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Influence of process parameters on distribution of shear strain through sheet thickness in asymmetric rolling

Pesin Alexander[1,a], Pustovoytov Denis[1,b]

[1] Nosov Magnitogorsk State Technical University,

38, pr. Lenin, Magnitogorsk, 455000, Russia

[a]pesin@bk.ru, [b]pustovoitov_den@mail.ru

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Abstract. Materials with ultrafine grain structure and unique physical and mechanical properties can be obtained by methods of severe plastic deformation, which include asymmetric rolling processes. Asymmetric rolling is a very effective way to create ultrafine grain structures in metals and alloys. Since the asymmetric rolling is a continuous process, it has great potential for industrial production of ultrafine grain structure sheets. Basic principles of asymmetric rolling are described in detail in scientific literature. Focus in the well-known works is on the possibility to control the structure of metal sheets. However the systematic data on the influence of the process parameters (e.g., ratio of rolls velocity mismatch, reduction per pass, friction and diameter of rolls), and the shear strain rate required to achieve a significant grain refinement in asymmetric rolling are lacking. The influence of ratio of rolls velocity mismatch, reduction per pass, friction and the rolls diameter on the distribution of shear strain through the sheet thickness in asymmetric rolling has been studied in DEFORM 2D. The results of the study will be useful for the research of evolution of ultrafine grain structure in asymmetric rolling.

Introduction

Ultrafine grain structure materials with unique physical and mechanical properties can be obtained through severe plastic deformation processes with asymmetric rolling among them. The asymmetric rolling is quite an efficient method of obtaining an ultrafine grain structure in metals and alloys. Since the asymmetric rolling is a continuous process, it possesses great potential for an industrial-scale manufacturing of sheet with ultrafine grain structure. The basic principles of asymmetric rolling are studied and presented extensively in scientific literature.

Asymmetry during rolling can be achieved due to different angular speeds, roll diameters, different friction conditions of the strip with the top and bottom rolls [1-4]. And many simulations and analytical studies have been done to these techniques [5-11].

It is well known that the mechanism of severe plastic deformation comes from its large equivalent strain, which is composed of compressive strain and additional shear strain. The shear deformation in asymmetric rolling was experimentally observed by Zuo et al [12]. Equivalent strain up to 3 was achieved in sample rolled to about 70%. Yet similar work has rarely been performed to asymmetric rolling, except that mentioned by Cui et al [13].

However the works and projects known to the authors of this paper lack the integrated data on influence of asymmetric rolling parameters (e.g., mismatch ratio of the roll velocities, reduction per pass, friction and diameter of rolls) on the shear strain values and their distribution through the sheet thickness.

This research presents the results of computational investigation of the influence of different parameters of asymmetric rolling on the shear strain distribution through the sheet thickness. The results of this research work will be useful for the analysis of ultrafine grain structure evolution of metal in asymmetric rolling.

1. Evaluation of equivalent strain during asymmetric rolling

Fig. 1 shows the scheme of asymmetric rolling process. The peripheral speed of bottom roll V_1 is higher than that of the top roll. The sheet is rolled through the gap between the top and bottom rolls and as a result the thickness is reduced from h_0 down to h_1. The deformation zone is defined by the area between the entrance and the exit. On the one hand the asymmetry factor results in reduction of negative influence of Coulomb friction forces and consequently in a possible increase of compression deformation during rolling; on the other hand additional shear strains are generated in the deformation zone.

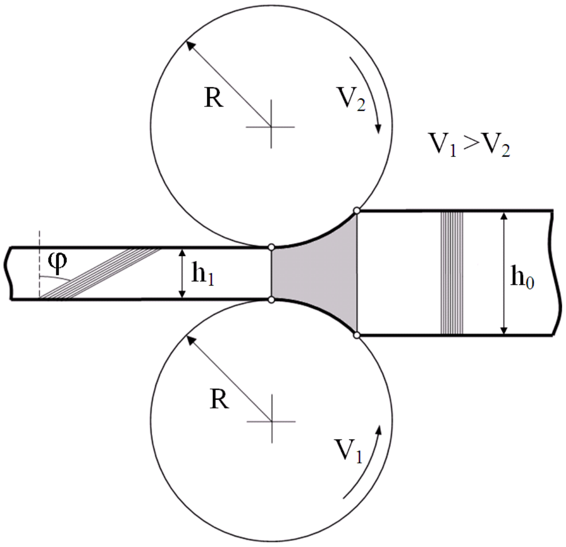

Fig. 1. Schematic illustration of asymmetric rolling

Equivalent strain ε_i can be calculated by the following equation:

