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

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14.1 Project Overview and Industrial Relevance

Titanium is a lightweight, high strength material with excellent corrosion resistance. The most commonly used titanium alloy, Ti-6Al-4V, is used heavily across many cutting-edge industries, particularly the aerospace industry. Ti-6Al-4V is a two-phase alloy with a hexagonal closed packed (HCP) α-phase at room temperature and a body centered cubic (BCC) ß-phase above the transus temperature of 995°C [14.1]. After experiencing typical processing conditions and heat treatment, an ideal Ti-6Al-4V part will have a majority α microstructure with less than 10% retained ß-phase. The α-phase exhibits a highly anisotropic plastic response because of the limited slip systems in HCP crystal structures, which combined with transformation from the metastable ß phase can lead to microtextured regions (MTRs) developing in finished products [14.2].

Thermomechanical processing (TMP) of Ti-6Al-4V is a topic of great interest, and the effects of forging parameters on resultant microstructure have been thoroughly studied. Simulations have been developed in order to optimize process paths, but there is significant work yet to be done in predicting local texture and material properties. Previous efforts to model texture evolution in Ti-6Al-4V have been focused on prediction from an averaged standpoint, calculating how distributions of orientations within volume elements change. However, even with the lessons learned from these models there are still a significant number of defective parts produced throughout the titanium industry, owing largely to MTRs and other microstructural inhomogeneities. Thus there is a need for greater understanding and control of microstructural evolution during processing.

Modeling deformation texture is not trivial, but the barrier to entry has been greatly reduced by implementation of these calculations into DEFORM®, a finite-element solver that is tailored to metalforming processes. The software incorporates polycrystal plasticity models into metalforming simulations, an approach that has previously been successful in predicting deformation texture [14.3]. However, these codes strictly account for lattice rotations that accommodate deformation, neglecting twinning or phase transformations. Since the majority of Ti-6Al-4V's microstructure is composed of transformed ß, the decomposition of the parent phase will play a significant role in dictating final texture and may provide greater understanding into the conditions where MTRs form. Specifically, the models that determine when a particular variant forms preferentially in a given location will need to be assessed. In order to understand texture development, it is essential to first understand what variants will form under given conditions.

14.2 Previous Work

This project is focused on both experimentally observing and modeling the anisotropy in Ti-6Al-4V forgings. Early efforts were focused on literature review and experimental simulation in order to determine the parameters necessary to construct a well-posed, solvable problem with physically significant results. Samples were subjected to uniaxial compression, seeking to simulate conditions similar to industrial forging practices to obtain material response data while also gleaning insight into the effects of plastic strain on resultant microstructure. The material data was unable to be obtained due to shear localization in a majority of samples. Focus was summarily shifted to simulation of an experimental forging from literature as a means to gauge the accuracy of the models currently developed within DEFORM®.

The experiment to be modeled was that of Glavicic et. al, which started with cylinder of Ti-6Al-4V material and compressed it uniaxially to 70% of its height [14.5]. In their work, pole figures were taken from six locations to show the spatial variation of texture pre- and post-deformation. Glavicic's experiment was of particular interest to this project as the models it used served as the basis for the crystal plasticity models built into DEFORM. Pole figures were successfully generated from the current simulation but showed significant deviation from previously predicted or measured values. The differences between the current work and results previously obtained were attributed to the lack of phase transformation relationships or variant selection schemes as well the current work's use of an initially random texture that was said to be uniform throughout the workpiece.

14.3 Recent Progress

The following sections focus on work that has been completed since the last reporting period. The most notable milestone that was reached was obtaining resources from a collaborative workshop between several titanium forging companies and the Air Force Research Laboratory (AFRL). The workshop was spent obtaining information about the accessibility of measurements, samples, and results; all of which have potential to greatly advance the pace of this project. Chief among those resources are variant selection codes as well as the texture measurements from Glavicic's experiments that will allow for the removal of some simplifying assumptions currently limiting the predictive capabilities of the model.

14.3.1 Current Model Construction and Assumptions

The current simulation is designed to model the processing conditions of Glavicic's experiments. This experiment was chosen due to the availability of measurements and samples through collaboration with AFRL. The sample geometry, induced deformation, and heat treatments are identical to those described in the paper.

