Finite element simulation and comparison of a shear strain and equivalent strain during ECAP and asymmetric rolling

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Abstract. The level of a shear strain and equivalent strain plays a key role in terms of the possibility of using the asymmetric rolling process as a method of severe plastic deformation. Strain mode (pure shear or simple shear) can affect very strongly on the equivalent strain and the grain refinement of the material. This paper presents the results of FEM simulations and comparison of the equivalent strain in the aluminium alloy 5083 processed by a single-pass equal channel angular pressing (simple shear), symmetric rolling (pure shear) and asymmetric rolling (simultaneous pure and simple shear). The nonlinear effect of rolls speed ratio on the deformation characteristics during asymmetric rolling was found. Extremely high equivalent strain up to e=4.2 was reached during a single-pass asymmetric rolling. The influence of the shear strain on the level of equivalent strain is discussed. Finite element analysis of the deformation characteristics, presented in this study, can be used for optimization of the asymmetric rolling process as a method of severe plastic deformation.

1. Introduction
Severe plastic deformation (SPD) is a very effective way to improve mechanical properties of metallic materials due to creating an ultrafine grain structure [1]. Nowadays many variants of SPD methods are available. The best known and well-studied of them is equal channel angular pressing (ECAP) [2]. In many works [1-3] it was proved that grain refinement and formation of high angle boundaries during ECAP comes from large shear strain. The main limitation of the application of ECAP is the small size of the samples. Therefore ECAP has low potential for producing materials that may be used in a wide range of structural applications. Contrary to ECAP the asymmetric rolling (AR) can provide the possibility for overcoming the limitation of producing ultrafine grained materials with large dimensions due to its continuous feature [4-6]. Many works studied the shear strain and equivalent strain during ECAP and AR by using finite element method (FEM). Ji and Park analyzed various AR processes by the rigid-viscoplastic FEM [4]. The results of the numerical simulation demonstrated that shear strain is more severe in the material layers, where the circumferential speed or friction coefficient is greater. Kim et al. [7] analyzed the effect of speed ratio on the development of shear strain and texture during AR. FEM simulation results showed that the equivalent strain during AR increased with high-speed ratio. Influence of process parameters on distribution of shear strain through sheet thickness during AR was investigated by FEM in [8]. It was found that to obtain a high uniform shear strain through the sheet thickness the rolls speed ratio should be equal to thickness reduction per pass. The main disadvantage of AR is a formation of a vertical bending of the sheet. This creates significant difficulties in multi-pass AR. So it is very important to find the optimal process parameters, which can provide extremely high shear strain and equivalent strain up to e > 3.0 during a single-pass
asymmetric rolling. The level of a shear strain and equivalent strain plays a key role in terms of the possibility of using the AR process as a method of SPD [9]. Two types of shear strain are known: pure shear and simple shear. During pure shear the axes of the strain ellipsoid do not rotate and the incremental and finite strain ellipsoids are coaxial. Simple shear involves rotation of the axes of the strain ellipsoid. Exactly rotation leads to grain refinement and formation of high angle boundaries. Simple shear (Fig. 1a) corresponds to ECAP. Pure shear (Fig. 1b) corresponds to symmetric rolling (SR). Simultaneous pure and simple shear (Fig. 1c) corresponds to asymmetric rolling. Therefore, for better understanding of a maximum possible level of equivalent strain, generated during a single-pass SPD, it is necessary to compare different strain modes. The goal of this investigation is a numerical simulation and comparison of the equivalent strain in the sample processed by a single-pass ECAP (simple shear), symmetric rolling (pure shear) and asymmetric rolling (simultaneous pure and simple shear). The results of investigation can be used for design of technology of producing ultrafine grained materials.

2. Research method

Simulations of a single-pass ECAP, SR and AR were carried out using the commercial FEM code DEFORM 3D. The geometry model of ECAP is shown in Fig. 2a. For ECAP process, workpiece with dimensions of 8.0×8.0×40.0 mm³ was used for processing. The workpiece was pressed through a die with two channels of equal cross section, intersecting at an angle 90° (channel angle). A Coulomb friction model was used. The friction coefficient at the die-workpiece interface was considered as 0.05, and the plunger moved with the velocity of 5.0 mm/sec during the process. The workpiece was meshed with ≈10000 brick elements.

Schematic illustration of the AR is shown in Fig. 2b. Workpiece with initial dimensions of 1.0×40.0×40.0 mm³ was meshed with ≈40000 brick elements. AR was performed for a single pass with a thickness reduction 60%. Simulation was carried out at a constant angular speed of the top roll 0.4 rad/s. Angular speed of the bottom roll was reduced by 10...60%. The diameters of the rolls were 500 mm. A Coulomb friction model was used between rolls and workpiece. The friction coefficient on the contact surfaces was 0.4. The modeling of the all processes (ECAP, SR, AR) was performed at room temperature without taking into account the increment of the metal’s temperature due to the thermal effect of deformation and friction. Aluminium alloy 5083 was chosen as a hardened rigid-plastic material for the workpiece in all calculation variants. The die, plunger and rolls were assumed as rigid. Symmetry plane was taken to improve computational efficiency. The stress-strain state of metal during a single-pass ECAP, SR and AR was compared and analyzed by FEM.

Figure 1. Schematic illustration of different strain modes: simple shear (a), pure shear (b), simultaneous pure and simple shear (c).

