HIGH TEMPERATURE DYNAMIC FRACTURE TOUGHNESS INITIATION IN GAMMA MET PX

Mostafa Shazly & Vikas Prakash
Case Western Reserve University
Department of Mechanical and Aerospace Engineering
Cleveland, OH 44106-7222

ABSTRACT

Gamma titanium aluminides are inherently brittle low temperature alloys. Recently, Gamma Met PX has been developed for better rolling and post rolling characteristics that enable manufacturing of thin foils and sheets. Previous work on this alloy has shown that the material has high strength at room and elevated temperatures when compared to other gamma titanium alloys. It also showed increased ductility at elevated temperatures under both quasi-static and high strain-rate uniaxial compressive loading. However, the high strain rate tensile ductility at room and elevated temperatures was observed to be limited to a maximum of 1%.

The objective of the present paper is to investigate the effect of loading rate and temperature on the dynamic fracture initiation toughness of Gamma Met PX. An instrumented Modified Split Hopkinson Pressure Bar (MSHPB) was used as the loading device. A high-speed digital camera (Hadland ULTRA 17) was used to determine the critical crack initiation time and correlate it to the strain gage measurements on the MSHPB. An induction coil heating system was used to heat the specimens in the range from 200^{o}C to 1200^{o}C. Experiments were conducted using three point bend specimens at impact speeds of approximately 1 m/sec. Such low impact speeds were necessary to avoid effects of material inertia. The results show that the dynamic fracture initiation toughness decreases with increasing test temperatures beyond 600^{o}C. Furthermore, the effect of high temperature exposure for long times on the dynamic fracture initiation toughness was investigated by conducting relatively low. impact speed tests at room temperature. The dynamic fracture initiation toughness of the material was found to decrease with increasing exposure time. SEM investigation showed the formation of an oxide scale on the surface of the specimen, the thickness of which increased with increasing exposure time.

1 INTRODUCTION

Over the last two decades a large body of research has been developed that characterizes the quasistatic fracture toughness of gamma titanium aluminides in terms of chemical composition [1-3], microstructure and microstructural features [2-7]. However, research to characterize dynamic fracture toughness of gamma titanium aluminides has been limited to a few studies involving the use of either servo hydraulic machines and/or the Charpy impact method. These studies include the effect of loading rate on the dynamic fracture toughness [5, 8], and the effect of microstructure on the Charpy impact energy [5]. At high strain rates and elevated temperatures, Matsugi et al. [9] studied Charpy impact properties of two different spark sintered Ti-53Al (mol.%) alloys having different microstructures in the notch region. It was found that the Charpy impact energy increases monotonously with an increase in test temperatures, and is almost the same for the two microstructures at each test temperature. However, the maximum load measured during the tests was observed to be independent of the test temperatures up to 600°C for the first microstructure and 520°C for the second microstructure. This was followed by a continuous drop in fracture toughness up to 1127°C. Although this behavior could be explained in terms of a change in fracture mode, no attempt was made to correlate this to the uniaxial response of the material. Fukumasu et al. [10] studied the dynamic fracture toughness of Ti-45Al-1.6Mn alloy at elevated temperatures and at loading velocities of 0.1 and 1 m/sec using a servo hydraulic machine. The fracture toughness at 0.1 m/sec was observed to be always slightly higher that that at 1 m/sec. Moreover, the fracture toughness was observed to increase with increasing test temperatures for the two loading velocities up to 600°C. At higher temperatures the fracture toughness is observed to drop. This behavior is consistent with the uniaxial data obtained for this material which showed yield anomaly at 600°C.

The objective of the present paper is to investigate the effect of loading rate, test temperature and long time-high temperature exposure on the dynamic fracture toughness initiation in Gamma Met PX.

2 EXPERIMENTAL WORK

2.1 Material

The Gamma Met PX material used in the present study was supplied by Plansee AG in the form of sheets having a thickness of 5.5 mm. It has a chemical composition of Ti-45Al-X (Nb, B, C). Microstructural investigation shows that the material consists of a duplex microstructure.

2.2 Dynamic Fracture Toughness Testing, the Modified Split Hopkinson Pressure Bar (MSHPB)

The Modified Split Hopkinson Pressure Bar has become an attractive alternative technique to the Charpy Impact test methods to determine the dynamic fracture initiation toughness of engineering materials. The advantages of MSHPB over Charpy methods include (a) it's relatively simple set-up, (b) accurate determination of both the load and the load-point displacement using one-dimensional wave analysis, and (c) minimization of material inertia effects.

