International Journal of Plasticity 66 (2015) 103–118

Contents lists available at ScienceDirect

International Journal of Plasticity

journal homepage: www.elsevier.com/locate/ijplas

Evaluation of biaxial flow stress based on elasto-viscoplastic self-consistent analysis of X-ray diffraction measurements

Youngung Jeong [a,b], Thomas Gnäupel-Herold [c], Frédéric Barlat [a,**], Mark Iadicola [b], Adam Creuziger [b], Myoung-Gyu Lee [d,*]

[a] POSTECH, Graduate Institute of Ferrous Technology, Republic of Korea
[b] NIST, Materials Science and Engineering Division, United States
[c] NIST, Center for Neutron Research, United States
[d] Korea University, Dept. of Materials Science and Engineering, Seoul, Republic of Korea

ARTICLE INFO

Article history:
Received 28 October 2013
Received in final revised form 27 May 2014
Available online 16 July 2014

Keywords:
A. Microstructures
B. Constitutive behaviour
B. Crystal plasticity
B. Elastic-viscoplastic material
X-ray diffraction

ABSTRACT

Biaxial flow behavior of an interstitial free steel sample was investigated with two experimental methods: (1) Marciniak punch test with in situ X-ray diffraction for stress analysis; (2) hydraulic bulge test. The stress analysis based on X-ray diffraction using {2 1 1} lattice planes was accompanied by the use of stress factors and intergranular (IG) strains. Stress factors and IG strains were experimentally obtained *ex situ* on samples after prescribed equi-biaxial deformations. An elasto-viscoplastic self-consistent (EVPSC) crystal plasticity model was used to predict the stress factors and the IG strains. The model predictions of the stress factors were in good agreement with the experiments. However, the predictions of IG strains were in poor agreement with their experimental counterparts. As a result, the flow stress solely based on the computationally predicted stress factors and IG strains was unrealistic. The input of the experimental stress factors and IG strains for stress analysis improved the agreement with a reference flow curve obtained by a hydraulic bulge tester. The resulting flow curves based on X-ray diffraction were in good agreement with that of the bulge test up to an effective strain of 0.3. However, an unrealistic softening was observed in larger deformations regardless of whether the stress factor used were experimentally measured or determined from EVPSC calculations.

1. Introduction

1.1. Importance of biaxial flow behavior

Constitutive models, which link imposed strains to resulting stresses, are often populated with experimental flow behavior in uniaxial tension. Uniaxial tension tests are relatively easy to conduct compared to multiaxial experiments such as tests conducted in Mohr and Jacquemin (2008) and Mohr and Oswald (2008), yet, provide useful information (Hill, 1948, 1979; Logan and Hosford, 1980). However, relying solely on uniaxial tension data may lead to erroneous descriptions of biaxial states for anisotropic materials and may prove to be inaccurate. In such cases, the experimental measurement of biaxial properties for comparison with the constitutive model predictions (Kuwabara, 2007; Kuwabara et al., 1998; Xu and

* Corresponding author. Tel.: +82 02 3290 3261; fax: +82 02 928 3584.
** Co-corresponding author.
E-mail addresses: youngung.jeong@nist.gov (Y. Jeong), thomas.gnaeupel-herold@nist.gov (T. Gnäupel-Herold), f.barlat@postech.ac.kr (F. Barlat), mark.iadicola@nist.gov (M. Iadicola), adam.creuziger@nist.gov (A. Creuziger), myounggyu.lee@gmail.com (M.-G. Lee).

http://dx.doi.org/10.1016/j.ijplas.2014.06.009
0749-6419/

Barlat, 2008) may be required. In parallel with experimental progress, some advanced constitutive models have been developed. These advanced models allow the direct input of the in-plane biaxial yield stress in addition to that of uniaxial tension, enhancing the accuracy of finite element (FE) predictions (Barlat et al., 2005, 2003, 1997).

The biaxial behavior is also important for the assessment of sheet metal formability, conventionally characterized by the forming limit curve (FLC). A strain-based FLC is usually represented in the space of the two in-plane principal strains (Marciniak et al., 1973). A stress-based FLC has been proposed to deal with path dependency of the FLC, as the path dependency in strain space is remarkably reduced in stress space (Stoughton, 2000; Stoughton and Zhu, 2004; Wu et al., 2005). However, verification of a path-independent stress-based forming limit approach often relies on constitutive models where stresses are inferred from measured plastic strains.

