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Finite element modeling of shear strain in rolling with velocity asymmetry in multi-roll calibers

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Abstract

Severe plastic deformation is now recognized the most efficient way of producing ultrafine grained metals and alloys. At the present time a lot of severe plastic deformation methods have been proposed and developed. They differ in the deformation schemes. Unlike such severe plastic deformation methods as high pressure torsion and equal- channel angular pressing, rolling with the velocity asymmetry is a continuous process. It helps to solve the problem of the limited length of manufactured bars with semi ultrafine structure. Rolling process with roll velocity asymmetry generates high shear strain necessary for obtaining ultrafine structures of the processed material. A new process of asymmetric rolling of profiles in multi-roll passes has been developed. This process can be used for production of high-strength profiles such as circles, hexagons, wire rods, etc. Compression of the bar in multi-roll passes can be done not only from two, as usual, but from three or four sides. In case of a multi-crimped bar, a uniform compression scheme with large hydrostatic pressure is created in the deformation zone. It enhances the ductility of the material and allows increasing the strain intensity. Simulation in DEFORM 3D^{TM} proved that the process of asymmetric rolling in multi-roll calibers allows to obtain higher values of shear strain and strain effective.

Introduction

The last two decades saw dynamic development of severe plastic deformation methods, which are one of the most state-of-the-art and economically feasible ways of obtaining high mechanical properties of metals and alloys. The methods of severe plastic deformation enable deriving ultrafine grain materials with the grain size of less than 1000 nm. Such changes in structure result in significant improvement of strength; it gets almost 2.0-2.5 times higher in pure metals and increase by 40-80% in alloys; this fact allows considerably expand the range of such materials application in various industrial sectors.

The efficiency of severe plastic deformation methods in terms of formation of ultrafine grain structures depends on the deformation value, transmitted to the metal during processing prior to its destruction, on the thermal and velocity conditions of deformation and hydrostatic pressure, on the path of loading (monotone, non-monotone, sign-variable), as well as on the strain rate gradient.

Despite this great variety of methods the development of severe plastic deformation technologies for industrial application and particularly for commercial product manufacturing is a complicated scientific and technical problem. To solve this problem it is required to develop so called “continuous schemes” of severe plastic deformation. The continuous scheme of severe plastic deformation is a high-productive process where a long bar is subject to severe plastic deformation, i.e. in the deformation scheme there are no fundamental limits for the length of the processed bar, neither structural, nor technological.

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To date certain progress has been made in this area. First of all it covers manufacturing of long ultrafine grain bars in renovated facilities for equal-channel angular pressing, for instance, those based on CONFORM scheme. Between the central roll and a stationary holder-up there is a groove where the bar is loaded. Friction forces occur between the bar and the rotating roll thus making the bar move following the rotating roll. The stationary holder-up directs the bar to the horizontal channel there the bar material is exposed to shear strain. However the continuous equal-channel angle pressing based on CONFORM scheme can deform the bars of not longer than 3m only and has some technological limitations.

One of the most advanced methods of severe plastic deformation for manufacturing of long ultrafine grain metal products is the asymmetric rolling process based on the purposefully generated asymmetry due to the mismatch of the work roll velocities, difference between the diameters of the work rolls, contact friction conditions, etc. [1-10]. Asymmetric rolling processes belong to the severe plastic deformation methods and have some fundamental characteristics required for obtaining ultrafine grain structures in long metal products, such as: 1) realization of high shear strain in each process cycle; 2) high level of accumulated deformation; 3) significant non-monotone deformation; 4) realization of high compressive stress in the deformation zone; 5) synergetic effect of simultaneous action of high compressive stress and shear strain on the metal; 6) high produceability of the process.

