Effect of sample geometry on the macroscopic shear deformation of the titanium alloy Ti-10V-2Fe-3Al subjected to quasi-static and dynamic compression-shear loading

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Abstract. We investigate the evolution of shear bands in a Ti-10V-3Fe-2Al alloy with three different initial microstructures: solution-annealed β-titanium, β-titanium with primary α-phase precipitates as well as a condition with primary and secondary α-phase precipitates. Quasi-static and dynamic testing of compression-shear specimens with strain rates of \(10^{-3}\) s\(^{-1}\) and \(10^{2}\) s\(^{-1}\) is performed at room temperature. The influence of two different sample geometries on the macroscopic shearing tendency is investigated: samples with a cylindrical cross section and samples with a square cross section. The results of digital image correlation and the nominal stress-strain behavior under quasi-static and dynamic loading indicate a stronger localization tendency of the aged conditions with additional α-phase precipitates compared to the solution-annealed pure β-condition. Our results also demonstrate that compression-shear testing with samples with a square cross-section reduces faceting loss, increases the resolution even at high strain rates and therefore allows to analyze strain distributions during shear band formation and propagation with higher accuracy.

1. Introduction

When subjected to dynamic loading, titanium alloys tend to fail spontaneously by the formation and growth of adiabatic shear bands [1,2]. This is primarily due to their low thermal conductivity [3]: High strain rates (>\(10^{2}\) s\(^{-1}\)) lead to a local temperature increase since the heat cannot be transferred quickly enough into the surrounding material. This effect results in local thermal softening which further leads to a concentration of deformation and finally to the formation of an adiabatic shear band [4–6]. The macroscopic deformation is therefore concentrated in relatively thin, microscopic regions, and microstructural evolution in these regions ultimately leads to spontaneous material failure by crack nucleation and growth [7,8].

The mechanical behavior of body-centered cubic (bcc) β-titanium alloys is strongly affected by microstructural parameters like β-grain size, morphology and volume fraction of primary and secondary hexagonal close-packed (hcp) α-phase precipitates [9–12]; the effect of these microstructural features on shear band formation and growth is not yet well understood. The present study is part of an ongoing experimental and theoretical investigation on the evolution of adiabatic shear bands in the β-titanium alloy Ti-10V-2Fe-3Al for different types of initial microstructures [13]: β-titanium with primary α-phase and β-titanium with primary and secondary α-phase precipitates. We carried out extensive compression-
shear tests in a previous experimental study [14,15] to specifically characterize the influence of the different initial microstructural characteristics on the formation of adiabatic shear bands. Compression-shear specimens, first proposed by Meyer et al. [16], are geometrically derived from conventional cylindrical compression samples, but the top and lower surfaces are cut at a small angle of inclination with respect to the central axis. When loaded in compression, this special geometry leads to a superposition of shear stresses. While the resulting stress state is inhomogeneous and thus not easy to interpret in terms of nominal stress-strain curves [17], compression-shear specimens have the advantage of allowing to test a material for its tendency to exhibit localized (shear) deformation. Compression-shear testing has been successfully used to characterize localized deformation in functional materials [18,19] where complex stress-states can considerably affect phase transitions [20,21]; this experimental approach is, moreover, specifically well-suited to analyze the shear tendency and further the formation of adiabatic shear bands and subsequent material failure in structural materials at high strain rates. To evaluate sample deformation during compression-shear experiments with respect to the shear tendency, the local strain fields can be documented and analyzed by means of digital image correlation (DIC). In experiments with high strain rates, however, the very short testing time and the three-dimensional measurement of the surface typically lead to increased facet failures during the measurements. The missing facets have to be interpolated numerically, which effectively leads to a reduction of the local resolution of the DIC measurements. This effect limits the general analysis possibilities and especially affects the determination of the shear tendency.

In the present study, modified compression-shear specimens with a square cross-section are used in an attempt to significantly increase the resolution in dynamic tests and reduce facet failures. As with the more common cylindrical compression-shear specimens, the inclination is also 6°. The advantage is that the surface to be measured is completely flat. For this reason, it is possible to work with a simpler experimental technique using only one camera for the two-dimensional evaluation of the strain field (instead of two cameras needed in a 3D setup for cylindrical specimens). We show that the shear zone is homogeneous in the entire cross section of the sample and that, by using the optimized specimens, the formation of shear bands can be documented in-situ on the surface of the specimens during mechanical testing using digital image correlation. The DIC results are further compared with those of cylindrical specimens.

