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INFLUENCE EXERTED BY THE SHAPE OF THE SURFACES OF WORKING ROLL BARRELS UPON THE COURSE OF THE MEFASS (METAL FORMING AIDED BY SHEAR STRESSES) ROLLING PROCESS

The essential aspect of the MEFASS rolling process is introducing the cyclic axial counter movement of the rolls transverse to the direction of rolling in the course of a band pass through a rolling gap. The effect of a change in the way of deformation obtained in this manner makes it possible to set in one roll pass a deformation several times larger than it is possible in a conventional process. In this paper, upon the basis of the computer model of the MES process, supported by experimental research, the analysis of the influence exerted by the shape of the surface of roll barrels upon the distribution of the intensity of stresses σ_i and deformations ε_i in the section of the band being rolled, and also upon the kinematic and force parameters of the process.

Keywords: rolling process with cyclic horizontal movement of rolls, MEFASS, FEM

1. Introduction – the directions of research into plastic working processes with a controlled deformation path

The requirements formulated in the case of constructions are ever more rigorous in terms of strength and operating them in our times. That requires, apart from introducing new materials, undertaking research the objective of which is to gain a profound insight into the opportunities related to the nature of metals itself, and to take advantage of them.

It is possible to believe that the greatest opportunities within that scope are provided by plastic working processes with the controlled course of a deformation path [1-3].

Forcing a change in a deformation path causes a significant weakening effect because the instances of slip blocking in particular crystallites are less difficult to be passed by, and there occurs the formation of the new, advantageously oriented in terms of energy, micro and macro sheer bands. Micro shear bands may collaborate with the mechanisms of crystallographic slip, frequently taking over the control over plastic flow process. Slips, and the concentrations of dislocations in crystal, as the microstructural mechanism of material plastic flow in the course of a deformation, cause changes in the geometry in the structure of the deformed material and a change in the mechanical properties of it. The properties of dislocations give rise to the conclusion that the slip of them may exert influence upon the formation and relocation of a dislocation on a common plane. Areas in which dislocations relocate, and also the number of them, are the essential features determining the phenomenon of slip because they form natural obstacles which may set in motion the secondary slip systems. Those obstacles may be dislocations gathered in the different places of the crystal, and resulting in blocking the privileged directions of slips. The occurrence of such a phenomenon results in that, in the deformed material in the simple patterns of deformation, the substructure may look like in tests on it after a complex deformation [4].

That, in turn, exerts a significant influence both upon the technological plasticity of the metal being deformed (the possibility of causing large deformations in the course a single operation), as well as upon obtaining the high strength properties impossible to be achieved in conventional processes. It is no less important to decrease the values of loads acting on the construction of devices in the course of process. The results of research into changes in the characteristics of metals in the conditions of a complex deformation path gave rise to searching for the possibilities of taking advantage of that phenomena in actual industrial processes such as forging [5] or rolling [2,6-8]

2. Characteristics of rolling process (MEFASS)

The MEFASS rolling process was developed by a team under the guidance of F. Grosman [7]. The kinematic diagram of the MEFASS system roll is presented in Figure 1.

In the process in question, the effect of a change in a deformation path is brought about introducing additional, cyclic counter axial movement of the working rolls (transversely to the

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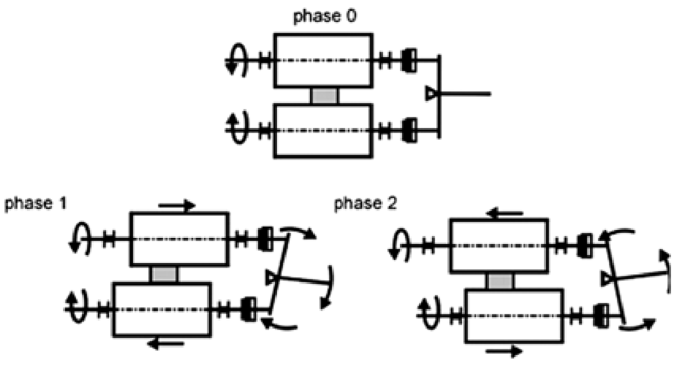


Fig. 1. Kinematic diagram of the MEFASS system roll having the axial movement of working rolls

direction of rolling) in the course of a band pass through a rolling gap. The result of that is applying an additional transverse force, causing shear stresses, to the band. However, a condition in this case is to eliminate, or, at least, significantly decrease the phenomenon of the axial slip of rolls on the band, which proved impossible in rolls having smooth ground barrel surface.

In the course of experimental research, attempts were made to solve this problem by means of cutting on barrel surfaces transverse furrows (grooves) having the following height: h = 0.14 mm and the following angle of flare: α = 60°. Such a solution because of tendency to shear furrow vertexes, or to them being worn out intensively, may not, however, be applied in the case of rolling non-deformable materials, having the high values of plastic strength and hardness.

In the case of rolling at high velocities v = 0.063 m/s and the maximum amplitude of the axial relocation of rolls A = 4 mm, there also appeared slip traces in the form of destroying band surface quality, in the way visible in Figure 2.