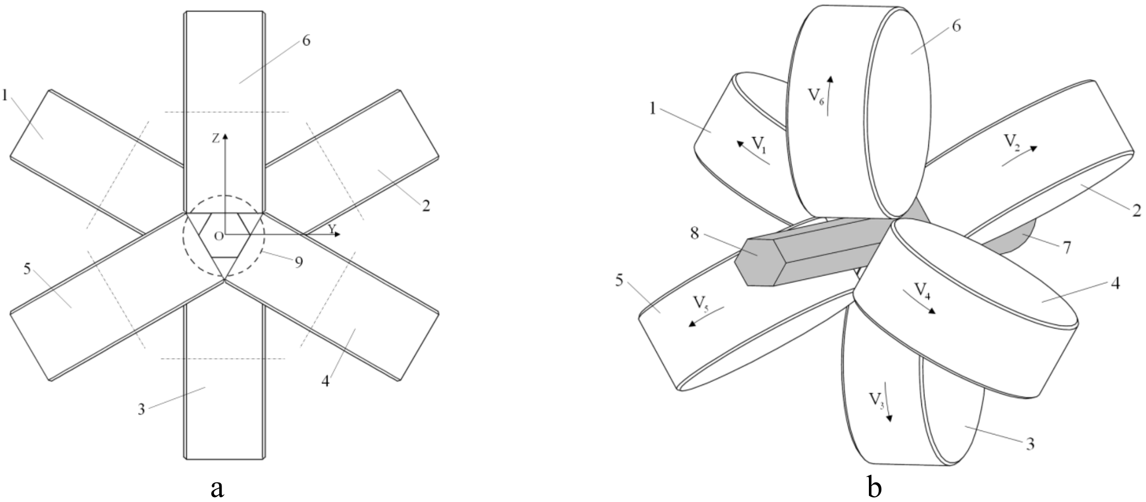
However the problem of an exploitable technology development for manufacturing of long metal products with ultrafine grain structure and enhanced performance characteristics remains unsolved yet.

1. Asymmetric rolling in multi-roll calibers

In order to get high-strength metallic materials with ultrafine grain structure there has been developed an original way of asymmetric rolling in a stand with two brought together three-roll calibers with additional shear strain due to work roll velocity mismatch (Fig. 1, 2).

The work roll velocity mismatch generates such a stress-strain state of the metal where in all contact zone points 13, 14, 18 (Fig. 3, a) the deformed metal has a lower flow speed than the peripheral speed of rolls 1, 2 and 6, correspondingly, i.e. contact zones 13, 14, 18 are the backward creep zones where the tangent friction forces τ_1, τ_2, τ_6 are directed along the profile movement.

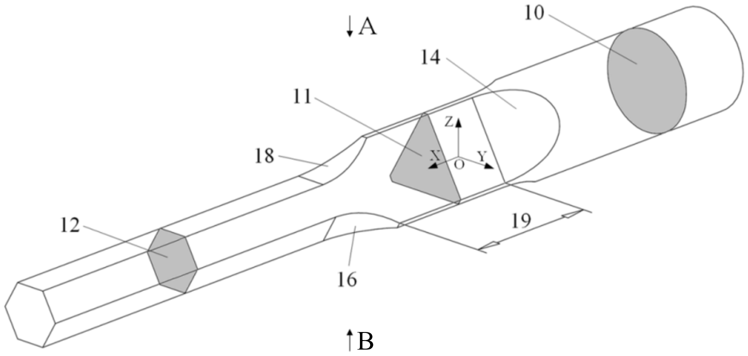
In its turn in all contact zone points 15, 16, 17 (Fig. 3, b) the deformed metal has a higher flow speed than the peripheral speed of rolls 3, 4, 5, correspondingly, i.e. contact zones 15, 16, 17 are the zones of slippage where the tangent friction forces τ_3, τ_4, τ_5 are directed opposite the profile movement. Consequently in the metal exposed to these opposite tangent friction forces high shear strain is formed; it results in the required refinement of the structure. With that the rate of shear strain significantly increases when applied simultaneously to the zone of high compression deformation.



