Experimental and Numerical Study of Through Thickness Residual Stresses Distribution in Sheet Metals Produced by ECAR

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Abstract: The equal channel angular rolling (ECAR) is one of the severe plastic deformation processes, which can develop a shear deformation into a sheet metal. In this process, internal stresses are created due to the different strain levels experienced in different locations at the same time. The incremental hole drilling method is an effective technique for the evaluation of the through-thickness residual stress distribution in the metal sheets processed by the ECAR. In this work, the residual stresses as the macro stresses have been considered by the help of the incremental method and FEM for numerical calculation of the calibration coefficients. In addition, the FE simulation has been used to investigate the residual stress profile through the thickness. It was observed that the ECARed sample was compressive at the top surface while it was in tension at the bottom surface and the stress profile was not uniform through the material thickness. A comparison between the hole drilling measurements and the FE simulation results showed a good agreement.

Keywords: ECAR, FEM, Incremental Hole Drilling, Residual Stress

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1 INTRODUCTION

The ECAR is a severe plastic deformation method by which the large strain can be introduced to the material [1]. This method is based on ECAP and recently has been applied on few sheet and strip metals to obtain ultrafine grain with desirable properties [2]. In the ECAR process, the material is passed through the channels of dies without changing the cross sectional area of the strip [3]. Therefore it can be used in a continuous manner and different passes [4], [5]. The high quality ECARed alloy sheets can be used in car and airplane manufacturing industry. When the metal sample passes through the intersection area of the die channels of ECAR, the shape zone is found to be non-uniform. Therefore the material at the same time undergoes plastic deformation in different strain levels and locations. The difference generates the internal stress and exerts a strong effect on the magnitude as well as on the distribution of residual stresses [6].
Study of the residual stresses in samples produced by a severe plastic deformation is important. The residual stress can effect on the failure caused by fatigue, stress corrosion or distortion happening during the metal processing and reduce their load carrying capacity [7], [8]. Among the methods for residual stress measurements, hole drilling is a semi-destructive technique for measuring the residual stress near the surface of the sample and through the thickness in depth [9], [10]. An incremental technique has been used to study the non-uniform residual stress. The technique is based on the measurement of the relieved strains during the material removal from a small hole [11-13]. Theoretical calibration coefficients from finite element calculation in correlation with experimental results have been widely used to determine the residual stress [14].
The residual stress has been studied for some cold and hot forming processes such as extrusion, wire drawing, rolling and multi layers, but the profile of residual stress in the sheet and strip metal processed by ECAR, has not been reported to this date. In this article the IHD method has been implemented to measure the residual stress through the thickness in the material processed by ECAR. In addition the finite element (FE) simulation has been used to study the residual stress profile and the results are compared together.

2 THE PROCESS OF ECAR

2.1. Experimental Procedure of ECAR Process

In this work a 2 mm thick sheet of commercial Al 5083 alloy (Al, 4.5%Mg, 0.75%Mn, 0.15%Cr, max 0.1%Fe and 0.1%Si) was used. The Al 5083 is a non-age-hardenable Al–Mg based alloy with moderately high strength, high formability in conjunction with super plasticity, and good corrosion resistance [15]. First, the strip of samples of 40 mm × 400 mm were prepared and then annealed at 450˚C for an hour. The strips were subject to a large shear deformation in a continuous behaviour in ECAR process. Fig. 1 is a schematic representation of the feeding rolls and dies in the ECAR equipment. The 2 mm thick Al strip is fed through the die channels by the means of feeding rolls. The ECAR technique was carried out for two passes using route A at a feeding speed of 3 m/min at the room temperature. In route A, the sample is fed through the channel without rotation during the passes along the x direction.

