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MICROSTRUCTURE AND FRACTURE OBSERVATION OF HOT-PRESSED AND AS-CAST γ-TiAl-BASED ALLOYS

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Microstructure and fractured surfaces in compression of Ti-48Al and Ti-48Al2Cr-2Mo alloys produced by hot-pressing and arc melting techniques were characterized by using scanning electron microscope (SEM) combined with energy dispersive spectroscopy (EDS). The results show that hot pressed TiAl Alloys exhibited microstructure consisting of the γ phase as the matrix (darker contrast areas) and α_2 phase (gray areas), while the as-cast TiAl alloys showed duplex microstructure consisting of primary γ grains and (α_2 +γ) lamellar colonies. As compared to hot pressed TiAl alloys, all the alloying elements were observed to be more homogeneously distributed in the as-cast TiAl alloys; the regions containing impurity elements in the microstructure of as-cast TiAl alloys were relatively lower. The fractured surfaces of hot pressed TiAl alloys exhibited transgranular fracture modes with apparent cleavage facets. Occasionally intergranular fracture mode was apparent in the fracture surface of hot-pressed Ti-48Al-2Cr-2Mo. In the fracture surfaces of as-cast TiAl alloys, the fracture modes were mixed transgranular and interlamellar. Due to the layered structure of lamellae, step-like transgranular fracture of lamellae was also apparent, particularly in the fracture surfaces of as-cast Ti-48Al-2Cr-2Mo. Both hot-pressed and as-cast TiAl alloys showed fracture surfaces having typical cleavage facets without the appearance of flat and featureless facets, which are a characteristic of brittle fracture with some ductility.

1. INTRODUCTION

Advanced engine concepts that incorporate light weight materials show potential for improvement in engine efficiency, environmental compatibility, economic performance and the safety of transport systems [1]-[3]. As compared to the metallic materials used in automotive and gas turbine engine industries today, γ-TiAl alloys were reported to have a lower density and higher modulus of elasticity with high specific strength and creep resistance. Gamma-TiAl alloys are targeted for temperature application range of 600 °C to 900 °C, as a material substitute for superalloys and must survive hundreds of hours in this temperature range. However, low room temperature ductility of these alloys has become the obstacles in handling, machining and processing.

The constituent phases of γ-TiAl alloys have been reported to be γ-TiAl (ordered face-centered tetragonal $L1_0$ structure) and α_2-Ti_3Al (ordered hexagonal DO_{19} structure) [4], [5]. The ductility depends on the prevailing fracture behavior [6]. Cleavage fracture is usually associated with low or zero ductility, but it may also occur after some plastic deformation, as in TiAl intermetallics [7], [8]. The fracture behavior in TiAl alloys is known to be sensitive to microstructure [5], [9]. Intergranular fracture and cleavage are the dominant fracture mechanisms in the duplex and equiaxed microstructures, while interfacial delamination, transgranular fracture and decohesion of lamellar colonies are the most important failure processes in lamellar alloys. The microstructure of an γ-TiAl alloy obtained depends on the processing routes [2], [5] such as powder metallurgy route through hot pressing and casting by arc-melting. Therefore, these techniques were expected to produce γ-TiAl alloys with improved properties, especially the room temperature ductility and strength.

In this study, microstructure and fracture behavior of hot-pressed and as-cast TiAl alloys were characterized by using the scanning electron microscope (SEM) combined with energy dispersive spectroscopy (EDS).

2. METHODS & MATERIALS

The raw materials used in this study were powders of titanium (average size of 83.81 μm and purity of 99.7 %, STREM Chemicals), aluminium (average size of 72.53 μm and purity of 95.7 %, BDH Laboratory supplies), molybdenum (average size of 122 μm and purity of 99.96 %, STREM Chemicals), and chromium (average size of 50.92 μm and purity of 99 %, STREM Chemicals). The powders were initially prepared to the desired compositions of Ti-48Al and Ti-48Al-2Cr-2Mo (all in at.%). The compositions were then mechanically alloyed at room temperature at a rotation speed of 125 rpm for a milling time of 3 hrs by using a planetary mill (Fritsch Pulverisette P5/4) [10]. The mechanically alloyed powders were subsequently hot pressed at the optimized conditions of 1100 °C for 1 hrs [11]. This will be referred to as-hot pressed γ-TiAl alloys.

