An Investigation of Fracture and Fatigue in a Metal/Polymer Composite

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This article presents the results of a combined experimental and analytical study of the fatigue and fracture behavior of a polymer/metal composite which was developed recently for self-lubricating applications in automotive engines that utilize liquefied natural gas as fuel. For comparison, the microstructure and the fatigue and fracture behavior of a nonpolymer-containing “matrix” material are also presented. Since the crack profiles observed in both systems under monotonic or cyclic loading reveal significant components of ligament bridging, micromechanics models are presented for the modeling of crack bridging. The resulting predictions of resistance-curve behavior are compared with measured resistance curves. The shielding effects of ligament bridging are also quantified under cyclic loading. The implications of the work are also discussed for the modeling of fatigue damage and fracture in polymer/metal coatings.

I. INTRODUCTION

There has been increasing pressure on the automotive industry to produce "environmentally friendly" non-gasoline engines that utilize alternative fuels which reduce NOx emissions. This has stimulated extensive research efforts that have led to the development of engines that operate on compressed liquefied natural gas (LNG). Unlike their gasoline or diesel engine counterparts, conventional surface/boundary lubricants cannot be applied to engines that operate using compressed liquefied natural gas. There is, therefore, a need to develop alternative concepts for the lubrication of liquefied natural gas engines.

One approach that has been explored in recent years involves the use of polymer/metal composites designed to provide an internal supply of polymeric lubricant during the extended service of an engine. Such composites provide internal sources of polymeric materials that flow to the surfaces to provide boundary surface lubrication. They also offer the added advantage of "self-healing," since the flow of polymeric material can "heal" damaged areas on the surface during extended service. In this way, a new generation of polymer/metal composites can be engineered with in-built wear resistance.

However, there are some concerns about the fatigue and fracture resistance of metal/polymer composites. Preliminary studies have shown that such composites may be susceptible to fatigue damage under the severe thermomechanical environments that are encountered in automotive engines. There is, therefore, a need to develop models for the prediction of fatigue and fracture damage in polymer/metal composites. However, the development of such models is hindered by the lack of physical insights into the micro-mechanisms of fatigue and fracture in polymer/metal composites.

The current article presents the results of a combined experimental and analytical effort to develop physically based models for the prediction of resistance-curve behavior and fatigue-crack growth in polymer/metal composites. For comparison, the fatigue and fracture behavior of a nonpolymer “matrix” material is also examined in detail. Following a description of the microstructures, the micromechanisms of fatigue and fracture are elucidated at room temperature. The observed mechanism of crack-tip shielding (ligament bridging) is then modeled using mechanics concepts. Finally, the implications of the results are discussed for the design of durable polymer/metal coatings.

II. MATERIALS

The materials that were used in this study were supplied by the Ford Scientific Research Laboratories (Dearborn, MI). They were produced using thermal spray techniques that are summarized in Reference 4. The tensile properties of these materials are summarized in Table 1. The polymer/metal composite consists of a matrix material of INCONEL.*

*INCONEL is a trademark for INCO Alloys International, Huntington, WV.

625, a high-carbon steel known as TUFTON*, and 3 to 7

*TUFTON is a trademark of E.I. DuPont de Nemours, Wilmington, DE.

vol. pct of PEEK (poly-aryl-ether-ether-ketone), the polymeric ingredient. The microstructure of the composite material is presented in Figure 1(a). For comparison, the microstructure of the nonpolymer-containing matrix material is presented in Figure 1(b). Note that both the matrix and composite contain some porosity. Also, both systems have a similar appearance, and they consist primarily of two major phases: a "darker" phase and a "lighter" phase. The darker phase is iron-rich, while the lighter phase is nickel-rich. This is shown in the energy-dispersive spectroscopy (EDS) analyses in Figures 2 and 3. Note that the two phases are multicompound in nature. The darker phase also contains detectable amounts of oxygen, titanium, chromium, aluminum, silicon, niobium, and iron, while the lighter phase