WC-17%Co (hereafter referred to as tungsten carbide), Cr_2C_3-20%NiCr (hereafter referred to as chromium carbide) or Inconel 625. The coatings were applied by The Welding Institute in Cambridge, England using the TopGun® HVOF system. Testing was conducted at room temperature, 400°F and 800°F at an applied load ratio of -1. All coated specimens were tested in the as-sprayed condition and the bare specimens were tested in the polished condition; coating surface roughness of the as-sprayed specimens ranged from 3.7-4.6µm Ra. Two coating thicknesses, 200µm and 400µm, were investigated for the Inconel 625 and tungsten carbide coating while the chromium carbide coating was tested at 200µm only.

TEST RESULTS

Because the simple beam equation used for calculating applied stress on a homogeneous material is not applicable to coated specimens the term "pseudo stress" is used on the Y-axis of the S/N curves in this report to represent the magnitude of the applied cyclic load. This "pseudo stress" is simply the alternating load multiplied by a constant that for this study was $32L/pd^3$, where "L" is the moment arm and "d" is the gage section diameter. The coated specimen diameters were taken exclusive of coating thickness because coatings are not considered to afford any strength to the substrate material. Finally fatigue strength comparisons are performed at the actual or extrapolated 10^7 runout values.

Effect of Temperature. At room temperature the presence of chromium carbide and Inconel 625 coatings appeared to enhance the fatigue resistance of the specimen slightly while the presence of tungsten carbide coatings reduced the fatigue resistance approximately 10% (Figure 1).

