ADP011823

TITLE: Review of Fatigue of Coatings/Substrates

TITLE: NATO Advanced Research Workshop on Nanostructured Films and Coatings. Series 3. High Technology - Volume 78

REVIEW OF FATIGUE OF COATINGS/SUBSTRATES

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ABSTRACT

A review of fatigue of coatings/substrates is presented. Fatigue damage is either local or general, depending on the range of cyclic loads. Local fatigue damage includes rolling contact fatigue (RCF), fretting fatigue, fatigue-wear and general wear. Applied loads are localized consisting of rolling contacts or sliding contacts, and the resulting damage is mostly surface related. Crack initiation, surface pitting, delamination, spalling, buckling and enhanced wear can result from local fatigue damage of coatings. General fatigue damage results when the loads are of longer range such as cyclic bending, torsion or uniaxial or biaxial tension/compression etc. The mechanics of fatigue, role of microstructure, micromechanics in terms of crack nucleation, growth and fracture are reviewed. Defects produced during processing form precursors for crack nucleation. It is shown that optimization of the processing conditions to minimize defect density is essential to enhance fatigue resistance of coatings/substrates.

1. INTRODUCTION

The integrity of coatings/substrate composite depends on the nature of applied loads, environment, temperature and internal stresses introduced from the processing route as well as on the accommodating micromechanisms present. Understanding of the interplay of these factors, and the mechanics of the failures is important for the development of efficient and cost effective coatings. In this review, we examine the fatigue behavior of coating/substrates composites to evaluate the mechanical and microstructural factors that are involved in their fatigue damage. Since the microstructure and intrinsic defects that are formed depend on the processing conditions, we limit our discussion mainly to

G.M. Chow et al. (eds.), Nanostructured Films and Coatings, 283–295.

thermal-spray coatings that are of current interest to US Navy, although the general principles discussed are applicable to all coatings. Through microstructural refinement, new nano-structured coatings are being developed to improve wear and corrosion resistance for many Navy structural components. The fatigue properties of these new nanostructured coatings are of interest, particularly in comparison to the conventional coatings. Some of these developments are also of interest to commercial sector under dual use technology.

2. MECHANICAL AND MICROSTRUCTURAL CONSIDERATIONS

Mechanical incompatibilities at bimaterial interfaces involving coatings/substrates result in internal stresses that affect the integrity of the coatings. The sources of internal stresses include:
(a) Elastic modulus mismatch
(b) Thermal coefficient of expansion mismatch
(c) Lattice parameter mismatch
(d) Plastic flow mismatch
Several analyses and reviews [1-7] exist in the literature quantifying the nature of the internal stresses that are generated at interfaces in coatings/substrates and resulting from these mismatches in the material properties at the bimaterial interfaces.

On the macroscale, response of coating/substrate composite to internal or external stresses depends on its flow behavior. Figure 1, for example, illustrates two contrasting coatings compared to stress strain curve of a substrate. Coating I has higher strength but lower ductility than the substrate, in comparison to coating II which is weaker but more ductile [8]. If such coating/substrate composite is stressed under equi-strain condition, the stronger but less ductile coating breaks giving rise to cracks in the coating. If interface is weaker, cracks can propagate along interface resulting in delamination and spalling of the coating. If the coating has lower strength but is more ductile than the substrate, then the coating deforms plastically, accommodating the stresses. In that case the composite will survive until the substrate fails or until the coating cracks when its fracture strain is reached. Most of the wear resistant coatings [9-12] such as WC/Co on steels or Al-alloys, are of the first type which are generally stronger and less ductile than the substrate. Their strength provides the needed wear protection.

