33A.0 IN-SITU STUDIES OF STRAIN RATE EFFECTS ON PHASE TRANSFORMATIONS AND MICROSTRUCTURAL EVOLUTION IN BETA-TITANIUM ALLOYS (LEVERAGED)

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33A.1 Project Overview and Industrial Relevance

Titanium alloys are heavily used in the aerospace and biomedical industries for their high specific strength and good corrosion resistance. However, low work hardening rates and uniform elongation have limited their applicability in deformation controlled applications, where high energy absorption or formability are required. The ability to develop novel titanium alloys that exhibit high work hardening rates would broaden their applicability, such as lightweight, blast-resistant, armor, crash resistant structural components and high-complexity plastically formed parts. Recent work [33A.1-33A.4] on metastable β-titanium alloys has shown promising results, wherein high work hardening rates and uniform elongations were achieved through TRansformation Induced Plasticity (TRIP) and TWinning Induced Plasticity (TWIP). These deformation mechanisms have been the subject of extensive study in ferrous alloys, while published work in other alloy systems, especially with BCC crystal structures, is limited in scope. The present project aims to study TRIP and TWIP effects in β-titanium to garner fundamental understanding of the intrinsic and extrinsic variables controlling TRIP and TWIP. The fundamental knowledge gained from this study will be used to develop an alloy design methodology that will enable the tailoring of microstructural evolution, deformation mechanisms, and mechanical response by means of alloying and processing.

33A.2 Previous Work

The previous reporting cycle's accomplishments consisted mainly of quasi-static tensile testing of Ti-10V-2Fe-3Al (wt. %) (referred to as Ti-1023) in different aged conditions and intermediate strain rate testing of Ti-1023 and Ti-15Mo (wt. %). The quasi-static testing schedule was aimed at identifying how aging affects the deformation microstructure in Ti-1023. Intermediate strain rate testing (10^{-1} - 10^{0} s^{-1}) was conducted in-house at Mines. Initial testing for Ti-1023 was aimed at ascertaining the effect of higher rates of deformation on the deformation microstructure found in Ti-1023 in various states of aging and Ti-15Mo.

33A.3 Recent Progress

33A.3.1 APS Dynamic Experiments

Beamtime was allotted at beamline Sector 32-ID for *in-situ* high-rate Kolsky bar experiments in February 2020. The preparatory work for this beamtime was built on the experience gained from the first beamtime in Feb 2019. Microstructural states and corresponding heat treatment of all tested conditions and alloys are presented in **Table 33A.1**. Two over-arching studies are included in this table. The first set of conditions, *i.e.* various aged conditions of Ti-1023, are aimed at understanding the coupling between aging and strain rate. Comparing the intermediate strain rate data to the quasi-static data already collected will reveal the effect of strain rate effects on Ti-1023. Second, testing of Ti-Mo binary alloys will allow for a comparison of chemistry effects at high strain rates. Also, the Ti-15Mo samples will allow for direct comparison with intermediate and quasi-static data already produced. Efforts were aimed at obtaining specifically targeted, high-quality diffraction data for this set of experiments at the APS to look for TRIP/TWIP, using forward modelling of detector positioning.

33A.3.2 Intermediate Strain Rate Testing of Ti-1023 and Ti-15Mo

Shortly after the last reporting period ended, intermediate strain rate testing was conducted at 10^{-1} & 10^{0} s^{-1} on Ti-1023 in the as-quenched and maximum TRIP stress (MTS) conditions, and Ti-15Mo in the as-quenched condition. Mechanical data indicates the behavior of these alloys at intermediate strain rates is typical of increased strain rate, wherein a slightly higher flow stress leads to a lower ductility. **Figures 33A.1** and **33A.2** show tensile data for both alloys at quasi-static (10^{-3} s^{-1}) and intermediate strain rate (10^{-1} s^{-1}). Microstructural characterization is underway for all of these conditions. Future reporting will include TEM and EBSD characterization of the 10^{-1} s^{-1} deformed samples.