$$\varepsilon_i = \sqrt{\frac{2}{3} e_{ij} e_{ij}}\ , \tag{1}$$

$$\varepsilon_i = \sqrt{\frac{2}{9}\left[(\varepsilon_{11}-\varepsilon_{22})^2+(\varepsilon_{22}-\varepsilon_{33})^2+(\varepsilon_{33}-\varepsilon_{11})^2+6\left(\varepsilon_{12}^2+\varepsilon_{23}^2+\varepsilon_{31}^2\right)\right]}, \tag{2}$$

$$\varepsilon_{11}=\varepsilon_x, \varepsilon_{22}=\varepsilon_y, \varepsilon_{33}=\varepsilon_z, \varepsilon_{12}=\frac{\gamma_{xy}}{2}, \varepsilon_{23}=\frac{\gamma_{yz}}{2}, \varepsilon_{31}=\frac{\gamma_{zx}}{2}\ , \tag{3}$$

$$\varepsilon_i = \sqrt{\frac{2}{9}\left[\left(\varepsilon_x-\varepsilon_y\right)^2+\left(\varepsilon_y-\varepsilon_z\right)^2+\left(\varepsilon_z-\varepsilon_x\right)^2+6\left(\frac{\gamma_{xy}^2}{4}+\frac{\gamma_{yz}^2}{4}+\frac{\gamma_{zx}^2}{4}\right)\right]}\ . \tag{4}$$

As asymmetric rolling is the plane-strain, that is

$$\varepsilon_x=-\varepsilon_y,\ \varepsilon_z=0,\ \gamma_{yz}=0, \gamma_{zx}=0\ . \tag{5}$$

Then Eq. (4) can be refined as

$$\varepsilon_i=\frac{1}{\sqrt{3}}\sqrt{4\varepsilon_y^2+\gamma_{xy}^2}\ . \tag{6}$$

Fig. 2 shows a schematic illustration of change in a single grid before and after asymmetric rolling.

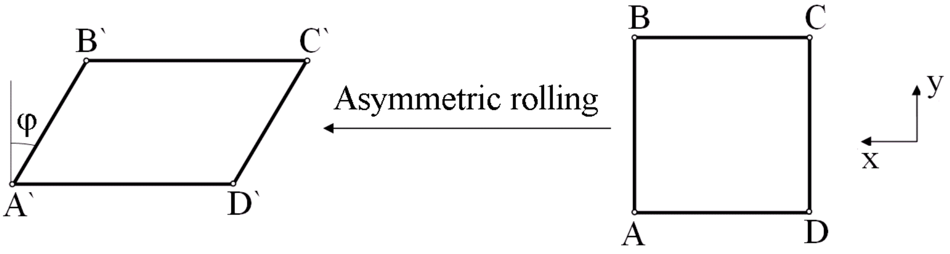

Fig. 2. Change in a single grid before and after asymmetric rolling

Square ABCD becomes shape A'B'C'D' after asymmetric rolling. The thickness of the square is reduced in y direction and the length is elongated toward x direction. In addition, angle $\angle$BAD, which was originally 90 degree, is decreased by a shear stress by φ angle. The strain components in y direction (ε_y) and shear strain component (γ_{xy}) can be calculated, respectively, as follows,

$$\varepsilon_y = \ln\frac{AB}{A`B`\cos\varphi}, \ \gamma_{xy} = tg\varphi . \qquad (7)$$

Eq. (6) represents the equivalent strain during asymmetric rolling (Fig. 3).