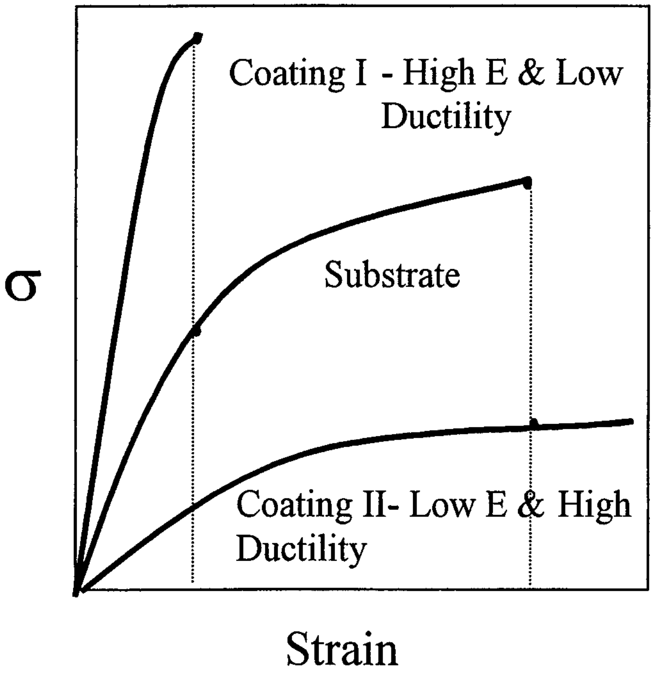

Fig. 1 Contrasting stress-strain behavior of ductile versus brittle coatings.

2.1 RESIDUAL STRESSES

Residual stresses arise from all of the above sources, but the thermal coefficient of expansion mismatch across the coating/substrate interface provides their major source. Residual stresses play a dominant role in the integrity of the coatings/substrates [13-17]. $\Delta\alpha$ is defined as $(\alpha_c - \alpha_s)$, where α_c and α_s are the coefficients of thermal expansion of coating and substrate, respectively. If the stresses are compressive in the coating, which is the case when cooled from high processing temperature to the application temperature and when $\Delta\alpha$ is negative. The residual stresses inhibit the nucleation and growth of cracks. On the other hand, they can augment the compressive forces that will be introduced during contact fatigue and accentuate failures associated with contact fatigue. In addition the compressive forces can cause buckling of the coating if the cracks are formed parallel to the stress axis. This leads to delamination and spalling of the coatings. Another source of residual stresses which is not discussed above, occurs due to mechanical impact when the coating particles impinge on the substrate at high velocities, such as during plasma spray or thermal spray processes [18]. Figure 2, for example, shows the nature of the residual stresses introduced in thermally sprayed WC/Co coatings, where spraying is done using high velocity guns.

3. CLASSIFICATION OF FATIGUE DAMAGE

One can classify the fatigue damage of coating/substrate assembly broadly into two types. They are (a) local fatigue damage and (b) bulk fatigue damage. The local fatigue damage is such that the scale factor is less than the coating thickness or volume. Local fatigue damage includes (a) rolling contact fatigue (RCF), (b) fretting fatigue, and (c) fretting wear, wherein the damage scale is smaller than the thickness of the coatings.

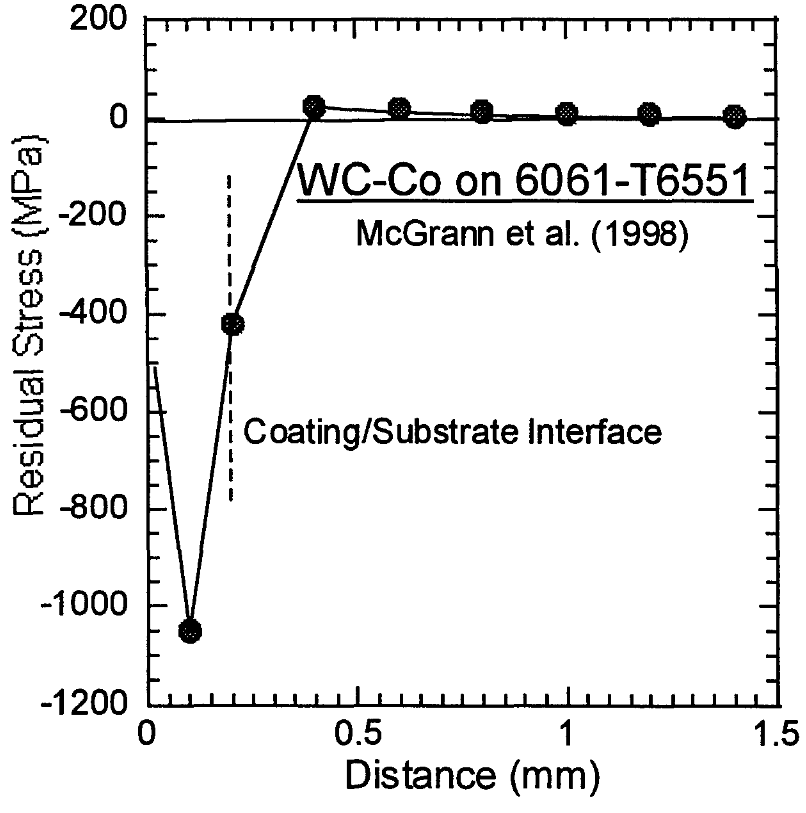

Fig. 2. Compressive residual stresses in WC-Co coating on an Al-alloy.