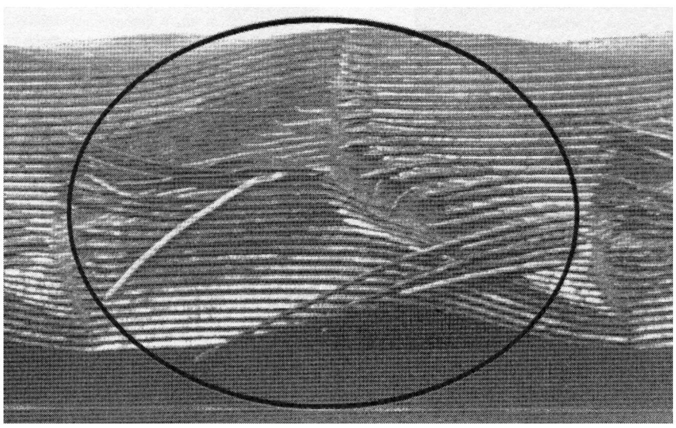


Fig. 2. Roll slip traces on a M1E copper band surface rolled in the MEFASS process

Therefore, it seems to be advisable to commence research into the assessment of the influence exerted by the shape of roll barrel upon the conditions of transferring the axial movement of rolls on bands, and into the state of stresses and deformations in the latter one, brought about by that.

3. Analysis of the state of stress and deformation in the band, and also the force parameters of the MEFASS rolling process

The subject-matter of the computer simulation with the application of the MES – DEFORM 3D v 6.1. software was the MEFASS cold-rolling process of rods having the following section: 8x8 mm and made of the M1E electrolytic copper after recrystallization annealing.

Five variants of the shape of the surface of roll barrel were considered, namely: a smooth barrel, having sharp-profile furrows (like in the research [7]), having rounded-profile furrows, positive curvature, and also ground until achieving an S-profile.

A deformation in the course of roll pass was presumed to be equal to ε_h = 20 %. Kinematic parameters were as follow: rolling velocity v = 0.029 m/s, velocity in axial movement ϑ = 0.02 m/s, the amplitude of the axial relocation of rolls A = 1.4 mm, and the frequency of axial movement f = 3.0 Hz. Thermal phenomena occurring in the process were not included into consideration at that stage of the analysis.

The conditions of friction on the band surface contact with rolls were described as isotropic adopting the 'Shear' model, with the (dedicated by the program) coefficient of friction μ = 0.18.

Contact pairs were modelled indicating the space including the band (plastic) and rollers (rigid), and also defining the value of interstitial tolerances equal to 0.0002 mm.

After defining the band as the object of the 'Slave' type, and also rolls (upper and lower) as the objects of the 'Master' type, the program automatically generated the contact pairs.

The location of the rolls was determined with the application of the coordinates of the CAD model, and afterwards boundary conditions were superimposed on them in the form of rotational speed ω, and also in that of velocity in axial movement ϑ.

However, it should be pointed out that the obtainable precision of the representation of the MEFASS process through the MES model is restricted in this case, too, because of the lack of detailed characteristics of the technological plasticity of material in the conditions of a cyclic change in the pattern of load.

In the subsequent steps of the calculations of the discrete MES models of the MEFASS process formed in this manner, the following were determined: the shape of band after rolling, distribution intensity of stresses σ_i and deformations ε_i in the longitudinal section and cross-section of the band, decreased in accordance with the H-M-H hypothesis, and also the course of the force parameters of the process.

a) The MEFASS rolling process in rolls having a smooth barrel

In the first step of the analysis, the MEFASS rolling process was modelled with the presumption that the shape of roll surface barrels was smooth, and also presuming that the coefficient of fricton on the contact surface between them and the material was in the following range: μ Є [0.16-0.27]. The results of the calculations made it possible to ascertain that, similarly to what had already been observed in the course of experiments, such conditions result in slip rolls on the band in the course of the axial movement of them, and, *ipso facto*, in the lack of, constituting the essential aspect of the MEFASS process, material deformation transverse to the direction of rolling. That is illustrated by the velocity vector field of plastic metal flow in the course of rolling – Figure 3.

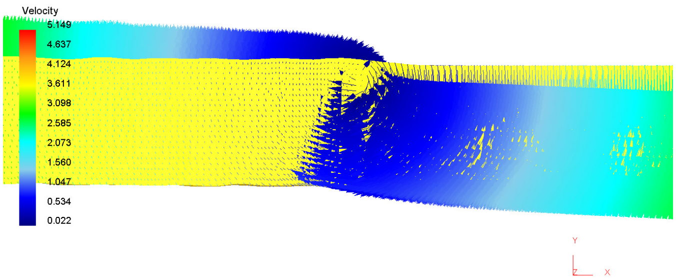


Fig. 3. Velocity vector field of plastic metal flow in the course of the MEFASS process conducted in rolls having a smooth barrel

b) The MEFASS rolling process in the rolls having sharp-profile furrows

In the further stage of the simulation, the shape of a roll barrel surface – with tooth-shaped furrows cut on it – was presumed in accordance with those applied in experimental research [7].

The accurate representation of the shape of a barrel surface – in connection with the relevant increase in the number of finite elements – resulted in the significant extension of the time of calculations. In the case of an operational memory the capacity of which amounts to using 8 Gb and 82% of a processor, the average time of a single simulation reached 62 h. However, it made it possible to reconstruct the real conditions on the contact surface between the metal and the rolls better.

