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Housseem BEN BOUBAKER, Charles MAREAU, Guénaël GERMAIN, Yessine AYED - On the formation of adiabatic shear bands in titanium alloy Ti17 under severe loading conditions - In: The 21st International ESAFORM Conference on Material Forming, Italie, 2018-05 - On the Formation of Adiabatic Shear Bands in Titanium Alloy Ti17 Under Severe Loading Conditions - 2018

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On the Formation of Adiabatic Shear Bands in Titanium Alloy Ti17 Under Severe Loading Conditions

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Abstract.

For metallic materials, fabrication processes (e.g. machining and forging) may involve important strain rates and high temperatures. For such severe loading conditions, the development of damage is often associated with the formation of Adiabatic Shear Bands (ASB). In this work, the impact of loading conditions (strain rate, temperature) on the formation of ASB in a beta rich titanium alloy (Ti17) is investigated. In this perspective, uniaxial compression tests have been conducted on cylindrical samples with a Gleeble-3500 thermo-mechanical simulator at temperatures ranging from 25°C to 800°C and strain rates ranging from 0.1 to 50 s⁻¹ with axial strains of approximately 50 %. According to the experimental results, the flow curves exhibit hardening from 25°C to 550°C and softening from 600°C to 800°C. When looking at the evolution of flow stress, the strain rate sensitivity is found to increase significantly with increasing temperatures. Also, adiabatic shear bands are preferably observed for high strain rates and low temperatures. The formation of ASB thus seems to be quite dependent on the evolution of the strain rate sensitivity of Ti17. Finally, metallographic observations have been carried out to better understand the process leading to the formation of ASB. Such observations demonstrate that the average width of ASB increases with increasing temperatures and decreasing strain rates. However, such observations do not allow for identifying whether some specific microstructural transformations (e.g. recrystallization or phase transformation) could explain the formation of ASB or not.

Keywords. Ti17, Strain rate sensitivity, Adiabatic shear bands, microstructure evolution

Introduction

Titanium alloys are widely used for aerospace applications because of their interesting properties, notably their high strength to weight ratio, good corrosion resistance and high mechanical resistance even at high temperatures. The Ti17 titanium alloy (Ti-5Al-2Sn-4Mo-2Zr-4Cr) is a near-beta alloy that has been designed for compressor blades in aircraft engines and gas turbine applications [1]. It offers higher mechanical properties and creep resistance than many other titanium alloys, such as Ti-6Al-4V [2]. However, the thermo-mechanical behavior of the Ti17 alloy under process conditions is quite complex, mostly because many physical phenomena tend to superimpose (e.g. crystallographic slip, phase transformation, recrystallization). As a result, different studies have been carried out to better understand the thermo-mechanical behavior of the Ti17 alloy.

For instance, Ayed *et al.* [3] investigated the behaviour of Ti17 alloy with uniaxial compression tests. According to the experimental results, the behavior of Ti17 is controlled by strain hardening from 25°C to 500°C while moderate softening is observed from 600°C to 800°C. Ning *et al.* [4] and Li *et al.* [5] also studied the deformation behaviour of the Ti17 alloy from uniaxial compression tests at temperatures ranging from 780°C to 920°C and strain rates ranging from 10⁻³ to 10¹ s⁻¹. They found that the apparent activation energy of Ti17 decreases with increasing strain but they did not analyze microstructural transformations. To better understand the process driving the formation of adiabatic shear bands (ASBs), Wang *et al.* [6] studied the dynamic behaviour of Ti17 at strain rates ranging from 2000 to 6000 s⁻¹ and temperatures from 25°C to 700°C using a Split Hopkinson Pressure Bar (SHPB). The obtained stress-strain curves exhibit a peak stress followed by a softening which is associated with the formation of ASBs. Yang *et al.* [7] used Transmission Electron Microscopy (TEM) to observe the microstructure of ASBs. They observed the microstructure of Ti17 to be composed of elongated sub-grains along ASB boundaries while the interior of an ASB is formed with fine equiaxed sub-grains.

The present research aims at investigating the thermo-mechanical behaviour of the Ti17 titanium alloy in a large range of loading conditions with uniaxial compression tests. In this paper, the experimental procedure is first presented and the impact of loading conditions on the mechanical behavior of Ti17 is then discussed. Finally, Optical Microscopy (OM) and Scanning Electron Microscopy (SEM) are used to investigate the conditions governing the formation of ASBs.