Gamma-TiAl alloys with similar compositions to the hot pressed samples were also produced by arc-melting. The compositions were thoroughly mixed in a plastic PE bottle for 5 hours. The mixture was then compacted in a die by applying a hydraulic press with a pressure of 100 MPa. The size of pellet was 25 mm in diameter. The pellets were then melted using an in-house made arc-melting furnace [12]. Ingots were remelted eight times to ensure good homogeneity. This will be referred as the as-cast TiAl alloys.

Diamond-coated blade cutting tool was used to cut the hot-pressed and as-cast alloys into small specimens. Metallographic samples were polished and then etched in a solution of 10 vol.% HNO_3, 5 vol.% HF, and 85 vol.% water [9]. A cubic specimen 7 X 7 X 14 mm in size was cut and used for the compression test. All specimens were polished before testing. Compression tests were carried out at room temperature by instron servohydraulic testing machine with a crosshead speed of 0.07 mm/min. Scanning electron microscope (SEM) combined with energy dispersive spectroscopy (EDS) was used to predict the phases formed, microstructure and fracture surfaces of compressive samples. The measurement of average grain size in samples was also determined by mean intercept length method [13].

3. RESULTS & DISCUSSIONS

3.1 Microstructure of Hot pressed and as-cast γ-TiAl Alloys

Fig. 1 shows the back scattered scanning electron micrographs representing the microstructure of γ-TiAl samples produced by hot pressing. According to EDS analysis (Table I) in the main phases, it is possible to identify that the dark contrast in the back scattering image as γ phase and the gray contrast as α_2 phase. The microstructure of Ti-48Al consists of the γ phase as the matrix and α_2 phase with the average grain size of all the phases being approximately in the range of 62-93 μm. As it was observed there are black regions appearing in γ grains. This is analyzed to be the impurity elements such as C, O, which was incorporated in these regions as confirmed by EDS analysis. Microstructure comprising of γ phase and α_2 phase was also found for the Ti-48Al-2Cr-2Mo (Fig. 1b), with the grain size ranging approximately 62.50-75.00 μm. It was also observed that in this microstructure, black regions containing impurity elements such as O, C were formed in γ grains. These undesired elements were most probably from the starting raw materials and from the environment during processing, particularly during the mechanical alloying of the raw materials in air.

It can also be seen that the microstructure of Ti-48Al is much more homogenous than that of Ti-48Al-2Cr-2Mo. The microstructures of Ti-48Al-2Cr-2Mo also confirm that there were a number of Mo-rich precipitates occurring both in γ and α_2 grains. Based on EDS analysis, The concentration Mo in Mo-rich regions Ti-48Al-2Cr-2Mo was found to be approximately 11.44 (at.%). This is believed to be caused by the high melting point of Mo (2610 °C) that would not be fully diffused in the matrix during hot pressing, thus leading to unwanted inclusions.

