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Work-hardening behavior of polycrystalline aluminum alloy under multiaxial stress paths

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ABSTRACT

A thin-walled tubular specimen of A3003-O is subjected to uniaxial, biaxial, and triaxial stress paths using an axial load-internal pressure-torsion type test machine. For linear multiaxial stress paths, the ratios of axial, circumferential, and shear stresses are kept constant, and the stress–strain relations for various stress paths are measured. The work-hardening behavior of the specimen is evaluated based on the plastic work per unit volume, and contours of equal plastic work are constructed. The shape of the contour changes progressively with increasing plastic strain. Therefore, the amount of work hardening of the specimen depends on the plastic work and the applied stress path. In order to clarify the source of such work-hardening behavior, numerical simulations are performed using the crystal plasticity model. Two hardening models are adopted. In one model, the slip resistance is given as a function of accumulated slip, and, in the other model, the slip resistance is given as a function of dislocation density. The evolution of macroscopic flow stress depends only on the plastic work for the accumulated-slip-based model, and this model cannot predict the experimental trend. On the other hand, the dislocation-density-based model reproduces the stress-path dependent work-hardening behavior observed in the experiments, although quantitative agreement is not fully achieved. In the simulation, the evolution rate of the dislocation density varies depending on the stress path, which is identified as the source of the stress-path-dependent work-hardening behavior.

1. Introduction

A number of experimental, theoretical, and numerical investigations have been conducted in order to clarify the work- or strain-hardening behavior of metal. Mechanical tests for single crystals revealed the existence of different stages in the shear stress-shear strain curve (e.g., Basinski and Basinski, 1979; Gil Sevillano, 1993; Nes, 1998; Kocks and Mecking, 2003). Stage I, which appears at the beginning of plastic deformation, is characterized by a low hardening rate and plastic strain emerges by dislocation glide in a single slip system. The transition from the Stage I to Stage II occurs when the multislip mode begins. Stage II is characterized by the steepest linear hardening interval. The slope of the stress–strain curve starts to decrease in Stage III and remains approximately constant. Linear hardening appears again in Stage IV. The critical resolved shear stress in a slip system τ_C is related to the total dislocation density ρ_{total} such that $\tau_C = \bar{\alpha}\mu b\sqrt{\rho_{total}}$, where μ is the shear elastic modulus, b is the magnitude of the Burgers vector, and $\bar{\alpha}$ is a parameter that, in general, ranges from 0.15 to 0.5 (c.f. Gil Sevillano, 1993). This equation is known as Taylor's relation (Taylor, 1934). In this equation, the contribution of the dislocation density of a certain slip system to the critical resolved shear stress of a slip system is considered to be equivalent regardless of the

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combination of slip systems. For a face-centered cubic (fcc) crystal with twelve {1 1 1}<1 1 0> type slip systems, there are $12 \times 12 = 144$ combinations of interactions among slip systems. However, due to the symmetry of the crystal structure, these combinations of interactions are classified into only six types: self-interaction, collinear interaction, Hirth lock, coplanar interaction, glissile junction, and Lomer–Cottrell lock (Franciosi et al., 1980; Hull and Bacon, 2011). In order to take into account the anisotropy in the interaction, Taylor's relation was extended by introducing an interaction matrix, and the coefficients in the matrix were determined experimentally (Franciosi et al., 1980). Recently, these interaction coefficients were identified for fcc crystal with the aid of dislocation dynamics simulations (Madec et al., 2003; Devincre et al., 2005; Devincre et al., 2006; Alankar et al., 2012a,b). Collinear interaction, which had previously been believed to be a softer interaction than the Hirth lock, glissile junction, and Lomer–Cottrell lock, has been revealed to be the strongest interaction. Storage of dislocation is a fundamental mechanism of work hardening, and annihilation of dislocation occurs as a result of dynamic recovery. The evolution of dislocation density is often modeled by taking into account these storage and annihilation mechanisms (Mecking and Kocks, 1981; Kocks and Mecking, 2003).