Material description and experimental procedure

The initial lamellar microstructure of the as-received Ti17 alloy is shown in Fig 1. The microstructure is composed of α phase lamellae (with a volume fraction of 67%) being embedded in a β phase matrix (with a volume fraction of 33%). The thickness of α phase lamellae is approximately of 8-10 μm while the size of former β grains is about 700 μm .

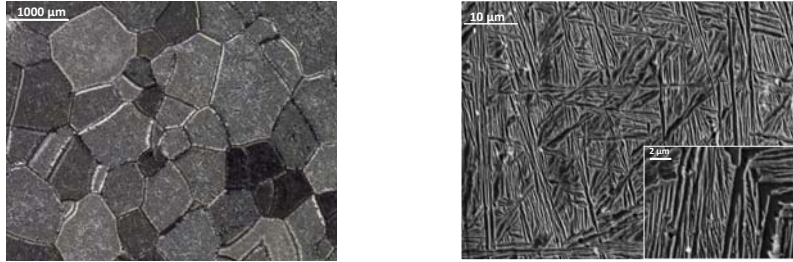


FIGURE 1: observation of the initial microstructure of the Ti17 alloy: OM (left) and SEM (right).

To investigate the mechanical behavior of Ti17, uniaxial compression tests have been performed on a Gleeble 3500 machine under vacuum condition (10^{-5} bar) with cylindrical specimens. The elongation has been measured from an extensometer and temperature has been controlled with a K-type thermocouple. It is necessary to point out that every test has been repeated at least three times. In this work, the imposed strain rate ranges from 10^{-1} to 50 s^{-1} and the test temperature is comprised between 25°C and 800°C . For each test, the experimental procedure is as follows. The specimen is first rapidly heated from room temperature to the test temperature with a rate of 100°C/s . The temperature is maintained for 5 seconds to limit temperature gradients. The compression test is then carried out with a constant nominal strain rate up to an axial strain of 50%. The deformed specimen is finally quenched immediately after the compression test using a compressed-air jet. It should be noticed that, with the above procedure, the total duration of a compression test is low enough to avoid phase transitions.

Experimental results and discussion

The evolution of the true stress σ as a function of the logarithmic strain ε is shown in Fig 2 for different loading conditions. According to experimental results, an increase of the strain rate and/or a decrease of the temperature is generally associated with an augmentation of the flow stress and a reduction of the fracture strain. These effects are classically explained from the impact of short range obstacles, which can be overcome by thermal activation, on dislocation mobility [8]. Also, whatever the loading conditions are, the Ti17 alloy does not exhibit any steady behavior.

To better understand the impact of loading conditions on the mechanical behavior of Ti17, the strain hardening coefficient n and the strain rate sensitivity coefficient m have been evaluated. For given strain rate $\dot{\varepsilon}$ and temperature T , the hardening coefficient n is given by:

$$n = \left. \frac{\partial \log \sigma}{\partial \log \varepsilon} \right|_{\dot{\varepsilon}, T} \quad (1)$$

For fixed temperature and fixed strain, the strain rate sensitivity coefficient m is obtained from:

$$m = \left. \frac{\partial \log \sigma}{\partial \log \dot{\varepsilon}} \right|_{\varepsilon, T} \quad (2)$$