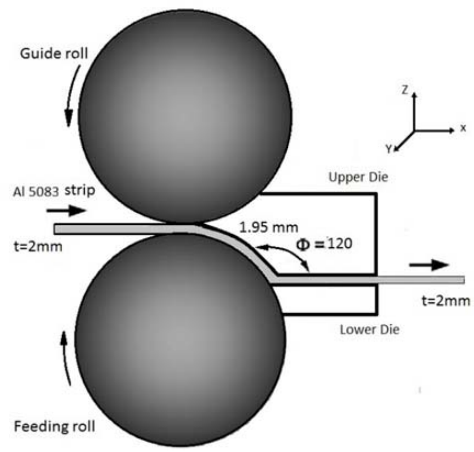

Fig. 1 Schematic representation of the ECAR process

The thickness of the inlet and outlet channel is 2 mm and the thickness of strip after reduction through rolling is 1.95 mm. The oblique angle (Φ) in the intersection area of channels is 120˚ with the curvature angle (Ψ) of 0˚. When the material is being passed through the shear deformation zone with non-uniform shape, the residual stress causes the curvature of the sample after ECAR. Fig. 2 shows the curved sample after ECAR process.

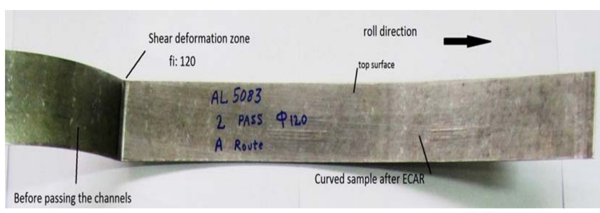

Fig. 2 The curved Al 5083 sample processed by ECAR through route A, φ=120 after 2 passes

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With the aid of Eq. (1), the effective strain ε_{eff} (or equivalent strain) imposed on the specimen per pass was calculated to be ~ 0.64; A strain of ~1.28 was determined to be accumulated in the sample after the second pass.

$$\varepsilon_{eff} = \frac{2N}{\sqrt{3}}.K^2 \cot(\frac{\phi}{2}) \tag{1}$$

where 'N' is the number of passes, 'φ' is the oblique angle and K=0.975, is the thickness ratio [1].

3 RESIDUAL STRESS MEASUREMENT BY IHD METHOD

In this research, the IHD method was applied to measure the residual stresses through the thickness in the ECARed samples.

3.1. Theory

In order to determine the residual stresses, the theory of measurement ought to be taken into the consideration. First the residual stress profile extending from surface into the sample is assumed to be non-uniform. This method utilizes the relieved strain data taken after several small increments of hole depth [16]. Then the residual stresses magnitude and distribution are calculated using a mathematical method. In order to obtain the strain data, the arrangement as shown in Fig. 3 was used.

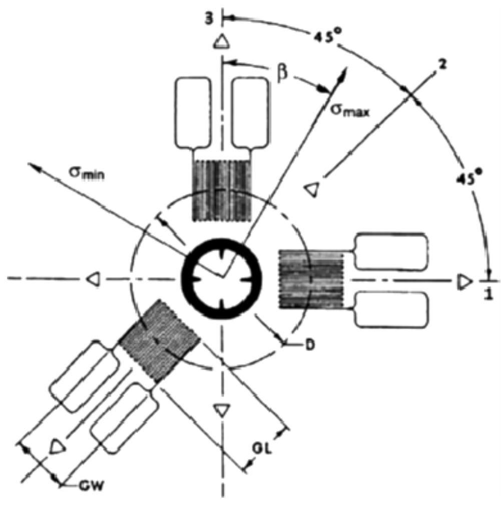

Fig. 3 Strain gauge rosette arrangement for determination of residual stress [17]

If $\varepsilon_n^1, \varepsilon_n^2, \varepsilon_n^3$ are the strain data taken after n $_{th}$ increment, then the principle residual stresses σ_{1n}, σ_{2n} can be calculated using Eq. 2 [17].

