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Estimation of Dislocation Distribution at Mid Thickness for 1050 Al

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Abstract

The current study reports three different techniques to estimate the distribution of dislocation density at the mid thickness of 1050 Al alloy. It is well known that the strain distribution is inhomogeneous through the thickness of rolled materials, which affects the evolution of dislocation density during the process of deformation. In this study, the number of dislocations was calculated experimentally using indentation technique in 46.8 % cold rolled 1050 Al sheet and the result was verified by two numerical methods.

Keywords: *dislocation density, microhardness, numerical models.*

1. Introduction

Aluminum alloys consist of high strength-to-weight ratio and hence are extensively used as a structural material in aerospace, manufacturing, transportation and mobile communication industries, enabling products with lower fuel consumption and environmental impact. However, most of the aluminum is used in the form of a sheet product, which is produced through numerous rolling schedules [1]. It is well known that plastic deformation enhances the quantitative amount of linear defects in materials, thereby increasing the work hardening of the final product [1, 2]. To efficiently study the work hardening effect due to different deformation techniques such as reducing material thickness by rolling, it is important to estimate the dislocation density (ρ) of the material [2]. On the other hand, at microscopic levels, the deformation mechanism is found to be inhomogeneous, which involves heterogeneous density distribution of dislocation throughout the material [3]. The inhomogeneous strain distribution over the thickness of a material can affect the work hardening of the respective area [1–3], which makes it important to extend the distribution of dislocations over the thickness.

In the present study, to calculate the dislocation density of mid thickness of the sample, one experimental method, i.e., indentation technique, and two numerical models, i.e., Kubin-Estrin (K-E) and modified K-E have been employed. By employing the indentation technique, the dislocation density can be calculated from the hardness response of the material [4–5], using following relation:

$$\boldsymbol{\rho} = \frac{1}{\alpha^3}\left(\frac{H_V}{3.06\,MGb}\right)^2 \tag{1}$$

In equation (1), H_V is the Vickers Hardness, M is a Taylor factor, G is the shear modulus, b is the Burgers vector and α stands for the geometric constant.

There are modelling techniques enabling the calculation of dislocation density. For instance in the K-E model the total dislocation density ρ is evaluated as the sum of forest ρ_f and mobile ρ_m dislocations. Both ρ_f and ρ_m are variable functions of the applied strain (ε) [6]:

$$\frac{d\rho_m}{d\varepsilon} = C_1 - C_2\rho_m - C_3\rho_f^{\frac{1}{2}} \tag{2}$$

$$\frac{d\rho_f}{d\varepsilon} = C_2\rho_m + C_3\rho_f^{\frac{1}{2}} - C_4\rho_f \tag{3}$$

In equations (2) and (3), the coefficients C_1 and C_2 stand for the multiplication of mobile dislocations and their significant trapping, whereas the immobilization via interaction with the forest dislocations is represented by the C_3 parameter. The C_4 parameter governs the dynamic recovery.

The K-E model was further simplified by Csanádi et al. by bringing the forest and mobile terms of dislocation density together and thereby reducing the number of modeling parameters. The modified K-E model is given as [7] :

$$\rho(\varepsilon) = \frac{2C_1}{C_4} - \left(\frac{2C_1}{C_4} - \rho_0\right)\left(1 + \frac{C_4\varepsilon}{2}\right) exp(-C_4\varepsilon) \quad (4)$$

For aluminum alloys the parameter: $C_1 = 2.33\times10^{14}$ m^{-2} and $C_4 = 1.15$ [8].

The present research aims to study the quantitative characteristics of dislocations accumulated at the core of a 46.8 % deformed 1050 Al sheet, using the above-mentioned techniques. Geometrically, the core of the sheet is also the mid thickness. The obtained results are compared to study the efficiency of each technique in 1050 Al.

2. Methodology

For the present study, 1050 Al is chosen for its minimum solute content property (99.7 % Al) making it an ideal yet fundamental system to examine the dislocation evolution in aluminum alloys. The thickness reduction was performed using a laboratory rolling set up with a roll diameter of 150 mm. A reduction of 46.8 % was obtained by a single pass employing a non-lubricated symmetric rolling procedure. Prior to the cold rolling experiment, the sample was annealed at 550 °C to reduce the internal stress associated with the thermomechanical processes (TMP) during manufacturing.

The rolled samples were mechanically grinded and polished with Struers®-type DiaDuo suspensions containing one and three micrometer diamond particles. The hardness testing experiment was performed using Zwick/Roell® ZHVμ-type Vickers microhardness tester. The sample was studied about its transverse direction (TD) plane by making diamond shaped indents on the studied plane and capturing their hardness response.

After reduction, the final thickness of the sample was 1044.50 μm and the half of the thickness was defined as 522.25 μm. In the current analysis the area of study is in the region of 348μm to 522.25 μm, which is considered as the mid-thickness (core) of the rolled sheet. The indents were made with care to avoid overlapping of the deformation zones, induced by indentation in the corresponding points.

3. Results

3.1. Indentation Technique

On the studied area, indents were imposed on the polished surface by employing various loads, ranging from 10gf to 500 gf. However, for the calculation of total dislocation density, hardness values with very high deviation were neglected to avoid the so-called indentation size effect (ISE), which induces high hardness response at lower loadings [9]. For the current study, the hardness response from 200 gf to 500 gf were taken into consideration, which falls into saturation zone of the ISE curve [4].