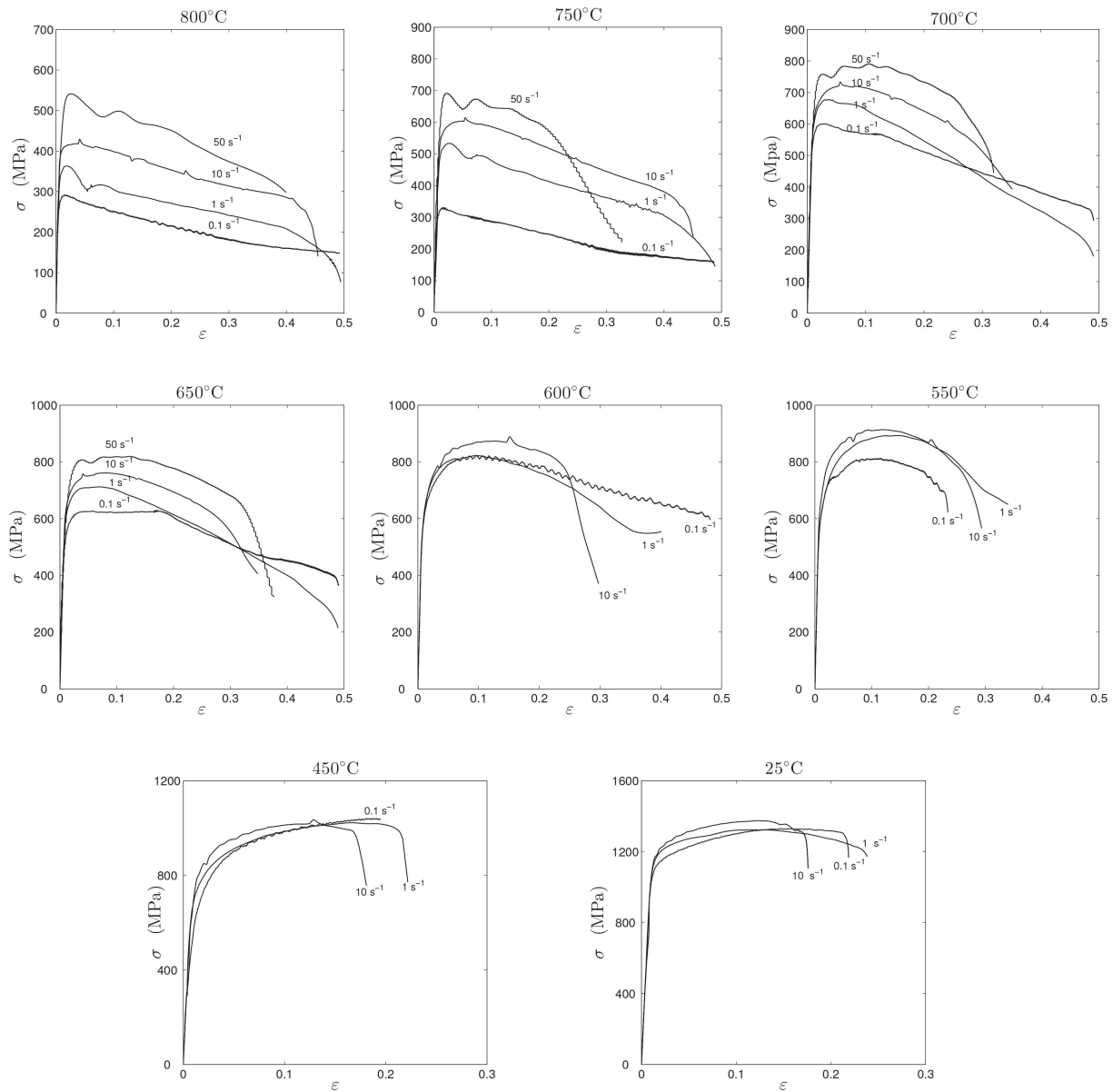


FIGURE 2: Stress-strain curves for temperatures ranging from 25°C to 800°C and strain rates ranging from 0.1 s⁻¹ to 50 s⁻¹

The above coefficients have been calculated for an axial plastic strain ε^p of 10%. The results are displayed in Fig 3. Strain hardening is significant for low temperatures (i.e. $T < 550^\circ\text{C}$) while the high temperature (i.e. $T > 550^\circ\text{C}$) mechanical behavior is controlled by strain softening. The temperature associated with the transition from strain hardening to strain softening is found to be independent on the strain rate. At this stage, the physical origin of strain softening is unclear. While a significant contribution of dynamic recovery is expected, some other phenomena cannot be excluded. Indeed, because of heat dissipation, compression tests are generally not isothermal. Softening may therefore be partly explained by the temperature increase resulting from heat dissipation. Also, for large strains,