Figure 2. Geometry model of ECAP (a) and asymmetric rolling (b).
3. Simulation results and discussion

Simulation allowed to carry out a comparison between simple shear, pure shear and simultaneous pure and simple shear in order to highlight differences in the equivalent strain generated in the workpiece by a single pass ECAP, SR and AR. Changes in a single Lagrange's cell (along the centerline of the workpiece) before and after ECAP, SR and AR are shown in Figures 3, 5, 8. Single cell with initial shape of square becomes the parallelogram with no change in thickness after ECAP (Fig. 3). Shear strain during ECAP can be presented as tangent of shear angle $\phi$. After a single pass ECAP shear angle is about 64 degrees. This leads to a high value of the equivalent strain, which is about $e \approx 1.15$ (Fig. 4). This fully corresponds to the analytical calculation of the equivalent strain during ECAP by the well-known formula:

$$e = \frac{\tan \phi}{\sqrt{3}}$$  \hspace{1cm} (1)

![Figure 3. Change of Lagrange's cells during ECAP.](image1)

![Figure 4. Distribution of the equivalent strain in the workpiece during ECAP.](image2)

Single cell with initial shape of square becomes the rectangle in the middle layer of the workpiece after symmetric rolling (Fig. 5). The thickness of the square is reduced in normal direction and the length is elongated toward rolling direction. It looks like the only deformation involved is compression and extension. However, if we examine the diagonals of the cell we see that there is indeed shear because the angle between the diagonals changes. This sort of shear is called pure shear. Single pass rolling with thickness reduction 60% leads to a high value of the equivalent strain, which is about $e \approx 1.1$ (Fig. 6). This corresponds to the analytical calculation of the equivalent strain during SR by the well-known formula:

$$e = \frac{2}{\sqrt{3}} \ln \frac{h_0}{h_1}$$  \hspace{1cm} (2)

where $h_0$ is an initial thickness; $h_1$ is a final thickness.

![Figure 5. Change of Lagrange's cells during SR.](image3)

![Figure 6. Distribution of the equivalent strain in the workpiece during SR.](image4)

Equivalent strain, generated in the workpiece during a single pass symmetric rolling by pure shear (with thickness reduction 60%), corresponds to equivalent strain during one pass ECAP by a simple shear. However, the key disadvantage of pure shear is the absence of a rotational strain mode, which is necessary for forming of high-angle grain boundaries.
The workpiece is deformed according to the scheme of simultaneous pure and simple shear during asymmetric rolling. Friction coefficient, the rolls speed ratio and the thickness reduction per pass are the main factors which provide synergistic effect on the amount of the shear strain and the equivalent strain during AR. Increasing the rolls speed ratio $\Delta V$ from 0 to 60% leads to serious increase of the equivalent strain (Fig. 7). The non-linear effect of the rolls speed ratio on the deformation characteristics during asymmetric rolling was found. The equivalent strain has the maximum value when the rolls speed ratio $\Delta V$ is optimal. Equivalent strain $e \approx 4.2$ when $\Delta V = 57\%$ (Fig. 7).

![Figure 7. Influence of the rolls speed ratio $\Delta V$ on the equivalent strain of the workpiece during AR (initial thickness is 1.0 mm; thickness reduction is 60%; friction coefficient is 0.4).](image)

Single cell with initial shape of square becomes the parallelogram with change in thickness after asymmetric rolling (Fig. 8). Shear strain also can be presented as tangent of shear angle $\varphi$. Single pass AR with thickness reduction 60% leads to a high value of the shear angle, which is about 83 degrees, and it leads to extremely high equivalent strain, which is about $e \approx 4.2$ (Fig. 9). This corresponds to the analytical calculation of the equivalent strain during AR by the formula [8]:

$$
e = \frac{2}{\sqrt{3}} \sqrt{\left(\ln \frac{h_0}{h_1}\right)^2 + \frac{\tan^2 \varphi}{4}}$$

(3)

![Figure 8. Change of Lagrange's cells during AR.](image)

![Figure 9. Distribution of the equivalent strain in the workpiece during AR.](image)

If shear angle $\varphi = 0$, then formula (3) transforms into (2). This corresponds to a pure shear during symmetric rolling. If an initial thickness $h_0$ is equal to a final thickness $h_1$, then formula (3) transforms into (1). This corresponds to a simple shear during ECAP. The shape of Lagrange's cell after ECAP, SR and AR highlights the remarkable action of the shear strain developed by simple shear, pure shear, and simultaneous pure and simple shear.

Severe plastic deformation usually corresponds to the equivalent strain $e > 3$. This requires at least 3...4 passes of ECAP with a simple shear. A single pass asymmetric rolling with simultaneous pure and simple shear is preferable to ECAP with simple shear in developing of extremely high equivalent strain up to $e = 3...6$, when shear angle $\varphi$ is no less than 80º (Fig. 10).
4. Conclusions

Finite element simulation and comparison of the equivalent strain in the sample processed by a single-pass ECAP (simple shear), symmetric rolling (pure shear) and asymmetric rolling (simultaneous pure and simple shear), were performed. The non-linear effect of the rolls speed ratio on the deformation characteristics during asymmetric rolling was found. The equivalent strain has the maximum value when the rolls speed ratio $\Delta V$ is optimal. It was demonstrated that during a single-pass asymmetric rolling of a 1.0 mm thick aluminium alloy 5083 by work rolls of $D = 500$ mm with thickness reduction per pass $\varepsilon = 60\%$, friction coefficient 0.4 and rolls speed ratio $\Delta V = 57\%$ the extremely high shear strain and equivalent strain up to $\varepsilon=4.2$ can be reached. A single pass asymmetric rolling with simultaneous pure and simple shear is preferable to ECAP with simple shear in developing of extremely high equivalent strain, when shear angle $\varphi$ is no less than 80º. FE analysis of the deformation characteristics, presented in this study, can be used to optimize the asymmetric rolling process as SPD method to improve the microstructure and mechanical properties of metallic materials. Further experimental investigation of the microstructure evolution during asymmetric rolling is required.

Acknowledgments

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