It is even more significant because, in the hitherto known, and proposed by Milenin, model of the MEFASS process [8], the problem of the time of calculations was solved by presuming the roll barrel having a smooth surface, and describing the conditions of friction on the contact surface between that and a material in the form of anisotropic model. That model was formulated taking advantage of the non-isothermal incompressible body (having non-linear viscosity) flow theory and by means of introducing the original penalty function [9]. The intensity of stress and of deformation distributions determined in the course of simulations are presented in Figure 4.

Those distributions manifest strong non-uniformity, being the consequence of setting an additional axial movement for rollers, and a change in a deformation path in the course of rolling, brought about that.

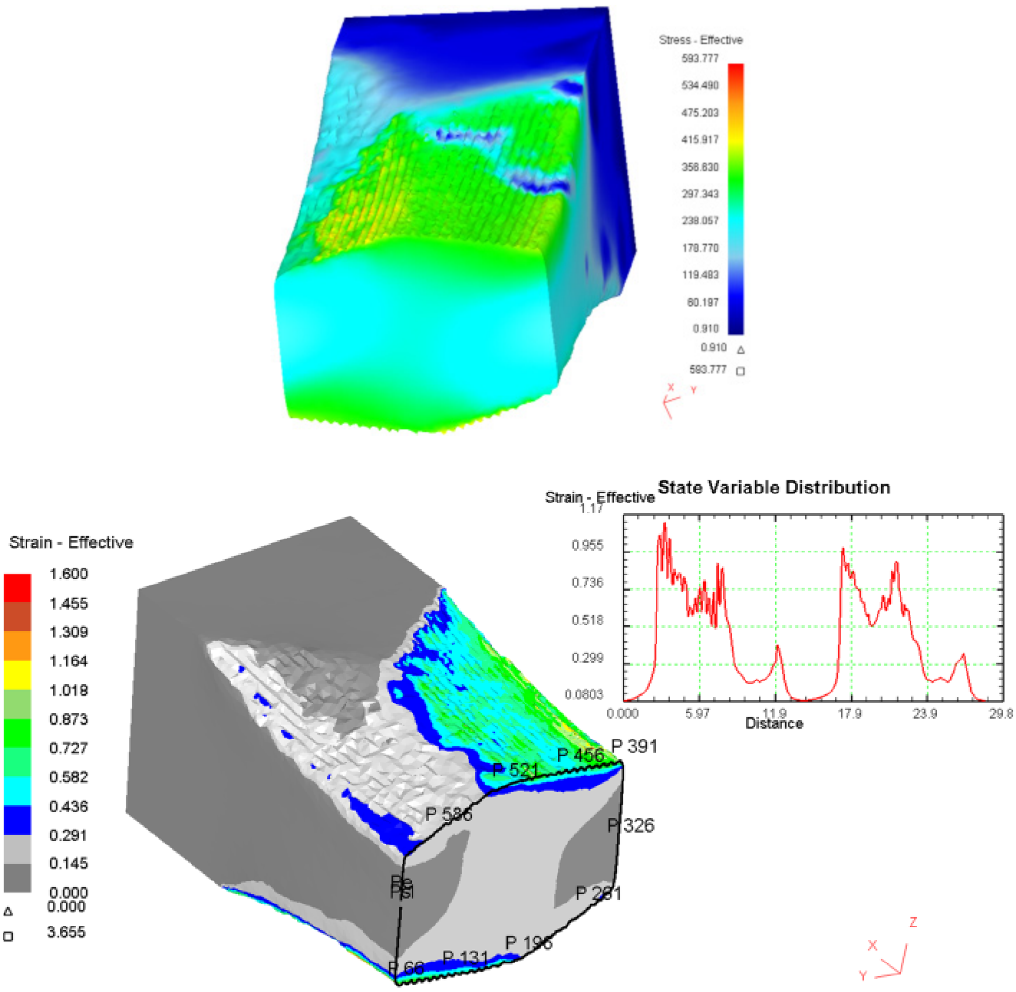


Fig. 4. Distribution intensity of stresses σ_i and deformations ε_i in the cross-sections of the band rolled with the application of the MEFASS method (rolls having sharp-profile furrows)

The greatest material flow in the transverse direction occurs in the layers directly touching the surface of rolls, and the degree of deformation of the section brought about it is dependent upon the phase of the axial movement of rolls and changes along the length of a band.

That explains the causes of, observed in the course of industrial rolling process, band torsion tendency, and the loss of the rectangularity of its section, as it is presented in Figure 5.

The greatest deformation occurs in the plane compatible with the maximum deflection of rolls, which indicates the necessity of restricting the values of the amplitude of their relocation *A*. The heterogeneity, confirmed by the results of the experiment, and concerning the degree of deformation on the cross-section of the band, finds its reflection, in turn, in this same heterogeneity of the microstructure of material after roll pass (Fig. 6).

It is justifiable to expect in this case that restricting this adverse heterogeneity would require conducting rolling at a sufficiently small velocity, so as to ensure the effective influence of recovery and recrystallization processes brought about the influence exerted by thermal effects accompanying deformation.

In this case, an essential aspect is such a selection of the parameters of the process in the final roll passes, so as to, in accordance with the fundamental presumptions of the MEFASS process, obtain as the result the strongly disintegrated structure having the high level of mechanical properties.

