EFFECT OF THE STRAIN RATE ON THE MECHANICAL BEHAVIOUR OF A Ti-6Al-4V / SiC COMPOSITE MATERIAL

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The effect of the strain rate (in the range of 2×10^{-5} to 500 s^{-1}) on the mechanical behaviour of a Ti matrix (Ti-6Al-4V) composite material, with a 35% in volume unidirectional reinforcement of SiC continuous fibres, has been studied. Tensile experiments have been carried out on a servo-hydraulic testing machine and using a split Hopkinson bar, instrumented with extensometers and strain gauges, respectively, to obtain data on the stress versus strain behaviours. After completion of the mechanical tests, the test-pieces were subjected to fractographic analysis to reveal the underlying fracture mechanisms.

INTRODUCTION

Titanium alloys and composite materials with a titanium matrix and ceramic reinforcements have a large technical interest for aeronautical applications and more precisely for aero-engine components, because of their excellent properties in relation with strength, stiffness and creep. On this paper, the mechanical properties under tensile loading conditions, aligned with the continuous fibre reinforcement of SiC fibres (35% in volume), are studied. Three different strain rates were used in the analysis: 2×10^{-5}, 2×10^{-3} and 500 s^{-1}. Tests conducted at the two lowest strain rates were performed on a conventional servo-hydraulic testing machine, while the tests conducted at the highest strain rate were carried out by means of a split Hopkinson bar technique. From the tests carried out it is possible to know the effect of

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the strain rate on the tensile strength, yield stress, modulus of elasticity and ultimate tensile strain.

MATERIAL

The material used in the experiments is a titanium alloy reinforced with SiC continuos fibres. The matrix material is the alloy Ti-6%Al-4%V. Fibre reinforcement is arranged in 8 layers with a mean spacing of 168 mm with a 35% volume fraction of fibres. The SiC fibres are Sigma 1140+ with a total diameter of 104 mm including the tungsten core (15 mm in diameter) and the C coating (2 mm thickness).

EXPERIMENTAL TECHNIQUES

Tensile test-pieces were cut with a diamond saw with a dog-bone shape. The same gripping fixture was used to fix the ends of the specimens for both experiments (at low and high strain rates) in such a way that the same load distributions were obtained in both experimental arrangements. The grips were specifically designed for the highest strain rate tests at the Hopkinson bar with a smooth transition between the loading bars and the specimen itself to reduce the reflection of the incident load pulse.

Tests conducted at the lowest strain rates were performed on a conventional servo-hydraulic testing machine. The load was recorded during the test from a load cell (with strain gauges) and by means of a conventional extensometer. Tests were performed under displacement control where velocity at the actuator ram was imposed. Target speeds were 0.08 mm/minute and 9 mm/minute at the actuator. From these actuator speeds, the resulting mean strain rates at the specimens were 2×10^{-5} s^{-1} and 2×10^{-3} s^{-1}, respectively.

The tests carried out at the highest strain rate were performed using a Hopkinson bar. The first experiments performed for characterisation of material using such technique were carried out by Kolsky (1) and the modifications to adapt these experiments to tensile experiments were performed by Harding (2). From this kind of experiments it was possible to obtain load versus displacement records. The experimental arrangement of Hopkinson bar for tension experiments is composed of two steel bars, the test-piece is placed between both bars by means of the gripping fixture (see Fig. 1). The influence of the gripping system on the results was studied by Chocrón et al. (3). Along the first bar, incident bar, a projectile is shot in the reverse direction to the end that fixes the specimen and blows the end of the bar. In this way, a tensile pulse is generated that runs along the bar and reaches the specimen. A fraction of the tensile pulse goes through the sample (transmit pulse), another is reflected on the incident bar (reflected pulse). The transmit pulse then goes through the second bar (or output bar).

