FATIGUE CRACK PROPAGATION IN FeAl AND TiAl ALLOYS AS INFLUENCED BY ENVIRONMENT AND TEMPERATURE

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The influence of environment and temperature on the fatigue crack propagation behavior of two intermetallic alloys based on different aluminides, namely TiAl and FeAl, has been investigated on the basis of crack-closure corrected data. A pronounced environmental effect is observed for the various temperatures investigated. Moreover this environmental contribution seems to remain constant whatever the temperature, at least for the TiAl alloy. At room temperature water vapor is shown to be responsible for the observed embrittlement ; in addition oxygen seems efficient to prevent it in the case of the FeAl alloy, but not for the TiAl alloy.

INTRODUCTION

Ordered intermetallic alloys based on aluminides are currently holding great promise as elevated-temperature structural materials in place of superalloys used at present. Their attractive properties include excellent oxidation and corrosion resistance, light weight and superior strength at elevated temperatures. During the last ten years, considerable efforts have been devoted to the research and understanding of factors controlling brittle fracture in intermetallic alloys based on aluminides. Parallel works on alloy design have led to the development of more ductile and strong intermetallic alloys, and among them those based on TiAl and FeAl. However the fatigue crack propagation resistance of these materials remains ill-known although their damage tolerance assessment might be of high interest.

The present study is addressing this issue. The fatigue crack growth resistance of two TiAl and FeAl alloys has been investigated for temperatures ranging from ambient to 800°C and under various environmental conditions. Indeed it has been shown by Liu (1) that aluminides are prone to environmental embrittlement during tensile tests in moist environments. As a consequence environment is expected to play a detrimental role in the fatigue damage in these compounds. In order to overcome possible confusion in the

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analysis that may arise from interactions between closure mechanisms and environmental effects, only effective data, that means crack-closure corrected data, have been considered here. The influence of environment has then been studied as a function of temperature. Comparisons between the two aluminides, namely TiAl and FeAl are expected to provide information, especially on surface reactions.

EXPERIMENTAL PROCEDURE

The gamma titanium aluminide alloy considered in this study is a quaternary alloy of nominal composition Ti-48Al-2Mn-2Nb (at.%). The material was provided as a piece of ingot produced in a large-scale plasma furnace by the IRC (Interdisciplinary Research Center) in Birmingham (UK). Further details are given by James and Bowen (2). In the as-cast condition the microstructure is nearly fully lamellar, consisting of coarse alternating γ and α_2 plates grains with a grain size of approximately 300-400 μm.

In order to gain further insight into the embrittling mechanisms, another kind of aluminide, namely a B_2 FeAl alloy of composition Fe-39.7Al-0.05Zr-50ppmB (at.%), is considered. The material was provided by CEA/CEREM/DEM in Grenoble (F) in the form of bar. The composition of the alloy is selected in order to provide the best room-temperature ductility by grain boundaries strengthening. Grain size reduction is obtained by mechanical alloying. This powder metallurgy technique also let to introduce a nanometric oxide dispersion of Y_2O_3 particles (1 wt.%) within the microstructure in order to enhance strength and inhibit grain growth during consolidation of the material and thermal treatments. The material is subsequently either hipped or extruded. The alloy designed as HIP-FeAl is hipped at 1100°C under a pressure of 100 MPa during 2 hours. The one designed as FeAl40 grade 3 is extruded at 1100°C using an extrusion ratio of 30:1. The grain size is approximately 1 μm. More information about the microstructures of the material is available in references (3-4). Previous tests conducted in air and in vacuum on HIP-FeAl and on FeAl40 grade 3 with different notch orientations have shown that the microstructures considered in this study have no influence on the effective fatigue crack propagation (4).

Fatigue crack growth experiments were generally carried out using CT type specimens (W=22 mm, B=5 mm). Tests in vacuum at high temperature were conducted on KTr type specimens (5). In the case of FeAl40 grade 3, due to the small diameter of extruded bars, small DCT specimens with W=10 mm and B=2.5 mm were used.

