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FINITE ELEMENT SIMULATION OF SHEAR STRAIN IN VARIOUS ASYMMETRIC COLD ROLLING PROCESSES

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Abstract. Materials with ultrafine grain structure and unique physical and mechanical properties can be obtained by severe plastic deformation methods including the asymmetric rolling processes. Asymmetric rolling is a very effective way to generate ultrafine grain structures in steels, magnesium alloys and other materials. Since the asymmetric rolling is a continuous process, it has great potential for industrial production of ultrafine grain structure sheets and bars. 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. This study reflects the investigation findings regarding the impact of speed asymmetry on shear strain during rolling of sheet and bars in the three-roll passes. Numerical comparison of shear strain ratios in case of symmetric and asymmetric rolling is made in this study. Adequacy of the developed models is demonstrated. The results of this research work will be useful for the analysis of ultrafine grain structure evolution of metals in various asymmetric cold rolling processes.

Keywords: asymmetric rolling, finite element method, shear strain, severe plastic deformation

1. Introduction

Materials with ultrafine grain structure and unique physical and mechanical properties can be obtained by methods of severe plastic deformation (SPD), with asymmetric rolling processes among them. The basic principles of asymmetric rolling are studied and presented extensively in academic literature (Pesin et al., 2000, 2002, 2003). Asymmetric rolling is a very effective way to generate ultrafine grain (UFG) structures in steels (Lee et. al., 2010), magnesium alloys (Chang et al., 2011) and other materials. Since the asymmetric rolling is a continuous process, it has great potential for industrial production of ultrafine grain structure materials (Weijun Xia et. al., 2009).

It is well known that the mechanism of SPD comes from its large equivalent strain, which is composed of compressive strain and additional shear strain. Zuo et al. (2008) experimentally observed the shear strain during asymmetric rolling. Effects of reduction ratio and speed ratio on the shear strain have been studied. It has been found out that with speed ratio of 1.5 the shear strain ratio is the lowest one, and the shear deformation ratios of 1.27 and 2.1 are comparable.

Many works have studied the shear strain during asymmetric rolling by using finite element method (FEM). Ji et al. (2007) investigated deformation mechanics of differential-speed rolling with a high speed ratio between the top and the bottom rolls by rigid-plastic FEM. It has been found out that the shear strain takes a great portion of the total effective strain (~3.5) in average. Sverdlik et al. (2013) has demonstrated that during asymmetric rolling shear strain along the strip cross-section increase more than 9 times in comparison with symmetric rolling. Ji and Park (2009) have analyzed various asymmetric rolling processes by the rigid-viscoplastic FEM. The findings of the numerical simulation have revealed that differences in size, rotational speed or friction condition between the top and the bottom rolls can cause asymmetric deformation in the sheet. Shear strain is more severe in the lower layer, where the diameter, rotational speed or friction factor is greater than in the upper layer. Kim et al. (2011) has analyzed the effect of speed ratio on the development of shear deformation and texture during differential speed rolling. FEM simulation results have shown that the effective strain accumulated during asymmetric rolling increases with high speed ratio. Angella et al. (2013) has researched the strain distribution developed during asymmetric and symmetric rolling with a large number of passes. FEM results have demonstrated that surface strain effects related to local friction between working rolls and sample surface regions promote an additional deformation leading to a significant contribution at large plastic strain and generate discrepancies between equivalent strain values assessed by continuum theories and those evaluated by FEM models. Saeed Tamimi et al. (2014) have investigated the impact of process parameters on the onset and growth of shear strain throughout the thickness of sheet samples by finite element simulations. In accordance with the FEM predictions, the experimental results have shown that the shear strain spread throughout the thickness of sheet samples during asymmetric rolling and developed the shear texture.

This study reflects the investigation findings regarding the impact of speed asymmetry on shear strain during rolling of sheet and bars in three-roll passes. Shear strain values in case of symmetric and asymmetric rolling are numerically compared in this work. Adequacy of the developed models is demonstrated. The results of this research work will be useful for the analysis of ultrafine grain structure evolution of metal in various asymmetric cold rolling processes.

2. Simulation of asymmetric rolling

2.1. Asymmetric sheet rolling

Fig. 1 shows the scheme of asymmetric sheet rolling process. The circumferential speed of bottom roll V_1 is higher than that of the top roll. The sheet is rolled throughout 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. Speed asymmetry coefficient during the sheet rolling process:

$$K_v = \frac{V_1}{V_2}, \text{ where } V_1 > V_2, \quad (1)$$

where K_v – speed asymmetry coefficient between the top and the bottom rolls; V_1, V_2 – circumferential speed of the rolls.