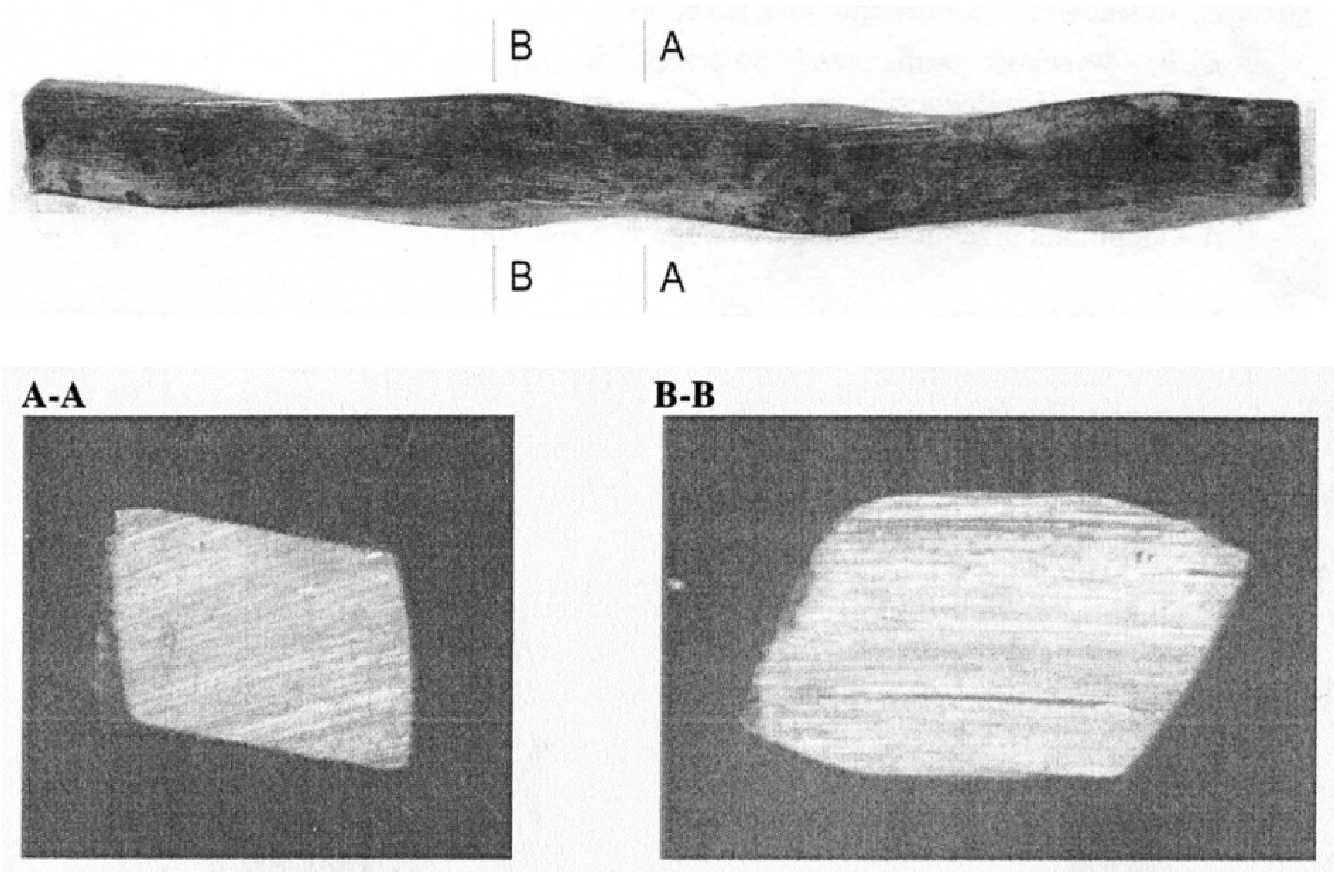


Fig. 5. View of the cross-section of a band after rolling in the MEFASS roll (rolls having sharp-profile furrows)

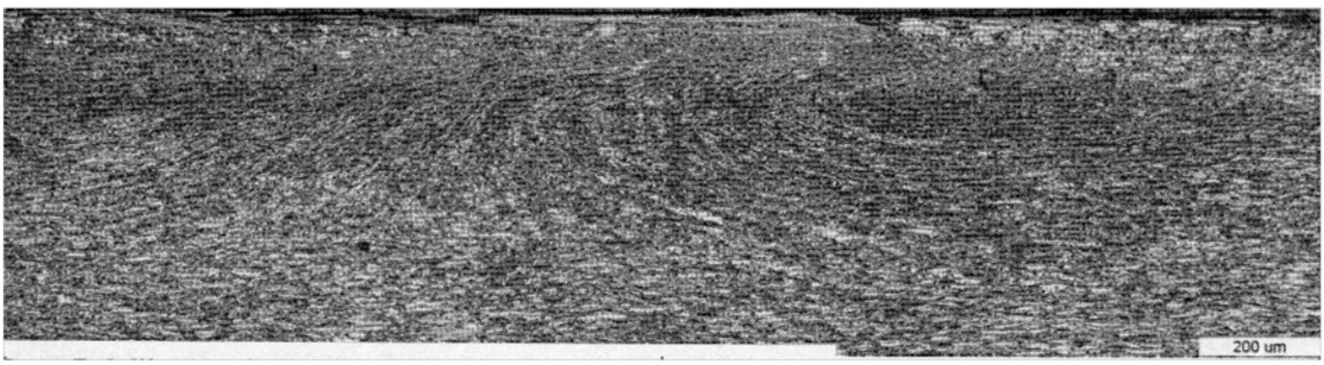


Fig. 6. View of the microstructure on the cross-section of a band after deformation its rolling in the MEFASS process. Rolls having sharp-profile furrows

c) The MEFASS rolling process in rolls having rounded-profile furrows

The technological problems connected with the application of the barrels of rolls having sharp-profile furrows gave rise to searching for the alternative solutions of roll barrel surfaces. The first of those actually proposed was a change in the shape of furrows, as it is presented in Figure 7.