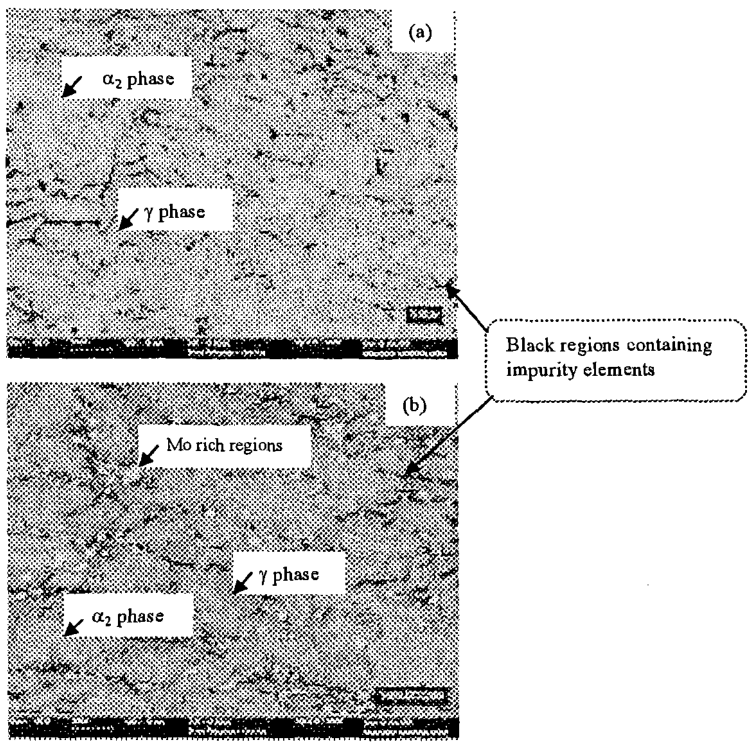

Fig. 1. Back scattered SEM micrographs showing the microstructures of hot-pressed TiAl alloys: (a) Ti-48Al and (b) Ti-48Al-2Cr-2Mo. Note: darker areas as γ phases and gray areas as α_2 phases.

Table I: Results of EDS analysis for hot-pressed TiAl alloys

Hot pressed TiAl alloys (at.%)	Phases	Ti (at.%)	Al (at.%)	Cr (at.%)	Mo (at.%)	Impurities (at.%)
Ti-48Al	γ	52.35	46.67	0.98	-	-
	α_2	62.29	29.22	-	-	8.49 %C
	Black region	33.91	54.02	-	-	10.06 %C
Ti-48Al-2Cr-2Mo	γ	42.26	52.87	4.13	0.4	0.35 %S
	α_2	59.70	37.85	2.12	0.33	-
	Mo-rich	47.96	38.41	2.19	11.44	-
	Black region	8.96	9.85	0.43	0.76	65.69 %C 14.32 %O

The non-uniform distribution of Mo during mechanical alloying could also increase the presence of Mo-rich area. Therefore, to eliminate Mo-rich regions, mechanical alloying with longer time would be required in order to enhance solubility of Mo in solid state [14], [15]. However, longer time for mechanical alloying would require more protective conditions in terms of milling media and the environment to prevent contamination of mechanically-alloyed powders. The incorporation of impurity elements such as oxygen in black regions in the microstructure of hot pressed samples is probably due to the mechanical alloying technique under air environment used in this study. Oxygen has high solubility in Ti and shows very limited solubility in aluminium [16].

Fig. 2 shows the back scattered SEM micrographs representing the microstructures of as-cast Ti-48Al and Ti-48Al-2Cr-2Mo alloys. Based on EDS analysis provided in Table II, it can be identified that there are primary γ phase and lamellar colonies with a small amount of α_2 phase being presents in all the revealed microstructures of as-cast TiAl samples. From the analysis of the phase diagram [5], the formation of the as-cast microstructure can be explained. After solidification from the liquid state, the binary Ti-48Al alloy passes through the single-phase field of the α solid solution and this is then followed by a solid state transformation, based on the reaction of $\alpha \rightarrow \alpha + \gamma \rightarrow \alpha_2 + \gamma$ to finally form the primary γ phase and $(\alpha_2 + \gamma)$ lamellae. The microstructure of Ti-48Al exhibits a duplex microstructure, which consists of the primary γ phases and $(\alpha_2 + \gamma)$ lamellar colonies, with grain size ranging approximately 47.59-71.39 μm (Fig. 2a). Non-uniform distribution of Ti-rich regions was also detected in the γ phases and lamellar colonies. A combined addition of Cr and Mo to Ti-48Al also shows a duplex microstructure comprising of primary γ phases and lamellar colonies, with grain size ranging approximately 51.23-70.44 μm (Fig. 2b).