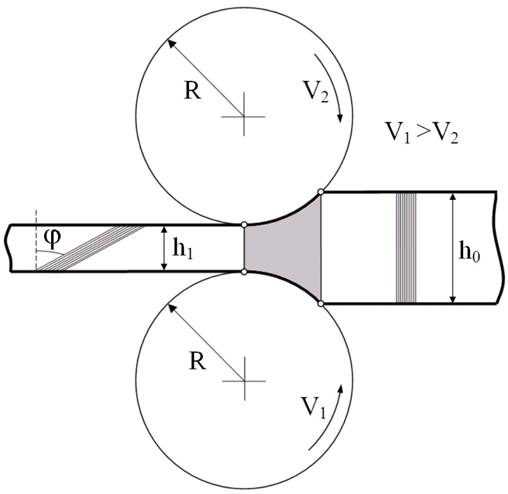


Fig. 1. Schematic illustration of asymmetric sheet rolling

Equivalent strain ε_i can be calculated by the following equation:

$$\varepsilon_i = \sqrt{\frac{2}{3} e_{ij} e_{ij}}, \quad (2)$$

$$\varepsilon_i = \sqrt{\frac{2}{9}\left[(\varepsilon_{11}-\varepsilon_{22})^2 + (\varepsilon_{22}-\varepsilon_{33})^2 + (\varepsilon_{33}-\varepsilon_{11})^2 + 6(\varepsilon_{12}^2 + \varepsilon_{23}^2 + \varepsilon_{31}^2)\right]}, \quad (3)$$

$$\varepsilon_{11} = \varepsilon_x, \varepsilon_{22} = \varepsilon_y, \quad \varepsilon_{33} = \varepsilon_z, \varepsilon_{12} = \frac{\gamma_{xy}}{2}, \quad \varepsilon_{23} = \frac{\gamma_{yz}}{2}, \varepsilon_{31} = \frac{\gamma_{zx}}{2}, \quad (4)$$

As asymmetric sheet rolling is the plane-strain, that is

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

Then Eq. (3) can be refined as

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

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

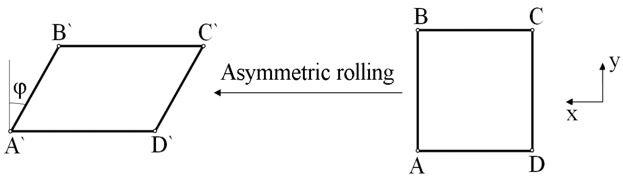


Fig. 2. Change in a single grid before and after asymmetric sheet rolling

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 towards "x" direction. In addition angle $\angle BAD$, which was originally 90 degrees, is decreased by a shear stress by φ angle. The shear strain component (γ_{xy}) can be calculated, respectively, as follows,

$$\gamma_{xy} = \operatorname{tg}\varphi. \quad (7)$$

Eq. (7) represents the shear strain during asymmetric sheet rolling. More detailed analyses of irregular distribution of shear strain across sheet thickness have been carried out by FEM simulation.

2.2. Finite element simulation of asymmetric sheet rolling

Commercial software DEFORM 2D/3D, based on FEM, was used to analyze asymmetric sheet rolling process. In the course of simulation the following assumptions were made: 1) plane strain of metal; 2) material under deformation – hardened rigid-plastic material; 3) work rolls – absolutely rigid; 4) conditions of deformation – isothermal. A Coulomb friction model was used between rolls and metal bar which assumes that no relative motion occurred if the equivalent frictional stress was less than a critical value. The friction coefficient was calibrated by experimental tests and FEM simulations. Friction coefficient μ was equal to 0.24.

The material of the sheet was CuZn5 and the yield stress at 20°C was set by

$$\sigma = 109 + 26.7\varepsilon^{0.64}, \quad (8)$$

where σ was the yield stress and ε was the effective strain.

Rolling was carried out with rolls of 100 mm in diameter. The circumferential speed of the rolls was set at V_2=0.2 m/sec. Speed asymmetry coefficient was set at K_v = 1.0; 1.16; 2.0. In the course of simulation of asymmetric sheet rolling process the influence of the speed asymmetry coefficient on distribution of shear strain γ_{xy} throughout the sheet thickness was studied. The strain was cold rolled to achieve final 70% thickness reduction in three passes **(Table 1)**.

Table 1

Pass schedule

Pass No.	0	1	2	3
Thickness, mm	0.80	0.42	0.32	0.24
Reduction, %	0	47.5	23.8	25.0

Fig. 3 shows the flow net and distribution of shear strain throughout the strip thickness after cold rolling to 70% of thickness reduction with the different values of the speed asymmetry coefficient K_v. Shear strain is distributed irregularly throughout the cross section of the strip in all cases of rolling. In case of symmetric rolling (K_v=1.0) the shear strain is maximum (~0.9) on the top and bottom surfaces of the strip. In the middle of the strip the shear strain during symmetric rolling is zero **(Fig. 3d)**. The larger the speed asymmetry coefficient the higher the shear strain is, particularly on the bottom surface of the strip where the roll has faster circumferential speed. With K_v=1.16 the shear strain of the bottom surface of the strip is ~1.6, and with K_v=2.0 the shear strain is equal to ~3.1 **(Fig. 3d)**. For verification of the numeric modeling results the following experimental analysis has been carried out.