Both, the incident bar and output bar have glued strain gauges which allow to measure the deformations experimented by the bars and, from there, to monitor the applied loads on the specimen extremes and the relative displacement between the ends of the test-piece. The applied loads on the specimen can be computed by means of the theory of unidirectional wave propagation of elastic pulses from the equations:

$$F_a = AE(\varepsilon_i+\varepsilon_r) \tag{1}$$

$$F_b = AE\varepsilon_t \tag{2}$$

where A and E are the cross-section and elastic modulus of the bars, respectively, and ε_i, ε_r and ε_t are the deformations corresponding to the incident pulse generated at the impact, the pulse reflected on the surfaces at the transition between the bar and specimen and the pulse transmitted to the second bar. These strains are continuously recorded by the strain gauges on the bars. Anyway, the only information required to estimate the load carried by the specimen is the transmitted pulse, that is calculated as:

$$F = F_b = AE\varepsilon_t \tag{3}$$

From the velocities of both bar extremes (V_a and V_b) it is possible to compute the relative displacement between both extremes, δ, equal to the displacement between both ends of the specimen:

$$V_a = c(\varepsilon_i-\varepsilon_r) \tag{4}$$

$$V_b = c\varepsilon_t \tag{5}$$

$$d\delta/dt = V_a-V_b \tag{6}$$

where c is the propagation velocity of elastic waves in the bars. In addition, on the specimen itself its strain gauges are glued, so, strains and strain-rates are continuously monitored at the specimen. In this way, it is possible to obtain the stress versus strain record. It is easy to prove that, during most part of the experiment, the test-piece is under quasi-static equilibrium conditions even for the very high strain rates imposed to the test-piece. A detailed description about the hypothesis of a Hopkinson bar experiment can be found in Zukas (4), the way to process the obtained information is described in Liftshitz and Elber (5).

The characteristic fracture mechanisms at different strain rates were analysed by fractography of the samples in a scanning electron microscope JEOL-JSM-6300.

RESULTS

Eight tests were carried out, two at a slow strain rate, two at an intermediate strain rate and four to a high strain rate. Table 1 summarises the obtained results. In one of the experiments, there was a problem to record the signals from the strain gauges and only the fracture load was recorded.

TABLE 1- Summary of the experiments at different strain rates on Ti64 reinforced with continuous Sigma fibres in 0º.

Strain rate	E (GPa)	σ_Y (MPa)	ε_Y (%)	σ_r (MPa)	ε_r (%)
2×10^{-5} s^{-1}	184	1100	0.60	1485	0.84
2×10^{-5} s^{-1}	185	1090	0.59	1517	0.93
2×10^{-3} s^{-1}	190	1250	0.65	1498	0.87
2×10^{-3} s^{-1}	210	1514	0.74	1514	0.74
500 s^{-1}	-	-	-	1495	-
500 s^{-1}	233	1393	0.60	1393	0.60
500 s^{-1}	300	1885	0.63	1885	0.63
500 s^{-1}	269	1470	0.68	1470	0.68

Figure 2 shows the stress versus strain records at three different strain rates. Figure 3 shows, as four plots, the evolution of the modulus of elasticity, yield stress, ultimate tensile stress and fracture strain versus the strain rate. The stress versus strain record has two linear portions at slow strain rate with a decreasing slope until fracture, while at high strain rate the plot is linear until fracture. From the obtained results it is clear that the yield stress increases with the strain rate. There is a 35% increase when comparing the slowest with the highest strain rates. However, the ultimate tensile strength is not affected by the strain rate. All fracture stresses are close to 1455 MPa with a maximum deviation of 60 MPa. On the contrary, the fracture strain decreases with increasing strain rates.

The fracture surfaces of the specimens show fibre/matrix debonds, indicative of a weak interface between the Ti alloy matrix and SiC fibres. This weak bonding improves the fracture behaviour of the composite material (see Fig. 4). On the other hand, the fracture of the matrix takes place by a process of nucleation, growth and coalescence of voids at all the examined strain rates. The most important difference between the fracture surfaces at different strain rates is the mean pull-out length, mean pull-out being much larger for the specimens tested at the slowest strain rate, 2×10^{-5} s^{-1}.

