14.0 MEASUREMENT AND MODELING OF ANISOTROPY IN TI-6AL-4V FORGINGS

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14.1 Project Overview and Industrial Relevance

Titanium alloys are widely used in advanced structural applications, due to their remarkable specific strength and corrosion resistance. The mechanical response of two-phase alpha/beta titanium alloys, the most common of which is Ti-6Al-4V, depends strongly on the microstructure and texture developed during thermomechanical processing (TMP). Primary TMP of conventional alpha/beta alloys is typically conducted in multiple hot-working and heat treatment steps with the intent of ultimately achieving a uniform and fine microstructure of globularized alpha (hcp) in a transformed matrix of alpha and beta (bcc) phase [14.1]. This microstructure is often desirable, because it suppresses the anisotropic properties of the alpha phase, reducing microstructural variance while increasing workability and ultrasonic inspectability [14.2]. The steps to produce this microstructure often consist of hot working and heat treatment in the high-temperature single-phase beta field, followed by breakdown of the transformed, lamellar microstructure in the lower-temperature two-phase alpha/beta field [14.1].

Localized heterogeneous deformation often arises during TMP of titanium alloys, particularly when deforming colonies of alpha lamellae. This is primarily due to the anisotropy of the critical resolved shear stress (CRSS) in alpha lamellae, which results in colonies being either hard- or soft-oriented with respect to the applied load, depending on which slip systems are operational [14.3]. Previous work from Bieler and Semiatin has shown that in regions where both prismatic and basal slip systems are non-operational, macro shear bands develop that lead to kinked lamellar microstructural features. These shear bands produce localized shear that flows easily around hard regions, preventing these hard colonies from undergoing dynamic spheroidization (also referred to as globularization, or geometric dynamic recrystallization) [14.4, 14.5]. If colonies are not properly spheroidized, the resulting microstructural heterogeneity may have consequences at every subsequent stage of processing. Ultimately, if the microstructure is not sufficiently uniform, it is possible that the part will produce a false positive during ultrasonic inspection.

The presence of insufficiently spheroidized colonies will impact material properties and the variance of said properties. Recrystallized regions will consist of more equiaxed, smaller grains with a weaker crystallographic texture and lower ultrasonic attenuation than those of coarse, relatively large alpha colonies. The texture, grain size, and uniformity thereof is of tremendous importance when determining the strength, fatigue response, and ultrasonic inspectability of a part. Microstructural uniformity also plays a significant role in avoiding the formation of defects during processing, such as strain-induced porosity. For these reasons, the forming conditions under which alpha colonies recrystallize most effectively is of great interest to titanium producers.

14.2 Previous Work

This project is focused on experimentally observing and quantifying the heterogeneous deformation of alpha colonies in the early stages of Ti-6Al-4V processing, with the ultimate goal of providing a dataset that may be used for future model development. Early efforts were focused on literature review and isothermal, uniaxial compression experiments. Material was donated from Weber Metals after processing in the fully beta condition and slow cooling, producing a fully lamellar alpha microstructure. The sample material was received as a 56 cm x 56 cm round-cornered square slab, cut from a billet, from which simple cylindrical samples (10mm diameter x 15mm height) were machined from the center. The cylinders were isothermally compressed to varying strains (30% and 70% average height reduction) at varying temperatures (900°C, 925°C, and 950°C) using a Gleeble 3500 thermomechanical simulator. Localized strain was observed in 90% of the >60 compressions performed, and could not be correlated to temperature, height reduction, or strain rate. The observed strain heterogeneity was attributed to the large alpha colony size of the center of the slab relative to the sample dimensions.

14.3 Recent Progress

The following sections focus on work that has been completed since the last reporting period. Highlights include additional Gleeble compression experiments with material taken from the billet's edge, and characterization of alpha colonies in various states of spheroidization.