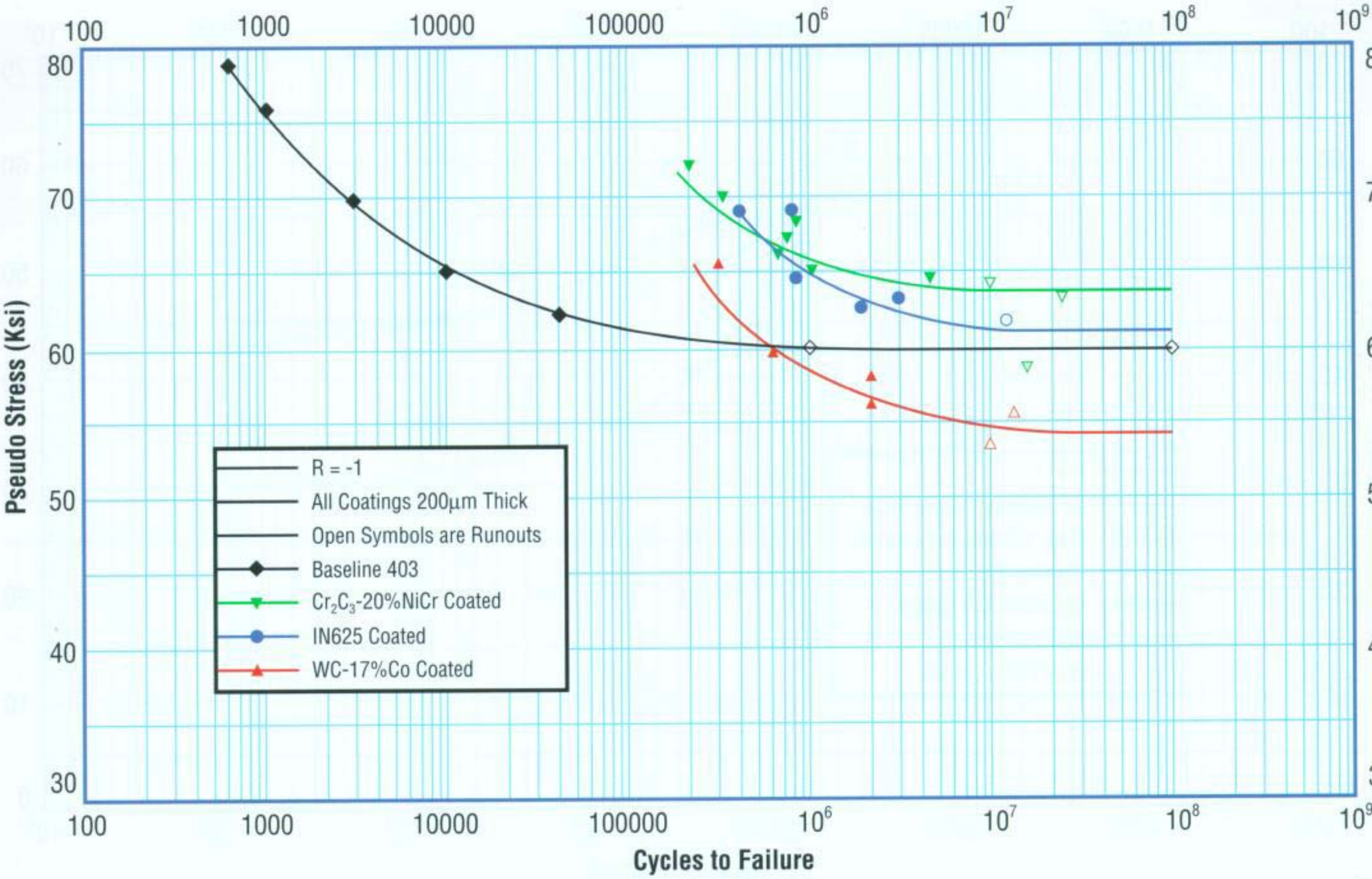

***Figure 1.** Effect of HVOF Coatings on the Room Temperature Fatigue Behavior of AISI 403 Stainless Steel*

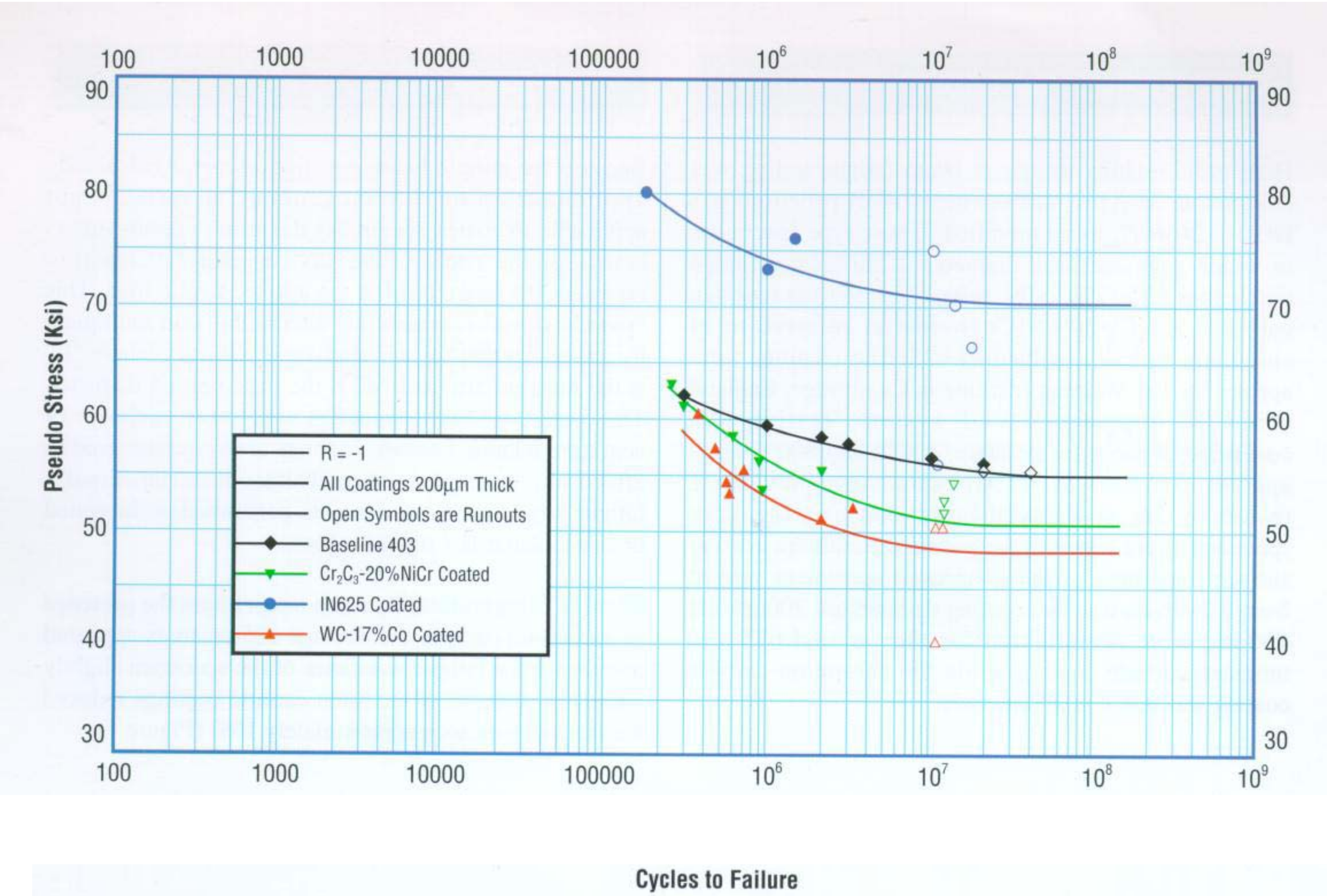

Figure 2. *Effect of HVOF Coatings on the Fatigue Behavior of 403 Stainless Steel at 400°F*