a b

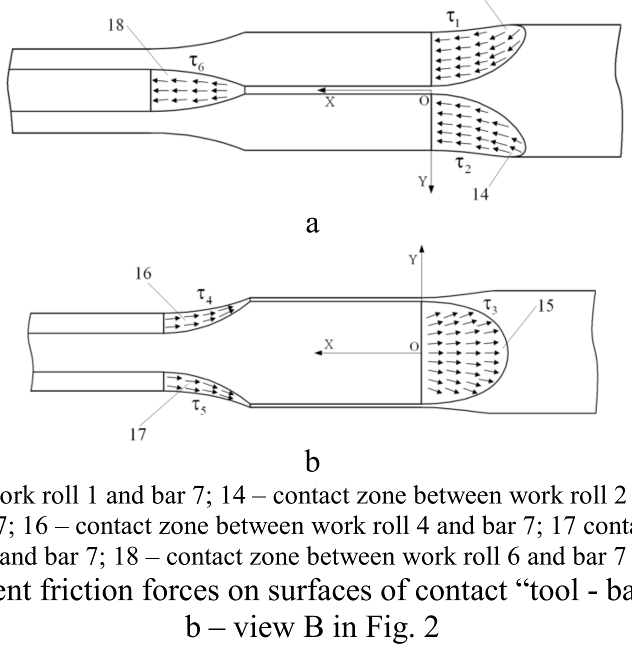
1, 2, 3 – work rolls forming the first three-roll caliber; 4, 5, 6 – work rolls forming the second three-roll caliber; 7 – original bar; 8 – resulting hexagonal section; 9 – outline of the set section; $V_1 - V_6$ – peripheral velocity of rolls (marks correspond to positions of the work rolls)

Fig. 1. Arrangement of rolls (a) and the scheme of asymmetric rolling of metal in double three-roll calibers (b)



10 – cross-section area of the original bar; 11 – cross-section area of the bar after deformation in the first pass formed by rolls 1-3; 12 – cross-section area of the bar after deformation in the second pass formed by rolls 4-6; 14 – contact zone between work roll 2 and bar 7; 16 – contact zone between work roll 4 and bar 7; 18 – contact zone between work roll 6 and bar 7; 19 –distance between deformation sites of the first and second three-roll passes

Fig. 2. Deformation of the hexagonal profile during asymmetric rolling



a

b

13 – contact zone between work roll 1 and bar 7; 14 – contact zone between work roll 2 and bar 7; 15 – contact zone between work roll 3 and bar 7; 16 – contact zone between work roll 4 and bar 7; 17 contact zone between work roll 5 and bar 7; 18 – contact zone between work roll 6 and bar 7

Fig. 3. Direction of tangent friction forces on surfaces of contact “tool - bar”: a – view A in Fig. 2; b – view B in Fig. 2

Introduction of the velocity asymmetry of rolls in one pass results in profile bending. In view of this fact, to achieve higher shear strain, it is suggested that the system of double three-roll passes be used. However asymmetric deformation in the single three-roll pass remains unexamined. Therefore this paper covers the performed research of influence of different technological factors on metal total elongation, shear strain and strain effective in the single three-roll caliber.

2. Finite element simulation

A commercial software DEFORM-3D, based on finite element method (FEM), was used to analyze asymmetric rolling process in three-roll calibers.

A round bar of d=4mm diameter of CDA-110 (fig. 4) copper was used as an original bar. Rolling was performed with smooth rolls having the roll body of R=180mm. Peripheral rotating speed of the first roll was set equal to $V_1 = 1.0\ \mathrm{m/sec}$. Peripheral speeds of two other rolls were set based on: $V_2 = V_3 = 1.0 \ldots 1.7\ \mathrm{m/sec}$. Hybrid friction low was used. The friction ratio when the metal bar contacted the work rolls varied within the range of 0.06 - 0.36. The front tension varied within the range of 10...60 MPa, the back tension – within 10...30 MPa. To approximate the geometric parameters of the bar, tetrahedral elements were used.

This paper contains research of influence of velocity asymmetry, different friction conditions and values of the front and back tensions on the metal total elongation and the value of strain effective.