Fatigue crack growth tests were carried out on servohydraulic machines equipped with an environmental cell permitting tests in high vacuum (10^{-3} Pa) or in controlled atmosphere at room temperature, and/or a resistance furnace operating up to 1000°C. The tests were conducted under sinusoidal loading at 20 Hz or 35 Hz generally with a constant load ratio R=0.1. The crack length was determined by the use of a direct current potential difference technique. At room temperature it was also possible to optically measure the crack length on the polished side of the specimens by means of a travelling microscope. Crack closure measurements were performed at test frequency according to the unloading compliance method using, at room temperature, a back face gauge and, at elevated temperature, a sensor recording the rod displacement more precisely than the LVDT signal of the actuator.

RESULTS AND DISCUSSION

Fatigue crack propagation and environmental enhancement at room temperature

Experiments have been carried out under different environmental conditions. Two types of tests in vacuum were performed : tests in high vacuum of better than 5.10^{-4} Pa and tests under low vacuum of roughly 2 Pa. In both cases the residual atmosphere is mainly composed by water vapor. Additional tests under oxygen atmosphere have been conducted. The residual moisture content lies around 15 ppm, which was the water vapor content of low vacuum conditions. The fatigue crack growth rates of the Ti-48Al-2Mn-2Nb and the HIP-FeAl alloys tested at room temperature in laboratory air and under these various environments are shown in figures 1 and 2. The results indicate a significant environmental enhancement of the crack growth. For Ti-48Al-2Mn-2Nb, fatigue crack growth rates are some two orders of magnitude higher in air than in high vacuum ; the same trend can be seen for HIP-FeAl, with a difference of one order of magnitude.

As for conventional alloys, the deleterious effect of environment might be attributed to the presence of moisture in the test atmosphere and subsequent hydrogen embrittlement (6). In the case of aluminides Liu proposes a kinetic approach based on their ductility's evolution in air and in dry oxygen as a function of temperature (1). He supposes the existence of a competitive adsorption process between water vapor and oxygen on the crack surfaces. The embrittlement is attributed to the reaction of aluminum in the alloy with adsorbed water vapor producing Al_2O_3 and hydrogen which diffuse into the bulk material where the embrittling reaction takes place. This would explain the higher ductility observed by Liu and Kim in oxygen atmosphere with respect to air and even vacuum in the case of FeAl and TiAl alloys at room temperature (1, 7).

Therefore the question is to determine whether water vapor is actually the mere active species in terms of surface reactions, or whether oxygen adsorption might compete, in the particular case of a crack tip. Figures 1 and 2 show that the fatigue crack growth rates for Ti-48Al-2Mn-2Nb and HIP-FeAl alloys in a low vacuum atmosphere with an intermediate moisture level are consistently intermediate between those obtained in high vacuum and in ambient air. Very little differences between tests in low vacuum and oxygen have been seen for Ti-48Al-2Mn-2Nb. This suggests that the fatigue crack growth resistance for this γ titanium aluminide is essentially governed by the amount of water vapor present in the test atmosphere. In particular, oxygen is proved to be inefficient in competing with water vapor, at least for the compositions examined here, which is somewhat contradictory with the results of Liu and Kim (1,7) mentioned above. Figures 3 and 4 show fatigue crack growth rates obtained in the same environmental conditions for FeAl40 grade 3 under closure free conditions. In this case, the fatigue crack growth rates observed in oxygen environment are nearly similar to those observed under high vacuum and significantly slower than those observed in low vacuum. Therefore oxygen seems to be efficient in preventing the moisture-related fatigue crack growth enhancement for this compound.

The observations suggest that the two alloys behave differently with regards to the compound associated to aluminum. So the base alloy seems to have an essential influence on the competitive adsorption process. The role of metallurgical factors such as composition, as the peculiarity of the crack tip, should be more deeply examined.

