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Analysis of Shear Band Effects in Titanium Relative to High Strain-Rate Laboratory/Ballistic Impact Tests

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Abstract. Mechanical and ballistic tests were performed on Ti-6Al-4V titanium alloy subjected to three heat treatment conditions. For the samples annealed above the beta transition temperature, a loss in ballistic performance was noted and the samples exhibited little bulk deformation and bulging, but extensive adiabatic shear banding. Samples annealed below the beta transition temperature exhibited extensive bulk deformation and rear surface bulging, delaminations perpendicular to the penetrator path with shear bands parallel to the direction of impact. In mechanical tests, dynamic strength and failure behaviour of Ti-6Al-4V under compression and biaxial compression/shear loading has been investigated. Scanning electron microscopy (SEM) was used to correlate deformation structures of shear cracks from ballistic tests with that of shear laboratory specimens. Indications of an relationship between the ballistic performance and mechanical behaviour under compression/shear loading of different heat treated titanium targets were noted, e.g. dynamic strength and sensitivity to adiabatic shear failure.

Résumé. Des tests mécaniques et balistiques ont été conduits sur des alliages de titane Ti-6Al-4V soumis à trois conditions de traitement thermique. Chez les spécimens recuits à une température au-dessus de la température de transition bêta l'on pouvait constater une perte de la performance balistique. Ces spécimens faisaient état de déformations de gonflement et d'une expansion peu développées, mais également d'un développement important de structures filamenteuses adiabatiques. Chez les spécimens recuits à une température en-dessous de la température de transition l'on pouvait observer des déformations importantes de gonflement, une expansion de la surface arrière, des décollements interlaminaires perpendiculaires au sens de la pointe de pénétration et des structures filamenteuses allant dans le sens parallèle de la direction de l'impacte. Lors de tests mécaniques, la force dynamique et la défaillance de Ti-6Al-4V sous compression et sous compression biaxiale/charge de pression a été soumis a examen. La microscopie électronique à balayage de surface (scanning electron microscopy, SEM) a été utilisée afin de pouvoir établir une corrélation entre les déformations structurelles des fissures de compression venant des tests balistique et celles des spécimens en laboratoire. L'on a pu faire état d'indications d'une relation entre la performance balistiques et le comportement mécanique sous compression/charge de pression de différents objets de titane traités thermiquement, p. ex. La force dynamique et la sensibilité à la défaillance adiabatique sous pression.

1 INTRODUCTION AND BACKGROUND

Titanium alloys have been used successfully in aircraft applications for many years due to their high specific strengths and corrosion resistance. However, the relatively high cost of titanium coupled with the limited information on its ballistic properties have prevented widespread use of titanium as a protective material for application to ground vehicles.

The potential use of titanium for ballistic applications has accelerated recently with the development of low-cost alloys as well as the ballistic evaluation and development of penetration algorithms for titanium against modern long-rod penetrators [1,2]. The ballistic advantages of titanium targets against these rods was about 60% higher than reference ballistic steel and can be attributed to the lower density combined with uniform hardness and equal or greater strength over similar thick cross-sections of steel. Evident in the penetration channels of these semi-infinite titanium blocks was extensive radial adiabatic shear banding from the high-strain rate impacts [3,4]. The effect of shear banding during deep semi-infinite penetration is not understood, but significantly effects the breakout phase during perforation of finite

plates.

Subsequent work by Burkins et al [5] extensively analyzed the effects of annealing temperature on the ballistic resistance of Ti-6Al-4V alloys. Figure 1 and 2 shows representative cross-sections of the impact craters of two different titanium plates heat-treated above and below the 996 °C beta transus temperature. For the specimen annealed below the beta transus temperature (Figure 1), note the bulk deformation of the titanium and the rear surface bulging. The cross-section also reveals a pattern of delaminations perpendicular to the projectile impact and adiabatic shear failure parallel to the direction of impact that has formed a plug that is close to being ejected. Annealing above the beta transus, (Figure 2) caused a loss in ballistic performance with little bulk deformation, but extensive adiabatic shear effects were noted.