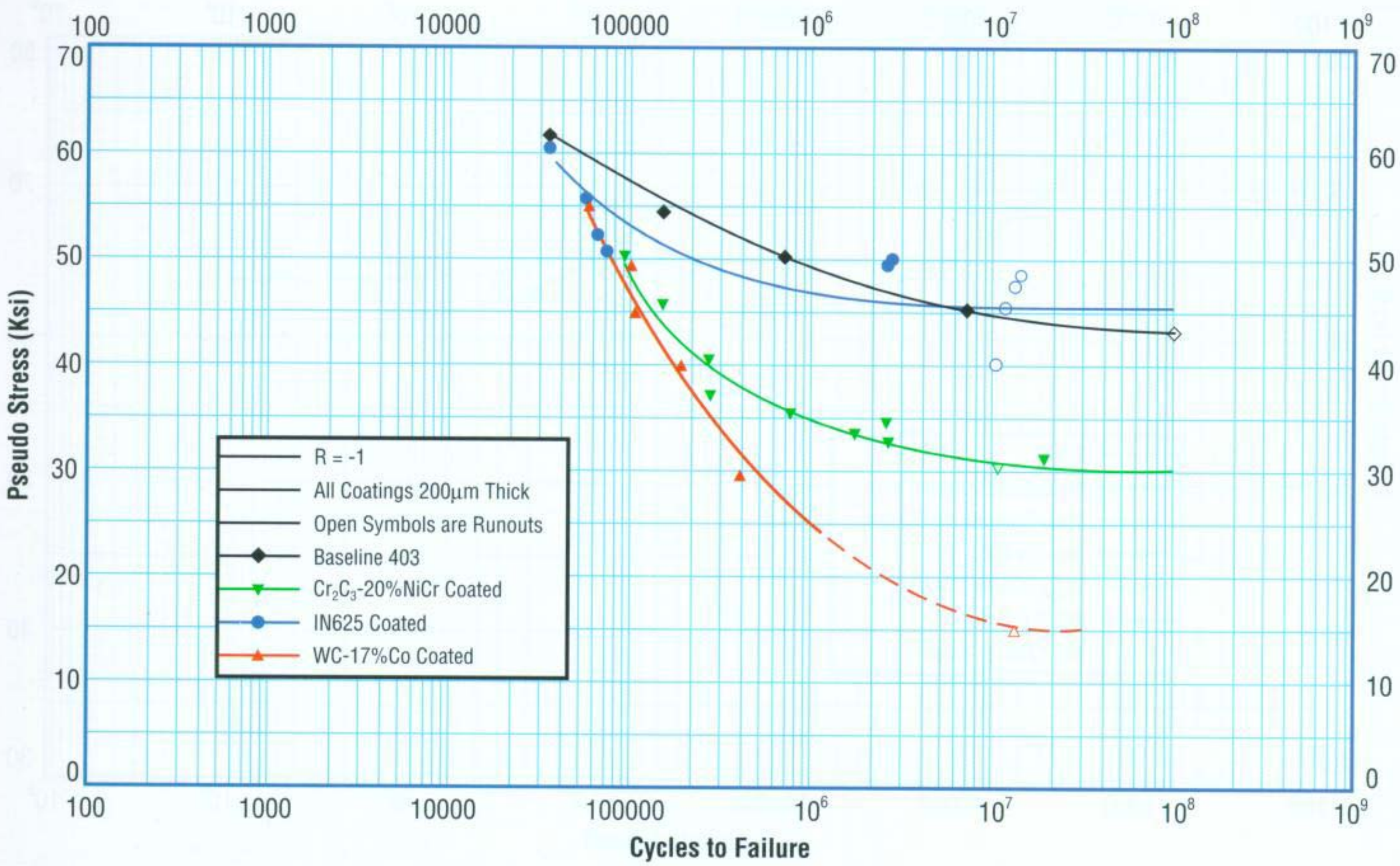

Figure 3. *Effect of HVOF Coatings on the Fatigue Behavior of 403 Stainless Steel at 800°F*

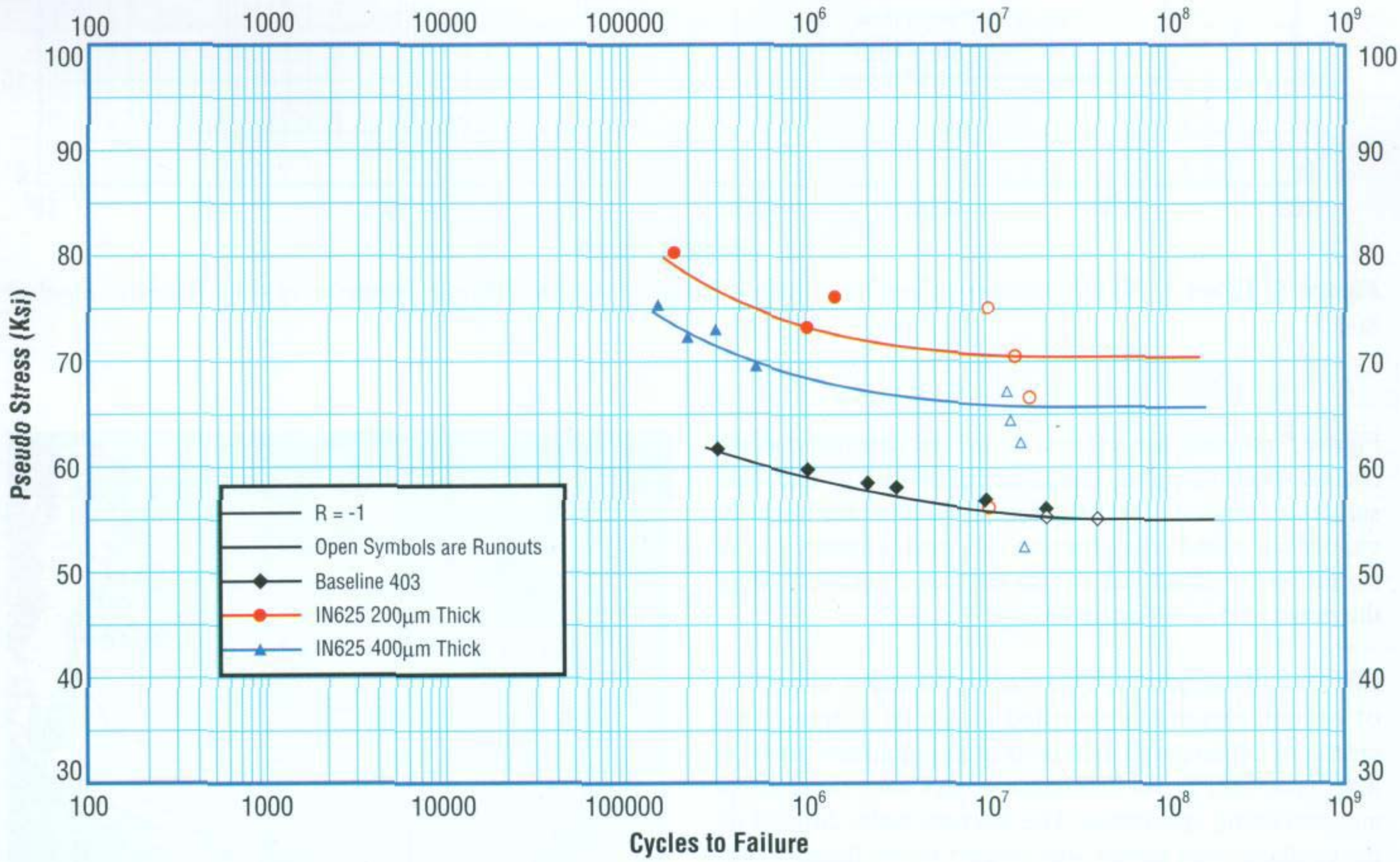

Figure 4. *Effect of HVOF IN625 Coating Thickness on the Fatigue Behavior of 403 Stainless Steel at 400°F*

