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Effective X-ray elastic constant measurement for in situ stress measurement of biaxially strained AA5754-O

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ABSTRACT

Accurate measurement of stresses by X-ray diffraction requires accurate X-ray elastic constants. Calibration experiments are one method to determine these for a specific material in a specific condition. In this paper, uniaxial tension experiments are used to investigate the variation of these constants after uniaxial and equal-biaxial plastic deformation for an aluminum alloy (AA5754-O) of interest to the automotive industry. These data are critical for accurate measurement of the biaxial mechanical properties of the material using a recent experimental method combining specialized sheet metal forming equipment with portable X-ray diffraction equipment. The measured effective X-ray elastic constants show some minor variation with increased plastic deformation, and this behavior was found to be consistent for both uniaxially and equal-biaxially strained samples. The use of two average values for effective X-ray elastic constants, one in the rolling direction and one transverse to the rolling direction of the sheet material, is shown to be of sufficient accuracy for the combined tests of interest. Comparison of uniaxial data measured using X-ray diffraction and standard methods show good agreement, and biaxial stress–strain results show good repeatability. Additionally, the calibration data show some non-linear behavior, which is analyzed in regards to crystallographic texture and intergranular stress effects. The non-linear behavior is found to be the result of intergranular stresses based on comparison with additional measurements using other X-ray diffraction equipment and neutron diffraction.

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1. Introduction

The mechanical response of sheet metals to large strains in biaxial tension (e.g., uniaxial, plane strain, and equal-biaxial strains) is of interest to the metal forming community. Many testing configurations exist to achieve some or all of the tensile strain states of interest including cylindrical tension-torsion-inflation, inflation bulge, hemispherical or flat ram, and cruciform testing, but all have inadequacies resulting from out of plane bending, application of non-uniform deformation, limited strain range, or the need for assumed constitutive laws to determine the stress in the sample. Iadicola et al. [1] used a combination of biaxial mechanical testing and X-ray diffraction (XRD) techniques to produce less ambiguous stress–strain measurements up to large plastic (strains > 15%) in-plane (biaxial) stretching of an as-received sheet metal sample. In this method of testing, XRD is used to measure the in situ interatomic lattice spacing in the sheet which is proportional to the stress through effective X-ray elastic constants (XECs). This method requires careful calibration, but removes the need for numerical modeling with an assumed constitutive law to determine the stress–strain behavior. In this paper, the calibration measurements of effective XECs for the biaxial experiments in Iadicola et al. [1] are described, with special attention to the possibility of effective XEC variation due to the macroscopic plastic strain history. Preliminary work on these measurements was presented briefly in Iadicola and Gnaeupel-Herold [2], but has been substantially extended here.

In this work, elastic uniaxial loading is used in conjunction with established XRD techniques to determine effective XECs for one material of interest. These experiments are performed on as-received material and material deformed equal-biaxially to various strain levels in a manner similar to Iadicola et al. [1]. Due to the orthotropic nature of the rolled sheet metal, the experiments are performed for samples in both the rolling direction (RD) and transverse to the rolling direction (TD).

2. Material & mechanical testing procedure

The material used in this investigation is commercially available 1 mm thick AA5754-O (which is of interest to the automotive industry). The microstructure of the as-received sheet shows recrystallized grains, which are relatively equiaxed in the rolling

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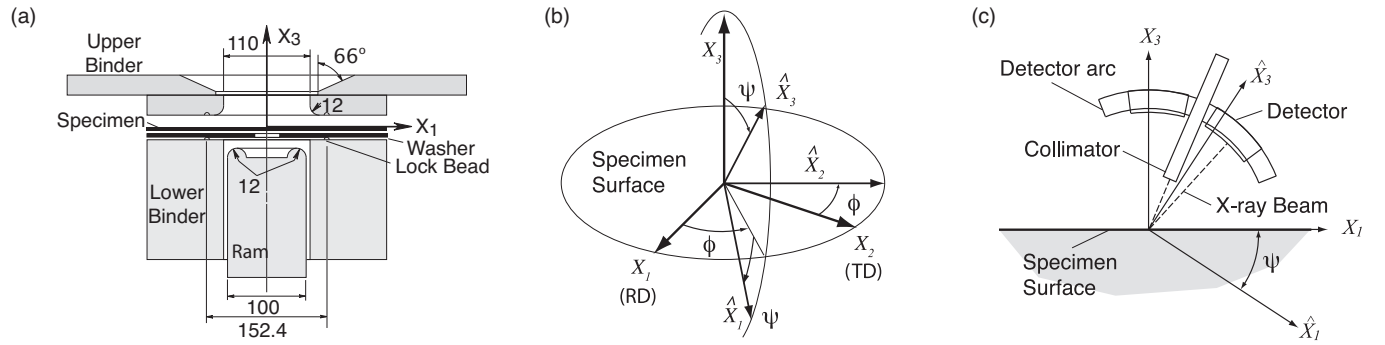

Fig. 1. Specimen and XRD axes defined by (a) through section of axisymmetric Marciniak tooling (dimensions in mm), (b) standard XRD angles, and (c) sketch of the XRD head.

plane, but slightly elongated when viewed in the transverse plane. The size of the grains is relatively uniform in each direction, with an average diameter of 40 μm in the normal plane.

