HYBRID TITANIUM COMPOSITE LAMINATES: A NEW AEROSPACE MATERIAL

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INTRODUCTION

In the realm of aerospace design and performance, there are few boundaries in the never-ending drive for increased performance. This thirst for ever-increased performance of aerospace equipment has driven the aerospace and defense industries into developing exotic, extremely high-performance composites that are pushing the envelope in terms of strength-to-weight ratios, durability, and several other key measurements.

To meet this challenge of ever-increasing improvement, engineers and scientists at NASA-Langley Research Center (NASA-LaRC) have developed a high-temperature metal laminate based upon titanium, carbon fibers, and a thermoplastic resin. This composite, known as the Hybrid Titanium Composite Laminate, or HTCL, is the latest chapter in a significant, but relatively short, history of metal laminates. During the mid-1960's, Kaufman [1] showed that it was possible to improve the fracture toughness of aluminum by laminating thin plies of aluminum together. During the latter half of the 1970's, Johnson and colleagues [2,3] demonstrated that adhesively laminating thin aluminum plies together would dramatically improve the fatigue resistance along with improving the crack growth resistance. In the early 1980's, Johnson followed upon his earlier findings to show that adhesively laminated titanium plies improved fracture toughness by almost 40%, increased fatigue life by an order of magnitude, and reduced through-the-thickness crack growth rates by 20% over an equivalent monolithic titanium plate. [4]

The next advancement in the history of metal laminates was made at Delft University, the Netherlands, in conjunction with Alcoa. In the mid 1980's they produced the ARALL family of fiber-reinforced metal laminates. The ARALL laminates included aramid fibers in the adhesive bondline between the aluminum plies, further improving the mechanical properties of the laminate.[5,6]

The HTCL family of metal laminates took the concept of adding fibers to the adhesive bondline and applied it to the high-temperature regime of supersonic flight. The high temperatures found in supersonic flight necessitate the use of titanium rather than aluminum, and the substitution of the adhesive with an adhesive that could withstand the higher operating temperature for extended periods of time.

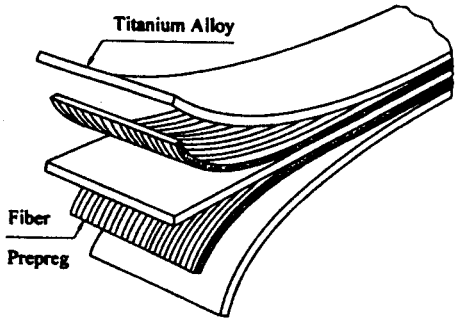

Fig.1 Schematic of a typical HTCL construction

Traditional polymeric matrix composites (PMCs) have demonstrated very good stiffness-to-weight performance as well as superior fatigue resistance when compared to traditional metal alloys. But due to the nature of the polymer matrix, some properties such as bolt-bearing capacity and lightning strike protection are reduced in comparison to traditional metal alloys. In addition, current PMCs are not useful in the temperature ranges required for supersonic aircraft. To overcome these issues, the HTCL family of laminates was developed, and they have shown great potential in initial studies.

INITIAL FINDINGS

In preliminary research performed by Miller *et al* [8] at NASA-LaRC, the first topic that was examined was the mechanical properties of HTCL. Using Ti-6Al-4V (Ti-6-4) titanium alloy, IM7 carbon fibers, and LaRC-IA polyimide as the constituent materials in the HTCL, the monotonic and fatigue properties of this laminate were determined. The polyimide adhesive and the IM7 carbon fibers were essentially a polymer matrix composite (PMC) layer that also served as an adhesive for the titanium foils. The Ti-6-4 foils were treated with Pasa-Jell 107, which produces a stable oxide and a micro-rough surface on the titanium foil. This surface treatment improves the durability and strength of the adhesive bond. The initial stress-strain response of the HTCL laminate was determined at room temperature and compared to the response of monolithic titanium. Miller *et al* found that the performance of the HTCL was dependent upon processing methods and procedures used.