The schematic of the Modified Hopkinson Pressure Bar (MSHPB) apparatus is shown in Figure 1. The diameter of the incident and the striker bars is 19.05 mm and the radius at the end of the incident bar that is in contact with the specimen, i.e. at the load point, is machined to be approximately 50 mm. The measured strain profiles are used in conjunction with one-dimensional elastic wave theory to obtain the load versus displacement history at the incident bar specimen interface, i.e. the load point. This load versus displacement history is used along with principles of linear elastic fracture mechanics (LEFM) to obtain the dynamic fracture initiation toughness.

In order to conduct the high temperature experiments, the three point bend specimens were heated using an induction coil heating system (Hüttinger TIG 10/100 RF generator). The temperature of the specimen was monitored by thermocouple wires attached to the specimen surface. A 0.015”chromel-alumel wire is spot welded to the specimen to monitor the specimen temperature prior to the test.

The specimen used in the present study was designed according to ASTM 812. Due to the brittle nature of this material no fatigue pre-cracking was performed, however, the notch was extended 1 mm beyond the V-notch using and EDM wire of diameter 0.006”giving a notch radius of 75 μm.

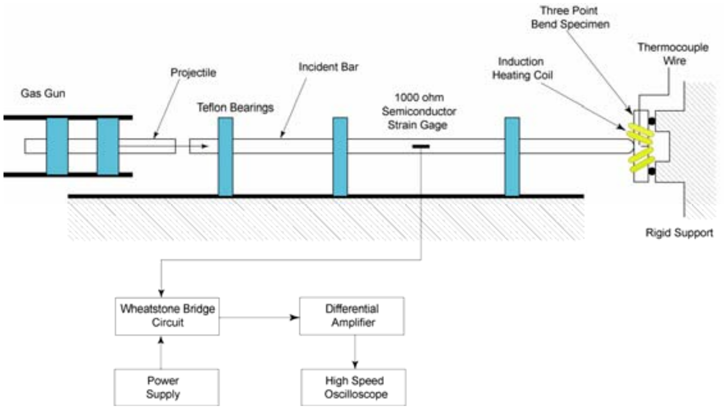

Figure 1: Schematic of the modified split Hopkinson pressure bar used for dynamic fracture testing in the present study.

2.3 Long-Time High Temperature Exposure:

Although gamma titanium aluminide is targeted for an operating temperature of 900°C, embrittlement by oxidation has limited it’s use to maximum operating temperature of 700°C. Several authors have studied the effect of chemical composition, microstructure, and environment on the oxidation behavior of gamma titanium aluminide alloys. Cheng [11] and Huang et al. [12] studied the effect of thermal exposure at 700°C for up to 3000 hours on the microstructure instability of different gamma alloys. Their studies showed that although there was evidence of microstructural instability in these alloys, it did not lead to degradation of the mechanical properties of these alloys. However, in their results the effect of formation of oxide scales on the surface of the specimen was not included. A detailed study by Pather et al. [13] showed that including the surface effects lead to a significant drop in the tensile strength. However, this drop was dependent on the alloy composition.

In the present study, in order to quantify the effect of high temperature exposure on the dynamic fracture toughness initiation in Gamma-Met PX, samples were exposed at 700°C for 100 hrs, 200 hrs and 300 hrs and then tested at room temperature under the same conditions as those used for the as-received samples.

2.4 Results and Discussions:

To determine the influence of material inertia effects, a series of experiments were conducted at room temperature and impact velocities ranging from 1.0 m/sec to about 4.0 m/sec. The high speed camera (Hadland ULTRA 17) was used to determine the initiation time. For impact speeds less than approximately 2.5 m/sec, the crack initiation time was observed to coincide with the maximum load. For higher impact speeds, material inertia effects were observed to important and the crack initiation times no longer coincided with the peak load, as shown in Figure 2. This observation is, however, consistent with the analysis by Nakamura et al. [14], which for the current specimen design and loading rate (Λ=1 and c_o =6622 m/sec) predict a transition time of $t_{\tau} \simeq 15\,\mu\mathrm{sec}$. The times corresponding to the occurrence of maximum load for the high impact speed experiments are approximately 15 and 21 μsec. Therefore, in order to avoid effects of material inertia and assure fracture initiation at peak load all high temperature experiments were conducted at impact speeds of approximately 1.0 m/sec and lower. Figure 2 also shows an increase in the dynamic fracture initiation toughness with increasing impact velocities up to the point where the critical crack initiation time corresponds to the maximum measured load. However, this contradicts the reported results for other gamma titanium aluminides by Sun et al. [8] where the fracture toughness initiation was independent on the loading rate, and the results by Fukumasu et al. [10] where higher fracture initiation toughness was observed at lower loading rates.