33A.3.3 Characterization of Quasi-static Tensile Testing of Aged Ti-1023

TEM characterization of Ti-1023 tensile specimens deformed at quasi-static strain rates is underway. **Figure 33A.3** presents XRD scans of fractured specimens in various aged conditions. It can be seen that martensite is present in all of the specimens after fracture, indicating that TRIP is still active even as aging progresses. Interestingly, TEM investigation of the MTS aged specimen has revealed that {332} twinning is also quite active in this condition. This finding presents interesting questions, as the activation of {332} twinning in these alloys is usually indicative of an increase in chemical stability of the β phase (increase in β stabilizer content). This finding indicates either chemical segregation during aging at 423 K, or a novel mechanism for affecting parent phase stability based on structural or elastic interactions. Ongoing work is aimed at elucidating this question.

33A.4 Plans for Next Reporting Period

Future work in this project is focused in two major areas. First, experiments are being conducted to understand the fundamental mechanism behind ω phase evolution during low-temperature aging. These experiments include elastic anisotropy measurements to evaluate structural changes in the matrix, atom probe tomography (APT) experiments to measure the presence of chemical segregation, high resolution and conventional transmission electron microscopy (TEM) to elucidate evolution of the ω phase, and dilatometry and *in-situ* XRD to characterize aging kinetics. The second major area pertains to the effect of high strain rate deformation on the deformation microstructures of these alloys. APS samples will undergo post-mortem characterization, as analysis of the *in-situ* data progresses.

Additional work planned includes two separate beamtimes at CHESS and the 1-ID beamline at the APS for concurrent SAXS and WAXS during quasi-static deformation and artificial aging, *in-situ* TEM deformation at LLNL, and bulk Kolsky bar experiments at LANL.

33A.5 References

[33A.1] C. Brozek, et al., A β-titanium alloy with extra high strain-hardening rate: design and mechanical properties, *Scripta Materialia* 114 (2016): 60-64.

[33A.2] F. Sun, et al. A new titanium alloy with a combination of high strength, high strain hardening and improved ductility, *Scripta Materialia* 94 (2015): 17-20.

[33A.3] M. Marteleur, et al., On the design of new β-metastable titanium alloys with improved work hardening rate thanks to simultaneous TRIP and TWIP effects, *Scripta Materialia* ,10 (2012): 749-752.

[33A.4] X. Min, et al., Mechanism of twinning-induced plasticity in β-type Ti–15Mo alloy, *Scripta Materialia* 69.5 (2013): 393-396.

33A.6 Figures and Tables

Table 33A.1 Heat treatment and alloys for APS tests

Alloys (wt %)	**Heat Treatments (Expected Microstructure)**		
Ti-10V-2Fe-3Al	As-quenched 1123 K-0.5 h-WQ	Max TRIP stress AQ + 423 K - 900 s	TRIP inhibited AQ+423K-7200 s
Ti-15Mo	As-quenched – 800 -1 h - WQ		
Ti12-Mo	As-quenched – 820 -1 h - WQ		