Figure 1: Cross-section of titanium impact crater heat-treated below the beta transus temperature (2x). Note the large parallel delamination/cracking and perpendicular shear bands. The penetration channel is deep into the plate.

Figure 2: Cross-section of titanium impact crater heat-treated above the beta transus temperature (2x). Note the lack of bulk deformation and bulging. The shear plug is being ejected from the plate along the perpendicular shear bands with little penetration of the plate itself (lower ballistic performance).

The aim of this joint research was to find indications for interdependencies between ballistic performance of the different heat treated titanium alloys and their material behaviour under high strain rates. This paper provides the subsequent analysis and extensive investigation of the mechanical strength and failure behaviour of three titanium samples taken from the previously tested ballistic plates and subjected to different strain rates under compression. Additional biaxial compression-shear experiments were also performed.

2 MATERIALS AND TESTING METHODS

2.1 Materials

The titanium specimens used in these tests were standard Ti-6Al-4V, the most common titanium alloy. This material contains mixtures of α and β phases and is classified as an α - β -alloy. For this investigations, extra-low interstitial (ELI) grade titanium produced by RMI Titanium of Niles, Ohio, USA was used. Table 1 summarises the chemical composition.

Table 1: Chemical composition of Ti-6Al-4V ELI, Weight Percent

Al	V	C	O	N	H	Fe	Ti
6,12	4,02	0,01	0,12	0,008	0,0058	0,19	Balance

Starting from a single Ti-6Al-4V ELI grade billet, RMI produced a large 28,5 mm thick plate by 1:1 cross rolling at temperatures below the well established beta transus (approximately 996 °C). A vacuum creep flatten (VCF) treatment was then performed to flatten and stress relieve the plate; this cycle took approximately 24 hours, including heat-up and cool-down time and reached a temperature of 788 °C. The plate was then cut into ballistic and mechanical test plates with most of the samples received additional annealing heat treatments. The microstructure of these samples were strongly influenced by the processing history and different heat treatment conditions.

Processing conditions and information about microstructure are found in Table 2. The grain sizes were determined according to the line sectioning method. The microstructure were typical when annealed at the various conditions. Ballistic and mechanical tests were performed on these same materials.

Table 2: Summary of microstructural data for Ti-6Al-4V ELI plates in various annealed conditions
VCF ... vacuum creep flatten treatment, AC ... air cooling

heat treatment condition	characterized microstructure	grain size
VCF only, no anneal	partially recrystallized alpha phase plus intergranular beta phase	α -grains: 16 μm β -grains: 4 μm
899 °C-30 min-AC	predominantly equiaxed alpha phase with progressively increasing amounts of beta phase	α -grains: 12,5 μm β -grains: 4 μm
1038 °C-30 min-AC	coarse prior beta grains which have transformed to a Widmanstätten alpha-beta microstructure	220 μm

2.2 Ballistic Test Methodology

The U. S. Army Research Laboratory (ARL) performed ballistic tests to evaluate the effect of annealing temperature on the ballistic resistance of the three samples. A standard 4340H steel 20-mm fragment simulating projectile was selected as the test projectile which has a hardness of R_c 29-31. The titanium plates were impacted normally (0 ° obliquity) and a V_{50} ballistic limit velocity was determined for each condition. This limit velocity defines the ballistic case where the titanium plate is just perforated by the projectile. Complete details of these experiments can be found in [5].

The titanium samples heat-treated above the beta transus temperature, (1038 °C-30 min-AC), exhibited a maximum reduction in ballistic resistance of approximately 29 % as compared to the other two samples. Significant differences in the cross-section of the impact craters were also noted, particularly the extent of bulk deformation and adiabatic shear banding.