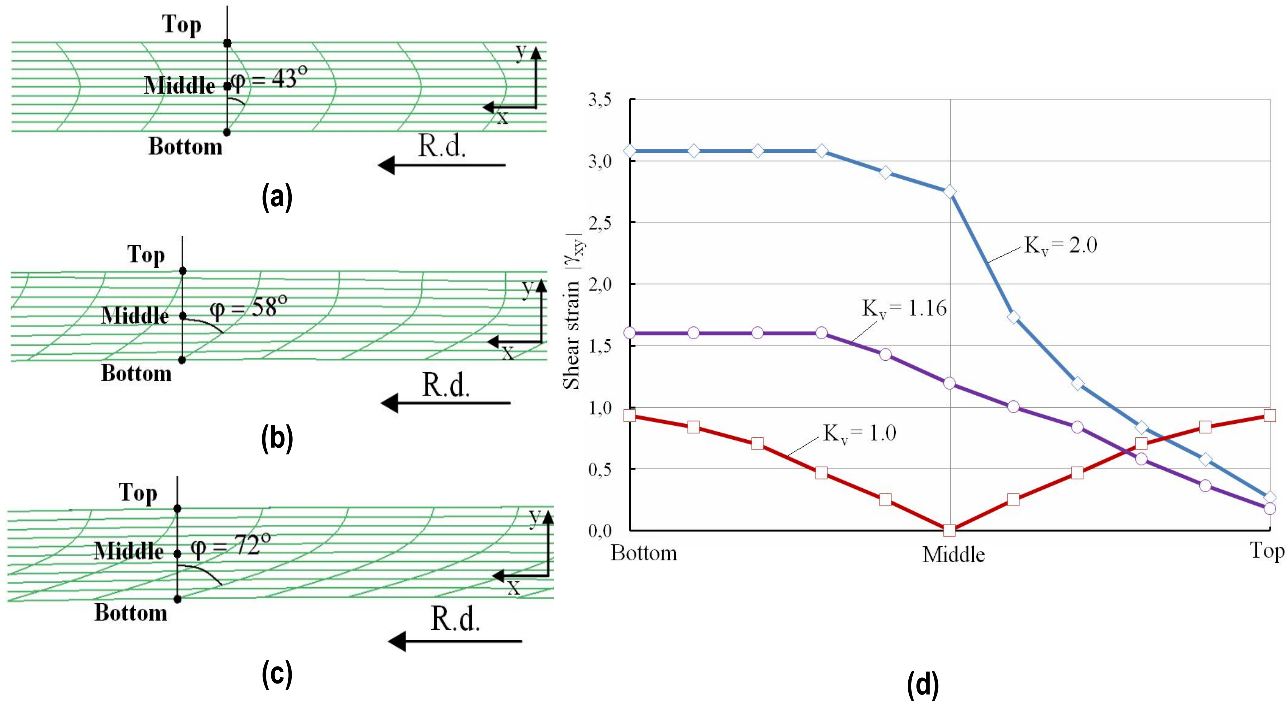


Fig. 3. Flow net after cold rolling to 70% of thickness reduction with the value of speed asymmetry coefficient K_v = 1.0 (a), K_v = 1.16 (b), K_v = 2.0 (c) and distribution of shear strain throughout the strip thickness (d) (R.d. – rolling direction)

2.3. Experimental details and discussion

The study was carried out on CuZn5 samples with dimensions of 0.8×30×150 mm (thickness×width×length). The material was cold rolled to a final 70% thickness reduction in three passes **(Table 1)**. Rolling was performed on a laboratory mill **(Fig. 4a)**, in which the working rolls had equal diameters of 100 mm. Rolling was carried out at constant circumferential speed of the bottom roll maintained at 0.2 m/sec, and with the variable velocity of the top one. No lubrication was introduced to the rolls. The following values of the speed asymmetry coefficient R_v were applied: $R_v = 1.0$ – symmetric rolling with equal speed of both rolls; $R_v = 1.16$ and $R_v = 2.0$ – asymmetric rolling, in which the circumferential speed of the bottom roll is, respectively 1.16 and 2.0 – times more than the speed of the top one.