For such a presumed shape of roll barrel surface in the subsequent stages of simulation, the shape of a band after rolling was determined, and so were the distributions of the intensity of stress and deformation in its cross-section (presented in Figure 8).

The computer simulation of the MES model also made it possible to determine the course and the values of the force parameters of the MEFASS rolling (presented in Fig. 9). It is an essential aspect, both for the selection of the technological parameters of the process, and for determining the requirements relevant to the strength of the construction of a roll alike.

The maximum values of axial forces – symmetrical for both of the rolls – are compatible with their central location in the case of zero deflection in relation to the axis of a rolling stand. Respectively, at the moments in which those deflections reach their maximum, the value of force decreases to zero, and they cross through one another.

It is also visible that as a band deformation is progressing along its length, oscillations of the course of axial forces are disturbed, which, as it may be presumed, it would be necessary to ascribe to a band torsion tendency, and to the loss of the regular shape of the section of it. Together with the oscillatory variable character of axial forces – changing the state of stresses and deformations in a rolling gap – such a variability is also transferred, upon the course of vertical rolling force F_z, and also on the rolling moments $M_{w\,1,2}$ (Fig. 9).

The amplitudes of the moments of rolling are compatible with the extreme location of rolls in the axial movement of them when in the case of a change in the velocity vector into an opposite one, there occurs a significant decrease in the values of it. Those amplitudes are shifted in the phase in relations to the amplitudes axial forces, and the values of them remain, as a general rule, higher than the values of moments determined for a conventional rolling process.

This oscillatory variable character of the loads of roller constitutes the essential aspect of the difference in relation to the relatively stable course of them in a conventional rolling process.

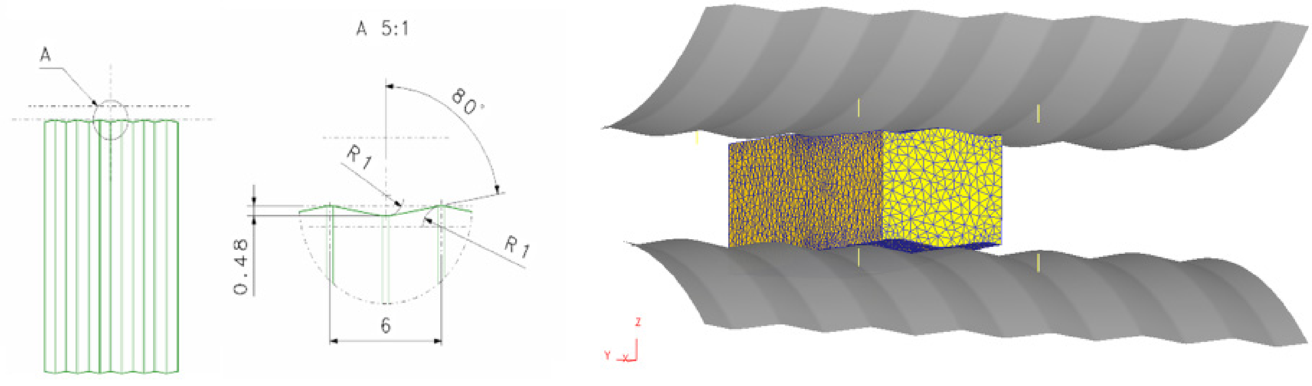


Fig. 7. Profile of a roll barrel having rounded-profile furrows, and also the MES model of rolling a band with the grid of four-stitch tetragonal elements