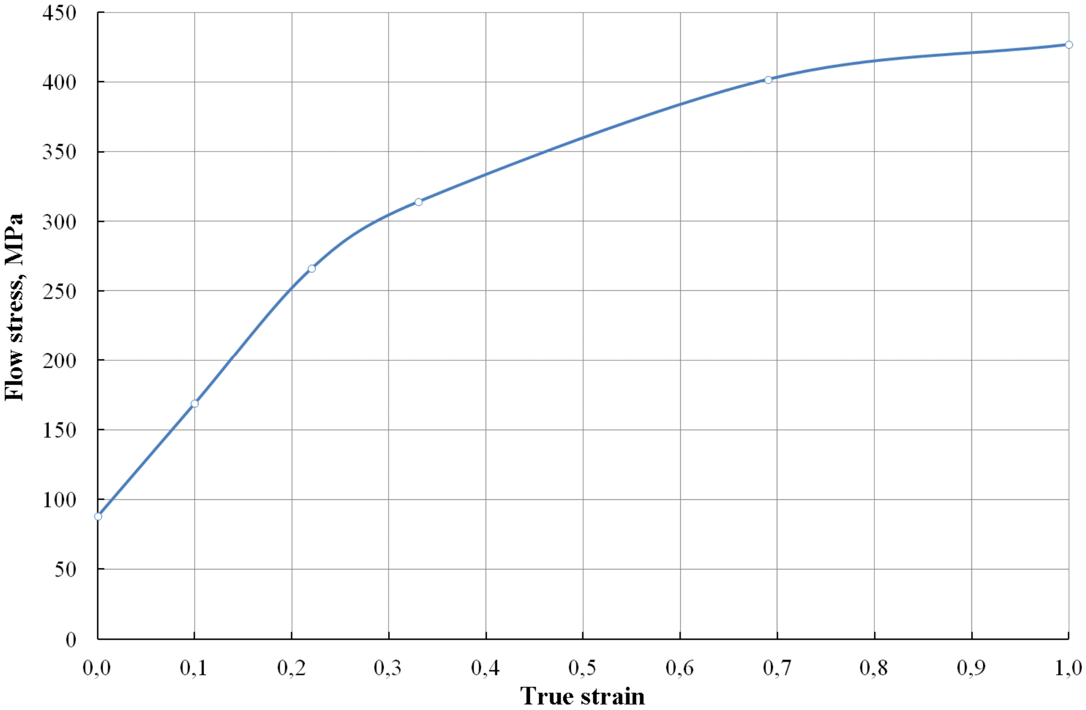


Fig. 4. Flow stress of CDA-110

3. Results and discussion

3.1. Influence of velocity asymmetry on the metal total elongation

Increase in roll velocity mismatch contributes to the increase in total elongation in the three-roll passes while other conditions being equal (Fig. 5). Thus the increase in the velocity mismatch ratio up to 1.7 enables increasing of the total elongation from 1.61 up to 1.68.

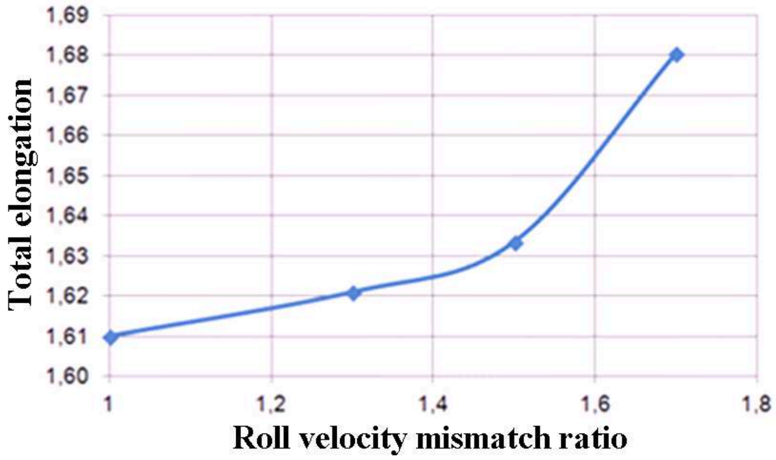


Fig. 5. Influence of the roll velocity mismatch ratio on the metal total elongation during asymmetric rolling

When the friction ratio is increasing, the metal total elongation is significantly decreasing (especially in the symmetric case) (Fig. 6).