The bulk fatigue damage, on the other hand, involves intrinsic fatigue properties of the coating and substrate, bulk stresses, which extend to larger volume and the presence of defects or formation of cracks that are larger than the coatings thickness. Fatigue evaluation tests of the coatings/substrates such as push-pull or four-point bend tests etc., fall under this category.

3.1. LOCAL FATIGUE DAMAGE

Local fatigue damage consists of fluctuating loads on a local scale, which could occur due to high frequency vibrations with associated small tangential displacements between two contacting components. The two components may be in close mechanical locking or in rolling contact with one or both components rolling, such as wheels on rails, rolling ball bearings or gear contacts etc. Hard wear resistant coatings are deposited on the substrates to provide surface protection. Failure of these coatings generally involve fretting fatigue, fretting wear or rolling contact fatigue with crack formation, formation of pits, delamination and spalling of coatings at a local scale. If the two contacting surfaces are relatively stationary, then small tangential cyclic displacements can lead to fretting fatigue especially when there are normal forces to reinforce their mutual contact.

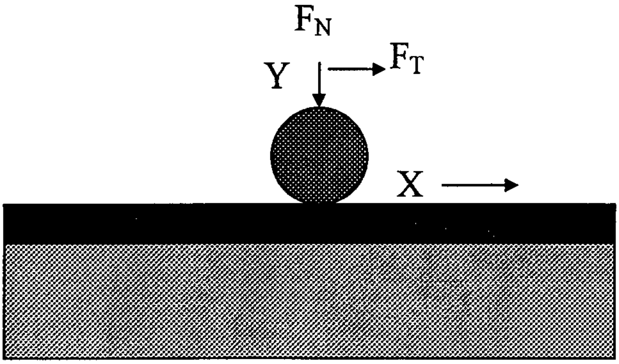

Fig 3. Rolling contact of a sphere on a half-space

The mechanics of the problem is somewhat similar for all local fatigue problems involving rolling contact, fretting fatigue, or fatigue wear etc. Complexities arise because of the three dimensional nature of the problem with local irreversible plasticity causing fatigue damage. Several analytical and numerical analysis techniques [19-24] have been presented in the literature considering the three dimensional nature of the contact problem. The problem has been simplified by considering an elastic analysis of a ball pressed against a flat surface characterized by half-space as shown in Fig. 3.

Fretting occurs in the regime depending on the frequency, displacement amplitude, δ, or amplitude of the tangential force. Examining the nature of the damage during cyclic contact displacement, Madlin [22-23] has shown that under contact pressure, the shear stress required to overcome the static frictional resistance will have a maximum at the center of the circular contact area. While Madlin's analysis assumes elastic conditions, the three-dimensional nature of the problem and local plasticity effects have been considered recently using numerical techniques[24-28]. There are three conditions - stick, partial slip and general slip [29-32]. The load-displacement curves for the three are schematically represented in Fig.4 based on which fretting maps have been developed. Case A is considered elastic with tangential displacements being small. F_T -d curve shows transition from predominately elastic to plastic shear, which represents the plastic yield of not only the asperities but also of the underlying bulk material.