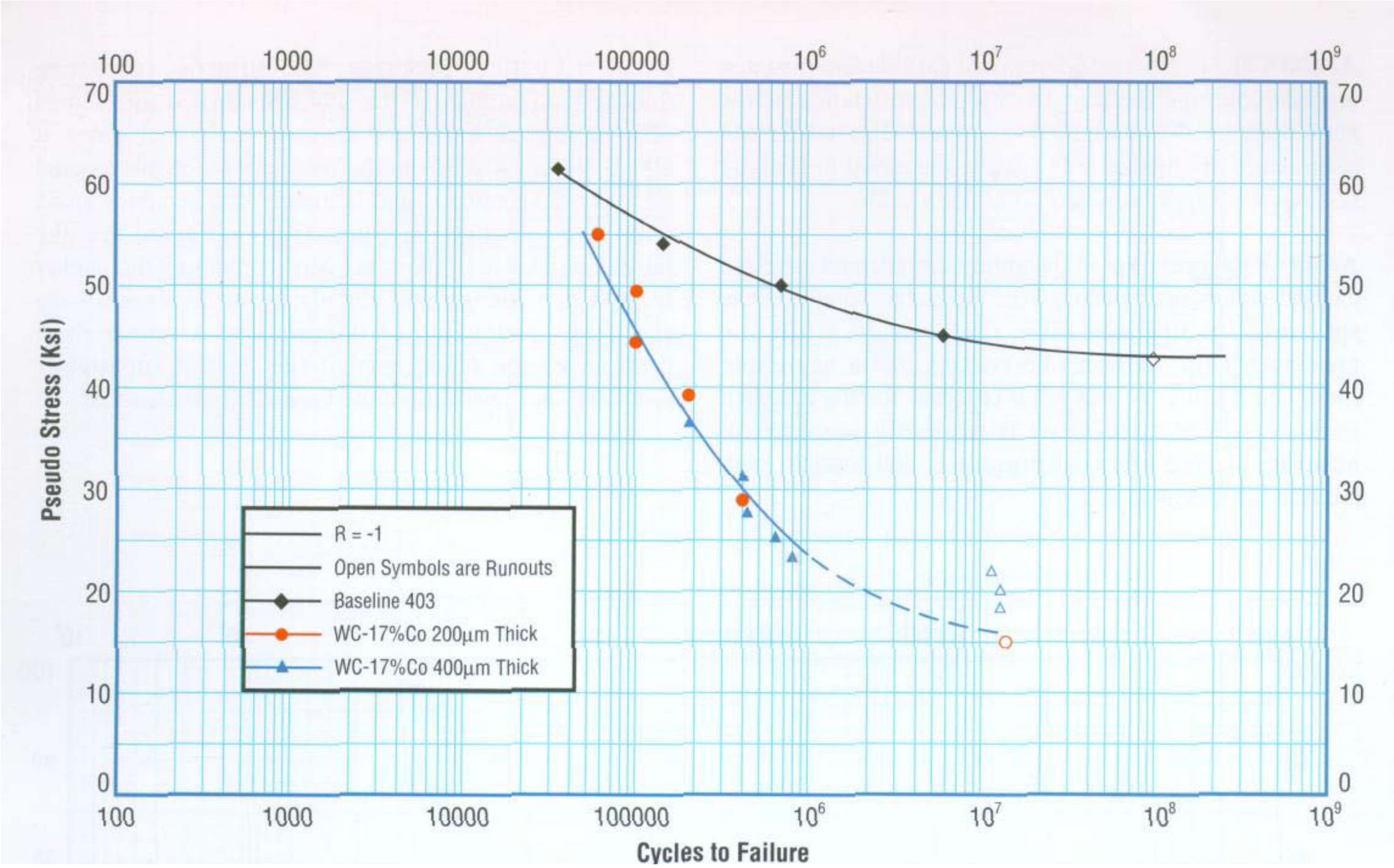

Figure 5. Effect of HVOF Tungsten Carbide Coating Thickness on the Fatigue Behavior of 403 Stainless Steel at 800°F

At 400°F the presence of chromium carbide and tungsten carbide coatings reduced the fatigue resistance of the specimen by 7% and 15%, respectively, while the presence of the Inconel 625 coating increased the fatigue resistance by approximately 27% (Figure 2).

At 800°F the presence of chromium carbide and tungsten carbide significantly reduced the fatigue resistance of the specimen by 30% and 60%, respectively, while the presence of the Inconel 625 coating had a negligible influence (Figure 3); the value reported for the tungsten carbide coated specimens is probably pessimistic however, a more accurate estimate is not possible with the limited data available.

Effect of Coating Thickness. The influence of coating thickness on fatigue resistance was evaluated for Inconel 625 coatings at 400°F and tungsten carbide coatings at 800°F. Figure 4 presents the test results for the Inconel 625 coated specimens and compares the behavior again with bare substrate material. It was observed that the fatigue resistance of the specimens containing the thicker Inconel 625 coating was slightly lower than that of the specimens containing the thinner coatings although in both cases the resistance of the coated specimens exceeded the capability of the bare substrate material.

NDT and Fractography. Fluorescent penetrant inspection of runout specimens revealed an array of transverse cracks in the tungsten carbide coated specimens tested at 400°F and 800°F. No detectable cracks were observed in any remaining specimens. The fracture paths through all the coatings were planar with respect to the fracture path through the substrate with the exception of the tungsten carbide coated specimens tested at room temperature and the chromium carbide specimens tested at room temperature and 800°F (Figures 6 and 7). One single origin area was identified on the peripheries of the substrate material for all specimens tested with the exception of the Inconel 625 and chromium carbide coated specimens tested at 800°F which exhibited multiple origins around the circumference of the substrate (Figure 8).

