STATIC VS CYCLIC WORK HARDENING BEHAVIOUR OF GAS ATOMIZED TiAl ALLOY POWDER COMPACTS

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ABSTRACT

Pre-alloyed powders of composition Ti49Al47Cr2Nb2 produced by inert gas atomization and consolidated by Hot Isostatic Pressing (HIP) have been investigated in terms of microstructure/static-versus-cyclic property relationships. A large variety of microstructures, typically from the fully lamellar microstructure to the near-γ equiaxed microstructure, have been tailored using different heat treatments. Room-temperature tensile properties and in particular the work hardening rate during plastic deformation appear to be markedly affected by the volume fraction of lamellar colonies and by the lamellar spacing. TEM investigations revealed that the microstructural developments that occur during post-consolidated heat treatments in the higher part of the two-phase domain impart a strong twinning activity in the test specimens at the expense of super-dislocation formation. The propensity of deformation twinning in the nearly lamellar microstructure is presumably the result of the high density of deformations twins that are formed at the lamellar interfaces. In contrast, a low density of deformation twins together with deformed sub-structures have been evidenced in duplex microstructures. Implications of such findings are discussed relative to the concomitant work hardening variation and to the requirements for aerospace gas turbine applications. A general good correlation between static and cyclic work hardening has been found in the present work. Fatigue specimens having lower work hardening rate were found to exhibit prolonged fatigue lives. Attempts to understand the fundamentals related to the microstructure which govern static and cyclic deformations are also adressed in the discussion.

1 INTRODUCTION

Gamma titanium aluminides are a new class of materials with attractive high-temperature mechanical properties [1]. Their development originated from the limitation in temperature of conventional titanium alloys. Therefore, such alloys are regarded as potent substituted candidates for conventional titanium alloys in the compressor part of aerospace gas turbine engines and also for Ni-based superalloys in the low pressure turbine. Considerable processing developments in the last years helped to assess the potentiality of the different cast, wrought and powder metallurgy (PM) routes. The latter offers a great deal of advantages with the uniformed and refined microstructure that can be obtained together with the versatility for secondary processing such as extrusion, isothermal forging or near net-shape HIP'ing [2]. The PM route also imparts attractive mechanical properties owing to this refinement of the microstructure. However, similarly to cast and wrought alloys, PM alloys undergo high work hardening during static and cyclic plastic deformation [3]. Since the response from such a material to cyclic deformation during transitional engine speed involves considerable work hardening, this could become deleterious for the component life due to the quite moderate intrinsic ductility of the gamma alloy. Attempts to ductilize these alloys have been found to be successful through further refinement and alloying additions. Yet the fatigue behaviour needs to be assessed in terms of microstructural evolution and of alloying additions for the different operative conditions of the aeroengines. The objective of this work was then to develop an optimized microstructure that exhibits a significantly lower work hardening rate while preserving the fatigue life of the material. This requires an understanding of the prevailing structural factors that govern the static and cyclic deformation modes of this particular PM alloy.

2 EXPERIMENTAL WORK

2.1 Material and experimental methods

Pre-alloyed powders of composition $Ti_{49}Al_{47}Cr_2Nb_2$ (at.%) have been produced from a single heat by inert gas atomization and delivered by Crucible Corp.. In order to retain the benefit brought about by the PM refinement, HIP'ing was carried out at 1200°C under a pressure of 140 MPa for 4 hours. A series of tensile and fatigue test specimens with an identical geometry have been used for comparative static and cyclic evaluations. They were machined by turning followed by mechanical polishing. Test specimens have a gage length of 14.1mm and a gage diameter of 4.7mm (Figure. 1) [4]. Room-temperature tensile tests were carried out on a Schenk TREBEL machine at a constant strain rate of 10^{-3} s^{-1}. Room-temperature low cycle fatigue tests were performed on a MTS 810 machine at the same constant strain rate. A total strain of 0.8% was applied with a strain ratio R_ε = -1 and with a triangular shape signal. The microstructure of the specimens was characterized by standard metallography by means of a scanning electron microscope (Zeiss DSM 962) involving backscattered electron imaging conditions and electron back scattered diffraction conditions (EBSD) [5]. TEM work was also carried out on a couple of deformed specimens with a Philips CM20 operated at 200kV. For this purpose, disks of 3mm diameter were sliced, mechanically ground to a thickness of about 150μm and electropolished (600ml of methanol, 350ml of 2-buthoxy-methanol, 60ml of perchloric acid, T=-40°C).