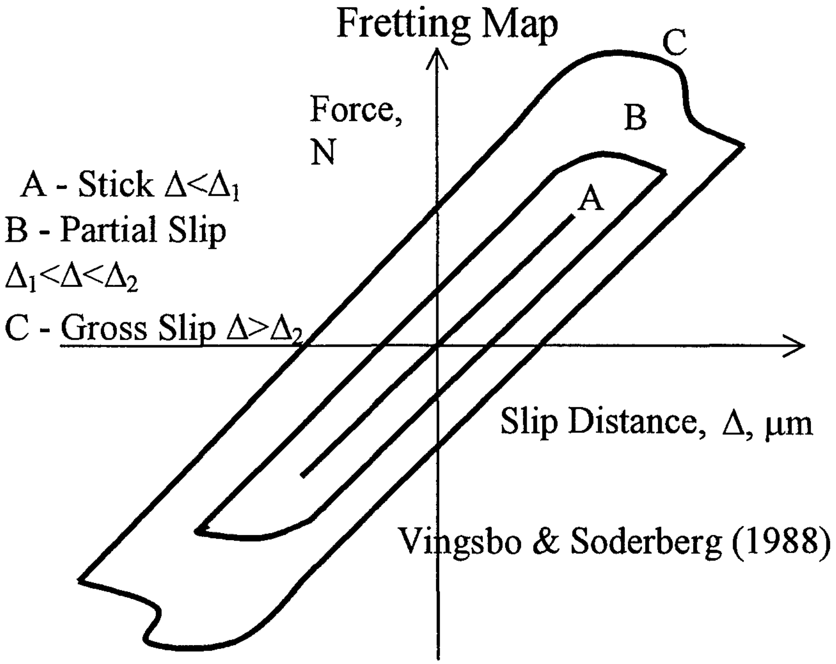

Fig. 4. Force-distance curve of contact bodies, stick, partial slip and gross slip regimes.

A second contribution to the leveling-off of the tangential force above a certain displacement stems from the fact that part of the applied shear stress is relaxed by the introduction of slip in the annular slip region. Figure 4 indicates that there are two critical displacements, Δ_1 and Δ_2, defining the three regimes, stick, partial slip and gross slip. Nonlinear displacements in contact fatigue, Figure 4, result in fatigue damage. If the frequency and the number of cycles become sufficiently large, the damage becomes significant and is termed fretting fatigue. Cyclic straining during continued fretting might lead to the nucleation and propagation of surface fatigue cracks, particularly along the rim of the contact area. Generally the displacement amplitudes are within the range of 1-2μm for fretting fatigue. But the damage can be significant when the number of cycles are in the range of 10^7 cycles.

Since fretting and wear both result from local fatigue damage, the fretting map can be superimposed on wear map using displacement amplitude as the independent variable. Although wear damage is not discussed here, the same region subjected to repeated rubbing by two contact surfaces exhibits both fatigue and wear. In fact wear itself could be due to fatigue, although characteristically referred to as wear fatigue to separate it from other forms of fatigue. Thus fretting damage manifests in two forms, fretting wear and fretting fatigue, which are somewhat related. Fretting wear starts when particles are formed within or at the edge of the contacts.

4. BULK FATIGUE

In addition to local fatigue problems, which are surface contact induced fatigue damage, the coatings/substrates are subjected to fluctuating gross scale loads that cause general or bulk fatigue. The mechanics of the problems and the nature and the extent of the damage are sufficiently general requiring separate evaluation. There have been several analyses of the coating/substrate mechanics to evaluate the fracture and fatigue properties of the coated material [1-7,33,34]. The analyses have been done considering combined Mode I and Mode II stresses for a body bonded by a thin adhesive layer. The difference in strength and elastic properties of the bimaterial and the strength of the interface along with the nature of the applied or induced stresses dictate the behavior of the coating/substrates.

4.1 FAILURE MODES

Under general loading conditions, there are three types of fatigue failures observed depending on the nature of residual stresses[5]. These correspond to delamination of the interface, splitting of the film and substrate cracking. There is also a fourth mechanism of failure that involves buckling of the coating and subsequent delamination of the interface. The later mode of failure relies on the existence of compressive stresses within the coating. The presence of a superimposed tensile stress can cause delamination along the interface, or cracking in the film or substrate. Failure induced by a compressive stress involves a complex interaction between buckling of the film and delamination along the interface.

Microstructure also plays a major role in crack nucleation and growth process. Process induced defects such as voids and inclusions etc. form nucleation centers for cracks. Grain size is expected to have dual roles. It is well known that decreasing grain size increases the endurance limit under fatigue. From the dislocation pile up analysis it is clear that decrease in grain size decreases the slip band length and hence increase the number of cycles (or endurance stress) for crack nucleation life. On the other hand, reducing grain size has been found to increase the resistance to crack growth particularly in planar slip materials. For coatings, in general, a reduction in grain size is expected to be beneficial in terms of fatigue life, since crack nucleation life has more sensitive dependence on grain size than the crack propagation life. In addition, fine grain size in the nano-range is expected to be beneficial in terms of increasing the strength of the coatings and in relaxing the residual stresses by grain boundary sliding.

5. APPLICATION TO THERMAL SPRAY COATINGS

In the following we discuss the application of the above understanding of the fatigue damage process to thermal spray coatings which are increasingly being used for many applications. The available experimental results on fatigue will be examined in terms of the resulting microstructure and the associated local and bulk fatigue damage.