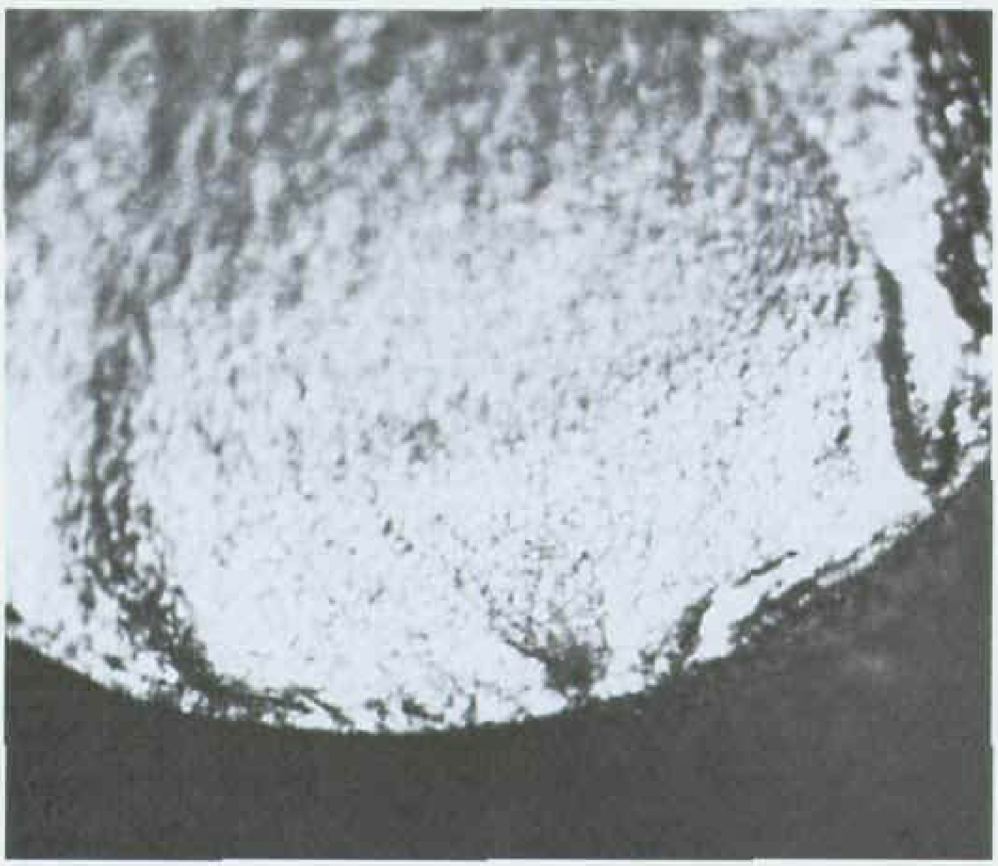

Figure 6-15X. *Photograph of fracture surface of an IN625 coated specimen tested at room temperature showing origin area.*

Figure 7-15X. *Photograph of fracture surface of chromium carbide coated specimen tested at room temperature showing origin area.*

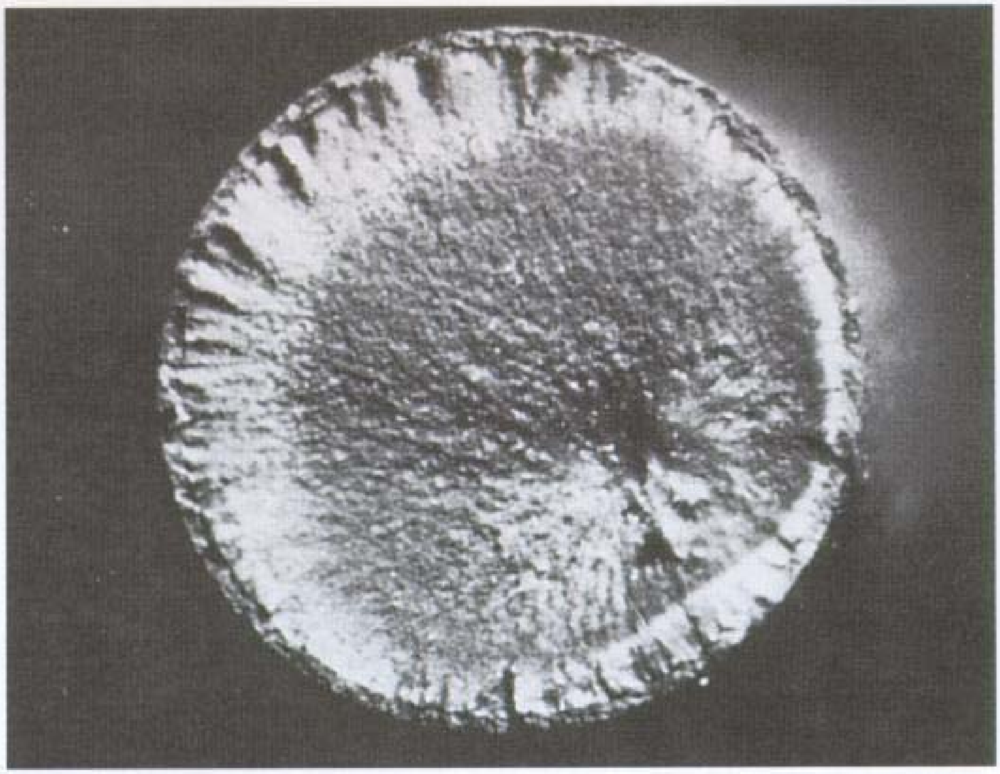

Figure 8-15X. *Photograph of fracture surface of tungsten carbide coated specimen tested at 800°F showing multiple origins.*

No definitive origins within or on the surface of the coatings could be identified; the fracture surface features through the coatings could only be described as nondescript and it was impossible to determine if the cracks grew outward through the coating from substrate origins or if the cracks had originally initiated in the coating and reinitiated in the substrate after crossing the coating/substrate interface. It was noted however, that the chromium carbide and tungsten carbide coated specimens tested at elevated temperature exhibited delamination along the coating/substrate interface (Figure 9); the Inconel 625 coating did not exhibit this characteristic.

