33B-L.1 In Situ Studies of Strain Rate Effects on Phase Transformations and Microstructural Evolution in Multiple Principle Element Alloys

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33B-L.2 Project Overview and Industrial Relevance

Multiple Principle Element Alloys (MPEAs) have gained recent interest, as they represent a heretofore relatively unexplored alloy design space, being centered in, rather than at the corners of ternary, quaternary and quinary phase diagrams [33B.1]. Most conventional alloys have only one or two elements in significant concentrations, and therefore relatively fewer possible combinations as compared to MPEAs, which have a multitude of possible combinations. Some MPEAs, especially those from the CoCrNi family have been shown to exhibit transformation and twinning induced plasticity (TRIP and TWIP respectively), where deformation is accommodated by a shift in local crystallographic stacking in addition to crystallographic slip [33B.2]. This results in a high work hardening rates, as dislocations cannot glide over the boundaries of transformation product and twin interfaces [33B.3]. Materials with high work hardening rates are, in turn, associated with increased ductility and strength when compared to materials with otherwise similar properties and lower work hardening rates, as predicted by the instability criterion $\sigma = d\sigma/d\varepsilon$. This effect is illustrated in **Figure 33B.1** By increasing the ductility of a material without a corresponding decrease in strength, improved toughness is achieved.

Materials with high toughness are useful, as they are able to absorb higher amounts of energy before failure. This is especially useful for blast resistance, the primary focus of this project. Increased toughness reduces the required amount of armor for similar protection against explosive reactions. Outside of blast resistance, the extended ductility of TRIP/TWIP materials improves their formability, allowing them to be worked into more complex geometries that require higher strains. Studies of the strain rate and state effects, as well as phase stability and deformation mechanisms, on the deformation behavior and microstructural evolution of MPEAS will enable alloy design for specific applications. Further, better fundamental understanding of TRIP/TWIP behavior also extends to more commonly used advanced high strength steels that exhibit TRIP/TWIP behavior, and metastable titanium alloys – a complementary project underway in CANFSA.

33B-L.3 Recent Progress and Previous Work

Currently, some mechanical property data for the $Co_{.55}Cr_{.05}Ni_{.40}$ alloy has been produced by CANFSA, specifically by Dr. Francisco Coury in his PhD work. This data does not include, however, the relevant microstructural evolution to fully evaluate the TRIP/TWIP behavior of the alloy. Initial microstructural characterization has shown evidence of TRIP/TWIP behavior, including deformation twinning and phase transformation, after cold rolling to 25%

33B-L.4 Plans for Next Reporting Period

Key for the next reporting period will be analysis of mechanical testing data to determine the evolution of deformation twins and transformation products as a function of strain rate and state. In-situ imaging and diffraction experiments are also planned for 2019 at the Advanced Photon Source at Argonne National Laboratory. The analysis will involve:

- Analysis of diffraction data for determination of phase fraction of transformation product with deformation
- Post mortem analysis of specimens for microstructural analysis and characterization of the deformation twins and transformation product

Other experiments will be performed to confirm and correlate the results, specifically characterization of the thermal effects on TRIP/TWIP behavior and mechanical properties. In-situ dynamic transmission electron microscopy (DTEM) experiments using a piezo-electric stage that allows TEM imaging at high

(10^4 sec^{-1}) strain rates, while capturing images at higher frame rates than traditional TEM imaging, will also be pursued in this project.

33B-L.5 References

[33B.1] D.B. Miracle, J.D. Miller, O.N. Senkov, C. Woodward, M.D. Uchic, J. Tiley, Exploration and Development of High Entropy Alloys for Structural Applications, Entropy 16 (2014) 494-525

[33B.2] Y. Deng, C.C. Tasan, K.G. Pradeep, H. Springer, A. Kostka, D. Raabe, Design of a twinning induced plasticity high entropy alloy, Acta Materialia 94 (2015) 124-133

[33B.3] L. Liu, B. He, M. Huang, The Role of Transformation-Induced Plasticity in the Development of Advanced High Strength Steels, Advanced Engineering Materials

33B-L.6 Figures and Tables

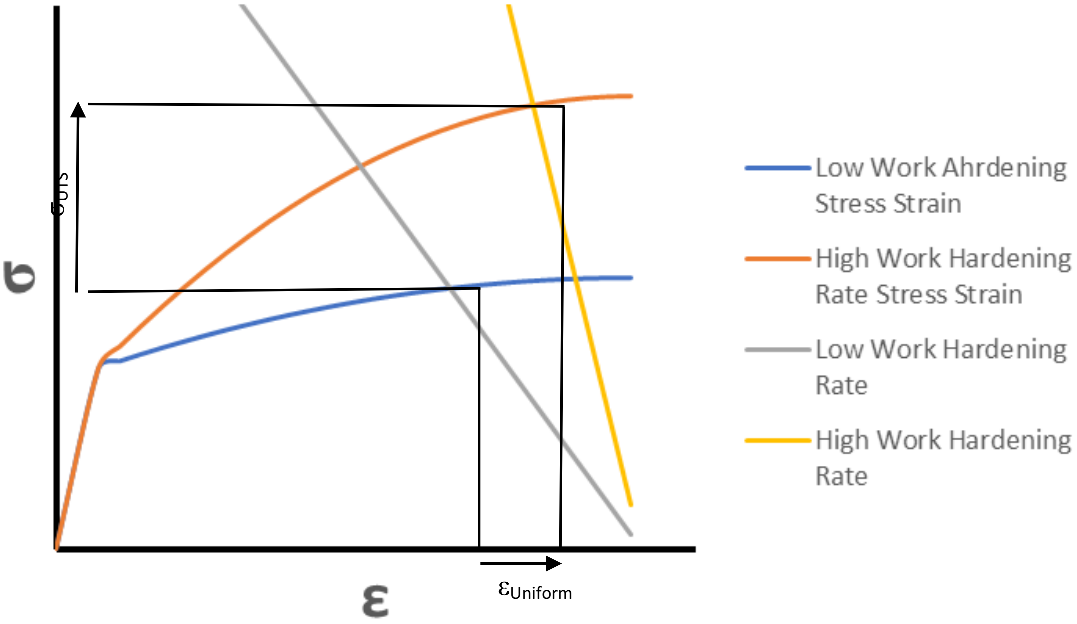

Figure 33B.1: Hypothetical stress strain curves for two materials with similar properties (elastic modulus, yield strength), but with different work hardening rates. Predicting the onset of necking by the instability criterion, $\sigma = d\sigma/d\varepsilon$, shows an increase in both ultimate tensile strength and uniform elongation associated with an increase in work hardening rate.