$$\begin{cases} \sigma_{1n} = \dfrac{\varepsilon_n^1 (A_n + B_n \sin 2\theta_n) - \varepsilon_n^2 (A_n - B_n \cos 2\theta_n)}{2A_n B_n (\sin 2\theta_n + \cos 2\theta_n)\Delta h_n} \\ \sigma_{2n} = \dfrac{\varepsilon_n^2 (A_n + B_n \cos 2\theta_n) - \varepsilon_n^1 (A_n - B_n \sin 2\theta_n)}{2A_n B_n (\sin 2\theta_n + \cos 2\theta_n)\Delta h_n} \end{cases} \tag{2}$$

where,

$$\theta_n = \frac{1}{2}\tan^{-1}\left[\frac{\varepsilon_n^1 - 2\varepsilon_n^2 + \varepsilon_n^3}{\varepsilon_n^1 - \varepsilon_n^3}\right] \tag{3}$$

A_n and B_n are the calibration coefficients computed by FEM.

3.2. Determination of the calibration coefficients by FEM

In this section, a 3D finite element model with the 4 nodes C3D4 elements was used in two different boundary conditions. Fig. 4 shows the two types of loading tension-tension and tension-compression applied on the model and analysed.

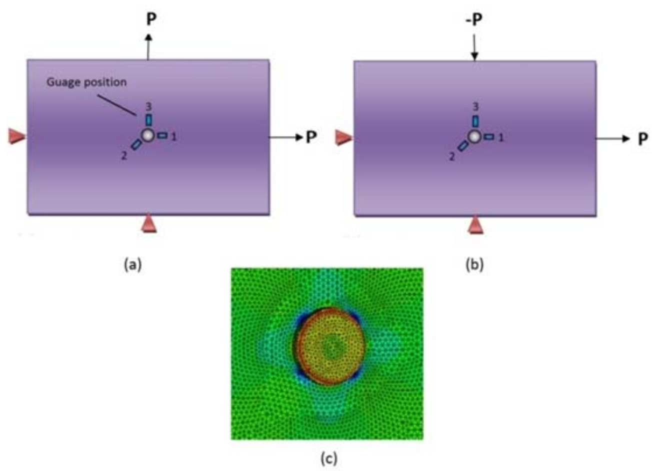

Fig. 4 Two types of loading applied on the model to obtain (a) calibration coefficients A_n , (b) calibration coefficients B_n and (c) strain result of FE simulation under loading

At first, the analysis was carried out for all increments with different hole depths and then the strain data ($\varepsilon_n^1, \varepsilon_n^2, \varepsilon_n^3$) were obtained. The calibration

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coefficients A_n and B_n were calculated using Eqs. (4) and (5).

$$A_n = \frac{\varepsilon_n^1 \sin 2\theta_n + \varepsilon_n^2 \cos 2\theta_n}{\Delta h_n(\sigma_{1n} + \sigma_{2n})(\sin 2\theta_n + \cos 2\theta_n)} \quad (4)$$

$$B_n = \frac{\varepsilon_n^1 - \varepsilon_n^2}{\Delta h_n(\sigma_{1n} - \sigma_{2n})(\sin 2\theta_n + \cos 2\theta_n)} \quad (5)$$

3.3. Experimental procedure

In order to measure the relieved strain in each increment, at first the rosette CEA-06-062UL-120 with the gauge circle diameter of 5.13 mm was bonded to the surface of the sample using M-Bond 200 adhesive. In this arrangement, the gauge 1 was in rolling direction. Then the sample was clamped onto a designed fixture. A high velocity drilling machine was used so as to perform a cylindrical hole (see Fig. 5). The relieved strain was measured by accurate strain instrumentation.

