NEUTRON DIFFRACTION STUDY ON PLASTIC BEHAVIOR OF A NICKEL-BASED ALLOY UNDER THE MONOTONIC-TENSION AND THE LOW-CYCLE-FATIGUE EXPERIMENTS

E-Wen Huang[1], Rozaliya Barabash[2,*], Bjørn Clausen[3], Yandong Wang[1, 4], Ren Yang[5], Li Li[1], Hahn Choo[1], and Peter K. Liaw[1]

[1]Department of Materials Science and Engineering, University of Tennessee, Knoxville, TN 37996, [2]Materials Science and Technology Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, [3]Los Alamos Neutron Science Center, Los Alamos National Laboratory, Los Alamos, NM 87545, [4]School of Materials and Metallurgy, Northeastern University, Shenyang, PRC 110004, [5]X-ray Science Division, Argonne National Laboratory, Argonne, IL 60439

ABSTRACT In the present study, the plastic behavior of the annealed HASTELLOY® C-22HS™ nickel-based superalloy is examined by the in-situ neutron-diffraction experiment at room temperature. Monotonic-tensile and low-cycle-fatigue experiments are conducted to observe the plasticity behavior of tension and cyclic loading of the alloy, respectively. The effects of the deformation are studied as a function of the stress, lattice-strains, and dislocation-density evolution.

INTRODUCTION: The subject of plasticity is considered important in designing for materials because the consideration of plasticity is vital. Since plasticity deals with the materials behaviors that are beyond Hooke's law, more information of the materials, such as the lattice imperfections and crystal structures, needs to be considered to describe the plastic deformation. In metals, such line imperfections as dislocations are responsible for most of the plastic deformation. To further understand the structure and the internal stresses contributed by the dislocations, Mughrabi [Mughrabi 1983] quantitatively studied the long-range internal stress in deformed metal crystals with the dislocation microstructures by the transmission-electron microscopy (TEM). The TEM work has demonstrated the powerful capability to study the dislocations in solids. However, since only a relatively small amount of materials is observed with thin specimens for one TEM experiment, the statistics of the experimental designs and the sample preparations need to be considered carefully. The X-ray experiments are applied to compromise the disadvantages of the TEM experiments for studying dislocation structures. For more details of diffraction-profile studies, Stephens [Stephens 1999], Barabash and Klimanek [Barabash 1999] have related it to anisotropic strain distributions caused by distinct dislocation arrangements and strain gradients in different grains. Recently, Jakobsen *et al*. [Jakobsen 2006] showed the inhomogeneous nature of the plastic deformation using the in-situ X-ray techniques to compare the dislocation substructures with the TEM results. These studies use models of different arrangements to determine the dislocation density from the X-ray peak-profile analysis and exhibit the important features of the

* Contact author e-mail:<barabashr@ornl.gov>

diffraction techniques to learn the dislocation properties during the plastic deformation. To utilize the advantage of the diffraction experiments on studying dislocations during the plastic deformation, the current study reports the in-situ neutron-diffraction measurements to investigate the plasticity mechanism during the in-situ neutron measurements of the plastic deformation. These measurements have several advantages for the study of the dislocations during the plastic deformation: (1) the high penetration of neutrons is used to reveal the bulk properties with larger gauge volumes, and, hence, better statistics. (2) Spectrometer for Materials Research at Temperature and Stress (SMARTS) can conduct in-situ measurements to observe the behaviors of the deformation from a single specimen to eliminate the possible confounding ex-situ observations.

PROCEDURES, RESULTS AND DISCUSSION: The testing material is a HASTELLOY® C-22HS™ nickel-based superalloy (Ni-21Cr-17Mo in weight percentage). After a hot-rolling process, the alloy was mill annealed at 1,080°C that allows for most precipitates and alloying elements to dissolve to form a faced-center cubic (FCC) single phase alloy according to a TEM study. There is no strong texture in the alloy, which is good to study the dislocation behaviors by eliminating texture and second-phase effects. The average grain-size of this alloy is about 90 μm. The gauge volume of the in-situ neutron measurements is 120 mm^3. These experiments were carried out with the SMARTS at room temperature. The specimens were aligned 45° to the incident neutron beam with two detectors fixed at $2\theta = \pm 90°$.

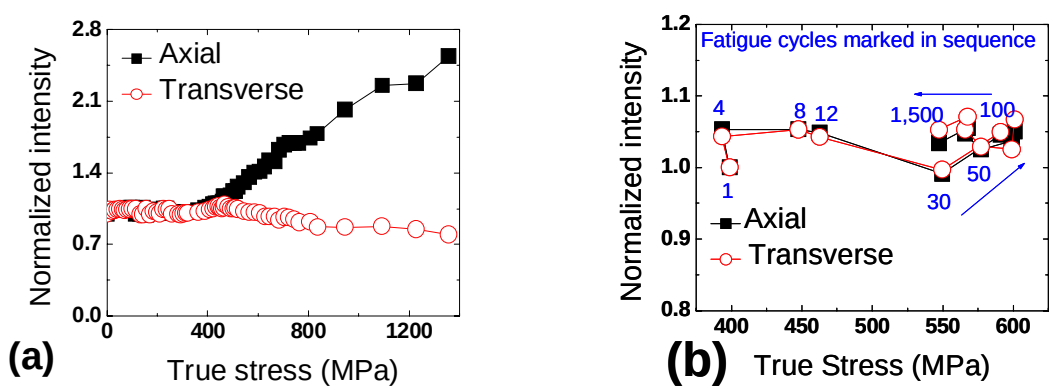

Fig. 1 The intensity evolution for the (111) diffraction peaks in axial (black) and transverse (red) directions for (a) tensile and (b) low-cycle-fatigue experiments.

