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Investigation of through thickness residual stress distribution in equal channel angular rolled Al 5083 alloy by layer removal technique and X-ray diffraction

M. Mahmoodi [a], M. Sedighi [a,*], D.A. Tanner [b]

[a] School of Mechanical Engineering, Iran University of Science and Technology, Tehran, Iran
[b] Materials and Surface Science Institute (MSSI), University of Limerick, Limerick, Ireland

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ABSTRACT

The layer removal technique and the X-ray diffraction method have been employed to evaluate the residual stresses through the thickness of aluminum alloy 5083 processed by equal channel angular rolling (ECAR). ECAR is a severe plastic deformation process that introduces shear deformation to sheet metals. The process has been completed on 2 mm thick strips passed three times through die channels in a continuous manner. In this work, the profile of residual stresses was quantitatively determined. It was observed that after the ECAR process, the residual stress magnitudes were changed from approximately zero in annealed condition up to half of the yield strength value of ECARed samples. The distribution of the residual stresses was found to be non-uniform through the thickness and the ECARed sample was compressive at the top surface while it was tensile at the bottom surface.

1. Introduction

Residual stresses are self equilibrium internal stresses that exist in manufactured parts with no external forces and constraints [1]. Equal channel angular rolling (ECAR) is a severe plastic deformation (SPD) method where the material can experience large strain magnitudes [2]. In this process, the material is passed through the channel of dies without changing the cross-sectional area of the strip [3]. Therefore it can be utilized in different passes to obtain ultrafine grain and desirable material properties [4,5].

In metal forming processes where material undergoes plastic deformation, different plastic strain deformation at the same times in different locations creates an internal stress distribution. One reason for different actual strains is due to the shape of deformation zone that exerts a strong effect on the magnitude and distribution of residual stresses.

For a material with a specific yield point, residual stresses as a pre-stress state causes a change in the yield strength [6]. In addition, the residual tensile stresses on the material surface are undesirable as it can lead to reduced fatigue life and make the material vulnerable to stress corrosion cracking [7–9]. The methods of non-destructive, destructive and semi destructive measurement can be applied to measure the residual stresses magnitude. In destructive methods such as layer removal method, the strain variation caused in relieving the residual stresses in the material is measured. For applying this method it is important to have information about the nature of the residual stresses field that is, magnitude and distribution of stresses in one, two or three directions [1].

Considering the layer removal technique there are some assumptions for the stress field in sheets, strips, wires and plates. The stress distribution can be assumed biaxial in the plane of the sample and vary through the thickness [10,11] or it can be uniform [12]. The layer removal technique and X-ray diffraction are applicable procedures to measure the biaxial residual stresses over the planar surface of the sheet or metal strips. The stresses on the plane of sample are assumed constant. Also this technique has been applied to determine the residual stress in thin films and coatings [13,14].

The residual stress distribution has been studied for cold and hot forming processes such as extrusion, wire drawing and rolling, but the magnitude and the distribution of residual stresses in the strips and sheet metals processed by ECAR, has not been evaluated up to now. The sheet metals are widely used in the transportation industries and it is important to know the specifications of the sheet metal such as residual stress distribution. In some sheet products, the amount of residual stress is not considerable and a few studies have been done for residual stress measurement in sheet metals produced by a forming process. Therefore the study of residual stress magnitude and distribution in ECARed materials has become a necessity. In this article, the methods of layer removal and X-ray diffraction have been utilized to determine the residual stress through the thickness in material processed by ECAR.

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* Corresponding author. Tel.: +98 21 77491228; fax: +98 21 77240488.
E-mail address: sedighi@iust.ac.ir (M. Sedighi).

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2. Experimental procedure

2.1. Material

In this research, a 2 mm thick sheet of aluminum alloy 5083 was used. At first, the material was cut to samples with the dimensions of 400 mm × 40 mm × 2 mm (length × width × thickness). Then they were annealed at 450 °C for 1 h before ECAR which minimized the residual stresses magnitude in the samples. The residual stress of near zero was measured after annealing. The chemical composition (in wt.%) of the material was determined by quantometery analysis and is listed in Table 1.

2.2. Equal channel angular rolling process

A schematic of the ECAR machine used to introduce the shear deformation into metal strips is illustrated in Fig. 1a. It was equipped by two feeding rolls and dies.

The thickness of the inlet and outlet channel is 2 mm. In Fig. 1b, the oblique angle (Φ) which is the intersection angle of outlet and inlet channels is 130° and the curvature angle (Ψ) is 0°. The Al strip having the initial thickness of 2 mm is fed through the feeding rolls and reduced into the 1.95 mm thick strip. After passing from the forming zone, the sample retains its initial thickness (2 mm). In the present work, the feed speed is 3 m/min and the Al strip is ECARed in three passes. The route *A* has been selected to do the process. In route *A*, the sample is fed through the channel with no rotation between the passes around the *x* direction [4].