In equation (1), the geometric constant α is generally considered to be a constant value for a wide range of straining, however, to ensure more accurate assessment of dislocation density, this parameter was calculated using the following equation [4]:

$$\alpha \cong \frac{(1-0.5\nu)}{4\pi(1-\nu)} ln\left(\frac{\rho^{-0.5}}{b}\right) \quad (5)$$

where ν = 0,35 is the Poisson ratio for Al.

The constant α has been calculated by equation (5) via defining ρ for varies strain ε values using equation (4). From the approximated $\rho(\varepsilon)$ values α is presented for a wide range of reductions in **Figure 1.** From the variation of α with strain, it has been reported that the value of geometric constant tends to saturate at ~ 0.5 as the amount of strain increases. The value of α is 0.5756 for the sample deformed with a true strain of 0.63 as per **Figure 1.**

The Taylor factor M (see **Table 1**) was recorded by texture maps obtained from the electron backscattering diffraction (EBSD) experiments. The Burgers vector b and shear modulus G for aluminum alloys are 0.2865 nm and 26 GPa, respectively. The final dislocation density value calculated by equation (1) is 1.7×10^{14} m^{-2}. The calculation details are presented in **Table 1.**

3.2. Numerical Models

In the numerical approach developed by Kubin and Estrin [6] the modelling parameters C_1, C_2, C_3 and C_4 are defined for aluminum alloys and given as: $C_1 = 2.33\times10^{14}$ m^{-2}, C_2 = 1.1, $C_3 = 4\times10^5$ 1/m, C_4 = 1.2 [8]. The dislocation density is calculated for aluminum alloys by both K-E and modified K-E

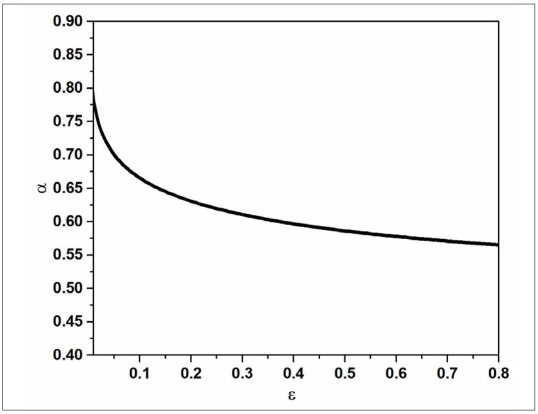

Figure 1. *Variation of α with strain predicted by eq.*

Table 1. *Evaluation of dislocation density by indentation technique data*

ε	α	M	Average HV (Pa)	ρ (m^{-2})
0.63	0.5756	3.16	4.11×10^{8}	1.7×10^{14} ±0.06

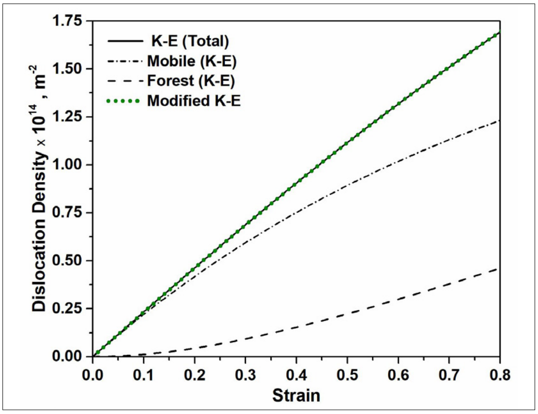

Figure 2. *Evolution of dislocation density predicted by the K–E* ***[6]*** *and modified* ***[7]*** *models over a range of strain.*

Table 2. *Dislocation density (ρ ×10^{14} m^{-2}) calculated by three techniques*

ε	Indentation	K–E	Modified K–E
0.63	1.7±0.06	1.4	1.4

technique using equations (2) to (4) for various straining level, which is represented in Figure 2.

Analyzing Figure 2 it becomes obvious that the *ρ(ε)* obtained by the K-E and simplified K-E methods are nearly identical, however, employing K-E technique one can evaluate the contribution of forest and mobile dislocations. The total dislocation density is found to be dominated by the amount of mobile dislocations over the range of strain as shown in Figure 2. The same is true for the respective strain of ε = 0.63.

The calculated values of dislocation density by the three techniques are represented in Table 2.

Table 2 shows that the dislocation density results obtained from both K-E and modified K-E is exactly same for the mid thickness layer of 46.8 % deformed 1050 Al, however, results obtained from the indentation method are slightly higher than the model predictions. This discrepancy can be explained by the presence of solutes in the investigated Al alloy, which additionally contributes to the hardening and therefore, the value of hardness in the investigated alloy is somewhat higher compared to pure Al. Another possible reason why the numerical approach provides slightly lower value is the complexity of dislocation interactions during deformation, which cannot be fully captured by the models employed.

4. Conclusion

Results of the current investigation clearly demonstrate that microindentation is capable of providing reasonable values of dislocation density, which tend to evolve during plastic deformation. The estimated dislocation density in 1050 Al alloy is in a good agreement with the theoretically assessed counterparts. The indentation technique makes possible to investigate the distribution of dislocation density across the thickness of deformed materials.

The Kubin-Estrin method can successfully provide a good approximation of the amount of mobile and forest dislocations responsible for work hardening at various levels of straining. On the other hand, modified K-E is a very simple and efficient approximation of the dislocation density. It has been shown that the modelling techniques employed slightly underestimate the density of dislocations most probably due to the complexity of dislocation interactions, which cannot be captured by these numerical approaches.

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