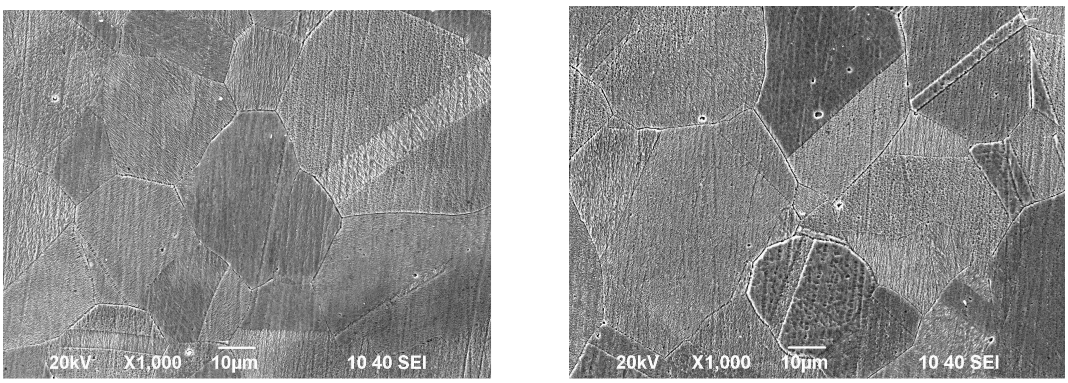
Speed asymmetry was generated by means of replaceable gear wheels **(Fig. 4b)** of the pinion stand of the rolling mill main line. The drive pinion gear having 25 teeth was mounted on the driving shaft. The replaceable gear wheels having 29 and 50 teeth were mounted on the driven idle shaft.

The microstructures of the samples before **(Fig. 5)** and after cold rolling **(Fig. 6)** were examined with a scanning electron microscope (SEM, JSM-6490LV) at accelerating voltage of 20 kV. The research was carried out with microslices used for optical microscopy in secondary and reflected electron modes with 5000 magnification.

Examination of the structure throughout the cross section of the strip was carried out in accordance with the scheme **(Fig. 3)**. The analysis showed that the metal structure throughout the cross section of the strip is inhomogeneous. It was explained by irregular distribution of shear strain across the thickness. In case of symmetric rolling ($K_v = 1.0$) in the middle of the strip there were no signs of UFG structure formation **(Fig. 6b)** due to the absence of shear strain in this zone. In its turn in case of asymmetric rolling the grain fragmentation took place down to ~1.0 μm along with speed asymmetry coefficient increase, in particular at $K_v = 2.0$ At that the greatest effect was achieved on the bottom surface of the strip **(Fig. 6i)**, i.e. in that part of the strip where the shear strains were maximum **(Fig. 3c)**. Thus the microstructure modification throughout the cross section of the strip was in accordance with the results of the numerical modeling of shear strain distribution across the thickness.

(a) **(b)**

Fig. 4. Laboratory mill (a) and replaceable gear wheels (b)



(a) **(b)**

Fig. 5. SEM micrographs of bottom surface (a) and middle (b) of the sample CuZn5 at the annealed condition