To develop some predictive techniques for HTCLs, the AGLPLY laminate code was employed. The AGLPLY code was originally developed to analyze metal matrix composites, based upon constituent properties. It had demonstrated good predictive ability for metal matrix composites, so its predictive ability was evaluated for this

laminate. The AGLPLY code performs an elastic-plastic analysis of symmetric laminated plates under in-plane mechanical loads (non-bending). The lamina properties are calculated via the vanishing fiber diameter (VFD) model; this model assumes a rule of mixtures contribution of the fiber modulus to the composite modulus in the longitudinal direction, but it does not allow for any transverse constraint by the fiber. AGLPLY calculates the overall laminate elastic moduli and the local fiber and matrix stresses and strain in each ply, as well as the overall laminate strains for the entire elastic-plastic loading regime.

After the static stress-strain performance was evaluated, specimens of HTCL and of Ti-6-4 were fatigued at a constant amplitude with an R-ratio of R=0.1 and at a frequency of 10 Hz. These fatigue specimens were straight-sided, containing a center hole. The applied fatigue loads were calculated by using an equivalent load-to-weight ratio for the HTCL and the Ti-6-4 specimens. The tests revealed that the HTCL displayed a dramatic increase in fatigue life of almost two orders of magnitude, when compared to monolithic titanium. This trend occurred both at room temperature and at elevated temperature fatigue tests.

HTCL MECHANICAL CHARACTERIZATION

Parametric Study

From this promising data, Li *et al* [7] began a systematic study of HTCL to determine the optimal combination of constituent materials, material volume fractions, and processing techniques. Li *et al* first performed a parametric analysis of HTCL with the AGLPLY laminate code. They investigated the effect of various fibers, fiber orientation, and the effect of different metastable titanium β-alloys on the mechanical performance of the laminate. In addition, Li *et al* varied the volume fraction of each constituent in the laminate. This parametric study focused on predicting the laminate stress-strain curve up to the failure point for each combination of constituent materials and volume fractions.

The AGLPLY laminate code output closely correlated the stress-strain response of the HTCL laminate investigated by Miller *et al* [8]. This good correlation helped validate the subsequent use of the AGLPLY laminate code in other analyses of HTCL. Using the stress-strain performance of each constituent material, the output from the AGLPLY laminate code provided insight into the performance of various HTCL lay-ups. As expected, the fiber properties had a pronounced influence upon the stress-strain response of HTCL.

The comparison made between various fiber orientations in HTCL found that the titanium foils made the HTCL much more isotropic without reducing the potential for high stiffness. In fact, the HTCL is nearly as stiff as the PMC in the fiber direction, but the HTCL modulus is more than ten times greater than the PMC modulus in the transverse direction.

Fatigue Properties and Damage Mechanisms

After completing the parametric study, Li and Johnson [9] examined the fatigue properties of HTCL and of the titanium foils used in HTCL. The HTCL that was used in these fatigue tests was a "baseline" laminate that consisted of thin titanium foils with LaRC-IAX polyimide adhesive and IM7 carbon fibers forming a PMC layer between the titanium foils. To improve the bond strength of the titanium to the LaRC-IAX adhesive, the Pasa-Jell 107 surface treatment was applied to the titanium foils.

The fatigue tests used straight-sided specimens for tests at room temperature, and also at 350°F (177°C). The HTCL specimens were cycled at an R-ratio of 0.1, and various load levels to produce the fatigue profiles. From these tests, the endurance limit, or maximum stress at 1×10^6 cycles, was greater than 100 ksi. This is approximately a 10% increase above the fatigue strength of the monolithic titanium alloy.

An important discovery made during fatigue testing was that the endurance limit actually *increased* slightly at an elevated temperature of 350°F (177°C). This endurance limit increase is primarily due to two factors: 1) the laminate realized a reduction in residual stress between the titanium foils and the PMC layers at higher operating temperatures, and 2) the titanium alloy showed an improvement in toughness at elevated temperatures.