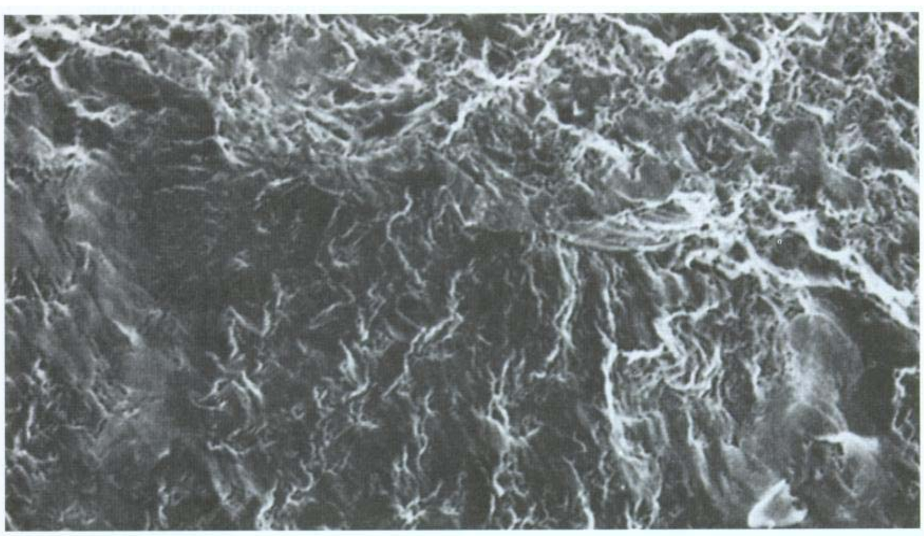

Figure 9-51X. *Scanning electron microscope photograph of fracture surface of chromium carbide coated specimen tested at 400°F showing delamination along coating/substrate interface.*

DISCUSSION

Before discussing factors that influence coated specimen behavior it is worthwhile to review the methods of testing, analysis and data presentation used to describe rotating beam fatigue testing of metallic specimens because as we shall see many of the assumptions that have been applied to homogeneous, isotropic metallic alloys are not valid for coated specimens.

Rotating Beam Fatigue Testing of Uncoated Specimens. By convention the stress plotted on the Y-axis of the S/N diagram represents only the applied stress although specimen behavior is actually a function of the effective stress. The effective stress is the sum of the applied stress and residual stress. The applied stress is calculated using simple fix ended beam equations which for standard configuration Krouse type specimens is given by Equation 1:

Equation 1

$$\sigma = \frac{MC}{I} = \left[\frac{32\,PL}{\pi d^3}\right]_{surface}$$

Where: P = *applied load*
L = *moment arm length*
d = *specimen gage diameter*

Residual stresses are present on the surface and slightly below the surface of all fatigue specimens, unless stress relieved prior to testing, due to the machining, grinding and polishing encountered during fabrication of the specimen. The residual stresses are compressive unless non-conventional machining methods were employed or the machining/grinding operations were carried out in an abusive manner. The existence of such a residual compressive stress reduces the mean stress that in the case of rotating beam fatigue testing at a load ratio of A the mean stress is numerically less than zero. Well-known empirical relationships describing the effect of the mean stress on fatigue strength include the Gerber, Goodman and Soderberg equations.

The magnitude of both residual stress and applied stress on a rotating beam specimen vary through the thickness of the specimen. Theoretically one could, after testing, identify the exact origin location relative to the specimen surface, measure the magnitude of the residual stress by XRD methods, calculate the actual applied stress at the origin from Equation I and plot S/N curves as a function of effective stress for a given effective mean stress. Unfortunately near surface residual stress gradients are quite steep and origin locations can not be identified with the necessary precision.

The foregoing does not imply that typical S/N curves generated on polished rotating beam fatigue specimens are unconservative or useless for design purposes but simply illustrates that such testing measures specimen fatigue strength not material fatigue strength; this is in fact true of all mechanical testing. The reason specimen fatigue properties can be used for design as material fatigue properties is that the residual stress profiles for conventionally machined components are quite similar to that of machined and polished fatigue specimens.

Before concluding discussion of testing of homogeneous metallic materials it is important to note that residual stresses do not influence fatigue characteristics of specimens subjected to axial loading. Axial loaded specimens are subjected to a constant net section stress. Subsurface origins are usually observed in axially load specimens that have residual compressive surface stresses. The mode of loading becomes very important when comparing fatigue behavior of coated specimens. The majority of data presented in the literature on coating effects have been generated on axially loaded specimens that masks some of the more important effects the coating has on the specimen under bending loads and misleading conclusions suggesting that coatings have no effect on fatigue behavior have arisen from such testing.

Rotating Beam Fatigue Testing of HVOF Coated Specimens. A coated component/specimen is by definition a composite structure and response of this structure is a very complex function of the physical and mechanical properties of all materials that make up the structure. Some of the properties of the coatings and substrate material tested are presented in Table 1.

Property	403 SS	WC-17%Co	Cr_2C3-20%NiCr	IN 625
Young's Modulus (10^6 psi)	29	27	18	30
Coefficient of Thermal Expansion (10^{-6} in/in/°F)	6.6 RT-1000°F	4.7 RT-1000°F	5.4 RT-1000°F	7.85 RT-1000°F
Strain to Failure Room Temp. (10^{-3} in/in)	NA*	1.3	2.5	NA*

Table 1. *Properties of Coating and Substrate Materials Tested*

Many of the simplifying assumptions applied to analyze system responses of homogeneous materials are not valid for such composite structures. The effective stress of a coated rotating beam fatigue specimen is a function of the applied load, residual stress profile, coating/substrate elastic modulus mismatch and at elevated temperature the coating/substrate thermal expansion mismatch. Furthermore, the magnitude of the effective stress varies from the specimen surface through the thickness. The influences of the physical interface between the coating and substrate, which is always present in thermally sprayed coatings unless diffusion alloyed at elevated temperature, on the stress profiles is still a matter of intense debate. Nevertheless, if these controlling factors can be evaluated in a qualitative sense then perhaps the fatigue behavior of coated materials can be represented, albeit with appropriate qualifications, using S/N curves in a manner not significantly different from that used for homogeneous material systems.