Fatigue crack propagation and environmental enhancement at elevated temperature

The fatigue crack growth rates of the Ti-48Al-2Mn-2Nb and the HIP-FeAl alloys tested in air at different temperatures (in the neighborhood of their potential applications temperature range) are shown in figures 1 and 2, with da/dN plotted as a function of $\Delta K_{eff}/E$ in order to take into account the Young modulus retention. The behaviors of the Ti-48Al-2Mn-2Nb alloy at room temperature, 750°C and 800°C are almost identical with only slight differences for crack growth rates between 6.10^{-8} and 5.10^{-7} m/cycle. The threshold values are similar for all temperatures. The same conclusions apply for the HIP-FeAl alloy.

This reduced effect of temperature on the fatigue crack growth resistance might results from a balance between a modification of the intrinsic behavior and environmental effects. The following aims to elucidate this point by analyzing the intrinsic fatigue crack propagation resistance of the Ti-48Al-2Mn-2Nb alloy on the basis of effective data generated in an inert environment. Figure 5 compares the effective results obtained at 20°C, 750°C and 850°C in vacuum to those obtained in air. The intrinsic behavior of the alloy seems to be slightly improved when temperature increases, at least above 10^{-8} m/cycle. In fact the threshold values are identical but the slopes of the curves are less important at high temperature. The resistance's variation observed between the different temperatures at high crack growth rates could be related to the variation of toughness as a function of temperature. Indeed Gnanamoorthy et al. report an increase in fracture toughness with increasing temperature for γ titanium aluminides (8).

Therefore the effect of environment in the Ti-48Al-2Mn-2Nb alloy remains roughly constant whatever the temperature. This is not consistent with the model proposed by Liu (1) since at higher temperature the effect of environment should decrease because of an enhancement of oxygen adsorption, and a subsequent decrease of hydrogen production. The analysis based on kinetics of surface reactions seems not to be sufficient to explain the process during cyclic loading. Further work is required to identify the controlling step of embrittling process with respect to temperature and to assess the role of hydrogen.

CONCLUSION

The fatigue crack growth behavior of two intermetallic alloys based on aluminum have been tested at room and elevated temperatures, as under various environmental conditions. The following conclusion have been reached from this investigation :

1. At room temperature, the fatigue crack growth resistance is deeply altered in ambient air as compared to vacuum. This loss of resistance appears to be governed by the water vapor content. Oxygen adsorption is inefficient in preventing this embrittling effect in the TiAl alloy, but oxygen competition adsorption exists in the case of the FeAl alloy.
2. Very little differences have been noticed between fatigue crack growth resistance in air at room temperature and at high temperature. In the slow growth rate regime, no marked variation in the environmental contribution has been observed whatever the temperature.

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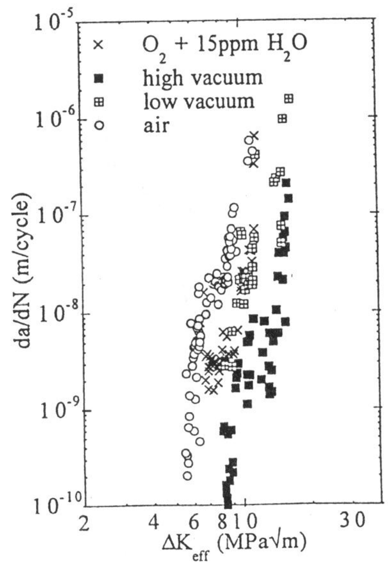


Figure 1. Influence of environment at 20°C in the Ti-48Al-2Mn-2Nb alloy.