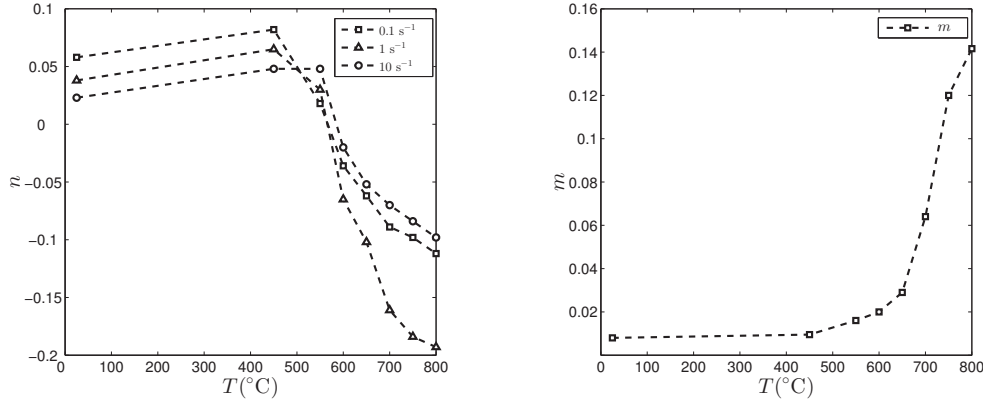


FIGURE 3: Evolutions of the hardening coefficient n and the strain rate sensitivity coefficient m as a function of temperature

both the morphological and crystallographic textures are significantly altered. A contribution from texture evolution to strain softening is thus possible.

TABLE 1: Summary of the conditions (strain rate and temperature) upon which an Adiabatic Shear Band (\bullet) or a Highly Deformed Region (\circ) is observed in Ti17.

	0.1 s^{-1}	1 s^{-1}	10 s^{-1}	50 s^{-1}
25°C	\bullet	\bullet	\bullet	\bullet
450°C	\bullet	\bullet	\bullet	\bullet
550°C	\bullet	\bullet	\bullet	\bullet
600°C	\bullet	\bullet	\bullet	\bullet
650°C	\circ	\bullet	\bullet	\bullet
700°C	\circ	\circ	\bullet	\bullet
750°C	\circ	\circ	\circ	\bullet
800°C	\circ	\circ	\circ	\circ

According to Fig 3, an important increase of the strain rate sensitivity coefficient is observed from 700°C. In the temperature range corresponding to low strain rate sensitivity (i.e. $T \leq 600^\circ\text{C}$), adiabatic shear bands are quasi-systematically detected. As shown in Fig 4, adiabatic shear bands are always oriented with an angle of $\pm 45^\circ$ with respect to the compression axis. For higher temperatures (i.e. $T \geq 650^\circ\text{C}$), the occurrence of adiabatic shear banding is dependent on the applied strain rate, strain localization being preferably observed for higher strain rates. The loading conditions (strain rate and temperature) upon which adiabatic shear bands are formed are summarized in Table 1.

As shown in Fig 6, the microstructure within an adiabatic shear band is composed of α phase lamellae which have been rotated toward the shear direction. This indicates that shear banding is not a consequence of the $\alpha \rightarrow \beta$ phase transformation. Also, the rigid body motion of α phase lamellae suggests that plastic deformation within an adiabatic shear band preferably occurs in the β phase matrix. In the exterior region of a shear band, the microstructure remains quite unchanged. The evolution of the average thickness L_{ASB} of an adiabatic shear band as a function of temperature and strain rate is plotted in Fig 5. As classically observed [9, 10], the average thickness is significantly reduced when the temperature is decreased and the strain rate is increased.

When the conditions for adiabatic shear banding are not met, plastic deformation concentrates in the central region of compression specimens. As illustrated by Fig 4, this alternative strain localization mode results in the progressive formation of a highly deformed region. According to metallographic observations, the microstructure of a highly deformed region is composed of α phase lamellae being perpendicular to the compression axis. The formation of a such layered microstructure could participate in strain softening.



FIGURE 4: Metallographic observations of Ti17 specimens after deformation at a strain rate of 1 s^{-1} for different temperatures.