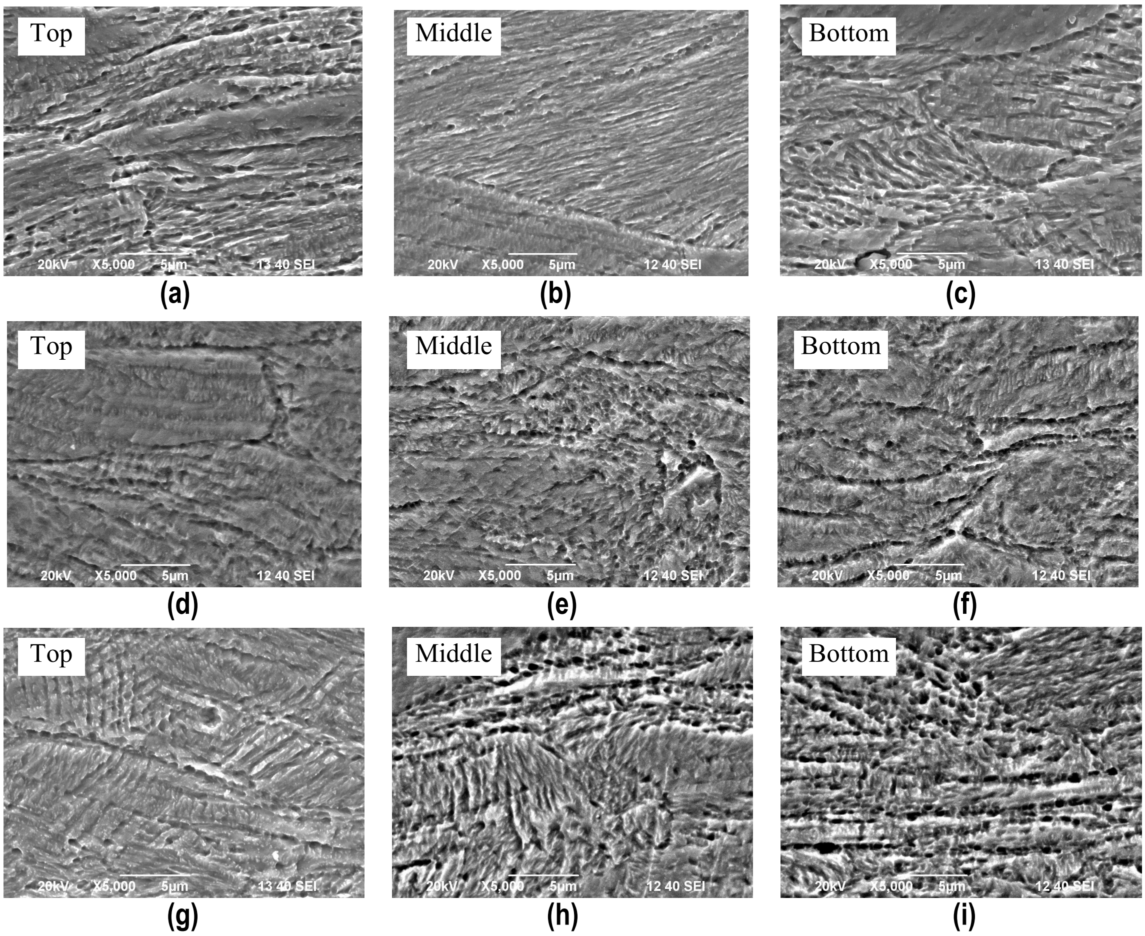


Fig. 6. SEM micrographs of CuZn5 after rolling to 70% of thickness reduction with the value of the speed asymmetry coefficient K_v = 1.0 (a, b, c), K_v = 1.16 (d, e, f), K_v = 2.0 (g, h, i)

The mechanical properties of the samples before and after cold rolling were investigated by uniaxial tensile test using an AG IC Shimadzu universal testing machine equipped with a 50 kN load cell. The tests were computer controlled registering strain and stress **(Fig. 7)**. Tensile samples with a gauge section measuring 30 mm in width and 100 mm in length were cut from the strips along the rolling direction. Tensile tests were carried out at room temperature and a constant cross-head speed of 2 mm/min, which was equivalent to a strain rate of 3.3×10^{-4} s^{-1}.

The quantitative characteristics of the curves in **Fig. 7** are described in Table 2. The analysis of the mechanical test results revealed that with augmentation of speed asymmetry coefficient K_v from 1.0 up to 2.0 the strength properties of CuZn5 got better and plastic properties remained unchanged (Table 2). In particular the yield strength (YS) increased from 478 MPa (at K_v = 1.0) up to 567 MPa (at K_v = 2.0), and the ultimate tensile strength (UTS) increased from 509 MPa (at K_v = 1.0) up to 603 MPa (at K_v = 2.0). In case of symmetric and asymmetric rolling with total reduction of 70% the uniform elongation and elongation to failure were extremely low and did not exceed 2% **(Table 2)**.

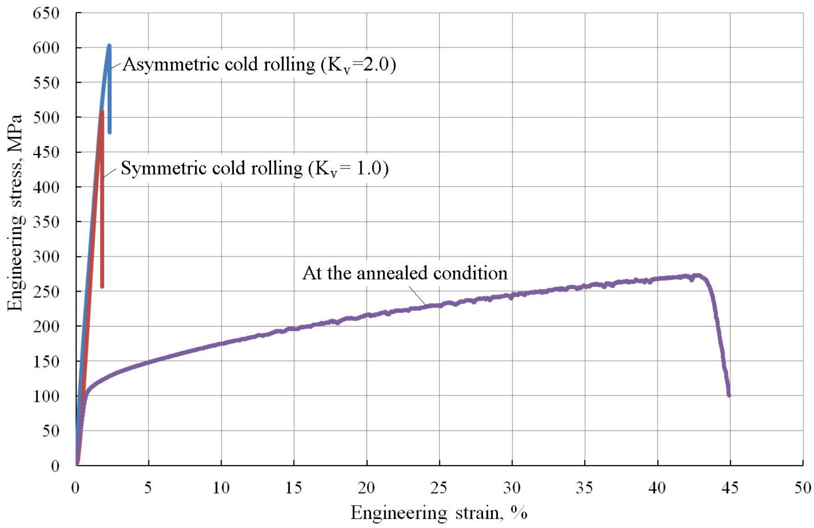


Fig. 7. Engineering stress-strain curves of the samples processed under various conditions

Table 2

Quantitative characteristics of the tensile stress-strain curves in Fig. 7

Conditions	Mechanical properties			
	UTS (MPa)	YS (MPa)	Uniform elongation (%)	Elongation to failure (%)
At the annealed condition	273	109	41	45
After symmetric cold rolling to 70% of thickness reduction with the value of the speed asymmetry coefficient K_v = 1.0	509	478	1.30	1.99
After asymmetric cold rolling to 70% of thickness reduction with the value of the speed asymmetry coefficient K_v = 2.0	603	567	1.36	1.88

Therefore the results of calculation and of the experiment show that the suggested mathematical model is appropriate.