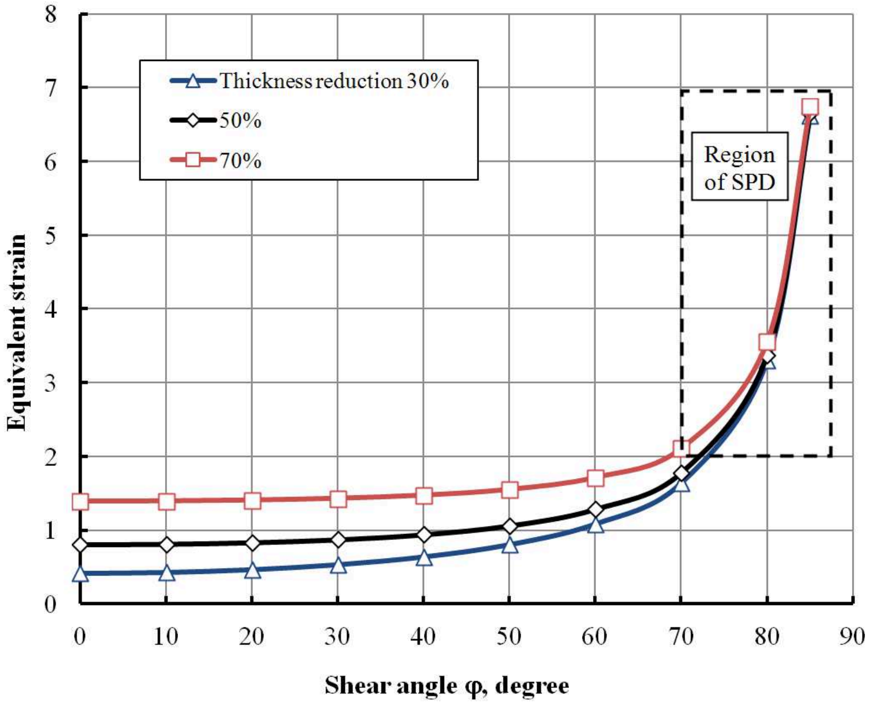

Fig. 3.Interrelation of shear angle φ and equivalent strain during asymmetric rolling

More detailed analyses of inhomogeneous distribution of equivalent and shear strain across sheet thickness were made by FEM simulation.

2. Finite element simulation

Commercial software DEFORM-2D, based on finite element method (FEM), was used to analyze asymmetric rolling process.

In the course of simulation the following assumptions were made: 1) plane strain of metal; 2) deformed medium – hardened rigid-plastic material; 3) work rolls – absolutely rigid; 4) conditions of deformation – isothermal.

A Coulomb friction model was used between rolls and workpiece which assumes that no relative motion occurs if the equivalent frictional stress is less than a critical value. The friction coefficient was calibrated by experimental tests and FEM simulations.

Pure aluminum DIN-Al-99.7 from DEFORM-2D data base was chosen as a material for simulation.

The initial data varied within the following ranges: 1) friction coefficient on the contact with the top and bottom rolls $\mu = 0.08 \ldots 0.32$; 2) work roll radius R = 50…200 mm; 3) mismatch factor of roll velocities $K_v = 1.00 \ldots 3.33$ (Eq. 8); 4) reduction per pass $\varepsilon = 30 \ldots 70\%$.

Peripheral speed of the bottom roll in all calculation variants was set constant, equal to $V_1 = 1000$ mm/sec; peripheral speed of the top roll was reduced by K_v times.

$$K_v = V_1/V_2\text{, where } V_1 > V_2. \tag{8}$$

In the course of simulation of asymmetric rolling process the influence of the process parameters on distribution of shear strain γ_{xy} through the sheet thickness was studied (Fig.4).