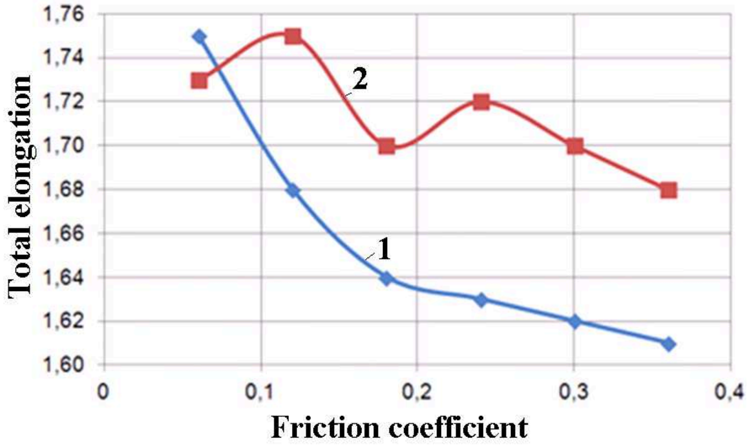


Fig. 6. Influence of the friction coefficient on metal total elongation during symmetric (1) and asymmetric (2) rolling

Fig. 7 shows that the increase in the front tension significantly enhances the total elongation during symmetric rolling and just slightly influences it during asymmetric rolling.