14.3.1 Gleeble Isothermal Compression and Sample Preparation

Simple cylindrical samples of the same dimensions as those compressed in previous work were machined from the edge of the billet, with the intent of obtaining samples with smaller average alpha colony size to reduce the extent of macroscopic heterogeneous deformation. Samples were heated rapidly to one of three temperatures, as before, and held for 30 s to allow for temperature equilibration prior to compression. Thermocouples were welded to the center of the samples to verify the sample surface reaching the required temperature, and surface temperature was recorded prior to, during, and after deformation. Following compression, samples were cooled under rough vacuum (on the order of 10^{-3} mbar). The samples were then cleaned and sectioned along their midplane using a diamond wafering blade at 300 rpm. Samples were subsequently prepared using standard metallographic techniques, ground to 1200 grit on silicon carbide paper before being chemomechanically polished in a colloidal silica suspension. A minor etching effect was observed after vibratory polishing, which slightly impacted image quality during electron backscatter diffraction (EBSD) characterization. As a result, an electrochemical polishing technique is being perfected and will be used during later characterization.

Heterogeneous deformation was observed in all samples, to varying degrees. A sample that exhibited particularly one-sided deformation was macro-etched in a solution of 10vol% hydrofluoric acid, 15vol% nitric acid, 75vol% water, the macrostructure of which is shown in **Figure 14.1a**. For comparison, a macroetched section of the as-received beta-forged material is included in **Figure 14.1b**. Macroetching provided a qualitative confirmation that the undeformed side of the sample exhibited the as-received microstructure, an observation that was confirmed later via EBSD.

14.3.2 Characterization of Deformed Microstructure

The deformed samples were observed using a JEOL JSM 7000F field emission scanning electron microscope. EBSD maps were generated for analysis via orientation imaging microscopy (OIM). Secondary electron images (SEI) were taken of selected areas prior to the EBSD scans to identify the regions of beta phase that could complicate OIM analysis. Scan areas were selected with the intent of imaging alpha colonies in various states of recrystallization, with an emphasis placed on regions exhibiting local heterogeneous deformation between colonies. **Figure 14.2a** shows an inverse pole figure map obtained from a moderately deformed region of a sample compressed to 30% height, with a colony beginning to bend and kink while the lamellae of neighboring colonies remain parallel. **Figure 14.2b** shows a colony that has undergone partial recrystallization, resulting in a subregion that is more equiaxed with weaker texture adjacent to a remnant of the prior colony (indicated in purple). Due to the heterogeneous nature of the imposed strain, it is difficult to quantify with certainty the amount of strain experienced at a given location. This is a challenge that may be addressed with finite element analysis, or approximated based on the change in dimensions of the samples.

The maps produced by EBSD scans were cleaned and analyzed using TSL/OIM software to determine grain size distribution, grain orientation, and subgrain development. Poor surface quality precluded subgrain analysis, but grain size was apparent and could be correlated with secondary electron images. Taylor and Schmid factors were also calculated, assuming that the strain in the scanned regions was equivalent to the macroscopic strain. Further analysis of these maps will be required, as the results they provide are counterintuitive. **Figure 14.3** shows a representative Schmid factor map, which seems to indicate that the bent, deformed colony is less likely to deform than the undeformed hard-oriented colony. While this could be an interesting result, more in-depth analysis is required to determine whether or not this is simply an artifact of the manner in which Schmid factors are calculated. While not included in this report, Taylor factor maps showed similar, counterintuitive trends.

14.4 Plans for Next Reporting Period

The plans for next reporting period are to finish the preparation and characterization of the samples, which will provide a dataset of microstructures deformed at three different temperatures. Locations will be scanned via EBSD in a manner similar to that above, but with an electropolishing technique implemented that should result in superior resolution for subgrain size analysis, as well as eliminate any issues that could be caused by a polishing-induced deformation layer. Once characterization is complete, colony interactions can be quantified in terms of recrystallized volume fraction and change in orientation. These datasets will be correlated to local strain, if possible, in order to relate the effects of temperature and strain on the degree and extent of recrystallization. The data will hopefully be of value for elucidating the conditions under which these colonies recrystallize, and the origins of microstructural heterogeneity in two-phase titanium forgings.