Figure 3 shows the effect of test temperature on the dynamic fracture toughness initiation. The room temperature dynamic fracture initiation toughness is approximately 22.5 MPa.m$^{1/2}$ and drops to about 13 MPa.m$^{1/2}$ at 1200^{o}C. The dynamic fracture initiation toughness is almost constant up to test temperatures of ~ 650^{o}C, after which it is observed to drop precipitously. Although it is expected that the fracture toughness will increase with increasing test temperatures, the situation is different under dynamic loading. This observation is consistent with results obtained for other Gamma titanium alloys with a different microstructure under dynamic loading conditions. The material showed increased ductility and drop in the flow stress with increasing test temperatures beyond ~ 650^{o}C under uniaxial dynamic compression. However, the situation was different under uniaxial dynamic tensile loading, where the material showed a drop in material flow stress while maintaining its room temperature ductility. Therefore, under dynamic three point bend loading, where the material is expected to fail in a tension mode, it fails at the same crack tip opening displacement regardless of the test temperature. Moreover, for tests at elevated temperatures, the material's flow stress drops, and hence requires less force to initiate the crack. This observation is somewhat consistent with the work by Matsugi et al. [9] and Fukumasu et al. [10]. To verify the effect of loading rate on the fracture toughness initiation, a screening test was conducted at 900^{o}C and a loading rate of 4.0x10^{-7} m/sec. In this test, substantial plastic deformation was observed in the vicinity of the specimen notch. A detailed study of the quasi-static high temperature fracture toughness of Gamma-Met PX is beyond the scope of the current study.

Figure 4 shows the effect of exposure time on the room temperature dynamic fracture toughness initiation. The fracture toughness is observed to drop as the exposure time increases. This behavior is understood to be due to the change in the oxide scale thickness and/or depth of oxygen diffusion with time. A detailed study of the oxide layer and oxygen diffusion is currently underway.

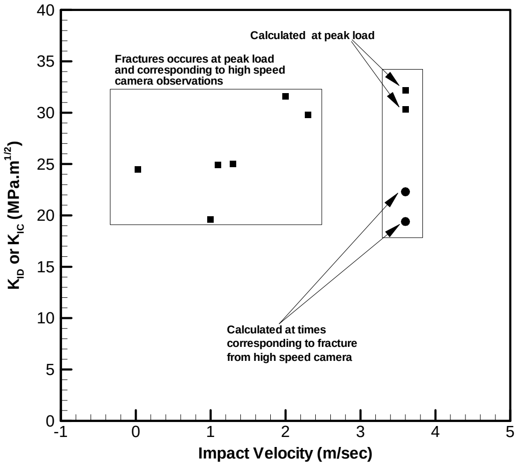

Figure 2: Effect of impact speed on the crack initiation time

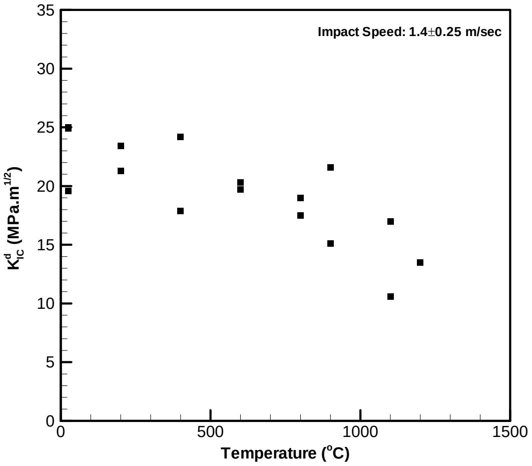

Figure 3: Effect of test temperature on the dynamic fracture toughness initiation.