3 RESULTS

3.1 Microstructural evolution

In order to investigate the relationships between microstructural parameters and mechanical properties, an expanded range of microstructure, typically from near-γ to fully lamellar (Figure 2), has been tailored in test blanks using different temperatures, durations and cooling rates for heat treatments. The related microstructures were then quantitatively analyzed in terms of grain size, surface fraction, lamellar spacing, serrated grain boundaries, etc.

HIP'ing at 1200°C produced a near-γ structure composed essentially of γ grains with a mean grain size of 9 μm and of a few α_2 grains. The generated structure also exhibits some mechanically twinned γ grains presumably as a result of HIP'ing. The response of the present alloy to heat treatments conducted either in the two-phase α+γ or in the single phase α phase fields can be described as follows:

- For sub-transus heat treatments, the annealing temperature was found to strongly modify the surface fraction of the γ and α phases present in this alloy (Figure 3).

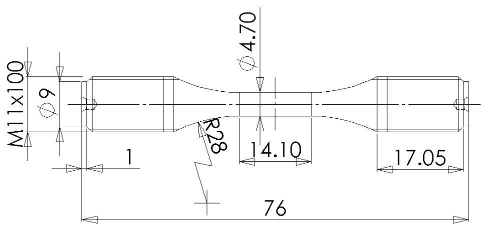


Figure 1: Test specimen geometry.

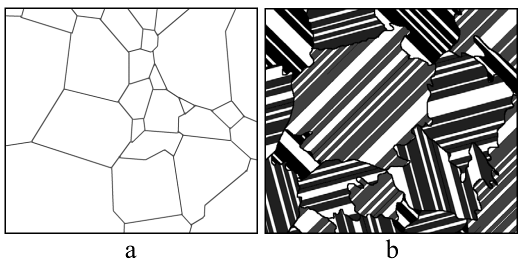


Figure 2: Schematic drawing of well-known TiAl microstructures: (a) Gamma - (b) Fully lamellar

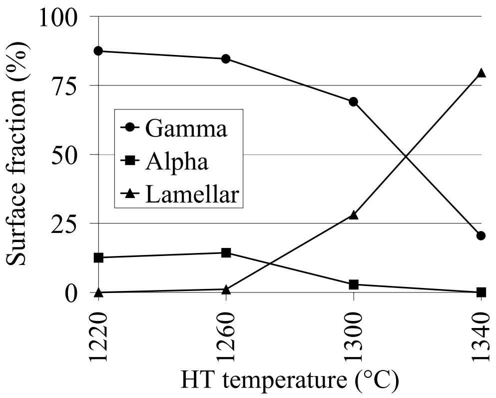


Figure 3: Phase evolution with annealing temperature for a 10-hours and air cooling treatment.