2. Experimental and materials
A metastable β-titanium alloy of commercial purity was received in a forged and solution annealed condition from Otto Fuchs KG (Meinerzhagen, Germany) as cylindrical billets with a diameter of 52 mm. The chemical composition of the alloy Ti-10V-2Fe-3Al (Ti-10-2-3) was determined by spark spectral analysis as 10.3V-1.71Fe-3.15Al-0.01C-(bal.) Ti (in wt.-%). Three different heat treatment strategies were used to modify the microstructure of the titanium alloy, conducted in a convection furnace with Argon atmosphere to prevent oxidation. The specific heat treatment sequences are shown schematically in Figure 1. In a first step, the material was solution annealed at 830 °C above the β-transus temperature (792 °C) for 30 min and water-quenched to room temperature to achieve a fully recrystallized microstructure in a β-phase condition without additional α-precipitates or orthorhombic martensite. Using additional aging treatments, modified microstructures with additional α-phase precipitates was produced: The alloy was annealed at 700 °C for 60 min followed by air cooling, which resulted in precipitation of the primary α-phase within the β-grains. In a third step, the material was annealed at 500 °C for 480 min followed again by air cooling, which led to the formation of additional fine, secondary α-phase precipitates. Consequently, the three microstructural conditions used for investigations in this study are: (i) a pure β-condition (SA(β)), (ii) a condition with additional primary α-phase precipitates (A(αp)), and (iii) a condition with additional primary and secondary α-precipitates (A(αp+s)). Microstructural investigations were performed by optical and scanning electron microscopy (SEM) to document the effects of heat treatment. For the SEM investigations, a Zeiss NEON40EsB field
emission SEM in QBSD (quadrant back scatter diffraction) mode with an acceleration voltage of 15 kV was used to visualize the material contrast between the α- and β-phases.

Figure 1. Schematic representation of the heat treatment sequences used in the present study. Solution annealing and subsequent aging results in three different conditions: solution annealed - SA(β), aged to precipitate primary α-phase - A(α_p), aged to form primary and secondary α-phase precipitates - A(α_p+s).

Compression-shear testing was performed to document and compare the shear tendency of the three microstructural material conditions. In contrast to simple compression testing, the compression-shear samples used in the present study have an angle of inclination of 6° with respect to the loading direction. In addition to the more common cylindrical samples, a new type of “inclined cube” (simply referred to as “cubic” in the remainder of this paper) compression-shear specimen was used. The geometries of both sample types are illustrated in Figure 2. The cylinders with a diameter of 9 mm were cut by spark erosion from the titanium billets; their front faces were ground under an angle of inclination of 6° to obtain a height of 9 mm. The samples with a square cross section of 8 mm x 8 mm were cut directly by spark erosion, producing an inclination angle of 6° and a height of 8 mm. The effective cross section of approx. 64 mm² was almost the same in both sample types. Both types of samples were used for testing at two different strain rates: Quasi-static tests (initial strain rate of 10⁻³ s⁻¹) were performed in a Zwick/Roell UPM 1475 universal testing machine with a maximum force of 100 kN. An additional compression fixture with an inductive sensor was used to measure displacements, excluding measurement error related to elastic deformation of the testing device. The dynamic experiments (initial strain rates of 220 s⁻¹ and 250 s⁻¹ for the cylindrical and cubic samples, respectively) were performed in a drop tower with a drop mass of 600 kg. All samples were coated with stochastic black and white patterns and surface displacements were recorded simultaneously for all quasi-static and dynamic experiments by DIC to estimate the magnitude of the shearing tendency for the three different microstructural conditions. A single camera was oriented perpendicular to the surface of all cubic samples (2D DIC measurements). For all cylindrical samples, a 3D DIC system with two high-speed cameras of the type SA5 from Photron were used. The ARAMIS software by GOM/Zeiss was used for subsequent analysis of the strain fields.
3. Results and discussion

