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Material modeling of 6016-O and 6016-T4 aluminum alloy sheets and application to hole expansion forming simulation

Toshihiko Kuwabara [a], [*], Takahiro Mori [a], Mineo Asano [b], Tomoyuki Hakoyama [a], Frédéric Barlat [c]

[a] *Division of Advanced Mechanical Systems Engineering, Institute of Engineering, Tokyo University of Agriculture and Technology, 2-24-16 Nakacho, Koganei-shi, Tokyo, 184-8588, Japan*

[b] *Automotive Material Development Section, No.6 Research Department, Research & Development Division, UACJ Corporation, 3-1-12 Chitose, Minato-ku, Nagoya, 455-8670, Japan*

[c] *Materials Mechanics Laboratory, Graduate Institute of Ferrous Technology, Pohang University of Science and Technology, San 31 Hyoja-Dong, Nam-Gu, Pohang, Gyeongbuk, 790-784, South Korea*

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ABSTRACT

This study investigates the influence of heat treatment on the anisotropic plastic deformation behaviors of 6016-O and 6016-T4 aluminum alloy sheets. The two material samples were fabricated from the same lot and, therefore, have the same grain size and crystallographic texture. Biaxial tensile tests using both cruciform and tubular specimens are performed for many proportional stress paths in the first quadrant of stress space. The test results reveal that the degree of differential hardening (DH) is much larger in 6016-T4 than in 6016-O. It is shown that the work contour shape of 6016-O is controlled by crystallographic texture, whereas that of 6016-T4 presumably depends on GP-zones as well. From the biaxial stress test data, an appropriate yield function for each material is determined and employed in the finite element analysis of the hole expansion forming process. It was found that the Yld2000-2d yield function provides proper material representations of the plastic behavior of both material samples in the sense that it correctly predicts the fracture or localized neck locations, which occurs in the hole edge vicinity. For 6016-O, the thickness strain profile predicted with the Yld2000-2d yield function, which accounts for the DH of the material, is in better agreement with the experimental results than that obtained with the isotropic hardening model. For 6016-T4, the Yld2000-2d yield function with an exponent of 8 with the isotropic hardening assumption leads to a fair prediction of the experimental data. In order to enhance the accuracy of forming simulations for 6016-T4, it is necessary to develop a material model that is capable of reproducing the significant DH resulting from the GP-zones.

1. Introduction

Lightweighting of automotive bodies is an urgent issue for the preservation of the Earth's environment. Aluminum alloy sheets are among the materials that are effective in reducing automotive body weight. However, aluminum alloy sheets are

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[*] Corresponding author.
E-mail address: kuwabara@cc.tuat.ac.jp (T. Kuwabara).

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prone to fracture during press forming because of low ductility. Therefore, the optimal tool geometry and forming conditions that do not cause fracture of the aluminum alloy sheets have been widely pursued in the automotive industry through finite element analyses (FEA).

Phenomenological plasticity models based on yield functions are widely used for FEA as they require much less computational time than polycrystal models. In order to improve the accuracy of fracture prediction, a proper material model that accurately reproduces the deformation behavior of the material should be used (Kuroda and Tvergaard, 2000). For aluminum alloy sheets it has been demonstrated that the exponent of non-quadratic yield functions (e.g., Barlat et al., 2003), which are suitable for cubic metals, has a significant effect on the accuracy of numerical deformation analyses (Fourmeau et al., 2011; Yanaga et al., 2012). It has been demonstrated that biaxial tension tests are effective in determining appropriate material models for steel sheets (Andar et al., 2010; Deng et al., 2015; Kuwabara et al., 2002), a pure titanium sheet (Ishiki et al., 2011), and a magnesium alloy sheet (Andar et al., 2012). Other types of multiaxial testing methods, such as combined tension-shear tests (Dunand et al., 2012; Khan et al., 2009; Luo et al., 2012; Dick and Korkolis, 2015) and combined axial force-internal pressure tests (Korkolis and Kyriakides, 2008a, 2008b, 2009) have been shown to be effective for constructing appropriate material models for 6000-series aluminum alloys. Grytten et al. (2008) evaluated four calibration methods for the linear transformation-based anisotropic yield function Yld2004-18p (Barlat et al., 2005). Banabic et al. (2010) and Barlat and Kuwabara (2016) published extensive reviews on anisotropic yield functions. Kuwabara (2007, 2014) provided detailed descriptions of multiaxial stress testing methods for the determination of proper material models in sheet metal forming applications.