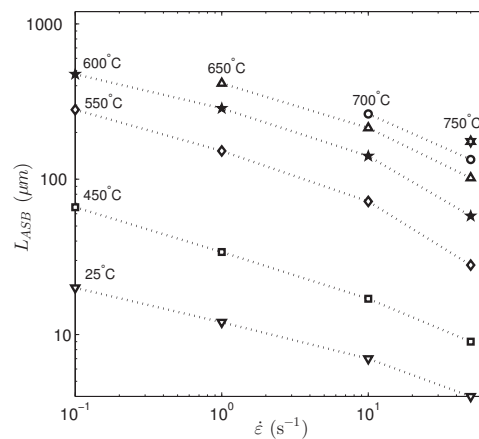


FIGURE 5: Evolution of the average thickness L_{ASB} of an Adiabatic Shear Band as a function of temperature and strain rate in Ti17 under uniaxial compression.

The contribution of α phase lamellae to the overall resistance is indeed limited in this specific microstructural configuration.

Conclusions

The dynamic response of the Ti17 titanium alloy has been investigated at strain rates ranging from 0.1 s^{-1} to 50 s^{-1} and temperatures ranging from 25°C to 800°C . To this end, different uniaxial compression tests have been performed. The main conclusions of this study are:

- The mechanical behavior of Ti17 is controlled by strain hardening at low temperatures (i.e. $< 550^\circ\text{C}$) while the high temperature behavior is significantly impacted by strain softening.
- Two different types of strain localization phenomena have been observed. At low temperatures and high strain rates, adiabatic shear banding is the favoured localization mode. At high temperatures, highly deformed regions are obtained from the localization of plastic deformation in the middle region of compression specimens.
- The thickness of shear bands is reduced when the strain rate is increased or the temperature is decreased.

The mechanical behavior of Ti17 titanium alloy allows the identification of a crystal plasticity model used to simulate machining. The crystal plasticity model will present the ability to simulate the evolution of the material texture under severe loading condition. It allows a better understanding of titanium alloys Ti17 chip formation in orthogonal cutting.

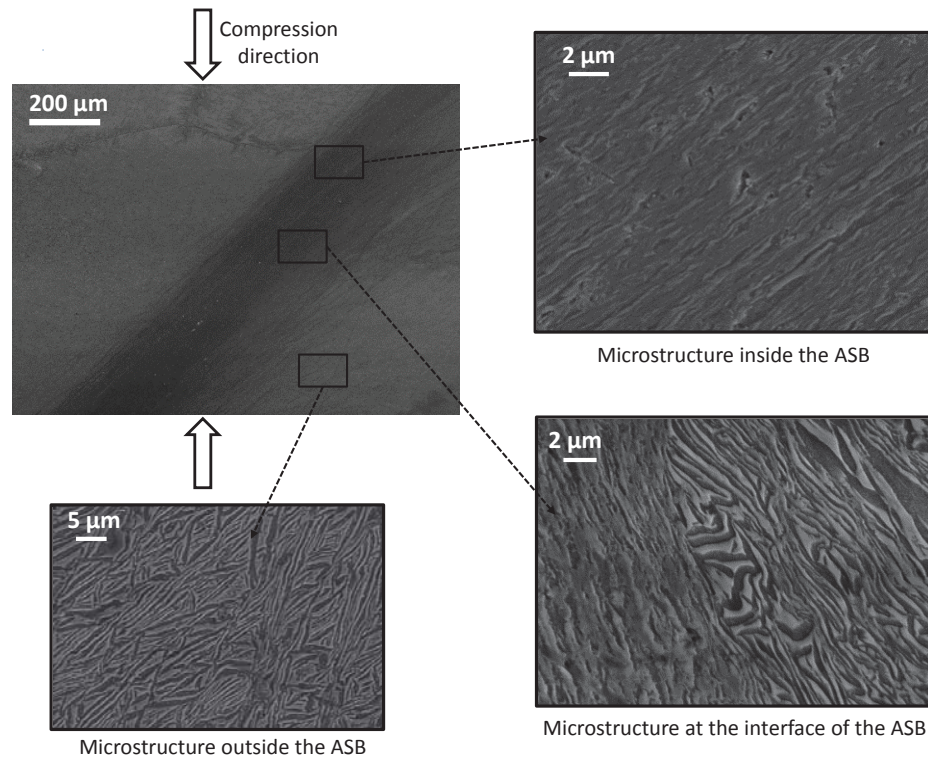


FIGURE 6: SEM observations of Ti17 specimen after deformation at a strain rate of 1 s^{-1} and temperature of 650°C .

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