3.1. Microstructural characteristics after different heat treatments

We first discuss the influence of the different heat treatments on the microstructure of the alloy Ti-10V-2Fe-3Al. Figure 3 shows optical and scanning electron micrographs of three differently heat-treated material conditions. All material conditions are characterized by a coarse-grained microstructure with globular grains and an average grain size of about 300 µm. Pure β-grains without precipitates are observed after solution annealing, as shown in the optical micrograph of material condition SA(β) (Figure 3a). Aging was conducted for additional precipitation of the α-phase. A significantly darker appearance in the optical micrographs, primarily due to the precipitation of primary α, is visible after etching of both aged conditions (Figures 3b&c). It is not possible to directly detect any differences between the aged conditions A(α_p) and A(α_p+s) by optical microscopy. Higher magnifications are necessary to detect size, type, morphology, or volume content of α-phases. The SEM micrographs (Figures 3d&e) show lamellar primary α-phases with lengths between 1 and 4 µm and a volume fraction of about 40% in both aged conditions. A typical microstructural orientation between bcc β-grains and hcp α-phases is observed, which is well-known as Burgers orientation relationship [22]. Two-step aging as expected leads to the additional precipitation of lamellar secondary α-phase, with lamella sizes of approximately 100 nm and a volume fraction of about 15% (Figure 3e). Furthermore, a regular arrangement of secondary α-needles, parallel to primary α precipitates, is observed in the SEM micrograph. The microscopic characterization therefore confirms that three distinctly different material conditions were produced by the different heat treatments, which subsequently allowed to study the effect of different initial microstructures on shear band formation during compression-shear testing.
Figure 3. Microstructures of Ti-10V-2Fe-3Al after different heat treatments. (a) Optical micrograph after solution annealing (830 °C for 30 min) – condition SA(β), (b) optical micrograph after one-step aging (700 °C for 60 min) – condition A(αₚ), (c) optical micrograph after two-step aging (700 °C for 60 min and 500 °C for 480 min) – condition A(αₚ+ₛ). Scanning electron micrographs indicate differences between both aged conditions: (d) One-step aging leads to a precipitation of primary α-phase precipitates within the β-grains. (e) Two-step aging leads to the additional formation of secondary α-phase precipitates.

3.2. Investigation of the shear tendency by DIC

In compression-shear samples, the angle of inclination of 6° leads to a complex stress state during nominally uniaxial compression; therefore, the stress-strain behavior can only be estimated by considering the compressive load component. Nevertheless, for a first-order, quantitative comparison of the mechanical behavior of the three different material conditions, nominal engineering stress-strain curves were calculated from the uniaxial load-displacement data recorded during compression-shear testing.

We first characterize the local strain fields at different stages of deformation as reflected by the nominal stress-strain data. With the help of DIC, we investigate to what extent optical measuring methods can be used to analyze shear band formation. Two different strain rates (quasi-static and dynamic) of both cylindrical and cubic compression-shear specimens are compared. Strain fields obtained by DIC are evaluated at 2%, 5% and 10% of axial compression. In all data sets discussed below, in case of a failure earlier than 10% (which occurred primarily when using the cubic specimens due to stress concentrations in the corners), strain data recorded immediately prior to failure was analyzed. Preliminary investigations showed that considering individual strain components in X- or Y-direction (where Y is the loading direction) are not sufficient for an unambiguous characterization of shear banding in compression-shear samples because the specimens deform in both directions during the test. To fully appreciate the multi-axial deformation of the samples, we instead calculate and visualize the major strain (determined at each measurement point from the 2D surfaces strain tensor information).

Figure 4 shows the behavior of the cylindrical compression-shear specimens under quasi-static loading. The solution annealed condition SA(β) exhibits a stronger strain hardening compared to both aged conditions A(αₚ) and A(αₚ+ₛ) but the corresponding nominal stress of SA(β) are at a lower level for any given strain. Already at 2% plastic (compressive) strain, an initial localization of shear deformation
can be seen in the DIC strain fields for all material conditions. The shear zone – the region where strains are increased compared to adjacent, less deformed regions – can be observed clearly in both aged states up to a plastic deformation of 10%. In contrast, the solution-annealed condition shows a somewhat more homogeneous deformation of the sample. With increasing plastic strains, several individual bands occur in the SA(β) samples, which are located either in the shear plane, parallel to the shear plane or perpendicular to the shear plane. A slightly stronger localization tendency with higher local strains under quasi-static loading of the two aged samples, compared to the solution-annealed samples is observed.

Figure 4. Nominal stress-strain curves of Ti-10-2-3 after different heat treatments under quasi-static loading of cylindrical compression-shear specimens. The corresponding strain fields (DIC) are shown at 2%, 5% and 10% nominal axial compressive strains, respectively. In the three material conditions, the formation of a shear zone with increased major strain values can be observed in the DIC data. In the aged conditions A(α_p) and A(α_p+s), this zone is narrower than in the solution annealed condition SA(β), where several parallel bands in and perpendicular to the shear plane are formed.