2.3 Mechanical Testing Methodology

The exact main stress state in the impact area and its history is not very well known. Nevertheless, it is assumed, that in the first part of penetration, compression and shear/compression stress states govern the procedure. Therefore, the material behaviour was characterized under both these loading states. The quasi-static compression tests were performed on a servohydraulic tension/compression test machine at a strain rate of $\dot{\epsilon} = 10^{-3} \text{ s}^{-1}$ and 1 s^{-1} . High strain rate experiments were carried out with drop weight tower at a strain rate of $\dot{\epsilon} = 200 \text{ s}^{-1}$.

Specimens for mechanical testing have been machined in thickness direction of the plate. The size of cylindrical compression specimen was 6 mm in diameter and 6 mm in length. To reach a combined compression/shear loading stress state, cylindrical specimens with different inclination angles were tested. Using relatively small inclination of 3 °, 6 ° and 10 °, nearly the same compressive stress distribution is

reached as in the non inclined compression specimens. However, this inclination applies additional shear stresses, for example, an inclination angle of 3° gives an additional shear loading of 5,2 % of the compression loading acting and an inclination angle of 10° yields an additional shear loading of 17,6 % of the axial compression load. The force was measured with calibrated strain gauges and the deformation of the specimens was determined with an opto-electrical system. The force/time and displacement/time signal were stored. Adjustable rigid stopping devices make it possible to arrest the impact test at any given point of deformation. Additional details of the experimental procedure have been reported in [6].

3 RESULTS AND DISCUSSION

Dynamic stress-strain curves up to final fracture were obtained for all heat treated conditions up to the strain rate of $\dot{\epsilon} = 200 \text{ s}^{-1}$. Microfracture mechanisms were then investigated using detailed scanning electron micrographs. Metallographic and fractographic appearance of the failure surfaces of both, penetration crater and tested specimens, were also compared.

3.1 Mechanical Tests

3.1.1 Results under compression loading

In general, under quasi-static loading the material failed at about 30 % compressive deformation for the coarse material and about at 38 % to 45 % for the fine grained microstructures with a nearly homogeneous distributed deformation around the 45° shear plane. The dynamic stress-strain behaviour at strain rates of about $\dot{\epsilon} = 200 \text{ s}^{-1}$ reaches a maximum compression stress, followed by a rapid drop at fracture. The deformability is limited by adiabatic shear failure, Figure 3.

The strain-rate dependence of the 0,2%-yield stress is shown in Figure 6. The high strain rate sensitivity is consistent with previous works and results measured by other investigators [7, 8].

Figure 3: Typical stress-strain curves at high strain rates ($\dot{\epsilon} = 200 \text{ s}^{-1}$) for Ti-6Al-4V, different heat treatment conditions

Figure 4: 0,2%-yield strength under compressive loading versus strain rate

3.1.2 Results under dynamic biaxial compression / shear loading

The values of compressive strength and compressive deformation at shear failure as a function of shear/compressive load ratio are given in Figure 5 to Figure 7. With increasing shear to compression ratio the adiabatic shear failure occurred at lower strains and lower loads.

Figure 5: Compressive deformation and compressive strength vs. biaxial shear/compression load ratio VCF, no anneal

Figure 6: Compressive deformation and compressive strength vs. biaxial shear/compression load ratio VCF and 899 °C-30 min-AC

Figure 7: Compressive deformation and compressive strength vs. biaxial shear/compression load ratio VCF and 1038 °C-30 min-AC

3.2 Metallographic and fractographic examination

The ballistic craters as well as the sheared compression/shear specimens were investigated using both, optical microscopy and scanning electron microscopy (SEM). Microstructure of the shear bands was observed by optical microscopy after polishing and etching. The specimens were investigated for microstructural defects, such as microcracks and voids within the shear bands. SEM was employed to observe the surface appearance of the fractured shear surface.