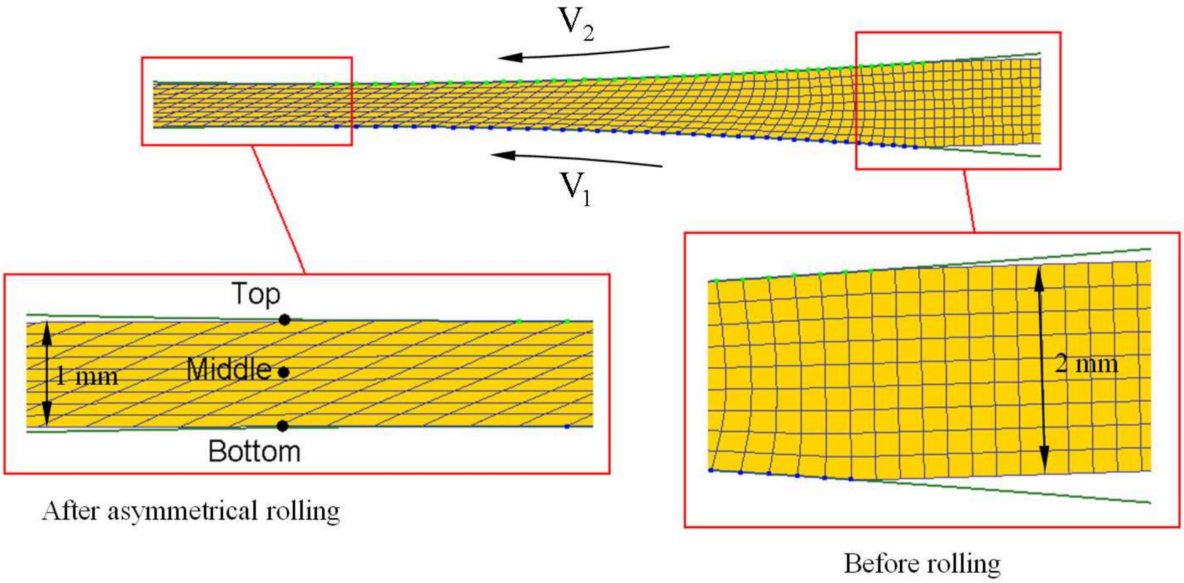

Fig. 4. Lagrange grid before and after the asymmetric rolling (R = 200 mm, $\mu = 0.32$, $h_0 = 2$ mm, $\varepsilon = 50\%$, $K_v = 2.00$)

3. Results and discussion

3.1. Influence of friction coefficient

The higher the friction coefficient, with all other conditions being equal, the greater is the shear strain (Fig. 5). Thus at $\mu = 0.08$ the maximum shear strain γ_{xy} does not exceed 0.3, at $\mu = 0.16$ – it is not more than 0.9, and at $\mu = 0.32$ – equals 2.2. It should be noted that homogeneous distribution of shear strain across the whole cross-section of the sheet can be obtained only with a high value of friction coefficient ($\mu = 0.32$).

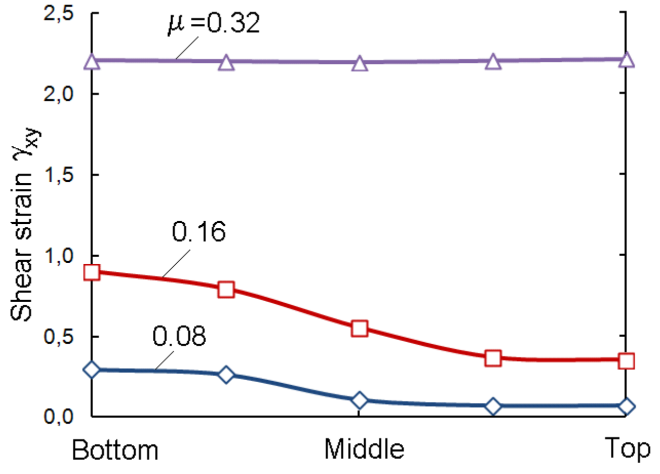

Fig. 5.Influence of friction coefficient on distribution of shear strain through the sheet thickness (R = 200 mm, h_0 = 2 mm, ε = 50%, K_v = 2.00)

3.2. Influence of roll radius

The less the roll radius, the lower is the shear strain across the sheet cross-section; at that inhomogeneous distribution is getting higher (Fig. 6).

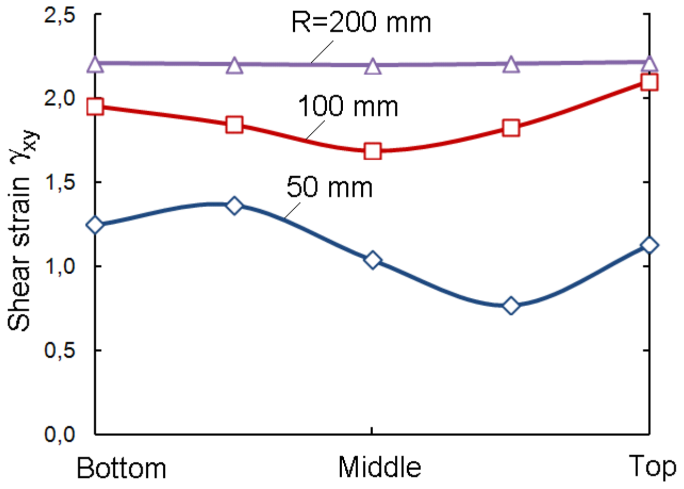

Fig. 6. Influence of roll radius on distribution of shear strain through the sheet thickness (μ = 0.32, h_0 = 2 mm, ε = 50%, K_v = 2.00)

3.3. Influence of roll velocities mismatch coefficient

During symmetric rolling (K_v = 1.00) the maximum shear strain can be observed on the top and bottom contact surfaces of the sheet, but in the center it equals zero. Increase of the roll velocities mismatch contributes to leveling of shear strain distribution across the whole cross-section of the sheet (Fig. 7). As it seen from Fig. 7, at K_v = 2.00 the value of shear strain varies across the cross-section within a very narrow range from 2.20 to 2.22.