Residual Stress Effects. Residual stresses are generated during the coating process due to microscopic forces established between individual "splats" that are physically unable to accommodate significant shrinkage arising from solidification and contraction of the splats as well as from the macroscopic effect resulting from thermal expansion mismatches between the coating and substrate during post-coating cool-down [3]. The macroscopic residual stresses generated in the coating during cool down can be calculated by the following equation:

Equation 2

$$\sigma_{coating} = \frac{E_{coating}\,\Delta T\left(\alpha^{coating} - \alpha^{substrate}\right)}{1 + 2\left(\dfrac{E_{coating}\,t_{coating}}{E_{substrate}\,t_{substrate}}\right)}$$

Where: E_i = *modulus of the coating/substrate*

ΔT = *difference between coating solidus temperature and substrate temperature*

α^i = *thermal expansion coefficient of coating/substrate*

t_i = *thickness of coating/substrate*

The overall state of residual stress in such coatings is a function of processing parameters, thermal expansion coefficients and elastic properties of the coating and substrate materials [3,4,5,6]. Unfortunately attempts to analytically predict or quantitatively measure these residual stresses have not met with much success due in part to a lack of accurate mechanical/physical properties of the coating materials or practical limitations of test methods [7,8]. It has generally been accepted that coating residual stresses are largely responsible for the increased/decreased fatigue strength of coated specimens versus bare specimens tested at room temperature. As will be shown in the following sections this is only true if the elastic moduli and the mechanical properties of the coating/substrate are equivalent.

Young's Modulus Mismatch. Next we shall consider the effect of coating/substrate elastic modulus mismatch. Equation 1 is not valid for calculating the applied stress of composite materials of differing elastic moduli. The deflection of a composite structure and hence bending stress is a function not only of the elastic moduli of the materials but also the thickness of the various materials making up the structure. In a finite element study it has been shown how the three coatings of the same thickness but differing elastic moduli applied to 403 stainless steel rotating beam specimens influences the state of stress at room temperature (Figure 10).

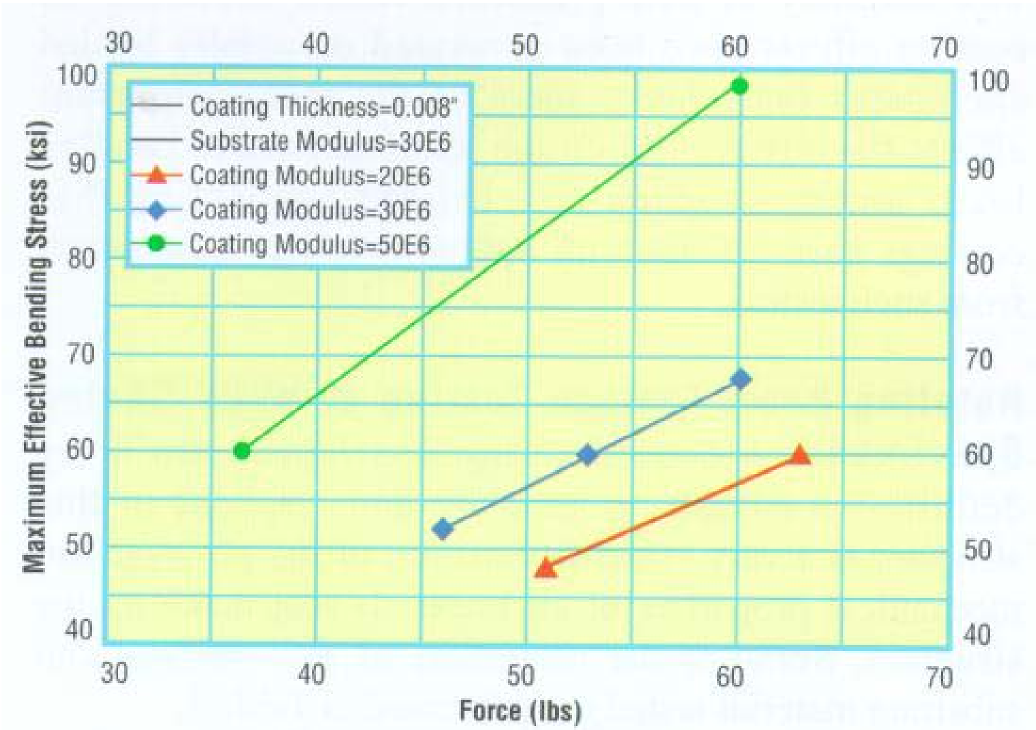

Figure 10. Effect of Elastic Modulus Mismatch on the Effective Bending Stress of Thermal Spray Coated Krouse Type Rotating Beam Fatigue Specimens at Room Temperature

From the graph shown in Figure 10 it is apparent how coatings with lower elastic moduli than the substrate can enhance the fatigue behavior of the specimen and conversely the negative influence of higher modulus coatings. In addition, it is obvious why it is incorrect to attribute differences in room temperature fatigue strength of coated specimens solely to residual stress effects. The elastic modulus mismatch not only influences the magnitude of the stress but also the location of the peak stresses as shown in Figures 11 and 12 and therefore once again we can not attribute fatigue strength differences of coated specimens simply to elastic modulus mismatch and/or residual stress effects except in the rare case where the mechanical properties of the substrate and coating are equivalent.