14.5 References

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14.6 Figures

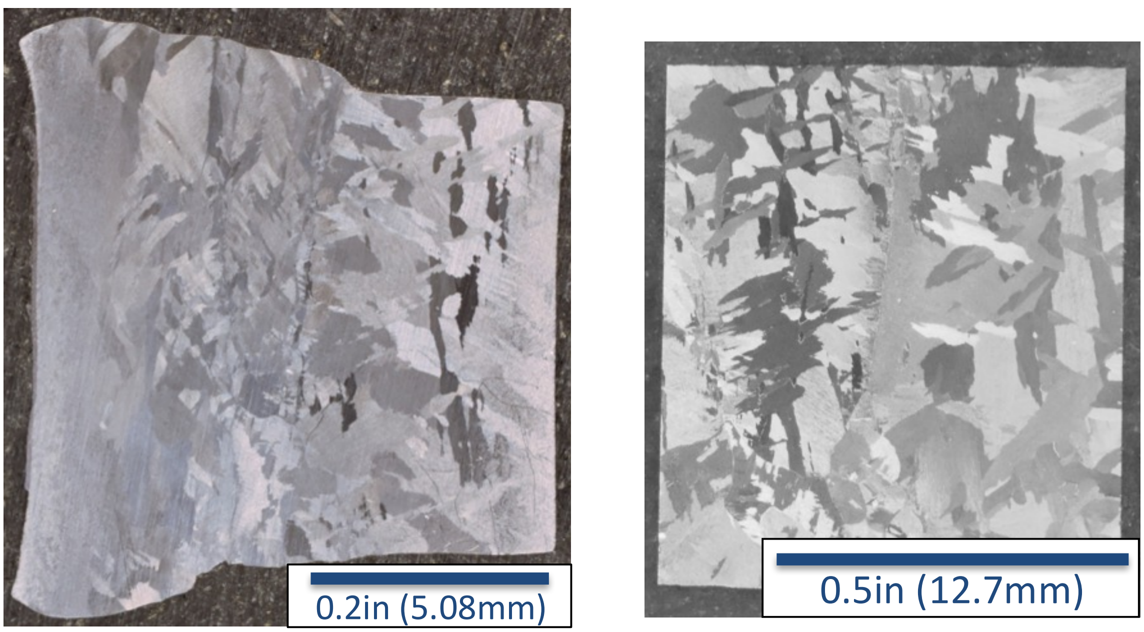


Figure 14.1: (Left) Representative sample compressed to 30% average height reduction at 925°C that exhibited particularly one-sided deformation. Direction of compression is horizontal. Sample was macroetched and compared to the as-received, beta-forged microstructure (Right), which was similarly macroetched.