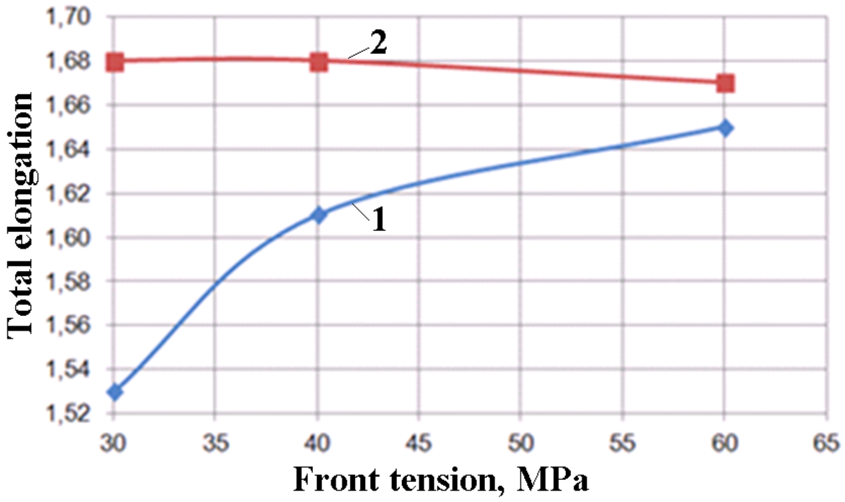
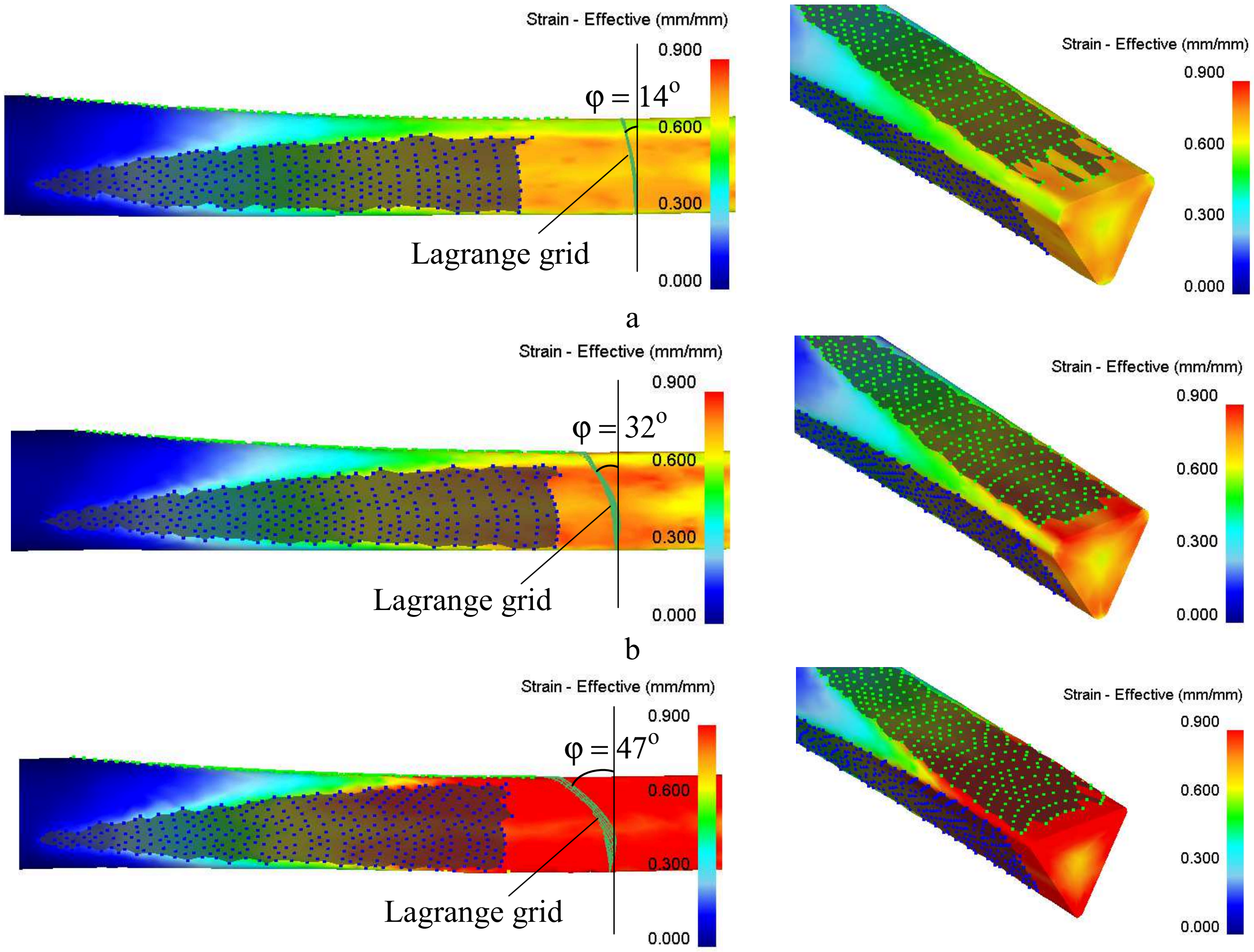


Fig. 7. Influence of the front tension on metal total elongation during symmetric (1) and asymmetric (2) rolling

3.2. Influence of the roll velocity mismatch ratio on shear strain and strain effective

When the roll velocity mismatch ratio is increasing, the initial Lagrange grid starts rotating (Fig. 8). Research shows that in the first three-roll pass the shear angle achieves 47°. The tangent of this angle is the characteristic of shear strain. Fig. 8 shows that with increasing the roll velocity mismatch ratio the strain effective values increased substantially. Use of the second pass will allow achieving shear strain values sufficient for homogeneity of the metal structure.



a

b

c

Fig. 8. Shear angle φ and strain effective in case of asymmetric rolling with the roll velocity mismatch ratio 1.3 (a), 1.5 (b), 1.7 (c)

4. Conclusions

It is suggested to consider the asymmetric rolling in a stand with two brought together three-roll calibers with additional shear strain due to work roll velocity mismatch. It is demonstrated that when work roll velocity mismatch is getting higher, the total elongation, shear strain and strain effective values are also increasing. Further investigation of the shear strain and microstructure evolution during deformation of metal in the three-roll pass is required.

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