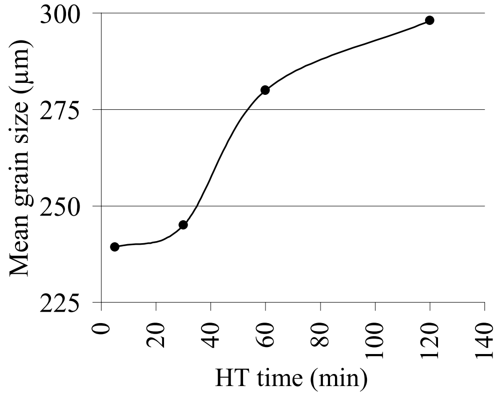
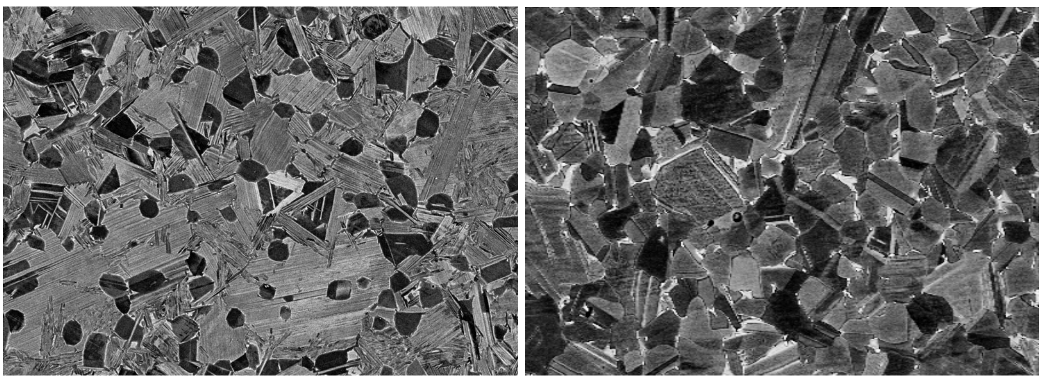


Figure 4: Mean grain size evolution with annealing time at 1375°C and furnace cooling.



a b

Figure 5: Effect of cooling rate for sub-transus treatments at 1340°C: (a) 10°C/s - (b) 0.15°C/s

Under air cooling condition, increasing the temperature leads to an increase in α phase at the expense of the γ phase, up to a point where the α phase is metastable enough to be transformed into α+γ lamellae. The resulting microstructure in such sub-transus conditions is called duplex, with a mixture of γ, α and lamellar grains. On the other hand, such a duplex microstructure is not really stabilized under furnace cooling condition. Instead, the microstructure is mainly composed of γ grains (Figure 5).

- As the solution treatments are conducted above the α transus temperature, a fully lamellar structure with alternating α_2 and γ lamellae is then obtained upon cooling from the high-temperature single phase region. The time and cooling rate are found to control the microstructure in terms of grain size and lamellar spacing. As the annealing time is increased from 5 minutes to 120 minutes, the lamellar grains are increased from 240 to 300 µm (Figure 4). In parallel, a lower cooling rate is found to increase the lamellar spacing and the grain boundary indentation.

3.2 Tensile tests

Tensile stress strain curves obtained for the as-HIP'ed condition and for microstructures that received a 10-hours anneal followed by furnace cooling are shown in figure 6. It can be emphasized the similar flow stress behaviour for these specimens annealed at different temperatures. YS is significantly higher for the as-HIP'ed condition, in particular with a pronounced peak stress followed by a transient softening regime; then the flow stress levels off up to about 1.2% plastic strain before a slight work hardening could be discernable at the higher strains. However, as the annealing temperature is increased towards 1340°C, YS values are significantly decreased from 407MPa to 313MPa while the onset of work hardening is progressively shifted towards lower plastic strain. From this onset, the flow curves show a rather linear increase with strain, however with a steeper slope for higher temperatures. Indeed, in the strain range 0.2-1%, an increasing work hardening rate $d\sigma/d\varepsilon$ from 1.8GPa to 7.7 GPa has been determined between 1220°C and 1340°C flow stress curves. Hence, the lower YS values at higher temperatures are compensated by an earlier onset of steeper work hardening, resulting in UTS values that are relatively closed to each others. In terms of microstructure-property relationships, the YS variations can be partly attributed to an increase of the mean γ grain size from 11 to 19µm whereas the increasing work hardening rate could be related to the increasing fraction of the stronger α phase

Figure 7 shows the tensile stress strain curves of four microstructures obtained with a 10-hours anneal but followed by air cooling. In a general manner, flow stress values are considerably increased with plastic strain leading to UTS values in the range 500-600MPa. The higher the annealing temperature, the higher the work hardening. For an intermediate strain range 0.1-0.2%, the work hardening rate $d\sigma/d\varepsilon$ is increased from 17.7 GPa to 38.6 GPa between 1220°C and 1340°C. Such a strong hardening effect is associated with a dramatic increase of lamellar phase fraction from 1 to 80% and a concomitant reduction in volume fraction of the γ phase. Therefore, higher work hardening for near lamellar microstructures is related to the absence of strain recovery which is ascribed to the build-up of dislocation interactions and to dislocation trapping at lamellar interfaces. On the other hand, the work hardening rate $d\sigma/d\varepsilon$ of the heat treated material become independent of the cooling rate provided the annealing temperatures is as low as 1220°C. Moreover, whereas for the 1220°C anneal the flow stress increases linearly with plastic strain, at higher annealing temperatures, the curves are progressively shaped concavely downward, i. e. the work hardening rate decreases.