Thermal spray coatings have a unique microstructure that affect their properties. It was noted earlier, Fig. 2, that compressive residual stresses are present in the coating due to high velocity impact of the particles during thermal spray [18]. As the molten or semi-molten feed particles impact on the cold substrate surface, they flatten and freeze. In addition to the impact stresses there will also be some residual stresses due to mismatch in thermal coefficient of expansion. The next incoming particle falls on the previous one thus forming a layer structure. In the inter-layers, the inter-particle boundaries called splat boundaries are formed, which are significantly weak[7-12]. Major concern is that these weak boundaries are parallel to the surface hence parallel to shearing forces that arise during Rolling Contact Fatigue. In addition to splat boundaries, there is grain nucleation and growth perpendicular to the splat boundaries. Thus each projectile particle during thermal spray forms a multigrain particles each separated from the others by splat boundaries. The size of each splat depends on the size of the feed particles. For micron size particles, high velocity oxy-fuel (HOVF) process resulted in splat boundaries that are about 30-40 μm wide, while the size of grain boundaries within the splat is about 2 μm. The aspect ratio of splat boundaries is very high [12].

5.1. FATIGUE OF THERMAL SPRAY COATINGS

The extent of the study of fatigue damage of thermal spray coatings is limited. McGrann *et al.* [18] have investigated the performance of WC-17%Co thermal spray coatings on SAE 4130 steel and 6061-T6511 Al-alloy substrates. The WC-Co coatings were applied by HVOF. Residual stresses in Fig. 2 were also determined. Fatigue tests were done using bending tests with zero mean stress. Three sets of thermal spray-coated Al-specimens were tested: Al-L, Al-M and Al-H, where L, M and H corresponds to light, medium and heavy coatings in terms of compressive residual stresses present. The stresses are of the order of 80, 500, and 760 MPa, respectively. For steel specimens,

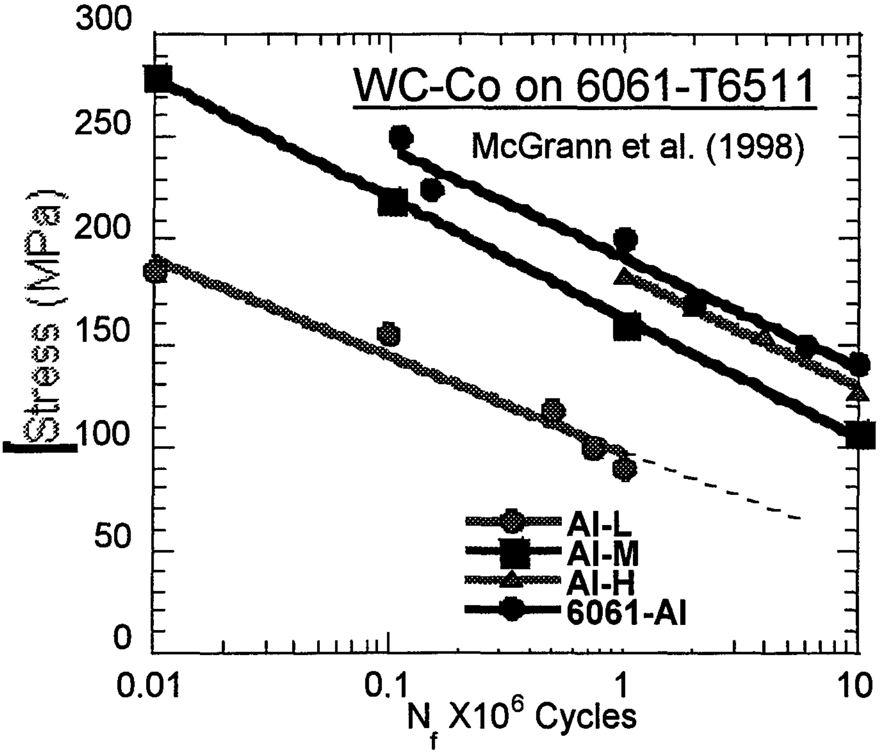

Fig. 5 Effect of WC-Co coatings on an Al-alloy substrate.