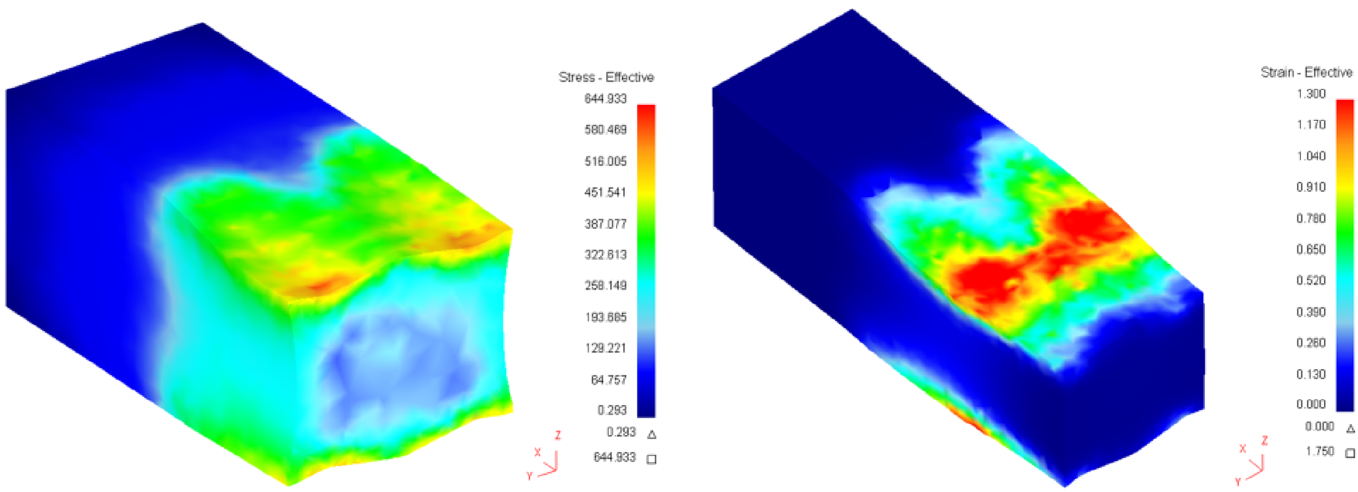


Fig. 8. Distribution intensity of stresses σ_i and deformations ε_i in the cross-section of the band rolled with the application of the MEFASS method – rolls having rounded-profile furrows

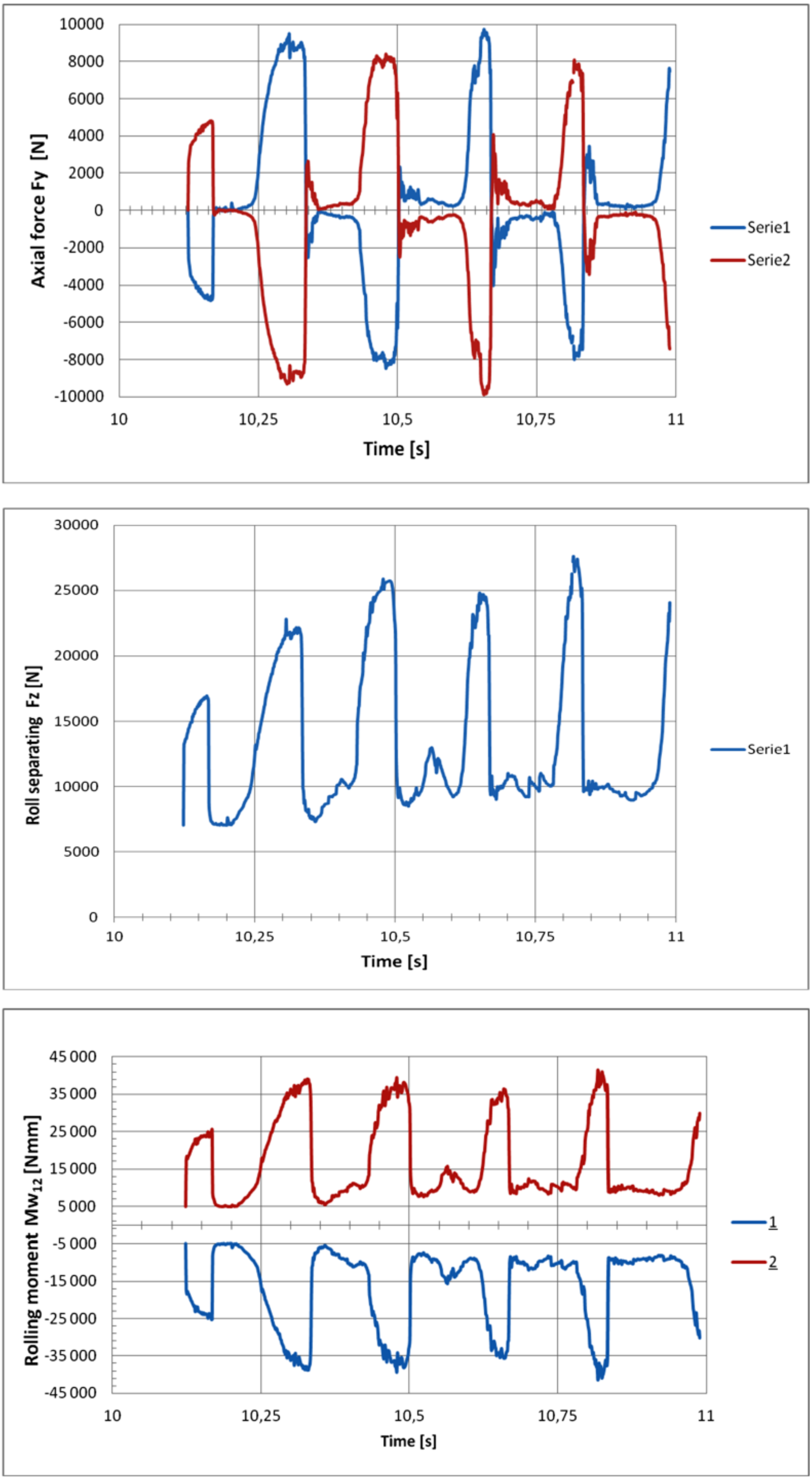


Fig. 9. Course of axial F_y and vertical F_z constituents of the rolling force acting on a roll, and also the rolling moments $M_{w\,1,2}$ (the upper roll – the red line, the lower roll – the blue line) in the of the MEFASS rolling process. Rolls having rounded-profile furrows

d) The MEFASS rolling process in rolls having the positive curvature of a barrel surface

The diagram of the MEFASS process conducted on rolls having a positive curvature of a roll barrel surface is presented in Figure 10, and the images of the state of stress and deformation in band are respectively presented in Figures 11 and 12.

Respectively, in Figure 13, the course of, and the values, of force parameters of the process are presented.