To reduce computational workload, the simulation was run in a decoupled fashion. First, the simple upset was simulated under the assumption that the material behaved isotropically. The sample geometry was a cylinder of 280mm diameter x 510mm height that was compressed at 955°C to 70% height reduction before being water quenched. It was subsequently heated to 30°C below the ß transus for an hour before being quenched again.. Subesquently to determine the evolution of texture, a post-hoc crystal plasticity simulation was run at six material points examined by Glavicic in his work, shown in **Fig. 14.1**.

With regard to the polycrystal plasticity parameters that were used by the simulation, an initially random texture was generated as a simplifying assumption in lieu of having access to Glavicic's initial measurements which were not published in the paper. Since texture development is highly dependent on initial texture, the present simulated pole figures were vastly different than those measured and predicted previously. Texture was evolved according to local strain increments from the forming simulation. Strain was partitioned between the phases using the viscoplastic self-consistent (VPSC) approach. VPSC strain partitioning requires phase fractions, which were initialized according to the ß-approach curve, and evolved according to the MEDC model, a vanadium diffusion-controlled model which dictates the growth of primary α upon cooling from the ß phase. The hardening parameters and strength of the ß phase slip systems were set to be 1/3 those of α, the values of which were simple "ballpark" figures obtained from DEFORM® support. All ß slip systems were activated, and pyramidal slip was penalized for the α phase.

$\{0001\}_\alpha$ pole figures were generated along the axis of compression at the six points identified by Glavicic, which served as a basis for comparison and are shown in **Fig. 14.2**. The generated figures showed spatial variation in texture, but neither qualitative nor quantitative agreement with predicted or measured results. Even if the generated figures were in agreement with Glavicic's results, there would still be significant work required in order to get them to match measured pole figures. Thus, it is necessary to perform a systematic analysis of the microstructural phenomena occurring during TMP, and determine the role of each process in the evolution of texture.

14.3.2 Computing Transformation Texture and Variant Selection

Computing the development of texture during sub-transus hot working of a Ti-6Al-4V part is complicated by several factors, among which are the uneven partitioning of strain between the two phases that results from their different strengths and temperature dependence of the strengths. This is how deformation contributes to texture, and models to predict this are well-established. Upon cooling from the α+ß field, several phase transformations take place, which results in the formation of transformation texture. If no α variant were preferred over the other, then the resultant transformation texture would be very weak. However, under most conditions some degree of preferential variant selection is observed [14.5-14.9].

Many variant selection schemes have been proposed and validated under specific conditions, however most fail to quantitatively match experimental measurements. Implementing these models into DEFORM® could be a great benefit to the titanium forging industry, should the results they provide prove relevant to industrial applications. These models will be applied to a variety of forming simulations literature in order to assess their accuracy, and a new model may be developed that addresses their deficiencies. Some models that can be assessed are listed below:

- At ß/ß grain boundaries that share a common {110} plane, the α variant with $\{0001\}_\alpha \| \{110\}_ß$ will be preferentially selected [14.6]

- The α variant with its basal plane parallel to the ß slip system with the greatest accumulated shear strain will be preferentially selected [14.7]
- The α variant with its c-axis nearest the orientation of adjacent primary α grains will be preferentially selected [14.8]
- The α variant that minimized the elastic strain energy of the system will be preferentially selected [14.9]

The algorithms to replicate these schemes will be provided by Dr. Adam Pilchak of AFRL. They will be modified for application to a three-dimensional system and implemented into DEFORM® through collaboration with developers at Scientific Forming Technologies Corporation. Once implemented, the models can be applied to the current simulation in order to assess their relevance.

14.4 Plans for Next Reporting Period

At the onset of this project, it was anticipated that the models were fully developed for use in DEFORM®. However, it has become apparent that the models in their current state need significant development and rigorous testing in order to ensure that they are robust. Priorities for the next reporting period are to focus on the exact microstructural phenomena that occur at given points during TMP of Ti-6Al-4V, and the improvement of current simulation outputs.

- First, a systematic analysis of microstructural evolution of Ti-6Al-4V during thermomechanical processing will be conducted through review of literature data.
- Following the analysis, the knowledge obtained will be applied to the simulation of Glavicic's work, in order to get results closer to expected values. The results from this will assess which microstructural phenomena are driving transformation texture evolution, and what deficiencies exist.