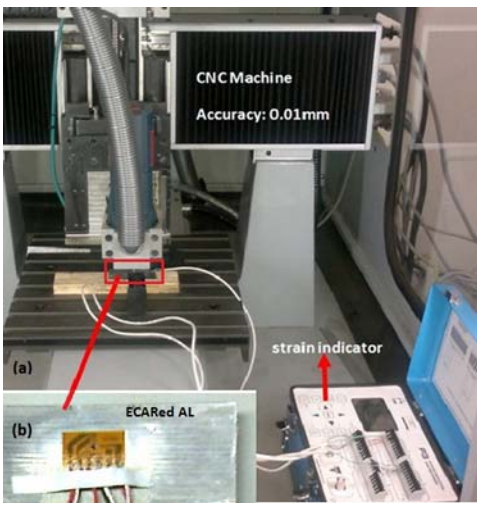

Fig. 5 (a) High speed drilling set up of relieved strains (b) The gauge rosette bonded to the surface of ECARed sample

4 RESIDUAL STRESS MEASUREMENT BY FINITE ELEMENT SIMULATION

The simulation of the ECAR process has been implemented by using Abaqus software Dynamic/Explicit analysis. The element for the Al strip is a 4-node plane strain element (CPE4R) and the structural technique is applied. The rolls and die set are assumed rigid. The mesh sensitivity analysis was used prior to determination of the suitable mesh size (0.2 mm). Fig. 6 shows the shear deformation patterns obtained by FEM calculation indicating the development of the strain field during forming of ECAR process.

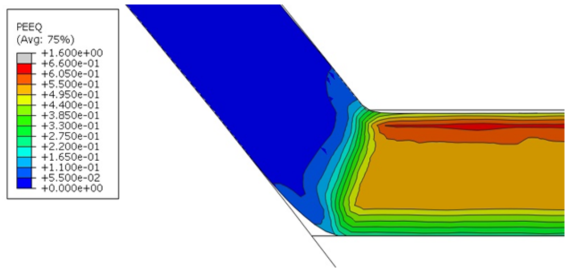

Fig. 6 The shear deformation patterns obtained by FEM calculation

5 RESULTS AND DISCUSSION

The variation of measured strains for three different directions during IHD is shown in Fig. 7.

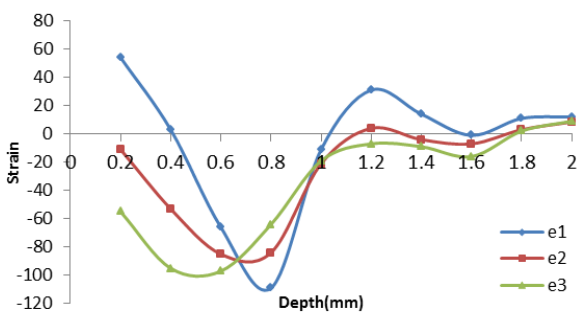

Fig. 7 Variation of strain values of gauges in three directions for different increments

To investigate the magnitude and distribution of the residual stresses through the thickness of ECARed samples, the calibration coefficients were obtained. The numerical values of A_n and B_n depend on material properties of the sample, the hole diameter and the depth were determined by finite element method using equations (4) and (5).

Fig. 8 shows the variation with the hole depth of calibration constants A_n and B_n for the hole diameter r_a/r_m=0.4 where r_a is the hole radius and r_m is the mean radius of strain gauge rosette.

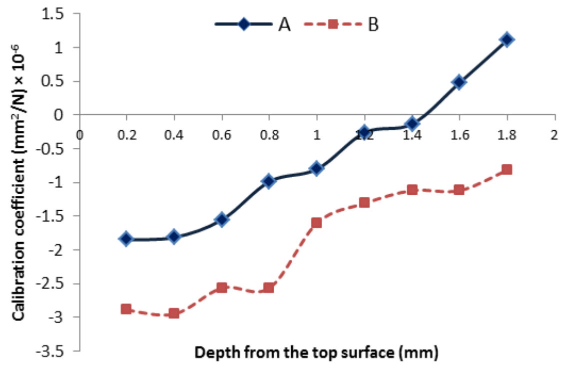

Fig. 8 Through-depth calibration coefficients A_n and B_n in ECA Red Al 5083 sample

The shape and the magnitude of residual stress profile were determined by using collected strains, calibration coefficients and Eq. (2). Fig. 9 illustrates the residual stress results in both rolling direction (x) and transverse direction (Y) and shear stress τ_{xy}. According to this figure, the τ_{xy} values are negligible and it can be assumed that the ECAR process introduces the principal stresses in both rolling and transverse directions.