Hence, one detector collected the diffraction data along the loading direction (axial data), and the other gathered the diffraction data normal to the loading direction (transverse data). For the tension experiment, the strain rate is 0.001 per second. The low-cycle-fatigue experiments were conducted at the maximum strain ($\varepsilon_{max.}$) of 1% and R-ratio of -1. The frequency of the loading cycle was 0.5 Hz. The diffraction data were collected at different cycles during the fatigue experiment. The measurements at the engineering strain of 1% with different fatigue cycles are examined. The in-situ neutron results are refined by the general structure analysis software (GSAS). The intensity evolutions of (a)

tensile and (b) low-cycle-fatigue are shown in Fig. 1. The pseudo-Voigt function is applied to distinguish Gaussian and Lorentzian components of the peak widths. The peak widths evolutions with the true stress are shown in Fig. 2. The peak widths start to broaden as the plastic deformations proceeds. The dislocation density is considered in connection with plasticity models for tensile and cyclic deformations. The dislocation density is calculated as in the reference [Sun 2007] and compared with the bulk properties, and, hence, the neutron diffraction profiles are used to characterize the dislocations.

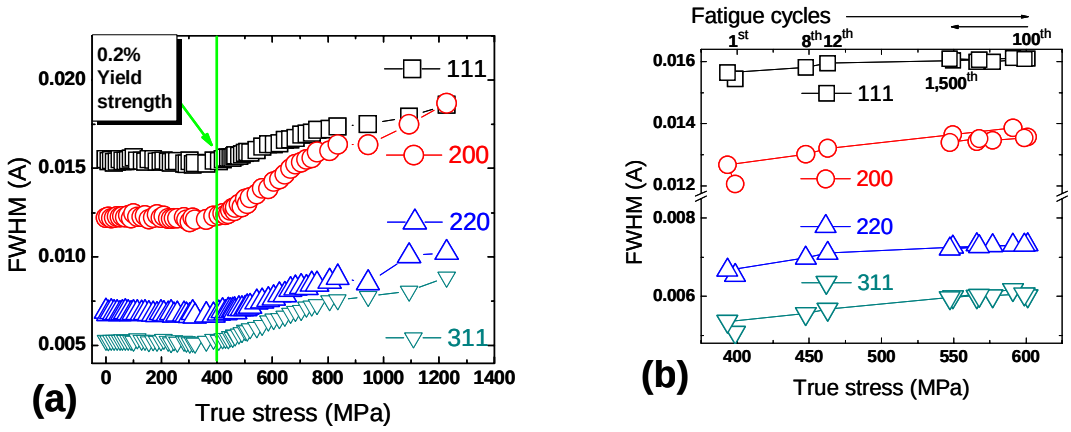

Fig. 2 The peak width evolution for the diffraction peaks 111, 200, 220, and 311 in axial directions for (a) tensile and (b) low-cycle-fatigue experiments.

Acknowledgement: Drs. D. L. Klarstrom and L. M. Pike supply the materials from Haynes International, Inc. This research is supported by the National Science Foundation, International Materials Institutes, (DMR-0231320). The work is supported in part by the Division of Materials Science and Engineering, Office of Basic Energy Science, U.S. Department of Energy under Contract DE-AC05-00OR22725 with UT-Battelle, LLC. The Lujan Neutron Scattering Center is operated by the Los Alamos National Security LLC under the DOE Contract DE-AC52-06NA25396. The use of the Advanced Photon Source was supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Science, under Contract No. W-31-109-ENG-38.

REFERENCES:

Barabash R. I. and Kimanek P., 1999, "X-ray Scattering by Crystals with Local Lattice Rotation Fields" J. Appl. Cryst. **32**, 1050-1059.

Sun Y., Barabash R. I., Choo H., Liaw P. K., Lu Y., Brown D. W., and Ice G., 2007, "Multiscale Plastic Deformation Near A Fatigue Crack From Diffraction" Solid State Phenomena **129**, 151-156.

Jakobsen B., Poulsen H. F., Lienert U., Almer J., Shastri S. D., Sorensen H. O., Gundlach C., and Pantleon W., 2006, "Formation and Subdivision of Deformation Structures during Plastic Deformation", Science **312**, 889-892.

Mughrabi H., 1983, "Dislocation Wall and Cell Structures and Long-Range Internal Stresses in Deformed Metal Crystals", Acta Mater. **31**, 1367-1379.

Stephens P. W., 1999, "Phenomenological Model of Anisotropic Peak Broadening in Powder Diffraction", J. Appl. Cryst. **32**, 281-289.