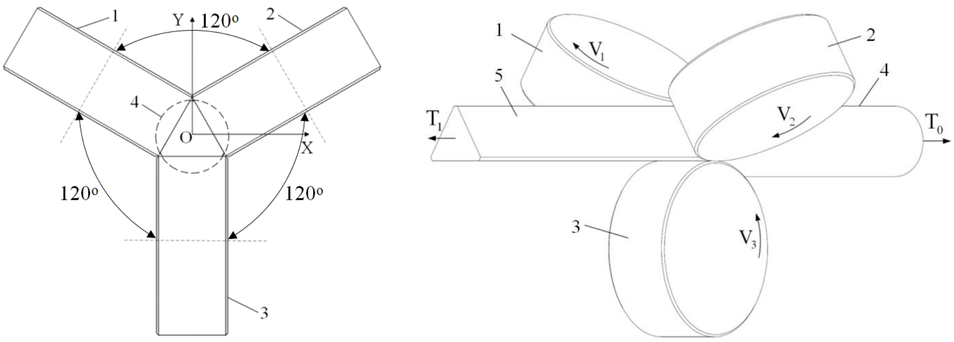
2.4. New method of asymmetric rolling of metal bars in the three-roll pass

In order to get high-strength metal materials with ultrafine grain structure there has been developed an original way of asymmetric rolling in the three-roll pass with additional shear strain due to work roll speed asymmetry (Fig. 8). Speed asymmetry coefficient in the three-roll pass:

$$K_v^{1-2} = \frac{V_1}{V_2},\ K_v^{2-3} = \frac{V_2}{V_3},\quad K_v^{1-3} = \frac{V_1}{V_3},\ \text{where } V_1 = V_2 > V_3, \tag{9}$$

where $K_v^{1-2}, K_v^{2-3}, K_v^{1-3}$ – speed asymmetry coefficient between work rolls 1 and 2, 2 and 3, 1 and 3, correspondingly; V_1, V_2, V_3 – circumferential speeds of rolls.

At the indicated conditions in the contact areas between the metal bar and rolls 1 and 2 the backward creep zone gets longer where the direction of tangential friction forces is along the metal bar movement. In its turn in the contact area between the metal bar and roll 3 the forward creep zone gets longer where the direction of tangential friction forces is opposite the metal bar movement. Thus in the deformation zone the oppositely directed tangential friction forces generate additional shear strains with shear angle φ **(Fig. 9)**. The tangent of this angle is the characteristic of shear strain.



(a) (b)

Fig. 8. Arrangement of rolls (a) and the scheme of asymmetric rolling in the three-roll pass (b) (1, 2, 3 – work rolls; 4 – original bar; 5 – resulting triangle section)

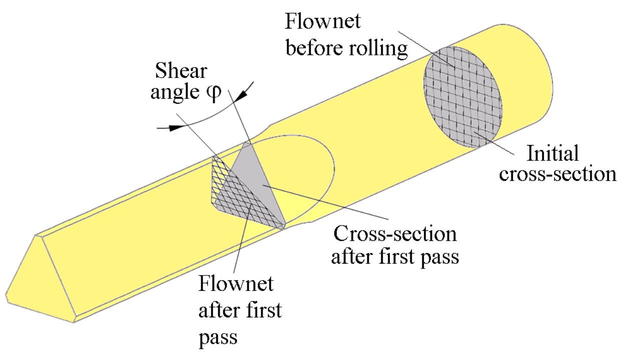


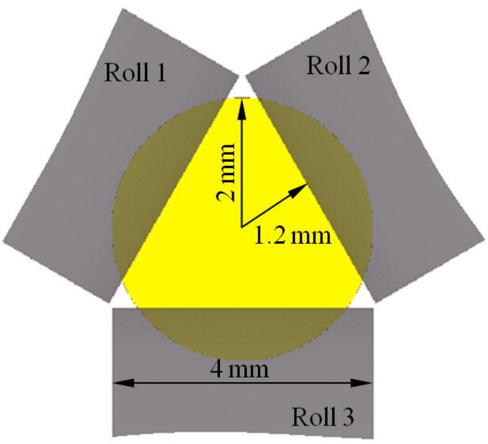
Fig. 9. Schematic illustration of shear angle φ during asymmetric rolling in the three-roll pass