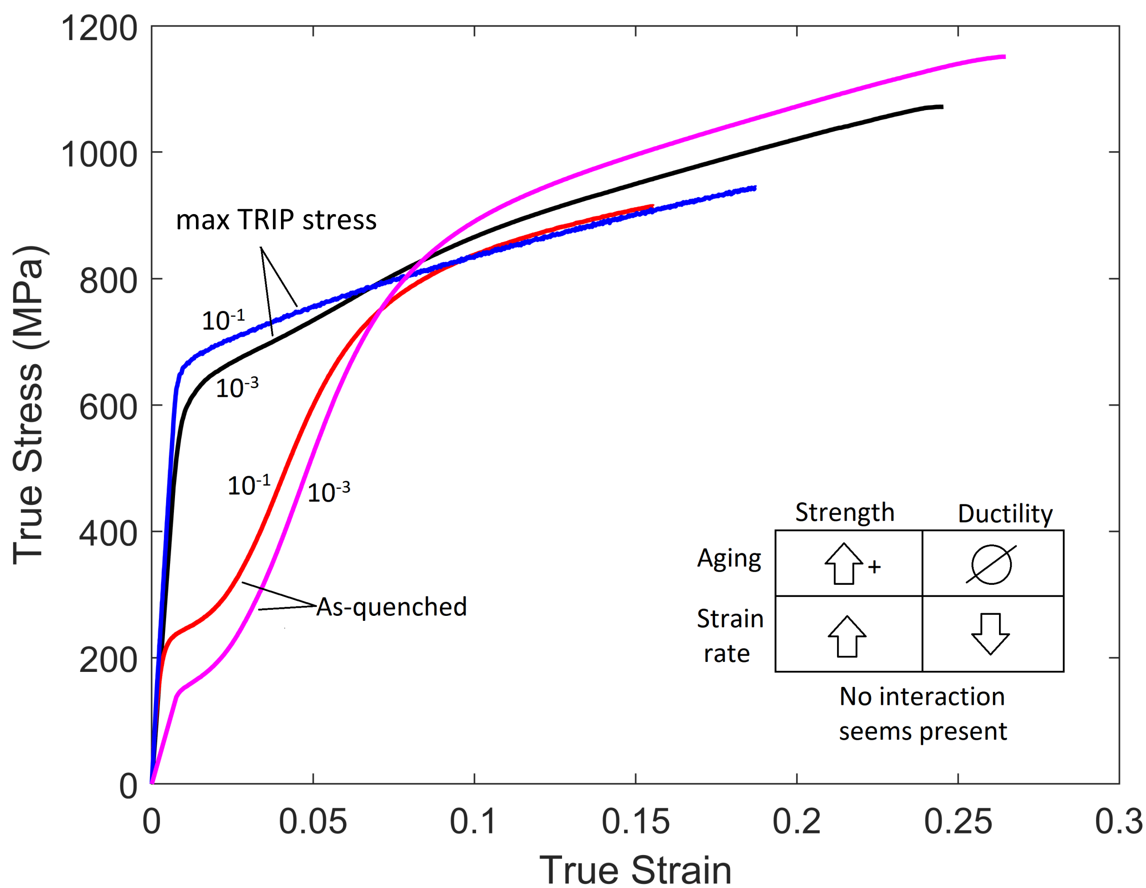

Figure 33A.2: True stress vs true strain plots of Ti-1023 in the as-quenched and the max TRIP stress (900 s at 423 K) at two different strain rates, $10^{-3}\ s^{-1}$ and $10^{-1}\ s^{-1}$. The inset indicates how each variable affects strength and ductility.