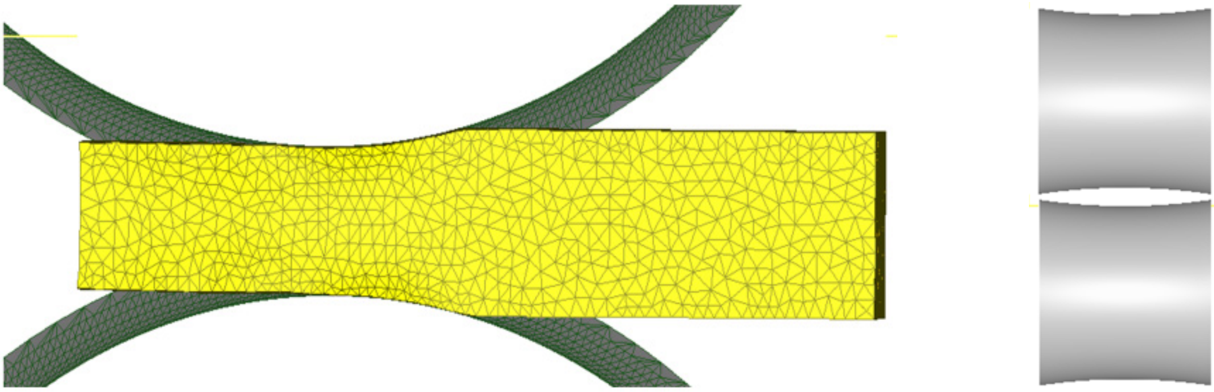


Fig. 10. Section of the band with the MES grid being rolled (with the application of the MEFASS method) on rolls having a positive curvature of a roll surface

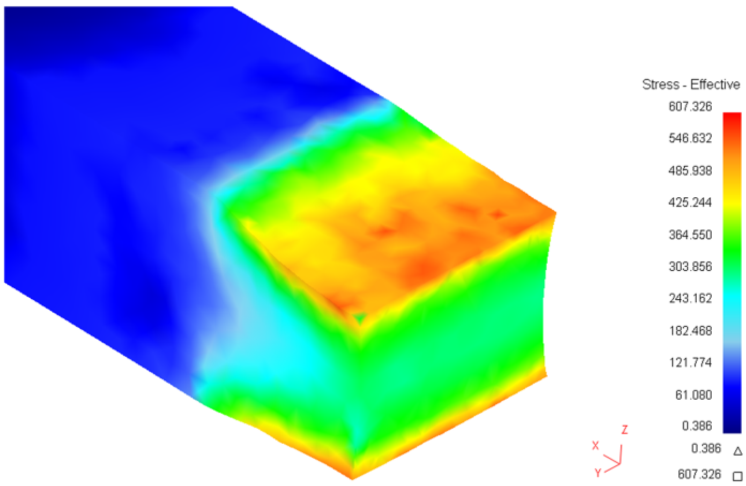


Fig. 11. Distribution intensity of stresses σ_i in the longitudinal cross-section of the band rolled with the application of the MEFASS method. Rolls having a positive curvature of a roll barrel surface

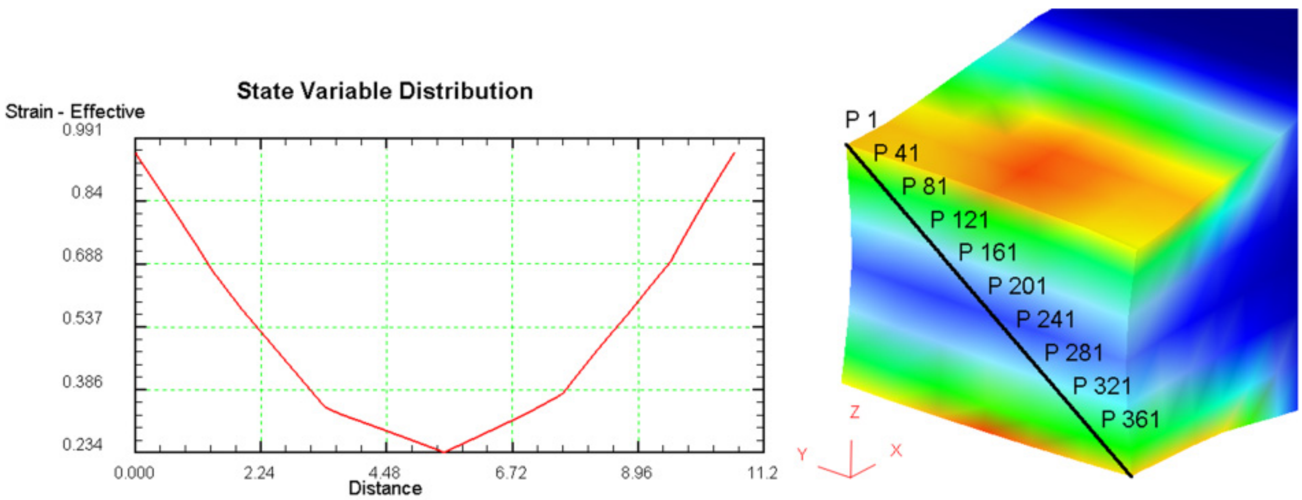
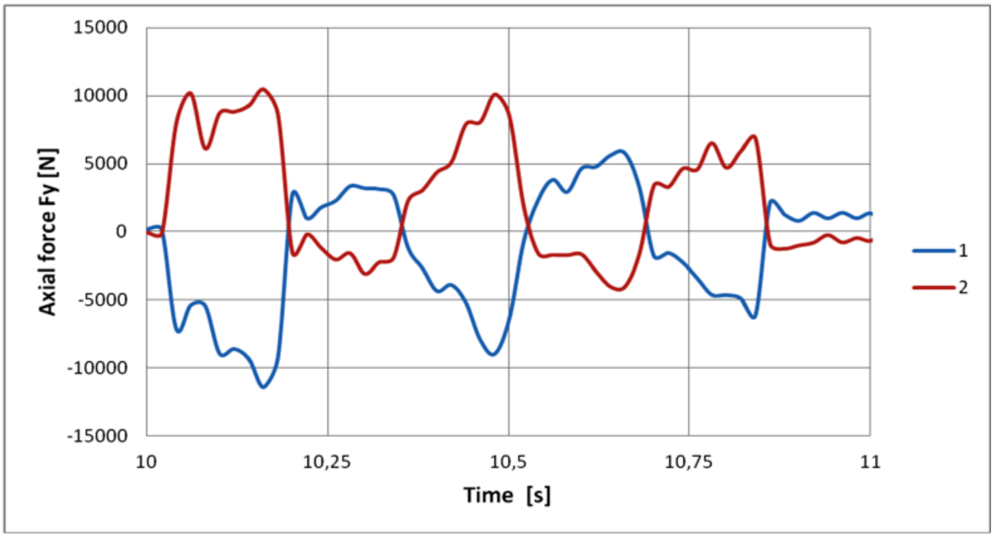