The effective XEC calibration experiments presented here use uniaxial tensile tests, of both as-received and equal-biaxially strained samples, in conjunction with XRD measurements to calibrate the effective XEC. A portable uniaxial testing frame is used to test ASTM-E8 sub-sized sheet metal specimen shape samples with a reduced tab length. During deformation, load (from a calibrated load cell) and strain (from a calibrated axial extensometer) are measured to determine the true stress in the gage section. At selected strain levels the specimen is unloaded (to a stress never less than 80% of the as-received initial uniaxial yield stress, approximately 94 MPa for the RD) and reloaded elastically. During these elastic unload/reload times, the uniaxial loading is paused at multiple points and XRD is used to measure the current interatomic lattice spacing. These experiments are performed on as-received samples and equal-biaxially strained samples (as in Iadicola et al. [1]) with approximately 5%, 10%, 15%, and 20% equal-biaxial true-strain, in both RD and TD.

The method of specimen deformation used here to perform the equal-biaxial straining is a variation [3] of the Marciniak flat bottom ram test [4] (Fig. 1a is a through section drawing of the axisymmetric tooling), which imposed near-linear strain paths in a range of strain states from uniaxial to equal-biaxial tension (under plane stress conditions on as-received sheets, stretching the sheet like a drum head). The upper surface of the specimen is exposed for metrology. In Iadicola et al. [1], biaxial stress–strain behavior was measured using a combination of this mechanical deformation and XRD to determine stress. A washer of mild steel is used to reinforce the specimen where it will bend around the ram radius, thus concentrating the deformation in the center of the specimen directly above the centerline of the ram. The upper and lower surfaces at this center section are traction free. The ram force cannot be simply related to the resulting in-plane stresses in this center section of the sheet, therefore XRD is used to measure the in situ interatomic lattice spacing, which is proportional to the in situ stresses in the sheet through an effective XEC.

The procedure used in Iadicola et al. [1] is similar to that used to calibrate the effective XEC. We briefly review the procedure here. In Iadicola et al. [1], after as-received sheet and reinforcing washer are initially clamped in the forming machine binder (or locked in the grips for the uniaxial experiments), the general procedure includes three steps: (1) the material is loaded by imposing tensile strains (by an increase in ram height for biaxial loading or by a crosshead displacement for uniaxial loading) at a quasi-static rate, (2) the displacement is held fixed and the XRD system is focused on the surface of the sheet, and (3) an XRD scan (described below) is performed. This procedure is then repeated for the next data point. For both the experiments in Iadicola et al. [1] and in this work, the entire procedure (1 through 3) takes approximately 8 min (due in large part to the low power of the XRD system and X-ray absorption by the sample). The macroscopic strain during this hold time is calculated by averaging the output of an extensometer for the entire scan time (standard deviations in these data were typically <0.005% strain). The biaxial experiments use a biaxial extensometer with similar performance to the axial extensometer used in the uniaxial experiments.

3. XRD procedure

A portable low-power (60 W) XRD system is mounted to the back of the biaxial sheet metal forming machine, and is used to measure the interatomic lattice spacing in the exposed top surface of the specimen as described in [5]. The system uses the $\sin^2\psi$-method [[6], pp. 122 ff.] in the ψ-geometry (Fig. 1b and c), with interchangeable single source X-ray tubes. The two coordinate systems in Fig. 1b are the material system and the XRD-head system. The material system is oriented with the X_1 axis in the RD, X_2 in the TD, and X_3 vertical to the sheet. The XRD system ($\hat{X}$) is offset to the material system first by a rotation (ϕ) about the sheet normal and then by a rotation (ψ) about the $\hat{X}_2$ axis, where the $\hat{X}_3$ axis is the bisector of the X-ray source and reflected beams. Fig. 1c is a sketch XRD-head (X-ray source beam with left and right detectors shown) and the axes for one ψ-angle at $\phi = 0$. In this figure, the $\hat{X}_3$ axis is oriented in the direction associated with the measurements using the right detector. Due to the space constraints, this system only permits tilting in one direction with respect to the specimen (ϕ = constant) over a limited angle range ($\psi = \pm 35^\circ$).

In this work, as well as in Iadicola et al. [1], Co Kα radiation is used. The beam is collimated and passed through a 5 mm long and 1.5 mm wide (in the ψ-tilt direction) aperture. The diffracted/reflected X-rays from the specimen are acquired by two 256 channel 10° linear position sensitive scintillation detectors (one placed symmetrically on each side of the source beam). Note that Fig. 1c shows both detectors, but the axes as shown are for the source beam and right detector only. The system is configured to acquire a single reflection peak profile in each detector at one time, and here the {4 2 0} family of planes (Bragg angle $\theta = 81.25^\circ$ for the Co X-ray source) is used exclusively. The profiles are fit using a two peak ($K\alpha_1$ and $K\alpha_2$) Pearson's VII function (with an exponent of 1.77) to the upper 85% of the total peak after background subtraction. Lattice spacing ($d_{\phi\psi}$) is computed from the peak position through Bragg's Law. The stress free lattice spacing (d_o) is not measured directly for the material, since the $\sin^2\psi$-method is not very sensitive to error in this value, and a system default value for aluminum is assumed. To verify this, an XRD measurement of a stress free powder is made, and the assumed d_o is considered acceptable if the measured lattice strains are less than