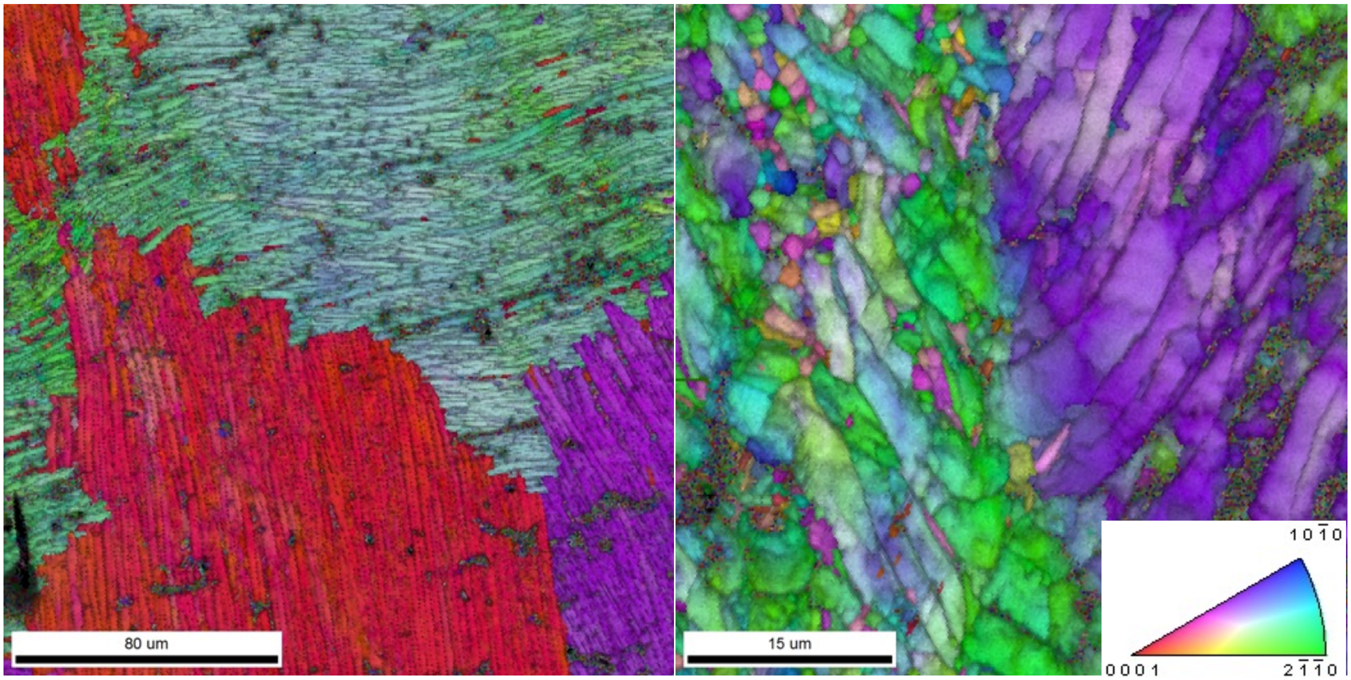
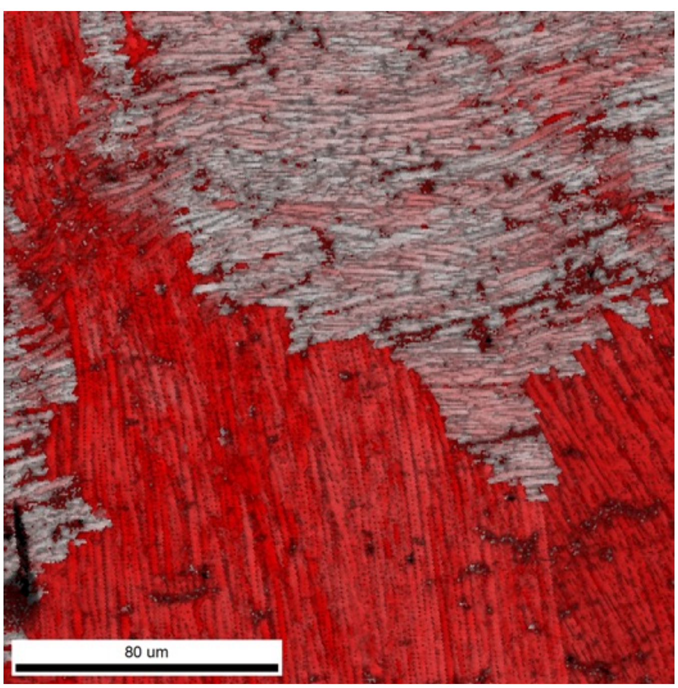


Figure 14.2: (Left): IPF map taken from a sample compressed to 30% average height reduction at 925°C, showing an alpha colony beginning to kink and bend (colony 1) while neighboring colonies (colonies 2 and 3) remain parallel. (Right): IPF map taken from a sample compressed to 70% height reduction at 925°C, showing a severely bent colony globularizing, forming a region of weaker texture and smaller, more equiaxed grains. The purple region is an example of a hard-oriented colony remnant that could contribute to microstructural heterogeneity. For both images, compression direction is horizontal.



Min	Max	Total Fraction	Partition Fraction
0.254329	0.499999	0.952	0.952
0.00865818	0.254329	0.047	0.047

Figure 14.3: Schmid factor map calculated via TSL/OIM software for a lightly deformed region of a sample compressed to 30% average height reduction at 925°C. Strain imposed was nominally horizontal, replicating the macroscopic strain induced in the sample. The red regions are calculated to be more prone to slip. This will be deconvoluted in future work.