Figure 5 shows the nominal stress-strain behavior of the cylindrical compression-shear specimens under dynamic loading in the drop tower and representative DIC strain fields. Similar to the results of the quasi-static compression-shear tests, the SA(β) condition shows strain hardening until failure. In contrast, both aged conditions A(α_p) and A(α_p+s) are characterized by a significantly lower strain hardening rate after reaching the yield point. After 5% axial compression a significant softening is noticeable for both aged samples. It is likely that from this moment on shear band initiation and subsequent growth occurred, which counteracted the material’s strain hardening due to local thermal softening [23,24]. In the DIC strain maps, the formation of a broad shear band region is confirmed. Compared to the quasi-static tests, the deformation in all three conditions is much more concentrated in the shear plane, and this effect becomes more intense with increasing axial strains. The shear zone of the SA(β) samples again is wider and, similar to the quasi-static tests, the main deformation appears to be localized in several bands. In the aged samples, a concentration of the main deformation in the “corner regions” indicates subsequent fracture initiation sites.
Figure 5. Nominal stress-strain curves of Ti-10-2-3 with different heat treatments under dynamic loading of cylindrical compression-shear specimens. The corresponding strain fields (DIC) are shown at 2%, 5% and 10% axial compressive strains. All material conditions show the formation of a shear zone with high major strain values. SA(β) forms deformation bands in the shear zone and perpendicular to it, similar to the quasi-static tests. The shear zone is slightly wider than in the aged samples. For A(α_p) and A(α_p+s), softening occurs, starting at about 5% axial strain. This indicates shear band initiation and propagation, which ultimately leads to material failure.

As a consequence of the high impact energy during drop tower tests, the DIC camera system is influenced by vibrations transmitted through the drop tower foundation into the ground. Especially in 3D DIC with two cameras, oriented and calibrated in a certain angle to each other, these vibrations can slightly change the camera positions. This affects the analysis of strain fields and may lead to the appearance of image correlation errors in individual image areas, which makes it necessary to subsequently interpolate facets, ultimately diminishing the resolution of strain measurements in the shear band regions. In order to address these issues, we additionally studied the deformation behavior of the cubic compression-shear specimens. The key advantage of this experimental approach is that the flat surface perpendicular to the shear plane of the specimen can be directly used for the DIC measurements. Most importantly, DIC can then be performed with only one camera in 2D mode. This leads to a reduced error rate and therefore to a significantly higher number of facets that can be analyzed and, accordingly, a higher resolution. The goal of the results presented below was to study whether the experimental observation and subsequent strain analysis of localized shear deformation processes can thus be simplified and improved.

Figure 6 summarizes the stress-compression behavior of cubic compression-shear samples under quasi-static loading. The nominal stress-strain curves are quite similar to the corresponding results determined from the cylindrical compression-shear specimens. In the solution annealed condition SA(β), the strain field clearly shows a local increase of major strain values; this localization becomes more distinct with increasing total deformation in the shear plane. Again, due to the quasi-static strain rate, a splitting of the deformation into several bands can be observed on the specimen’s surface already at low nominal strain values of about 2% (and very clearly from 5%). In the cubic specimens, shear bands occur parallel and perpendicular to the shear plane (see Figure 2) on the entire surface. One possible explanation for the observed grid-like structure in the strain field is the relatively large grain size of 300 µm: It is likely that individual grains that are well oriented relative to the maximum shear stress are plastically deformed earlier than adjacent grains. This leads to the formation of more strongly deformed areas that can be directly detected in the DIC strain field and thus to the observed lattice-like patterns in the image correlation data. In both aged conditions, the formation of a “forging cross” (i.e., an X-shaped strain profile typically associated with uniaxial compressive loading), dominates the surface strain
fields. A slight grid-like structure is also visible. Due to a force limitation of 100 kN of the testing machine, both aged conditions $A(\alpha_p)$ and $A(\alpha_{p+s})$ could not be deformed until fracture. Starting at a strain of 5%, shear localization in the shear zone also becomes evident.

Figure 6. Nominal stress-strain curves of Ti-10-2-3 with different heat treatments under quasi-static loading of cubic compression-shear specimens. The corresponding strain fields (DIC) are shown at 2%, 5% and 10%. All material conditions show the formation of a shear zone with increased major strains.