2.5. Finite element simulation of asymmetric rolling in the three-roll pass

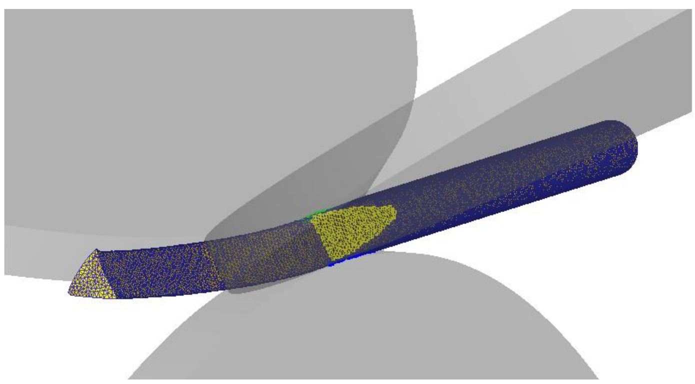
A commercial software DEFORM 2D/3D was used to analyze asymmetrical rolling process in the three-roll pass. A CuZn5 round bar with radius of r=2mm **(Fig. 10)** (see formula 8) was used as an original bar. Rolling was performed with smooth rolls having the roll body of R=180 mm. The circumferential speed of roll 3 was set equal to V_3=1.0 m/sec. Speed asymmetry coefficient were set equal: $K_v^{1-2} = 1.0$, $K_v^{2-3} = K_v^{1-3} = 1.0...1.7$. Coulomb friction law was used. The friction coefficient μ when the metal bar contacted the work rolls varied within the range of 0.12…0.36. The front tension T_1 = 60 MPa, the back tension T_0 = 30 MPa. To approximate the geometric parameters of the bar, tetrahedral elements were used. Rolling process was carried out with high elongation ratio per pass: $\frac{S_0}{S_1} = 1.7$, where S_0 is the cross section area of the bar prior to deformation; S_1 is the cross section area of the bar after the deformation. This elongation ratio corresponds to the reduction ratio 41.2%. In the course of simulation the impact of speed asymmetry on shear strain was assessed during rolling of the bar in the three-roll pass as per round-triangle scheme. The shear strain was assessed as per the value of shear angle φ.

In case of symmetric rolling (K_v^{1-3}=1.0) of the bar in the three-roll pass the shear angle φ is zero **(Fig. 11a)**. In its turn during asymmetric rolling the material undergoes significant shear strain. The maximum value of the shear angle φ = 48° **(Fig. 11b)** is achieved with the speed asymmetry coefficient of K_v^{1-3}=1.7 and high value of the friction coefficient μ = 0.36. The explanation is that the additional shear strain during asymmetric rolling in the three-roll pass is generated by oppositely directed tangential friction forces in the deformation zone. That is why the ratio of the shear strain significantly increases along with simultaneous augmentation of the speed asymmetry coefficient and contact friction coefficient. However it should be noted that distribution of shear strain throughout the cross section of the bar is irregular. The maximum shear strain appears on the contact surface between the bar and roll 3 having the lowest circumferential speed. The value of shear angle φ = 48° achieved during the asymmetric rolling in three-roll pass by one deformation pass with reduction ratio of 41.2% is well in accordance with the values achieved during equal-channel angular pressing per one pass (Furukawa et al., 2001).

Fig. 12 illustrates interrelation between the shear angle φ, speed asymmetry coefficient K_v^{1-3} and contact friction coefficient μ. During asymmetric rolling in the three-roll pass the shear strain φ increases from 0 up to 48 degrees that is equivalent to shear strain 1.1. Thus the findings of the research carry inference that the asymmetric rolling process in the three-roll pass can be utilized as an SPD method for manufacturing of plain long bars with UFG structure.



(a)



(b)

Fig. 10. Dimensions of the bar and rolls (a) and finite element model (b)

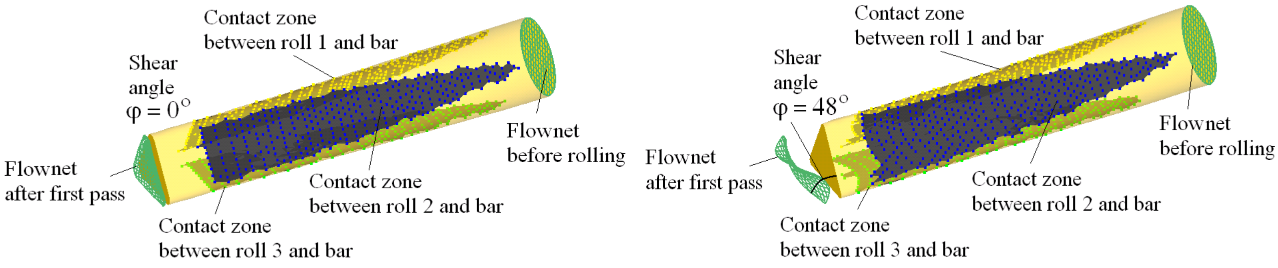


Fig. 11. Shear angle φ during symmetric (a) and asymmetric (b) rolling in three-roll pass