the coatings are of L and H types in addition to conventional chrome plated and shot-peened specimens. The average residual compressive stresses in the steel specimens were 125 and 365 Mpa for L and H types, respectively. Figures 5 and 6 show the fatigue results in terms of maximum applied stress versus the number of cycles to failure for each of the coated and uncoated specimens. For Al-alloys, in comparison to uncoated specimens, there is significant improvement (30 times) in life with coating. Examination of the results indicates that improvement is associated solely with the compressive residual stresses than coatings properties per sec, since with increasing residual stresses (for the same thickness) the fatigue life is increased significantly. Similar results are obtained for the steel specimens. The WC-Co with H type of coatings fared well in par with the shot peened specimens, where compressive residual stresses are deliberately introduced. The WC-Co coatings are much better than the conventional chrome plated specimens. Clearly the improvement arises from the compressive residual stresses since WC-Co coatings of L type did not show noticeable improvement due to low residual stresses. Figures 5 and 6 clearly demonstrate the importance of the residual stresses. The materials are coated to improve the wear resistance and bulk fatigue tests are only part of the acceptance tests for these coatings. There is no degradation of the properties as a result of the coatings. If fatigue is the life or performance-limiting factor then processing needs to be optimized to arrive at improved fatigue resistant coatings. The results thus indicate that WC-Co coatings can improve fatigue resistance compared to the conventional coatings currently used.

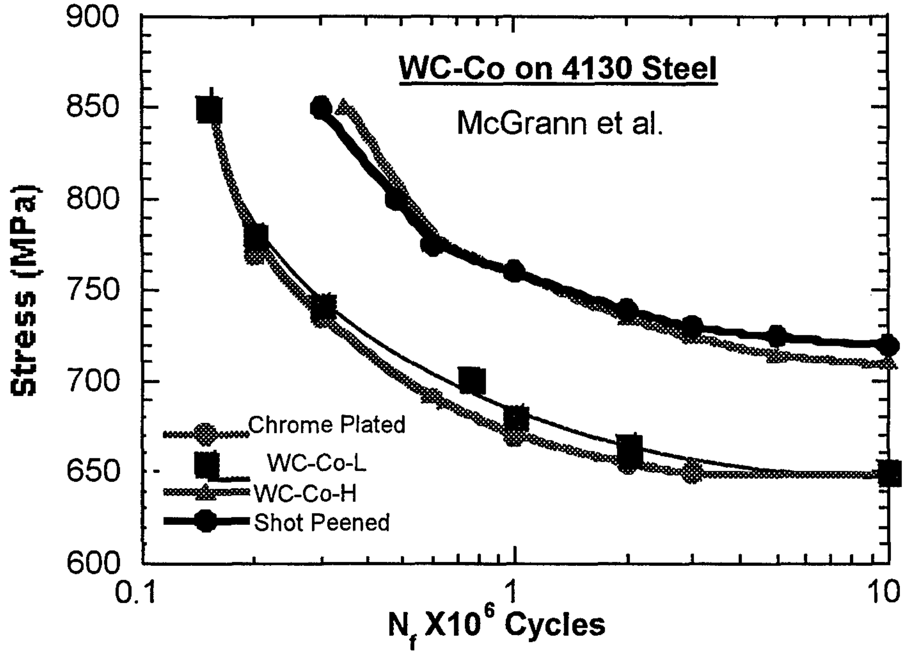

Fig. 6. Effect of WC-Co coating on fatigue life of 4130 Steel.

6. SUMMARY AND CONCLUSIONS

Coatings are provided to improve wear, corrosion, and oxidation of the substrates including as thermal barriers for high temperature components. Since the components are subjected to variable loads, the fatigue resistance of the coatings is of concern. Fatigue damage can result from local variations in loads such as in rolling contact fatigue, fretting fatigue or wear-fatigue or from global application of loads. Fatigue damage in general manifests in terms of irreversible plasticity, crack initiation, crack propagation and failure. Failure processes include cracking, pitting, particle decohesion, delamination, spalling, buckling etc. Mechanics of these are examined along with the review of available results. It is shown that fatigue performance of the coatings depends on the microstructure and residual stresses, and defect density and distribution. Processing optimization is essential in order to improve performance of the coatings.

7. ACKNOWLEDGEMENTS

The authors express their gratitude to Professor S. Sampath for providing data of thermal spray coatings. The review was completed when one of the authors (K.S) was on sabbatical at the Indian Institute of Technology, Madras. K.S expresses his appreciation to the Director of the Institute for hosting him during his sabbatical. The work is supported by the Office of Naval Research. Helpful discussions with Drs. L. Kabacoff and A.K. Vasudevan and their support are gratefully acknowledged.

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