Evaluation of the ballistic craters for the two conditions, VCF -not annealed and annealed at 899 °C, show similar failure modes. A series of parallel shear cracks are formed in the plane of the plate which link together in the direction of the projectile to cause significant deformation, bulging and cracking at the back surface. These separations appear to follow the elongated texture of the alpha-beta rolled and annealed structure. After sectioning the craters, the spalled parts and surfaces were investigated using SEM.

In comparison with the previous conditions, deformation and fracture characteristic's of the beta annealed condition (1038 °C) are different. Multiple shear cracks in layers were not evident. Instead, a fewer number of vertical or 45 ° cracks were present. The material tends to plug out but not to spall. Figure 8 shows an example of an adiabatic shear band in the ballistic crater of the coarse grained material. In all three microstructures tested under mechanical high strain rates and ballistic conditions, fracture always proceeds through the growth and coalescence of voids and cracks along the shear bands. Both, elongated ductile dimples and smoothed surface area are typical on most of the fracture surfaces of compression/shear and ballistic samples.

Figure 8: Adiabatic shear band as a precursor for voids and cracks.
Ballistic sample. VCF, 1038 °C - 30 min - AC

Figure 9 and Figure 10 show SEM-micrographs of shear bands in samples sheared under high rate mechanical conditions and from ballistic tests. Cavities are present in the shear band of the ballistic as well as laboratory samples. In shear cracks of the ballistic crater and on the surface of compression/shear specimens, fracture surfaces exhibit relatively smooth surfaces, which contain many dimples that are characteristic for ductile fracture.

Figure 9: SEM-micrograph inside of the cracked ballistic crater. VCF only

Figure 10: SEM-micrograph of the surface of the compression/shear sample. VCF and 899 °C-30 min-AC

Melting has occurred at the projectile-target interfaces. During examination of the ballistic craters deposits were observed on the interface. EDX-spectroscopy of the deposits showed a significant concentration of iron. Because of the negligible iron content of the titanium alloy it is assumed that the iron was transferred from the projectile.

3.3 Correlation between mechanical and ballistic data

Some indications of interdependencies between the ballistic performance of different heat treated titanium targets were noted, especially, the dynamic strength and sensitivity to adiabatic shear failure under dynamic biaxial conditions. As shown in fig. 11 and 12, when the ballistic performance decreases, the failure strain, the compressive plastic deformation of the occurrence of adiabatic shear failure, is reduced too. Therefore, the incidence of failure seems to correlate with the ballistic performance of these alloys. Furthermore, the influence of heat treatment on the energy consumption during dynamic compression/shear tests was investigated, Figure 12. The energy consumption of the compression/shear process is given by the integral of the force/displacement curve. Annealing over the beta transus temperature reduces the work of deformation, which correlates with the limit velocity.

Figure 11: Plastic deformation at failure under dynamic shear/compression loading (specimen inclination 10 °; $\tau/\sigma=17,63$, $\dot{\epsilon} = 200 \text{ s}^{-1}$)

Figure 12: Absorbed energy under dynamic shear/compression loading (specimen inclination 10 °; $\tau/\sigma=17,63$, $\dot{\epsilon} = 200 \text{ s}^{-1}$)

The difference in ballistic limit velocity between the ballistic best and worst material is about 29 %. The mechanical behaviour shows 16 % difference regarding the shear failure and 13 % if the energy consumption is compared. This means, the investigated mechanical properties are related meaningfully to the ballistic events and they can explain a reasonable part of the correlation.

4 CONCLUSIONS

Ballistic and mechanical tests were performed on Ti-6Al-4V subjected to three different heat treatments. Some indications of interdependencies between the ballistic performance of different heat treated titanium targets were noted, especially, the dynamic strength and sensitivity to adiabatic shear failure under dynamic biaxial conditions. The characteristic values obtained from dynamic shear/compression tests such as the engineering compressive strength, the strain up to failure and the absorbed energy are suitable to find interdependencies to the ballistic performance.

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