It is defined that the top and bottom surfaces of the sample are respectively in contact with the upper and lower dies.

Using Eq. (1) the effective strain imposed to the material per three passes is 1.54.

Table 1
Chemical composition (in wt.%) of Al 5083 alloy.

Al	Balance
Mg	4.5
Mn	0.75
Cr	0.15
Fe	Max 0.1
Si	Max 0.1

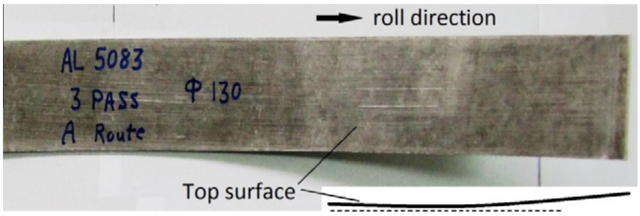

Fig. 2. Al 5083 sample processed by ECAR after three passes through route *A* with a small curvature.

$$\varepsilon_{eff} = \frac{2N}{\sqrt{3}} \cdot K^2 \cot\left(\frac{\Phi}{2}\right) \qquad (1)$$

In Eq. (1), N is the number of passes, Φ the oblique angle and $K = 0.975$ is the thickness ratio. This formula is obtained from the modified Segal model for calculation of shear deformation [2]. Based on the experimental observation it could be assumed that the dimensional change of length, width and thickness of the metal strip is negligible. The Al 5083 sample processed by ECAR at room temperature has been represented in Fig. 2.

2.3. Residual stress measurement by layer removal technique and XRD

In this research, the layer removal technique and X-ray diffraction method have been carried out to determine the residual stresses through the sample thickness. Electropolishing was applied for removing the material as a thin layer. This material removal creates a flat surface. For this procedure, sample and solution (electrolyte) form the part of DC electrical circuit. The Lacomit varnish was used for masking the sample to prepare only the area to be polished in contact with the electrolyte. The electropolishing was carried out using Barker's reagent (5 ml Fluoroboric acid in 200 ml water) at room temperature and the optimum voltage and current were 30 V and 1 A.

In order to do the layer removal, the layer thickness removed in each increment of electropolishing test was 0.2 mm. The thickness in each increment was measured with a micrometer.

Before using the layer removal technique, the X-ray diffraction method was applied to determine the residual stress magnitudes at the surface. The stresses have been measured in each increment

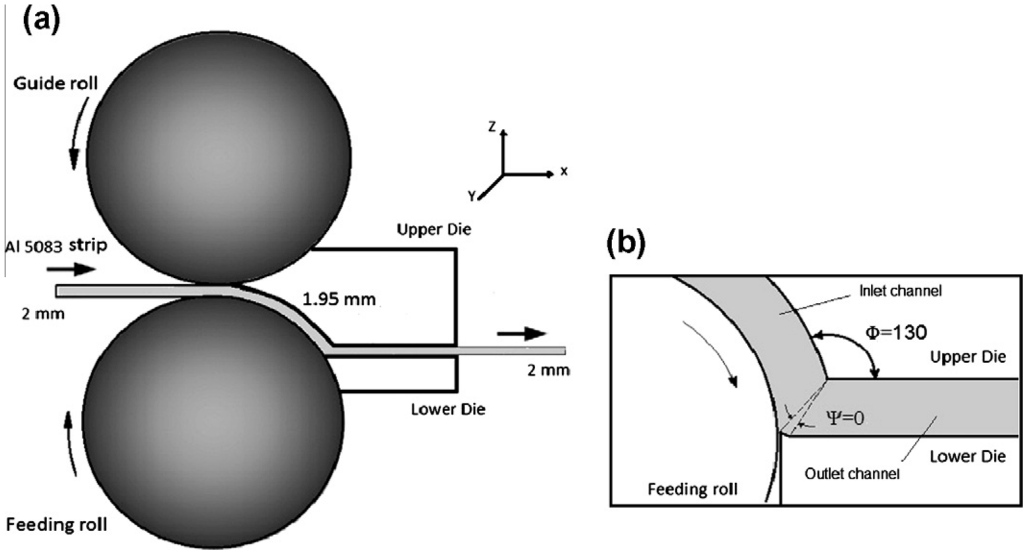

Fig. 1. (a) A schematic showing the equal channel angular rolling process and (b) channel angles in forming zone.