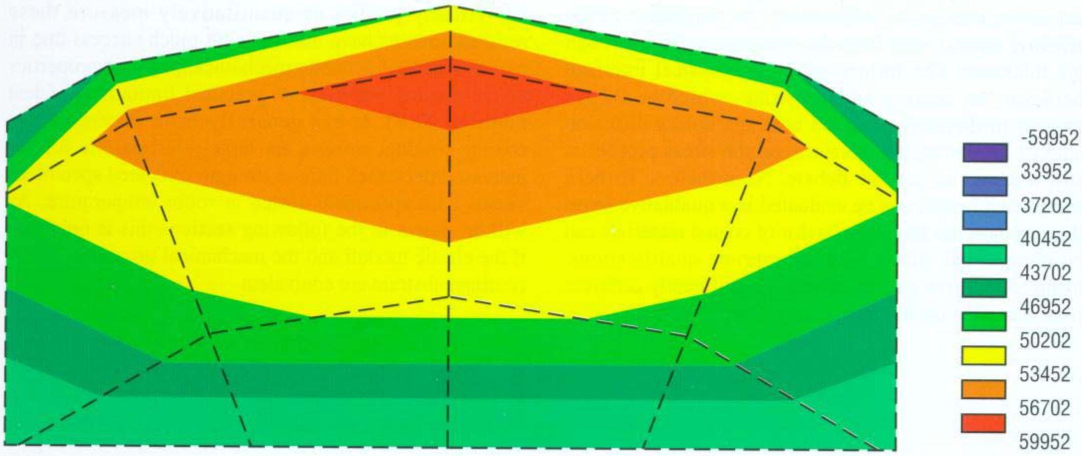

Figure 11. Effect of 0.008" Thick Coating ($E=20x10^6$ psi) on the Bending Stress of Krouse Type Rotating Beam Fatigue Specimen ($E=30x10^6$ psi) at Room Temperature

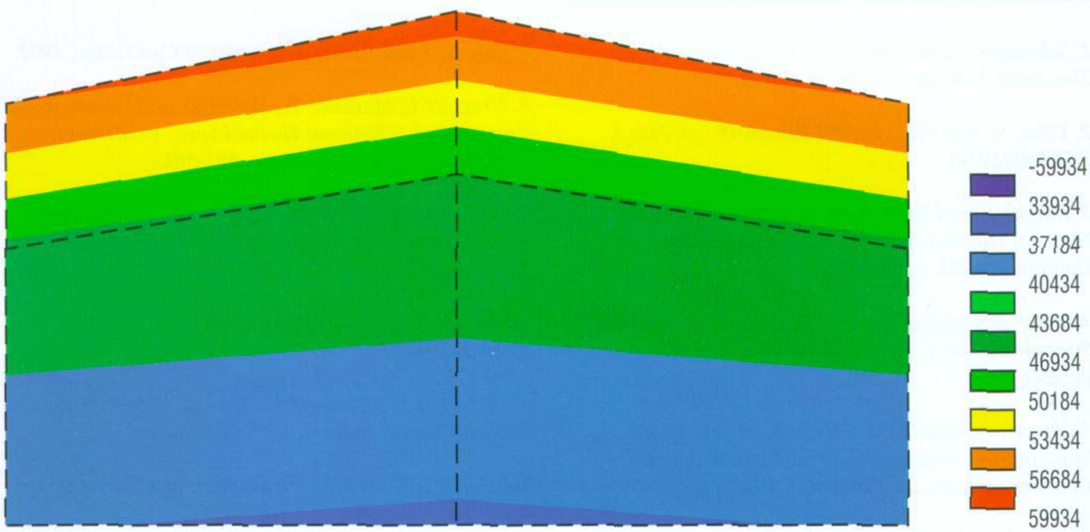

Figure 12. Effect of 0.008" Thick Coating ($E=50x10^6$ psi) on the Bending Stress of Krouse Type Rotating Beam Fatigue Specimen ($E=30x10^6$ psi) at Room Temperature

Thermal Expansion Mismatch. In general the thermal expansion of coatings and substrate materials are different and at elevated temperatures this mismatch stress will either increase or decrease the effective stress acting on the composite structure. The effect of the thermal expansion mismatch can be deduced straightforwardly from equations similar to Equation 2. Coatings having higher coefficients of thermal expansion than the substrate material, such as Inconel 625, will benefit from compressive stresses generated in the coating at elevated temperature and visa versa; there will be a counterbalancing effect on the substrate. The greater the thermal expansion mismatch and/or the higher the temperature difference the greater the resulting thermal stress magnitude.

Material Properties. The foregoing sections were directed at those factors influencing the effective stress acting on a coated structure. We now turn our attention to the issue of structure resistance. There are three specific areas of interest for thermally spray coated metallic components which are substrate, coating and substrate/coating interface. The applicable mechanical properties of the substrate are typically available or can be determined by testing. Bulk mechanical properties of coatings are generally not available and fabricating specimens for test are at best difficult. Anisotropy of the coating can have a significant influence on not only the bulk mechanical properties but also the physical properties [9]. The cermet type coatings that include tungsten carbide and chromium carbide are themselves composites consisting of a carbide phase(s) contained within a metallic matrix each having their own physical/mechanical properties that must be accounted for. The coating/substrate interface must also be considered not simply in regard to tensile bond strength but also shear bond strength due to the generation of longitudinal shear stresses when subjected to under transverse loading and thermal stresses due to CTE mismatches [10]. For some loading conditions the interface may be the weakest link in the composite structure. Data pertaining to the interfacial tensile bond strength is widely published however, scant data is available regarding the interfacial shear bond strength. Properties of both the coating and interface are dependent on any number of HVOF process parameters and will themselves vary from supplier to supplier.

CONCLUSIONS AND SUMMARY

HVOF thermal spray coatings can significantly influence the high cycle fatigue behavior of a martensitic 12Cr stainless steel at elevated temperature. The results suggest that a major controlling parameter influencing the behavior is the thermal expansion mismatch between the coating and substrate with residual stress profiles and elastic modulus mismatch having secondary effects.

A coated component/specimen must be analyzed as a composite structure however, due to the lack of adequate supporting data, i.e. residual stress gradients and material properties, and furthermore because some of this data is dependent on process parameters and therefore supplier specific, it is concluded that the high cycle fatigue characteristics of coated specimens cannot be considered in the generic sense as "material properties". Nevertheless, the fatigue characteristics can be represented by classical S/N curves provided that the appropriate qualifiers are noted. To use such curves for design requires that the specimen geometry and coating attributes conform as closely as practical to the component being analyzed. Further research is required with regards to residual stress gradients, anisotropic properties of coatings and shear bond strength before accurate modeling of coated components and extrapolation of fatigue data becomes a reality in design.

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