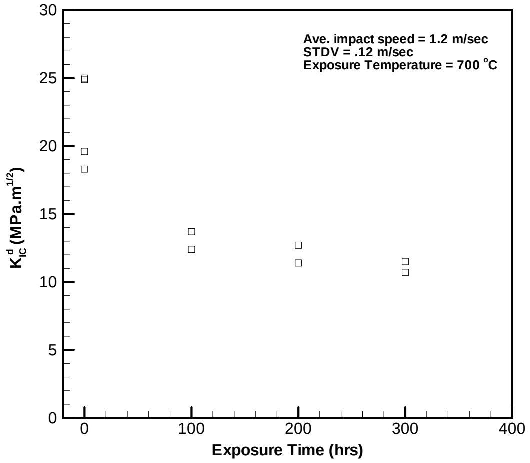

Figure 4: Effect of high temperature exposure times on dynamic fracture toughness initiation

REFERENCES

[1]. Huang, S-C; Hall, E.L.; Plastic Deformation and Fracture of Binary TiAl Base Alloys. Metallurgical Transactions A, 22A, 427-439, 1991.

[2]. Dogan, B.; Schöneich, D.; Schwalbe, K.-H.; Wagner, R.; Fatigue Precracking and Fracture Toughness Testing of TiAl Intermetallics. Intermetallics, 4, 61-69, 1996.

[3]. Liu, C.T.; Schneibel, J.H.; Maziasz, P.J.; Wright, J.L.; Easton, D.S.; Tensile Properties and Fracture Toughness of TiAl Alloys with Controlled Microstructure. Intermetallics, 4, 429-440, 1996.

[4]. Kim, Y-W; Effect of Microstructure on the Deformation and Fracture of γ-TiAl alloys. Materials Science and Engineering A. 192/193, 519-533, 1995.

[5]. Enoki, M.; Kishi, T.; Effect of Rate on the Fracture Mechanism of TiAl. Materials Science and Engineering A, 192/193, 420-426, 1995.

[6]. Rogers, N.J.; Crofts, P.D.; Jones, I.P.; Bowen, P.; Microstructure Toughness Relationships in Fully Lamellar γ-Based Titanium Aluminides. Materials Science and Engineering A, 192/193, 379-386, 1995.

[7]. Morris, M.A.; Leboeuf, M.; Grain Size Refinement of γ-Ti-Al alloys: Effect on Mechanical Properties. Materials Science and Engineering A, A224, 1-11, 1997.

[8]. Sun, Z.M.; Kobayashi, T.; Fukumasu, H.; Yamamoto, I.; Shibue, K; Tensile Properties and Fracture Toughness of Ti-45Al-1.6Mn Alloy at Loading Velocities of up to 12 m/sec. Metallurgical and Materials Transactions A, 29A, 263-277, 1998.

[9]. Matsugi, K.; Hatayama, T.; Yanagisawa, O; Impact Properties of Spark Sintered Titanium Aluminides at Elevated Temperatures. Intermetallics, 7, 1049-1057, 1999.

[10]. Fukumasu, H.; Kobayashi, T.; Toda, H.; Shibue, K; Dynamic Fracture Toughness of a Ti-45Al-1.6Mn Alloy at High Temperature. Metallurgical and Materials Transactions A, 31A, 3053-3061, 2000.

[11]. Cheng, T.T.; Effect of thermal exposure on microstructure and properties of a γ-TiAl based alloy containing 44Al-4Nb-4Zr-0.2Si-0.3B. Intermetallics, 7, 995-999, 1999.

[12]. Huang, Z.W.; Voice, W.; Bowen, P.; The effect of long-term air exposure on the stability of lamellar TiAl alloys. Intermetallics, 8, 417-426, 2000.

[13]. Pather, R.; Mitten, W.A.; Holdway, P.; Ubhi, H.S.; Wisbey, A.; Brooks, J.W.; The effect of high temperature exposure on the tensile properties of γ TiAl alloys. Intermetallics, 11, 1015-1027, 2003.

[14]. Nakamura, T.; Shih, C.F.; Freund, L.B.; Analysis Of A Dynamically Loaded Three-Point Bend Ductile Fracture Specimen. Engineering Fracture Mechanics, 25(3), 323-339, 1986.