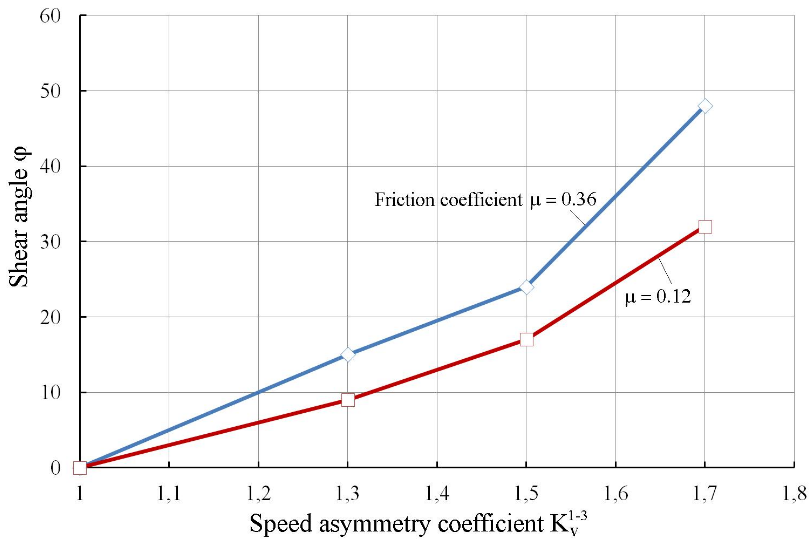


Fig. 12. Influence of the speed asymmetry coefficient K_v^{1-3} on the shear angle φ during asymmetric rolling in the three-roll pass

One of the problems of asymmetric rolling in the three-roll pass is bending of the bar at the exit from the deformation zone what makes its threading into the next pass more difficult. The solution of this problem can be utilization of special twin stands with individual work roll drive enabling installation of subsequent three-roll passes as close to each other as possible (Tkachenko et al., 2012). Further investigation of the shear strain and microstructure evolution during deformation of metal in the three-roll pass is required.

3. Conclusions

In case of symmetric rolling (K_v = 1.0) with total reduction of 70% the shear strain is zero in the middle of the strip and maximum (~0.9) on the bottom and top surfaces of the strip. The larger the speed asymmetry coefficient the higher the shear strain is, particularly on the bottom surface of the strip where the roll has faster circumferential speed. With K_v=1.16 the shear strain on the bottom surface is ~1.6, and with K_v=2.0 the shear strain is ~3.1. After cold rolling CuZn5 structure throughout the cross section of the strip is irregular what is explained by irregular distribution of shear strain across the thickness. In case of symmetric rolling there are no signs of UFG structure formation in the middle of the strip due to the absence of shear strain in this zone. During asymmetric rolling the grain fragmentation takes place down to ~1.0 μm along with speed asymmetry coefficient increase. A new method of asymmetric rolling of bars in the three-roll pass is suggested. On the basis of the finite element simulation it is stated that with reduction ratio of 41.2% in the course of increase of speed asymmetry coefficient K_v^{1-3} from 1.0 up to 1.7 and along with the friction coefficient increase from 0.12 up to 0.36 the shear angle φ grows from 0 up to 48 degrees what is equivalent to shear strain 1.1. This new method can be utilized as an SPD method for manufacturing of plain long bars with UFG structure.

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ИНФОРМАЦИЯ О СТАТЬЕ НА РУССКОМ ЯЗЫКЕ

КОНЕЧНО-ЭЛЕМЕНТНОЕ МОДЕЛИРОВАНИЕ СДВИГОВЫХ ДЕФОРМАЦИЙ В РАЗЛИЧНЫХ ПРОЦЕССАХ АСИММЕТРИЧНОЙ ПРОКАТКИ

Песин А.М., Пустовойтов Д.О., Корчунов А.Г., Ванг К., Танг Д., Ми Ж.

Аннотация. Материалы с ультрамелкозернистой структурой и уникальными физическими и механическими свойствами могут быть получены с использованием методов интенсивной пластической деформации. Асимметричная прокатка является одним из наиболее эффективных способов получать такую структуру в сталях, сплавах магния и в других материалах. В настоящей работе приведены результаты исследования влияния скоростной асимметрии на сдвиговые деформации при листовой прокатке и прокатке в многовалковых калибрах.

Ключевые слова: асимметричная прокатка, конечно-элементное моделирование, сдвиговая деформация, интенсивная пластическая деформация.