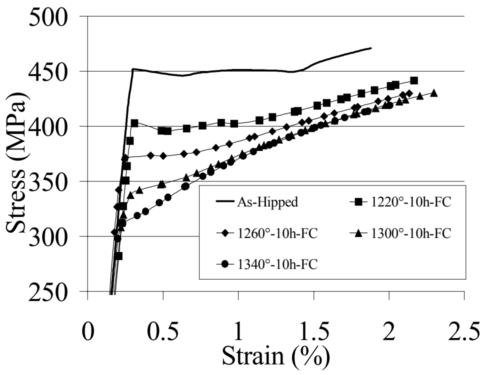


Figure 6: Evolution of tensile properties with annealing temperature for a 10 hours and furnace cooling treatment.

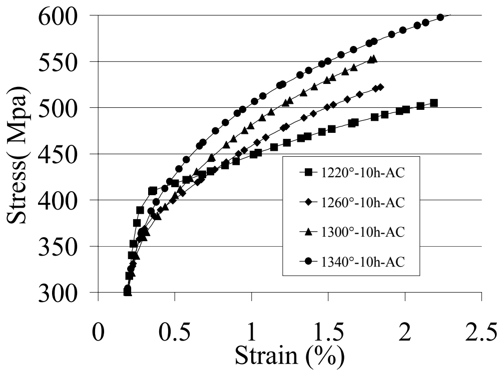


Figure 7: Evolution of tensile properties with annealing temperature for a 10 hours and air cooling treatment.

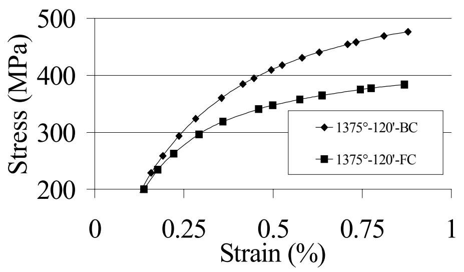


Figure 8: Evolution of tensile properties with cooling rate for a 2-hours in fully lamellar.

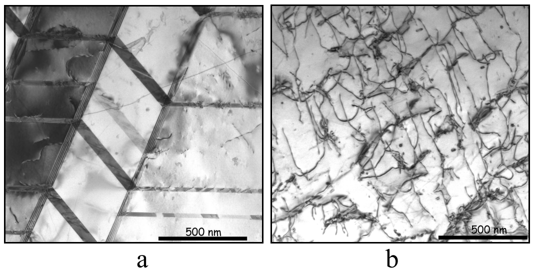


Figure 9: BF-TEM images taken from tensile specimens heat treated at 1340°C and cooled at : (a) 10°C/s – (b) 0.15°C/s

Such a slight decrease of the work hardening rate at higher strains might be caused by some damage mechanisms related to the presence of lamellar colonies. The latter may act as strong obstacles leading to the nucleation of some intergranular microcracks.

Tensile stress strain curves for two fully lamellar microstructures obtained after annealing above the α transus followed by cooling at 3°C/s and 0.15°C/s respectively are illustrated in figure 8. Quite clearly, a significant YS decrease is observed with respect to duplex and near-γ microstructures. It is anticipated in this context that the reduction of the glide resistance due to the grain coarsening is responsible for the lower yield strength. Moreover, in a similar manner as the one observed for sub-transus treatments (figures 6 and 7), the flow stress behaviour of the fully lamellar microstructures is found to be particularly sensitive to the cooling rate. In this case, the work hardening rate $d\sigma/d\varepsilon$ is affected by structural factors such as lamellar spacing, mean grain size and serration of grain boundaries.