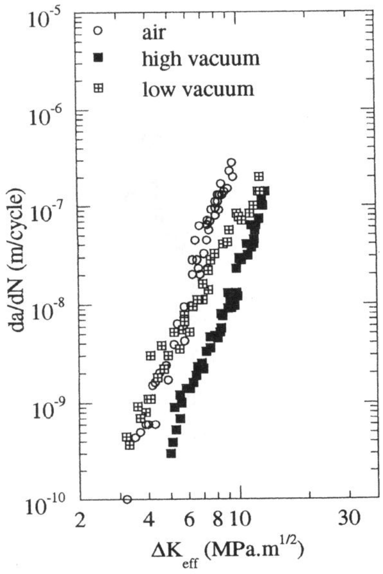


Figure 2. Influence of environment at 20°C in the HIP-FeAl alloy.

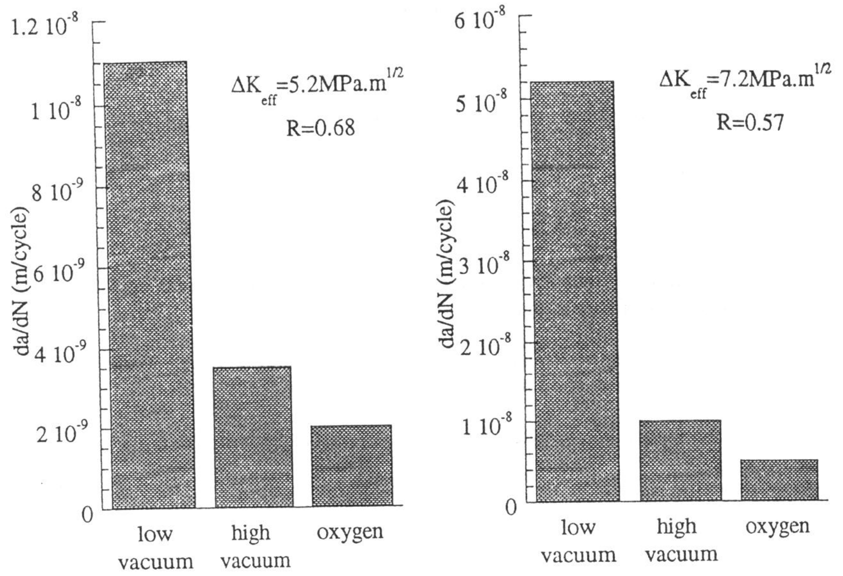
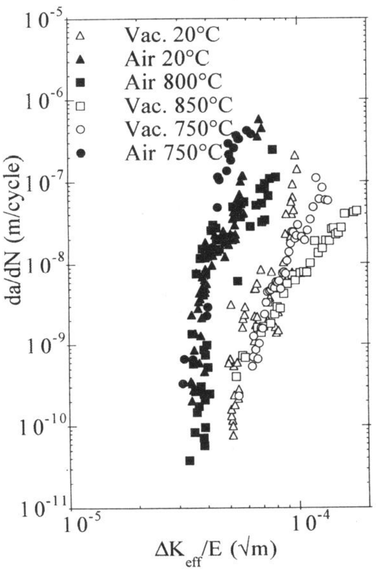


Figure 3. Fatigue crack growth rates obtained at 20°C under various environmental conditions in the FeAl40 grade 3 alloy.



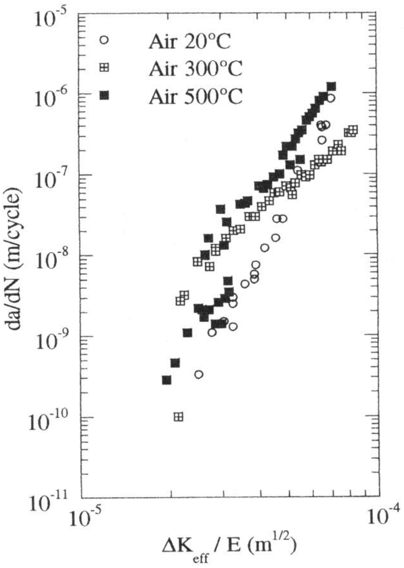


Figure 4. Influence of temperature in air and in vacuum in the Ti-48Al-2Mn-2Nb alloy.

Figure 5. Influence of temperature in air in the HIP-FeAl alloy.