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The Use of Neutron Diffraction to Study Plastic Deformation and Fatigue Failure in Structural Materials

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1. Introduction

Application of neutron diffraction in the characterization of structural materials becomes increasingly prevalent due to its unique capability to provide microscopic insights into the mechanical behavior of the materials. In this work, the use of neutron diffraction method to study plastic deformation and fatigue failure is highlighted with various case studies. More specifically, in-situ neutron diffraction has been employed to examine the plastic deformation behavior at the microstructural level in an extruded binary Mg-8.5wt.%Al alloy [1,2]. Lattice strains and diffraction peak intensity variations are measured during uniaxial tension and compression, in order to investigate the relative activities of deformation twinning and dislocation slip and their influence on the macroscopic plastic deformation behavior. The experimental data are used to validate an elastic-viscoplastic self-consistent model of polycrystal plasticity, from which the critical resolved shear stresses and hardening behavior of the available slip and twinning modes can be determined.

In addition, the fatigue crack growth mechanisms of various metallic alloys are studied via a neutron-diffraction stress mapping around the crack tip [3-5]. The distribution of residual stresses and the evolution of the stress fields around the crack tip are quantitatively determined to identify the fatigue crack growth mechanisms.

2. Methods and Results

2.1 Plastic deformation study of magnesium alloy

An extruded wrought Mg-8.5wt.%Al alloy is used to study the plastic deformation mechanisms of magnesium alloy. Initial texture T1 shows that the basal pole of most grains is preferentially oriented perpendicular to the extrusion direction (Fig. 1a). On the other hand, the modified texture T2 (Fig. 1b) shows that the basal pole of most grains is parallel to the extrusion direction. Elastic-lattice strains for each orientation were calculated using the following equation:

$$\varepsilon_{hk.l} = (d_{hk.l} - d^0_{hk.l}) / d^0_{hk.l}$$

where $d^0_{hk.l}$ and $d_{hk.l}$ are the *d*-spacings of a given diffraction (*hk.l*) peak in the unloaded and loaded conditions, respectively.

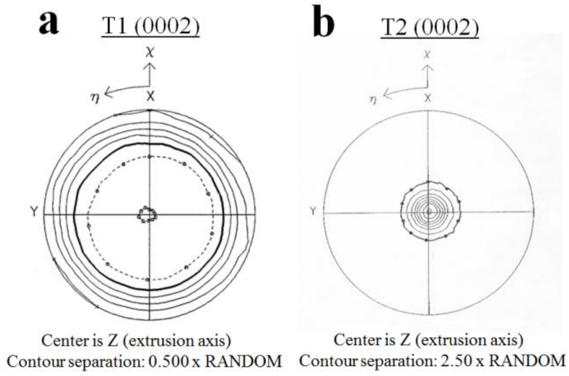

Fig. 1 Initial textures of (a) T1 and (b) T2 sample determined by neutron diffraction.

The use of two different starting textures in otherwise identical materials provides insights into the influence of both grain orientation and grain neighborhood on the development of lattice strain (and hence stress). Twinning activity is effectively tracked through the intensity variations of the diffraction peaks, providing insights into the state of stress before and after twinning in the parent grain and in the twinned volume for some grain orientations. When deformation is dominated by twinning, comparable hysteresis loops are observed during cycling, whether the loading is tensile or compressive. However, the intensity changes show that twinning/detwinning is more significant during compression than during tension. Thus, there appears to be a fundamental difference in pseudoelastic behavior between tension and compression cyclic loading in magnesium alloys when deformation is dominated by twinning.

2.2 Fatigue crack growth study of stainless steel

Fatigue crack growth experiments were carried out on a compact-tension (CT) specimen of 304L stainless steel. This material has a single-phase face-centered cubic (FCC) structure, yield strength of 241 MPa, ultimate tensile strength of 586 MPa, and elongation of 55 percent at room temperature.

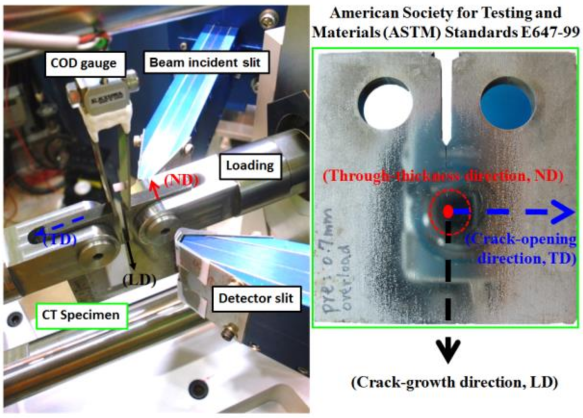

Fig. 2 Experimental set-up for neutron diffraction strain mapping experiments under in-situ loading.

In-situ neutron diffraction was employed to compare the evolution of internal strains around the crack tip between the steady-fatigued (Case 1) and overload-fatigued (Case 2) specimens where the stress intensity factor range is identical but a different fatigue history exists. While strains behind the crack tip in the Case 1 are irrelevant to increasing applied load, the strains behind the crack tip in the Case 2 evolve significantly under loading, leading to smaller maximum tensile strain and strain change right in front of the crack tip. In the Case 2, the transfer of stress concentration occurs toward the crack tip upon loading, resulting in a nonlinearity of the strain profile. The crack growth retardation after the overload can be attributed to a higher crack opening level measured for Case 2, by being correlated with a calculation of the effective stress intensity factor range as a driving force of fatigue crack growth.

3. Conclusions

Neutron diffraction provides the bulk-averaged information in terms of the stress/strain analysis of metallic alloys. Therefore, it can be effectively applied to study mechanical behavior and fracture mechanics of even very thick materials, due to its high penetration capability. The following researches can be achieved using a neutron beam, especially in the industrial application: (i) residual stress and internal stress investigations, (ii) crystallographic texture measurement, (iii) phase analysis and phase transformation study, (iv) volume fraction analysis of precipitates or nanoparticles in composite etc.

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