CONCLUSIONS

The obtained results from the tests conducted at slow strain rates are similar to those obtained by other authors in a similar material (6). The initial elastic behaviour in the stress versus strain plot corresponds to an elastic deformation of the matrix and fibres, and it extends until reaching the yield stress of the matrix. The second, and reduced, slope of the stress-versus strain record is due to the plastic deformation of the matrix and ends with the fracture of the composite material when brittle fibre fractures take place. The mechanical behaviour of the composite material, in both cases, can be estimated from an iso-strain model for the matrix and fibres because the radial residual stresses (from the mismatch of thermal expansion coefficients) at the interface are of compressive nature and render difficult the relative displacement between matrix and fibres. The relative displacement between both components is only produced at the final stages of the fracture process, when fibre fragmentation and cracks and voids appear at the matrix phase, relaxing the residual stresses at the interface.

From these results and models it is possible to explain the effect of the strain rate on the mechanical behaviour of the composite material taking into account the strain-rate sensitivity of the matrix phase (7). Particularly, the increase in the yield stress of the composite material can be explained arguing a larger yield stress for the matrix with increasing strain rates, which improves its ultimate strength but reduces its fractures strain. This loss of ductility of the matrix at increasing strain rates is also observed in the behaviour of the composite material, where the fracture strain is slightly reduced. Finally, the ultimate tensile strength of the composite material is nearly constant in the range of examined strain-rates. It is probably due to the independence of the fibre tensile strength with respect to the strain rates, and because the slight improve in the ultimate tensile strength of the matrix is balanced by the reduced ductility of the composite material.

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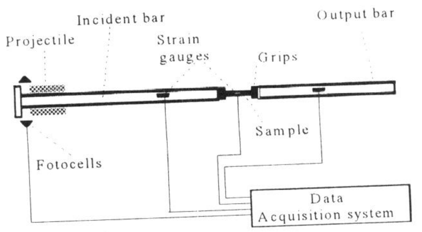

Figure 1. Experimental arrangement of a Hopkinson bar.

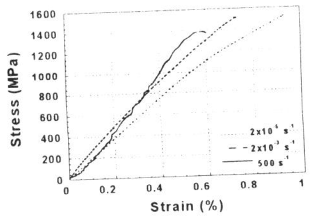

Figure 2. Stress versus strain records at different strain rates.

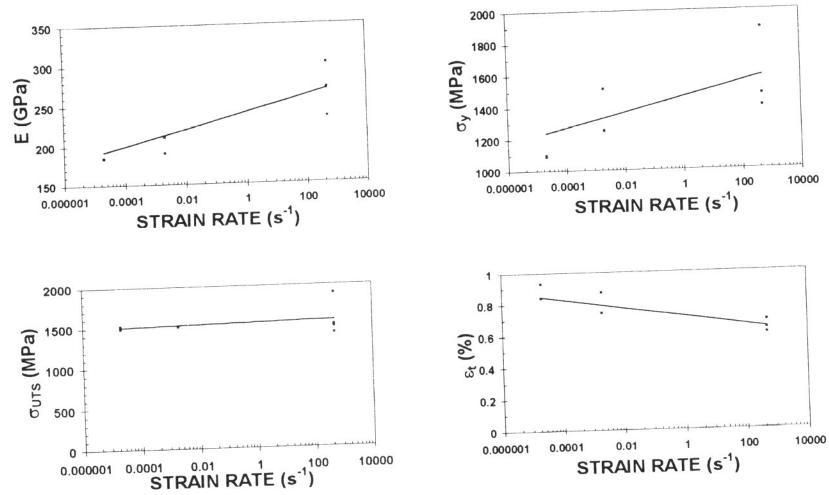

Figure 3. Evolution of E, σ_y, σ_{UTS} and ε_t versus the strain rate.

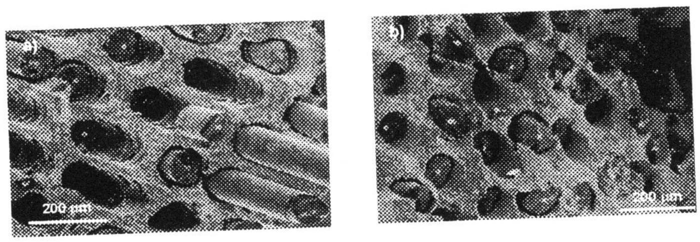

Figure 4. Fracture surfaces after testing at a strain rate of: a) 2×10^{-5} s^{-1}, and b) 500 s^{-1}.