In a crystal plasticity model, establishing a relationship between the slip rate and the evolution rate of dislocation density, slip resistances, and their evolution can be modeled based on the storage-annihilation model of dislocation density (Teodosiu et al., 1993; Teodosiu, 1997). Using the physically motivated dislocation-density-based constitutive model, the local deformation field in grains and the macroscopic stress–strain response of polycrystalline metal are analyzed. Unlike the shear stress-shear strain curve for single crystals, the slope of the stress–strain curve decreases continuously with plastic strain for polycrystalline aggregates. Then, the transition from Stage I to Stage II does not occur, because multiple slips occur from the start of plastic deformation due to the constraint caused by the grain interactions. When a precise description of the transition from Stage I to Stage IV is not important and the macroscopic stress–strain response and texture evolution of the polycrystalline aggregate is the target of investigation, simpler models are frequently used for the evolution of slip resistance. Instead of taking into account the dislocation density, the slip resistance is simply taken to be given by the accumulated slip (Peirce et al., 1982; Asaro and Needleman, 1985). A model dedicated to reproducing latent hardening behavior was also developed based on the accumulated slip (Wu et al., 1991; Bassani et al., 1991). The rate of evolution of the slip resistance is, also, taken to be a function of the slip resistance (Kalidindi et al., 1992). These models can predict the texture development and the anisotropy properties due to texture with sufficient accuracy. As such, these models are well accepted and have been used in various investigations.

When attention is focused on engineering problems in a much larger scale than the grain size, the phenomenological plasticity theory is applied, and direct evaluation of the macroscopic stress–strain relation is preferable to the evolution of slip resistance in a grain. Metallic parts in metal-forming processes undergo complex multiaxial deformation modes rather than uniaxial stress or simple shear states, and the work-hardening behavior under different deformation modes is of considerable practical concern. In the macroscopic plasticity model, the relations between stresses and strains in multiaxial stress states are derived from a single relationship between equivalent stress and equivalent plastic strain. Work-hardening or strain-hardening hypotheses are the most popular and simplest assumptions in the characterization of work-hardening behavior (Hill, 1950). Theoretically, in work hardening, the evolution of equivalent stress is assumed to be solely a function of plastic work, and, in strain hardening, the equivalent stress is assumed to depend only on the equivalent plastic strain, which is often defined as $\int \sqrt{(2/3)\mathbf{D}^{\mathrm{p}} : \mathbf{D}^{\mathrm{p}}}\, \mathrm{d}t$, where $\mathbf{D}^{\mathrm{p}}$ is the plastic component of the deformation rate. Anisotropic yield functions were proposed to capture the anisotropic yielding behavior of textured metals (e.g., Hill, 1948; Karafillis and Boyce, 1993; Barlat et al., 2005). Anisotropic coefficients in these yield functions express the distortion of the yield surface from the isotropic case. When the anisotropic yield function is used in conjunction with either the work-hardening or strain-hardening assumption, the yield surface expands while generally maintaining its shape. Then, anisotropic or differential hardening behavior is not predicted. If anisotropic coefficients vary continuously with plastic deformation, the yield surface shape changes progressively. Consequently, the degree of work hardening is dependent on the applied stress path. Such a change in the anisotropic coefficients is considered to reflect the development of crystallographic texture and/or the formation of dislocation cells. In the macroscopic plasticity theory, however, the evolution rule for anisotropic coefficients is not self-contained, and experimental observation and its modeling are inevitably required in advance.

In order to reveal the work-hardening behavior of metals under multiaxial stress states, experiments were frequently conducted using thin-walled tubular specimens. Biaxial and triaxial stress states are realized by applying axial loads, internal pressure, and torsion to tubular specimens, and the stress state can be determined based on force equilibrium equations. One of the first of such experiments was conducted by Guest (1900), and a number of related studies followed (e.g., Taylor and Quinney, 1932; Davis, 1943; Jenkins, 1965; Jones and Mellor, 1967; Frederking and Sidebottom, 1971; Hecker, 1971; Phillips et al., 1972; Ohashi and Tokuda, 1973; Phillips and Kasper, 1973; Shiratori et al., 1973; Lefebvre et al., 1983; Mallick et al., 1991; Bocher et al., 2001; Grabe and Bruhns, 2009; Korkolis and Kyriakides, 2009; Khan et al., 2009; Sung et al., 2011). These multiaxial stress experiments were reviewed by Michno and Findley (1976) and Kuwabara (2007). Using the experimental data of Stout and Hecker (1983), in which a tubular brass specimen was subjected to an axial load and internal pressure, Hill et al. (1994) evaluated the work hardening of the specimen based on the plastic work per unit volume, and successive contours of equal plastic work were constructed in axial stress-circumferential stress space. The strain range in the investigation was up to an equivalent plastic strain of about 0.2. The contour was flattened at axial-stress-to-circumferential-stress ratios of approximately 0.5 and 2 (the plane strain mode) and became sharp around the equi-biaxial stress mode with progressing plastic deformation. This change in the plastic work contour demonstrated that the amount of work hardening for a certain amount of plastic work is less near stress ratios of 0.5 and 2 compared to the other stress paths. Thus, stress-path-dependent