The knowledge obtained through application of current models to the present simulation will then be applied to an alternative process such as extrusion or rolling in the future. An experiment may be designed to allow for inspection of the microstructure at several points during the process, as well as greater control over test conditions.

14.5 References

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14.6 Figures

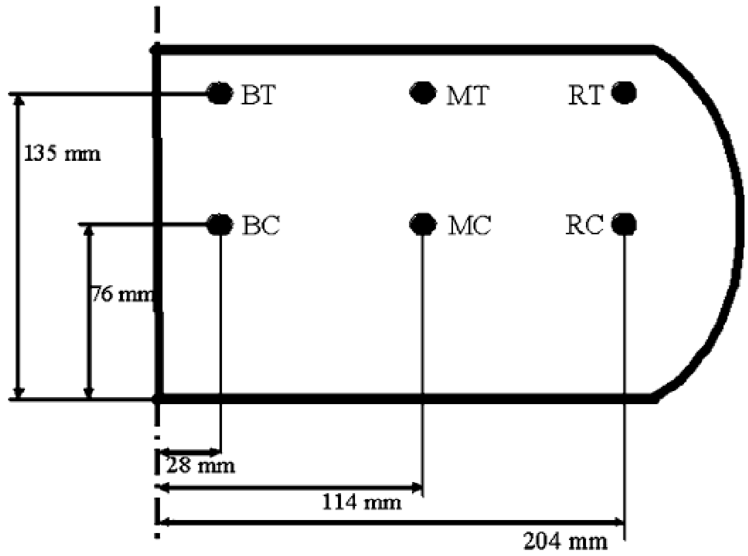

Figure 14.1: Material points inspected by Glavicic following the uniaxial compression of a cylindrical specimen. Samples were taken from either the bore, middle, or rim of the cylinder at either the centerline or top of the deformed cylinder [14.5].

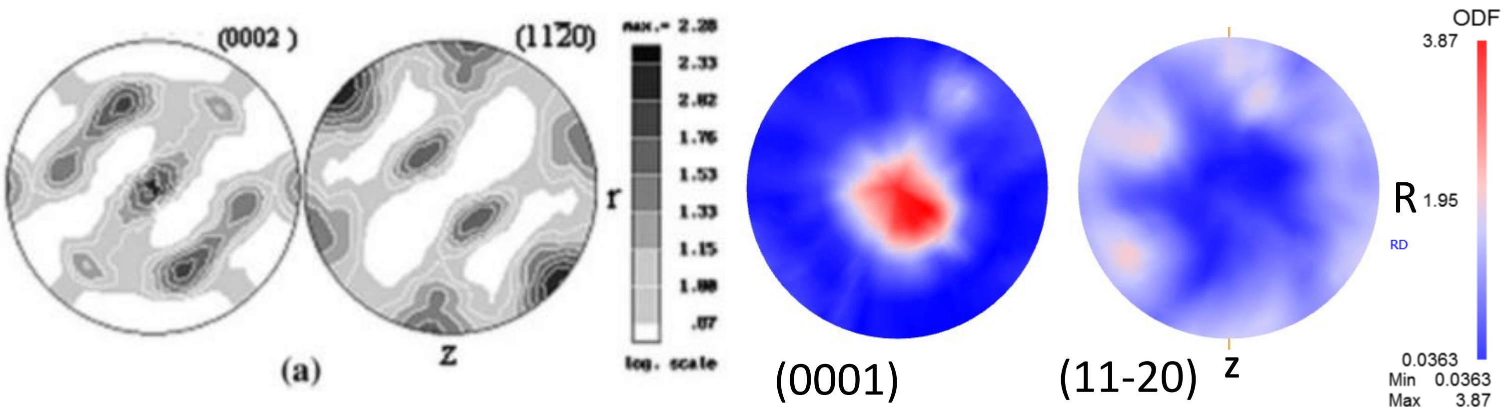

Figure 14.2: (Left): Pole figures measured by Glavicic from the RT material point labeled above. (Right): Pole figures generated by replicating the experimental conditions of Glavicic's work in DEFORM® but starting from an initially random orientation distribution among other simplifying assumptions. The figures show little qualitative agreement.