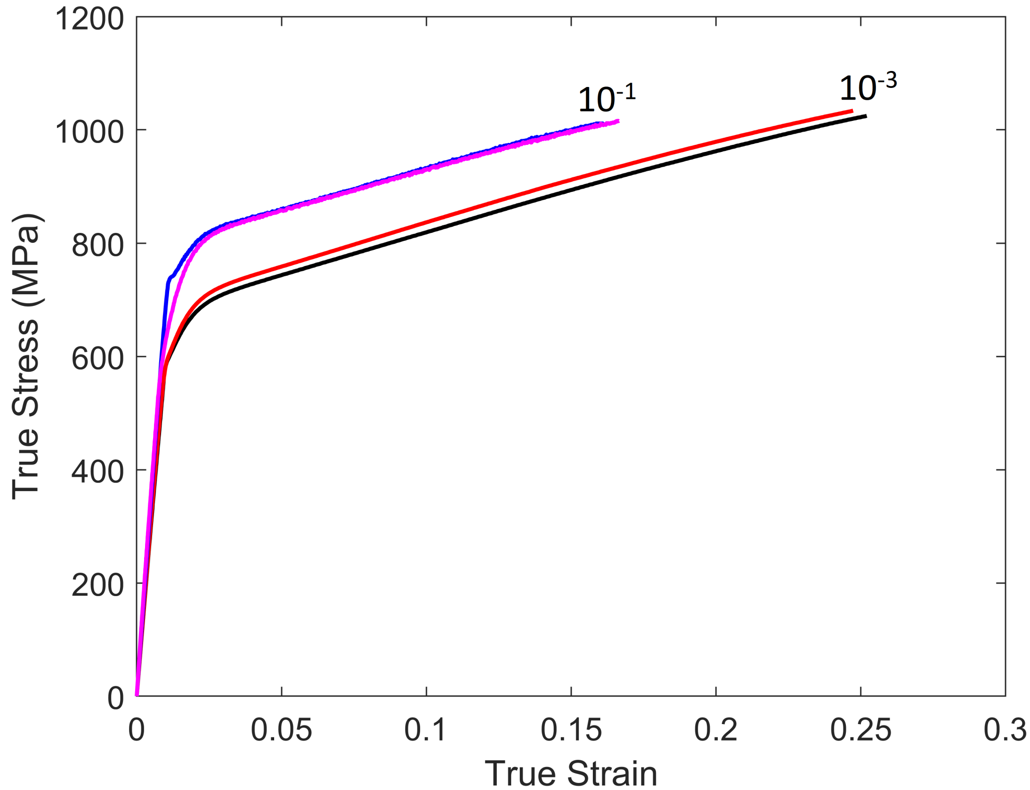

Figure 33A.3: True stress vs true strain plots of Ti-15Mo in the as-quenched state at two different strain rates, 10^{-3} s^{-1} and 10^{-1} s^{-1} .

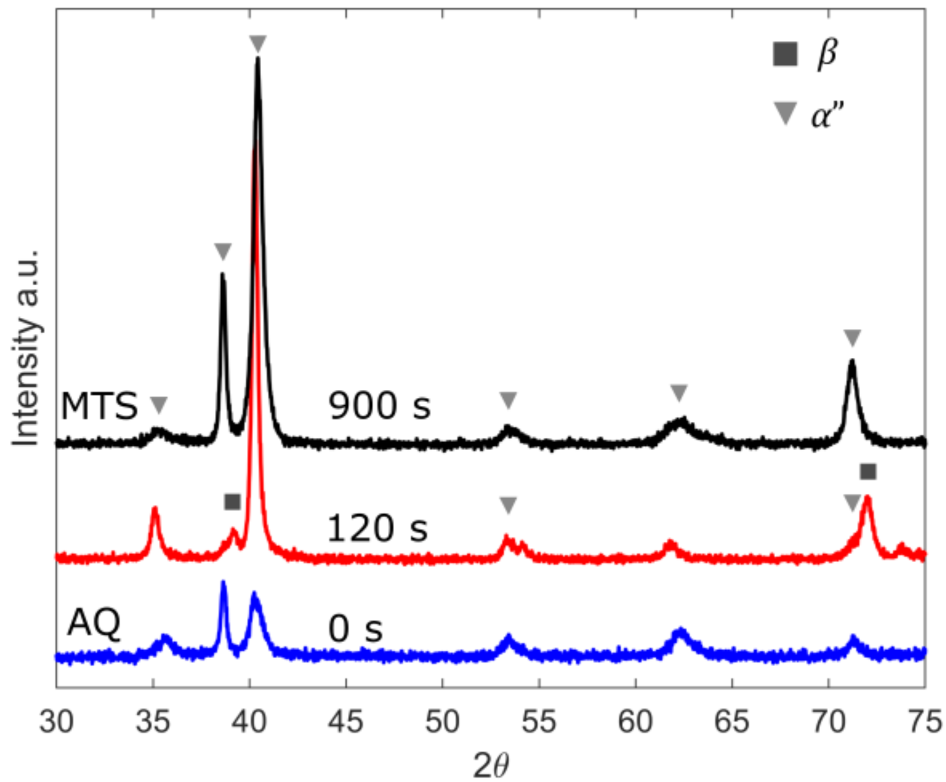

Figure 33A.3: X-ray diffractograms of fractured tensile specimens for each of the three aging conditions studied: As-quenched (0 s aging), 120 s aging, and 900 s aging (MTS, max TRIP stress) at 423 K. Tensile testing was done at room temperature and at quasi-static strain rates (10^{-3} s^{-1}).