Figure 7 shows the nominal stress-strain behavior of cubic compression-shear specimens under dynamic loading. Due to premature material failure, a high variation of the maximum achievable nominal strains was observed in the aged samples. This behavior is related to the sample geometry: Due to the small radii, local stress peaks occur in the corners of the sample. These corner regions are starting points for shear band initiation and, in some experiments, for early initiation of fracture. The representative stress-strain curves of the conditions $A(\alpha_p)$ and $A(\alpha_{p+s})$ shown in Figure 7 were selected from experiments where fracture occurred relatively late. For all material conditions, the strain fields show the formation of a well-defined, sharp shear zone with high major strain values, in which also material failure occurs in the later stages of deformation. These shear band regions are concentrated in the shear plane, and they are already formed at small strains. The solution annealed material condition also exhibits a more pronounced deformation in the regions adjacent to the shear band region. This is due to the fact that the $SA(\beta)$ condition shows a significantly higher amount of strain hardening and thus also reaches a higher total compressive strain. Consequently, localized shear deformation occurs much later compared to the aged material conditions.
Figure 7. Nominal stress-strain curves of Ti-10-2-3 with different heat treatments under dynamic loading of cubic compression-shear specimens. The corresponding strain fields (DIC) are shown at 2%, 5% and 10% axial compressive strains, respectively. All material conditions form a distinct shear zone with high major strains during dynamic compression. The material condition SA(β) is characterized by significantly higher strain hardening than the aged conditions and therefore reaches a higher total deformation before shear localization sets in.

The flat surfaces, the possibility to perform more stable 2D DIC measurements, and the resulting reduced loss of facets even in dynamically tested samples, make the cubic compression-shear specimens particularly useful for an in-depth analysis of local strain fields during shear banding. One possible method of evaluation is shown as an example in Figure 8: In order to evaluate and compare the shearing tendency of the three differently heat-treated material conditions, we consider strain maps that were recorded immediately prior to material failure during dynamic loading. The improved resolution allows to visualize the major strain distribution on the planar surface of the cubic sample with high accuracy. Moreover, we plot major strain values along the linear paths (red lines; length 10 mm) highlighted in each DIC strain map. It is possible to carefully evaluate the widths of the shear zones of the different material conditions – and thus to analyze their shearing tendencies under dynamic loading conditions. In all material conditions, strongly localized deformation in the shear zone is observed. There is no trace of grid-like patterns in the strain fields as in the quasi-statically tested specimens. The deformation therefore clearly predominantly takes place in the shear plane at increased strain rates. Only the solution annealed material condition SA(β) exhibits a somewhat increased deformation in the remaining parts of the sample volume, confirming the observations discussed above in relation to Figure 7. An evaluation of the width of the shear zones was performed at 1% below the respective maximum of the major strain. The resulting values are 675 µm for SA(β), 400 µm for A(αp) and 220 µm for A(αp+s). These results agree well with the qualitative observations of the different shear zones: The solution annealed condition shows a significantly wider shear zone than both aged conditions and the deformation is generally more widely distributed over the entire sample volume. With A(αp) and A(αp+s), the tendency for shear localization is considerably more pronounced. These results are fully in line with our previous investigations presented in [13]. The two-stage aged specimens with additional secondary α-phase show a very high shear tendency and are also characterized by the highest local major strain values of all tested conditions.
Figure 8. Analysis of the shear zones of the three heat-treated conditions under dynamic compressive shear loading of cubic compression-shear specimens. Additionally, the strain fields of the digital image correlation are shown. The corresponding diagrams show major strain values along a 10 mm long section (red lines, 0 – 10 mm, indicated in the DIC strain maps on the left). There is a clear localization of the shear deformation with differently pronounced peaks in all three material conditions. The solution annealed material condition SA(β) shows a slightly wider shear zone and the entire cross section of the sample exhibits more deformation than the aged samples. A(α_p) and A(α_p+s) show a strong localization of the major strain in narrower areas close to the shear zones.

4. Summary and conclusions
In the present study, we have investigated the influence of two different sample geometries and three different heat treatment conditions on the macroscopic shearing tendency of the titanium alloy Ti-10V-2Fe-3Al. Compression-shear tests with cylindric and cubic samples have been performed under quasistatic and dynamic loading in combination with digital image correlation. The results of the digital image correlation measurements and the nominal stress-strain behavior under quasi-static and dynamic loading
clearly show that there is a stronger localization tendency in the aged material conditions with primary as well as with primary and secondary α-phase precipitates compared to a solution-annealed β-titanium condition. Our results again demonstrate that the mechanical behavior of the titanium alloy is significantly influenced by the superposition of compressive and shear stresses. Using the cubic sample geometry, a strong localization tendency can be detected by digital image correlation with high accuracy even under dynamic loading conditions. The less accurate representation of 3D deformation fields on the cylindrical compression-shear specimens under dynamic loading is avoided by using the cubic specimen shape. The two-dimensional strain mapping significantly increases the effective resolution capacity while reducing facet loss, providing an opportunity for more detailed investigations on adiabatic shear banding.

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