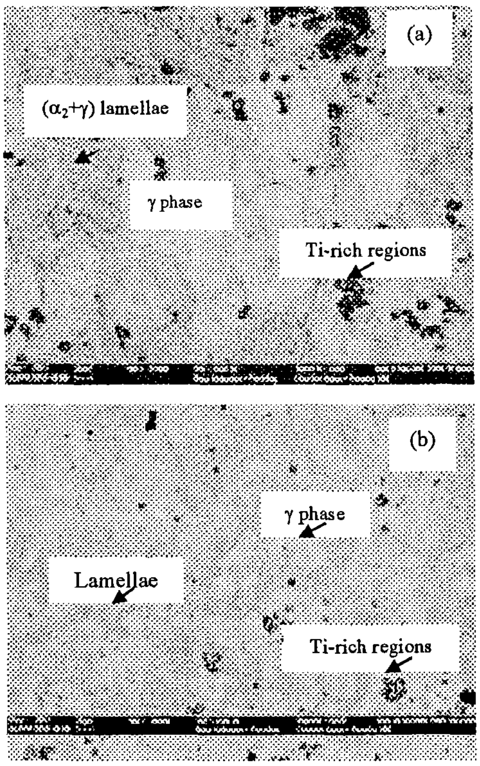

Fig. 2. The back scattered SEM micrographs showing the microstructures of as-cast TiAl alloys: (a) Ti-48Al and (d) Ti-48Al-2Cr-2Mo.

In addition, it can be observed that in all the revealed microstructures, lamellar colonies are randomly oriented. It can be also be determined that some Ti-rich precipitates in the γ phases, lamellar colonies and at grain boundaries had formed based on EDS analysis (Table II). It is suspected that the incorporated carbon in Ti-rich precipitates was most probably from the raw elemental powders used. This element has strong tendency to react with Ti at the melting temperature [17].

By comparing the microstructure of hot pressed and as cast TiAl alloys, it can be recorded that the two different processing techniques would produce two types of microstructures. All the alloying elements were observed to be more homogeneously distributed in the as-cast TiAl alloys. Because the as cast samples can be remelted several times in this study, the high melting point element of Mo can be ensured to be well dissolved in the melting state. The regions containing impurity elements in the microstructure of as-cast TiAl alloys were relatively lower, as compared to the hot-pressed TiAl alloys of similar composition.

Table II. Results of EDS analysis for as-cast TiAl alloys

As-cast TiAl alloys (at.%)	Phases	Ti (at.%)	Al (at.%)	Cr (at.%)	Mo (at.%)	C (at.%)
Ti-48Al	γ	45.98	54.02	-	-	-
	$(\alpha_2+\gamma)$	54.63	45.37	-	-	-
	Ti-rich	68.01	-	-	-	31.99
Ti-48Al-2Cr-2Mo	γ	51.61	44.85	1.4	2.13	-
	$(\alpha_2+\gamma)$	48.91	45.74	2.91	2.44	-
	Ti-rich	69.5	-	-	-	30.85

3.2 Fracture Behavior of Hot pressed and as-cast γ-TiAl Alloy

Fig. 3 shows the SEM micrographs of fractured surfaces of hot pressed TiAl alloys after compression tests at room temperature. The fractured surfaces of Ti-48Al exhibited transgranular fracture modes with apparent cleavage facets (Fig. 3a). The transgranular fracture mode was also predominantly found in the hot-pressed Ti-48Al-2Cr-2Mo (Fig. 3b) and occasionally intergranular fracture mode was apparent (enlarged micrograph). In addition, some microcracks were also observed as indicated by a black arrow in all the fractured surfaces.

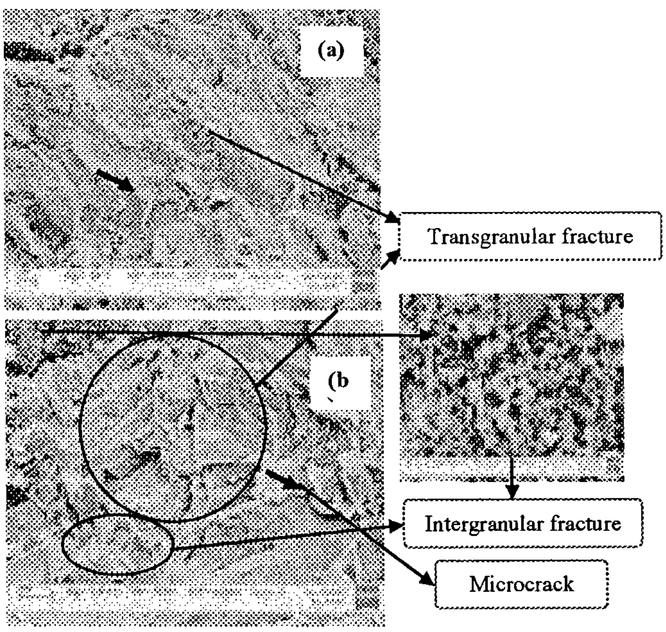

Fig. 3. SEM micrographs showing fracture surfaces of hot-pressed TiAl alloys after compression testing: (a) Ti-48Al and (b) Ti-48Al-2Cr-2Mo alloys.