1.2. Difficulties in biaxial stress measurement

The analysis of biaxial experiments to extract constitutive relationships is not a trivial task. There have been various experimental methods reported in the literature: bulge (Hill, 1950), Nakajima (Lee et al., 2004), Marciniak (Marciniak et al., 1973), tubular (Kuwabara et al., 2005), cruciform (Kuwabara et al., 1998; Verma et al., 2010) and disk compression (Xu and Barlat, 2008) tests. However, some of the listed test methods are only suitable for specific and limited information such as biaxial plastic flow anisotropy (disk compression) or maximum achievable biaxial strain (Nakajima and Marciniak tests). In tests where a punch applies deformation to the surface, the measurement of the stress in the sample is convoluted with friction tractions between the punch and the specimen surface. In tests based on cruciform samples, the achievable deformation is limited by premature fracture caused by the sample geometry. However, an extended deformation in this case is achievable, for instance, by thinning the gauge area (Lebedev and Muzyka, 1998). Samples subjected to either bulge or tubular hydraulic tests can experience an extended amount of deformation without the disturbance caused by friction. However, the deformation conducted in bulge systems contains a component of bending. A more detailed review of various biaxial testing methods is available in a recent article by Tasan et al. (2012). The Marciniak test has advantages such as the in-plane and frictionless conditions in a central area of the specimen (Bong et al., 2012). However, the unquantified friction tractions make measurement of the stress in the sheet from the punch force difficult to deconvolute.

1.3. Stress analysis based on diffraction measurement

Foecke et al. (2007) overcame the difficulties in stress measurement for Marciniak test by employing an in situ X-ray system to measure the stress. In their work, the stress–strain curves of an aluminum alloy were successfully measured based on the in situ lattice strain with known diffraction elastic constants. Later Iadicola et al. (2008) measured multiaxial stress states that included plane strain states to compare the results with predictions made by various yield functions. It is worth mentioning that both studies were conducted for aluminum alloys. Despite of these two successful examples, some issues need to be overcome in order to make diffraction stress analysis more practical for general applications.

For instance, it is well known that the commonly used $\sin^2\psi$ method, which was used in the mentioned work, is not suitable for many steel sheet products due to: (1) the elastic anisotropy, (2) crystallographic texture, and (3) nonspherical grain morphology (Daymond et al., 2000; Lebensohn et al., 1998; Wong and Dawson, 2010), which evolves as further deformation is applied. Steel alloys exhibit higher anisotropic elastic constants compared to the aluminum alloys mentioned earlier, which lead to more complex behavior in the plastic region (Clausen et al., 1998). The changes in texture and grain morphology lead to a strong directional dependence of the elastic constants used to convert lattice strain into macro-stress (Hauk, 1997). Insufficient knowledge of the diffraction elastic constants is one of the reasons why diffraction stress measurements in the presence of texture often lead to inaccurate results.

Whenever elastically anisotropic behavior is expected, stress analysis should be accompanied with the use of proper stress factors to obtain accurate data (Hauk, 1997). One should be cautious when considering use of the stress factor method, since stress factors are sensitive to various parameters. In the literature, stress factors have been shown to depend on (1) crystallographic texture and (2) grain morphology (Gnäupel-Herold et al., 2012). In addition, the influence of (3) the selected diffraction plane was demonstrated in a systematic study (Barral et al., 1987). It is also found that intergranular (IG) strain plays an important role for accurate stress analysis based on diffraction (Gnäupel-Herold et al., 2012). In the current paper, the term 'IG strain' exclusively refers to the intergranular strain as the grain volume averaged strain state of a group of grains with two key characteristics: (1) the grains in diffraction are oriented in the same manner and (2) the IG strains are still present in the absence of applied stresses. Variations in lattice strains that occur on even smaller length scales than the grain dimensions are excluded from consideration.

As the preceding discussion shows, the accurate determination of a stress state using a diffraction technique can be an extremely complicated task to properly account for the material states mentioned above. Fortunately, a number of advanced crystal plasticity frameworks, which can account for the mentioned material states, are available (Kanjarla et al., 2012; Lebensohn et al., 1998; Turner and Tomé, 1994; Wang et al., 2010; Wong and Dawson, 2010). Such models may provide a unified tool, by which the accurate analysis of stresses through diffraction can be better understood. Therefore, the goal of the current study is to demonstrate the validity of a chosen polycrystal plasticity model (Wang et al., 2010) in comparison with experimental results. It is expected that a better understanding of the complex nature of the stress analysis based on diffraction can be achieved by comparing model prediction and experimental results in parallel.