During fatigue, the progression of damage in the laminate occurs with the development of cracks in the outer titanium foils, and subsequent failure of the PMC layers through the thickness of the specimen. The PMC layers provide a damage tolerant mechanism by shielding adjacent titanium plies from the cracked ply. The ply-by-ply failure of the titanium foils requires a re-initiation of the crack at each titanium-polymer interface, thereby providing a fatigue resistant mechanism for the HTCL. Once the titanium ply is cracked, the applied stress that it was supporting is then transferred to the PMC layers, increasing the stress on the PMC. The failure of the entire HTCL is predicated by the failure of a sufficient number of the PMC layers, which occurs if the applied stress is large enough.

The absence of polymer on the titanium foils indicated that the interfacial strength was lower than the cohesive strength of the polymer, so the failure was between the PMC and the titanium foil instead of within the PMC. It is important to note that the HTCL can still carry a substantial fatigue load if that load is below the ultimate strength of the PMC

layers, even when all of the titanium plies are cracked and carrying no load.

DURABILITY OF HTCL

Some important issues surfaced during fatigue testing regarding the failure modes and damage mechanisms of HTCL. The extensive delamination observed during fatigue failure indicated that the bond strength between the titanium and the polyimide should be optimized to provide the desired amount of delamination. Also, durability issues regarding the titanium-polyimide bond need to be examined after long-term exposure in elevated temperatures and also in hot, humid environments.

The primary method to improve bond strength and durability is to prepare the surface of the titanium. The surface treatment produces a relatively continuous micro-rough surface on the titanium foil, which improves the mechanical interlocking between the titanium and the polyimide. The improved mechanical interlocking results in not only a stronger bond, but also a more durable bond, because the interface does not rely solely on chemical bonds that may be broken with the infiltration of water.

Materials

This durability study used 50 mil thick sheets of Ti-15Al-3Cr-3Sn-3Al (Ti-15-3 – a metastable β-alloy) in cracked-lap shear specimens. We examined three titanium surface treatments on the Ti-15-3 foils in this study: a) Sol-Gel, b) Turco 5578, and c) Pasa-Jell 107. Sol-Gel is a proprietary surface treatment developed by The Boeing Company for use in titanium bonding applications. It is a relatively new process, and it has shown good bonding strength on titanium. Turco 5578 is a more mature surface treatment process that is used by the Lockheed-Martin Corporation. It has shown good resistance to moisture and high temperatures in several bonding applications. Pasa-Jell 107 is a surface treatment that is used by NASA, and it also has shown reasonable moisture resistance and good performance at high temperatures. We did not include the well-known surface treatment Chromic Acid Anodizing (CAA), because of the environmental regulations that restrict the future use of many of these processes.

In addition to comparing the candidate surface treatments, this study also investigated the differences between two high-performance polyimides, FM5 and LaRC-IAX. FM5 (Cytec Industries) and LaRC-IAX (NASA-LaRC) have both shown very promising results in earlier studies.

Specimens

This study utilized a cracked-lap shear bonded joint specimen to quantify the adhesive strength of the polyimide-titanium bond. To simplify the analysis of the bond strength and durability, NASA-Langley manufactured cracked-lap shear specimens for this study that did not include reinforcing carbon fibers. The cracked-lap shear specimen configuration was chosen because of its close approximation to bonds that are commonly found in aerospace structures, and also because of numerous prior studies that demonstrated the viability of this configuration.

Mechanical Testing

With three titanium surface treatments and two polyimides, there were six specimen types that we tested. First, we tested the as-received fatigue performance of each specimen type at a variety of loadings to produce a da/dN versus ΔG graph. This graph gives an indication of the sensitivity of the bond to crack initiation and growth, and also of the minimum energy required to propagate a crack. After fatigue testing, we also measured the fracture toughness of each specimen type.

From these tests, we found that the Sol-Gel surface treatment increases the fatigue strength and fracture toughness significantly, as compared to the other two surface treatments. Another important finding is that there was only a slight difference in the performance of HTCLs made from the two polyimides.

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