Tensile testings have also been coupled with subsequent detailed TEM work to identify the role of dislocation formation and twinning activity on the static deformation behaviours. In a general manner, the deformed specimens at RT exhibit the presence of 1/2<110> ordinary dislocations and <011] superdislocations together with 1/6<112] mechanical twins, which is consistent with previous TEM investigations. More specifically, detailed analysis was carried out on two deformed specimens that received different cooling rates from 1340°C. As previously illustrated in figure 5, these specimens exhibit near lamellar and duplex microstructures respectively. In the lamellar one, a strong twinning activity is observed at the expense of super-dislocation formation (Figure 9a). The propensity of deformation twinning in the near lamellar microstructure can be ascribed to the high density of deformations twins that are formed at the lamellar interfaces. However, it is still unclear whether twinning directly affects the super-dislocation formation. Otherwise, super-dislocations may be not present because of their higher mobility in this particular specimen. In contrast, the duplex microstructure rather shows a low density of deformation twins whereas deformed sub-structures have evolved from heavily tangled ordinary dislocations and superdislocations (Figure 9b).

3.3 Low Cycle Fatigue

The results of fatigue tests conducted on the different heat treated specimens can be summarized as follows: in contrast to the low scatter in tensile tests, some incidence of the heat treatments on YS values as deduced from the first cycle, has been observed. Moreover, the occurrence of porosity coarsening during heat treatments and the existence of some ceramic inclusions are considered to be of primary concern for the fatigue life of the present test specimens. Indeed, examination of the fracture surfaces highlights some inclusions as preferential nucleation sites of fatigue cracks. Nevertheless, figure 10 gives a satisfactory relationship between the fatigue life and the mean work hardening rate. Sub-transus treatments followed by air cooling have a detrimental effect on fatigue properties due to a high work hardening. More surprisingly, in the case of the specimens heat treated above the α transus, the ones involving an intermediate cooling rate exhibit the lowest work hardening rate and a prolonged fatigue life. Detailed SEM fractography are currently underway to evaluate the deformation modes for the different fatigue specimens. In a further extent, figure 11 shows that no simple correlation occurs between static and cyclic work hardening rates.

5 CONCLUSION

On the basis of this preliminary work, tensile and fatigue properties have been described for a large range of microstructures. The constituent phases that have been quantitatively analyzed are strongly dependent upon the related heat treatments. However, from a metallurgical point of view, the good structural and chemical homogeneity of the present gas atomized powder should be responsible for the low property variability. Detailed experimental investigations confirmed that microstructure is a prevalent factor affecting the work hardening behaviour. For engineering applications, fully lamellar microstructures characterized by relatively small lamellar spacing, provide lower cyclic work hardening and longer fatigue life. Moreover, such microstructures are known to be adequate for enhanced creep resistance and fracture toughness properties.

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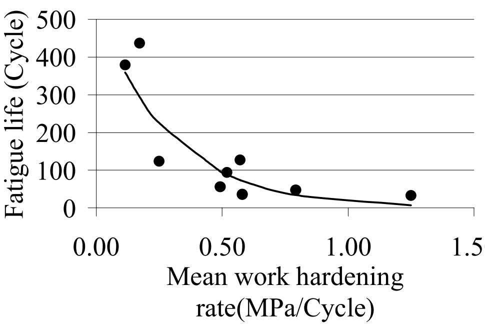

Figure 10: Evolution of fatigue life with mean work hardening.

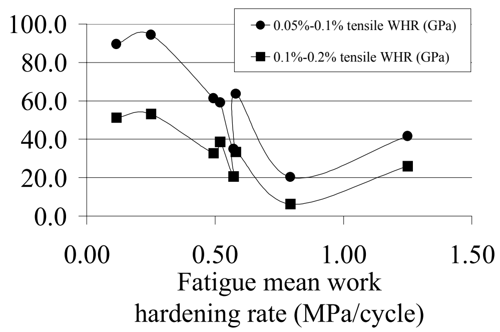

Figure 11: Static and cyclic work hardening rate relationships