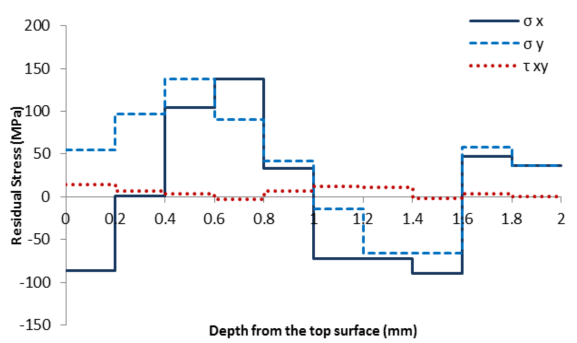

Fig. 9 Residual stress profiles σ_x, σ_y and τ_{xy} in the Al 5083 sample processed by ECAR

The through thickness residual stresses σ_{11} have been obtained by FE simulation. The comparison of the results for incremental method and FEM indicates a good agreement as shown in Fig. 10. In the ECAR process when the specimen passes from the forming zone (Figs. 1 and 2) regions of the material are non-homogeneous plastically deformed in such a permanent behaviour. The elastic response of the material to inhomogeneous distribution of non-elastic strains is the cause for the generation of the residual stress.

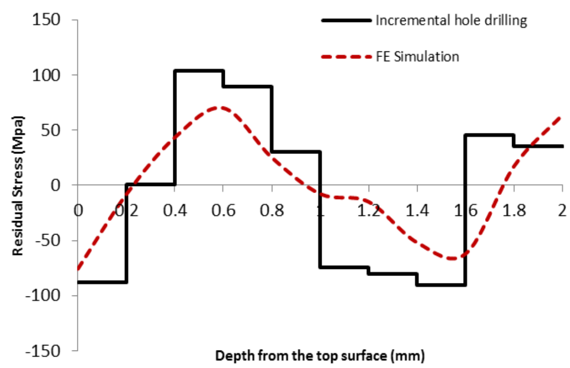

Fig. 10 Results comparison for the Incremental hole drilling and FE simulation

According to Fig. 10 the profile of residual stress is non-uniform and changes from the tensile condition to compressive. The residual stress at the top surface is compressive, but at the bottom surface is tensile. The maximum residual tensile stress is 138 MPa at the depth of 0.4-0.6 mm and the maximum compressive residual stress is -90 MPa at the depth of 1.4-1.6 mm. Therefore the maximum residual stresses of ECARed sample can be obtained up to nearly 45% of its yield strength. It can be stated that the ECAR process introduces a non-uniform residual stress profile to the non-stress annealed sample as the top surface is completely different with bottom surface. This trait caused a curvature in the strip. Fig. 2 shows the sample curved upward due to the different stresses on top and bottom surface layers and furthermore non-uniformity in the shape of residual stress profile.

6 CONCLUSION

The IHD technique and FEM were applied to determine the through thickness residual stresses distribution in the ECA rolled Al alloy. It was shown that the represented method can be effective in the determination of the residual stress profile for ECARed strip and sheet metals.
Based upon the results, the following conclusion can be drawn.

1. Finite Element Simulation was successfully applied to determine the residual stress profile in depth of the ECARed material.

2. In rolling direction, the ECARed sample was compressive at the top surface and in tension at the bottom surface.

3. The ECAR process introduced the non-uniform residual stress in both direction x and y to the free stress annealed sample.

4. The ECARed sample obtained the maximum residual stresses up to nearly 45% of its yield strength.

5. There was a good agreement between the results of IHD technique and FE simulation.

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