Many studies have clarified the effects of crystallographic textures on the plastic deformation characteristics and/or formability of aluminum alloy sheets and tubes through polycrystal analyses (Barlat, 1987; Barlat and Richmond, 1987; Guan et al., 2006; Khadyko et al., 2016; Yoon et al., 2005; Yoshida et al., 2007; Yoshida and Kuroda, 2012). Yamanaka et al. (2015) investigated a material modeling methodology of sheet metals using a numerical biaxial tensile test based on the crystal plasticity finite element (CPFE) method and a mathematical homogenization technique. These authors demonstrated that the accuracy of a hydraulic bulge forming simulation using the Yld2000-2d yield function identified by the numerical biaxial tensile test was comparable to that of the Yld2000-2d yield function calibrated experimentally.

The formability and strength of aluminum alloy sheets are also affected by aging treatments, which allow the development of precipitation strengthening. General considerations on the metallurgy of heat-treatable (HT) aluminum alloys can be found in Hatch (2004) and Starke (1989). A review on the effects of microstructure on the formability of 5000- and 6000-series aluminum alloy sheets was published by Asano and Yoshida (2013). Only those essential concepts needed for the purpose of the present work are summarized below. The final steps of HT aluminum alloy processing consist of a solution heat-treatment (SHT) at a suitable temperature to dissolve the soluble alloying elements and quenching in order to achieve high cooling rates. After quenching, alloying elements are mostly in solid solution in the material, which is not a stable thermodynamic equilibrium state. Then, the material is left for some time either at RT or subjected to an aging heat treatment at a much lower temperature than that of SHT. As a result, the solute atoms tend to form clusters, which evolve with time towards so-called Guinier-Preston (GP) zones or to nano-sized precipitates, depending on aging temperature, thus strengthening the alloy. This process is called natural aging (NA) if it occurs at RT and artificial aging (AA) if it occurs at a higher temperature.

1.1. *Artificially aged alloys*

The strength that can be achieved after aging at a given temperature depends on the aging time. As the aging time gets longer, the strength increases until it reaches a maximum value, after which it decreases. The aging condition at which the strength is at a maximum is called peak-aged (PA). The aging time correlates well with the precipitate size, which can reach lengths on the order of a micrometer. For aging times shorter than PA time, the material is said to be under-aged (UA) and the precipitate size remains small. When the material is subjected to plastic deformation, the precipitates are likely to be sheared by dislocations. However, when the aging time is larger than the PA time, the alloy is over-aged (OA). In this case, the precipitates become larger and are bypassed by dislocations during deformation. The transition between the mechanisms of particle shearing and bypassing roughly corresponds to the PA condition.

Of course, the precipitate microstructure has an influence on strength, mostly, as described previously, but also on strain hardening and other mechanical properties. Gerold (1979) provided a detailed description of dislocation-precipitate interactions leading to the strengthening of a material. The influence of precipitates on strain hardening was investigated by Brown and Stobbs (1971a and b) in an Al–Si system. Barlat and Vasudévan (1991) showed that the strain hardening rate of a 7075-UA sample was higher than that of 7075-OA, although both conditions exhibited the same strength, leading to a higher forming limit curve near the uniaxial and plane strain region for the UA sample. Plastic anisotropy, which is generally believed to be due to crystallographic texture, is also affected by the precipitate microstructure. This is relatively simple to demonstrate using single crystals or polycrystals because the textures of materials aged under different conditions are generally identical. After SHT, the driving force for recrystallization during aging is not sufficient to produce additional changes in texture. Moreover, whether the aging temperature is RT or higher, the grain size does not increase significantly. Thus, the only difference between two material samples aged under different conditions is the precipitate microstructure.

Binary aluminum alloys with a few percent copper have been particularly well investigated (Martin, 1968, 1980) because Al–Cu is a simple system but the general description is also valid for other alloys (Starke, 1989). It was shown by Hosford and

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