Fig. 4 shows SEM micrographs of the fractured surfaces of as-cast TiAl alloys after compression tests at room temperature. The fractured surfaces of all TiAl alloys were of mixed transgranular and interlamellar fracture modes, in which cleavage facets were dominant. Due to the layered structure of lamellae, a step-like transgranular fracture of lamellae was also apparent, particularly in the fractured surface of as-cast Ti-48Al-2Cr-2Mo (see the enlarged micrograph of Fig. 4b).

The transgranular and interlamellar fracture modes observed on fractured surfaces of the as cast TiAl alloys indicate that these alloys exhibit brittle fracture behavior. Nevertheless, typical cleavage facets observed in fractured surfaces of both hot-pressed and as-cast TiAl alloys without the appearance of flat and featureless facets are a characteristic of brittle fracture with some ductility [18], [19].

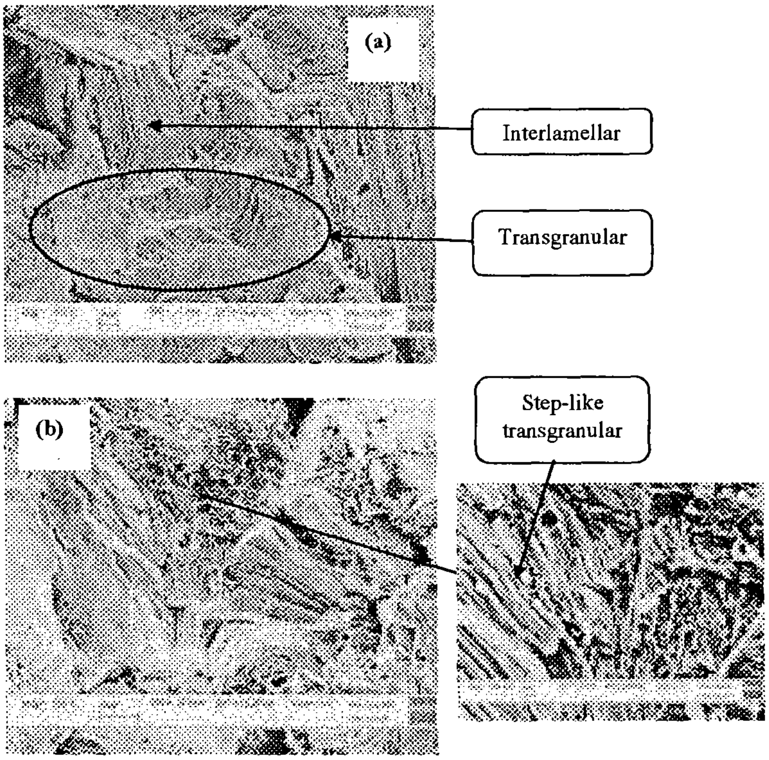

Fig. 4. SEM micrographs showing fracture surfaces of as-cast TiAl alloys after compression testing: (a) Ti-48Al and (b) Ti-48Al-2Cr-2Mo alloys

4. CONCLUSIONS

The microstructure of hot-pressed TiAl alloys was observed to consist of the γ phase as the matrix and α_2 phase with impurity elements, such as C, O was incorporated in γ grains. The microstructure of as-cast TiAl alloys was found to have exhibited a duplex microstructure, which consists of the primary γ phases and (α_2 +γ) lamellar colonies. Some non-uniform distribution of Ti-rich regions was also detected in the γ phases and lamellar colonies. The alloying elements of Mo were observed to be more homogeneously distributed in the as-cast TiAl alloy than in the hot-pressed one.

The fracture behavior of hot-pressed TiAl alloys was found to have exhibited the transgranular fracture modes with apparent cleavage facets and some microcracks were also observed in all fractured surfaces. The fracture modes of the as-cast TiAl alloys were mixed transgranular and interlamellar. The fracture surfaces of both hot-pressed and as-cast TiAl alloys were found to have shown typical cleavage facets without the appearance of flat and featureless facets, which are a characteristic of brittle fracture with some ductility.

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