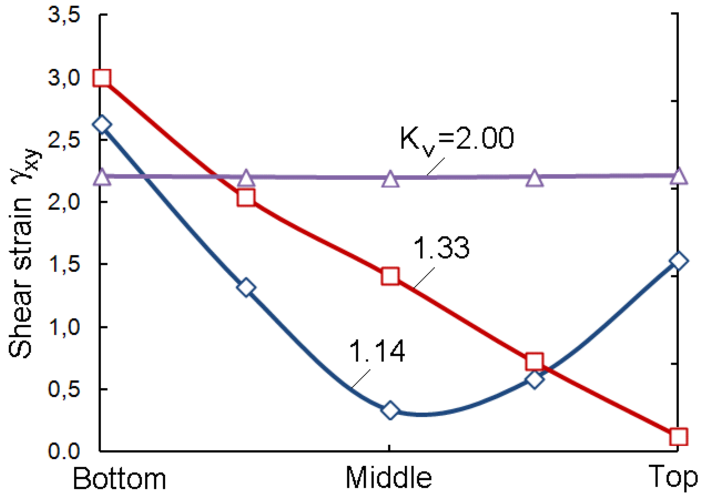

Fig. 7. Influence of roll velocities mismatch ratio on distribution of shear strain through the sheet thickness (R = 200 mm, μ = 0.32, h_0 = 2 mm, ε = 50%)

3.4. Influence of reduction per pass

Very high values of the shear strain can be achieved by means of combination of significant reduction (ε ≥ 50%) and velocities mismatch with (K_v ≥ 2.00). In this way the shear strain at ε = 70% and K_v = 3.33 can achieve 10 (Fig. 8). At that the value of equivalent strain amounts to 5.94 in accordance with formula (6):

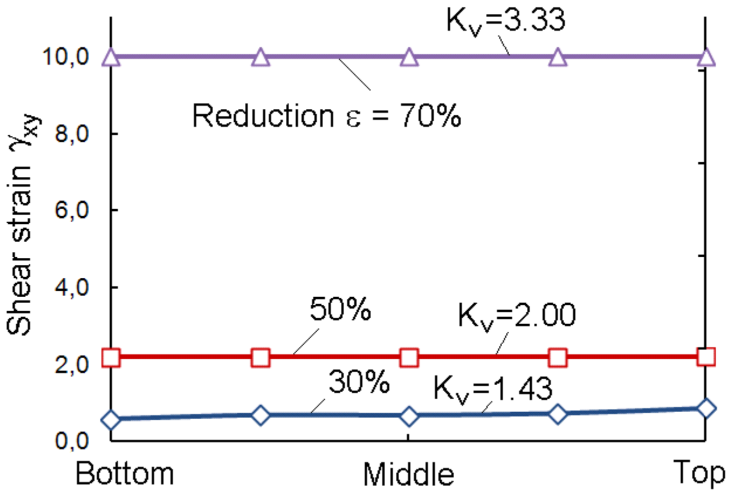

Fig. 8. Influence of reduction per pass on shear strain distribution through the sheet thickness (R = 200 mm, μ = 0.32, h_0 = 2 mm)

4. Conclusions

Shear deformation of pure aluminum during asymmetrical rolling process was investigated using two dimensional finite elements simulation. It was demonstrated that during rolling of a 2.0 mm thick pure aluminum sheet (acc. to DIN-Al-99.7) by work rolls of R = 200 mm with asymmetry ratio K_v = 3.33, reduction ε = 70% and friction coefficient μ = 0.32 the shear strain can achieve 10, and equivalent strain – 5.94. The results of this research work will be useful for the analysis of ultrafine grain structure evolution of metal in asymmetric rolling.

Acknowledgements

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