Fig. 12. Distribution intensity of deformations ε_i in the cross-section of the band rolled with the application of the MEFASS method. Rolls having a positive curvature of a roll barrel surface



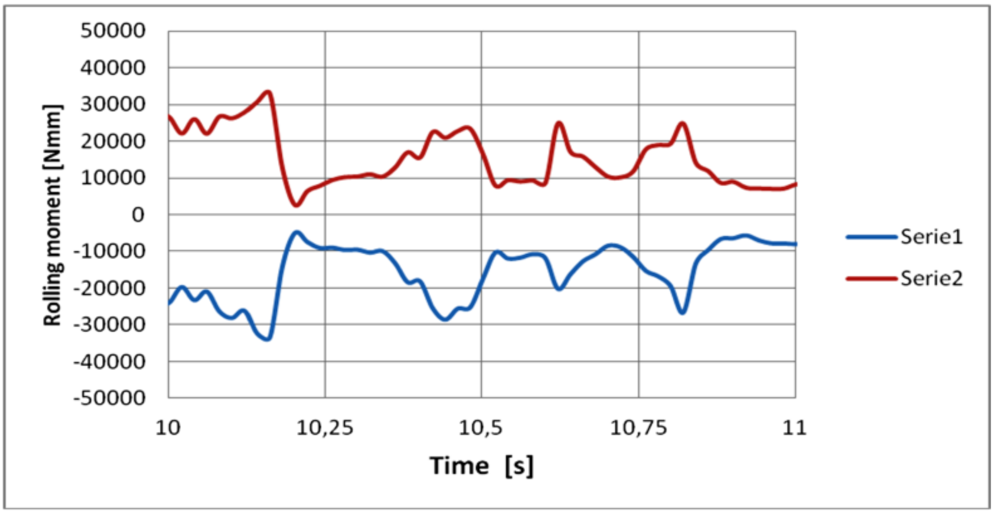
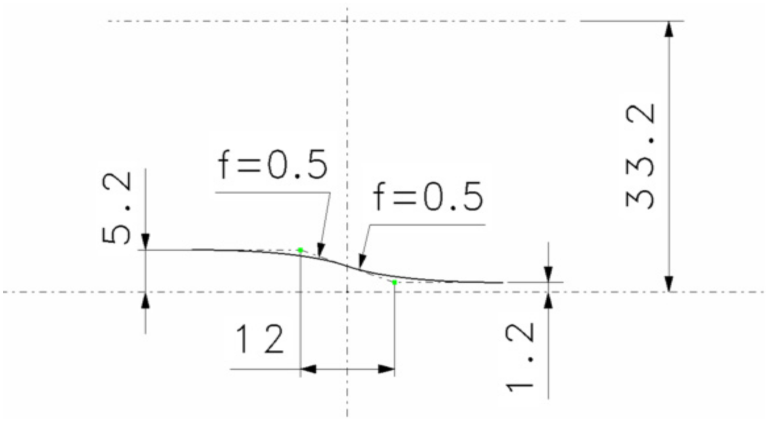


Fig. 13. Course of axial forces F_y applied to the upper (the red line, 2) and the lower roll (the blue line, 1), and also the rolling moments $M_{w\,1,2}$ in the MEFASS rolling process. Rolls having a positive curvature of a roll barrel surface

e) The MEFASS rolling process on roll barrels having S-profile

A direct inspiration for subjecting the MEFASS process taking place in rolls having S-profile roll barrels (Fig. 14) was the system of controlling the band contour CVC developed by SMS Schloemann-Siemag.

Below, in Figure 15, (obtained in the simulation, and matching the MEFASS process conducted in this manner) the images of the state of stress and deformation in a rolled band are presented.



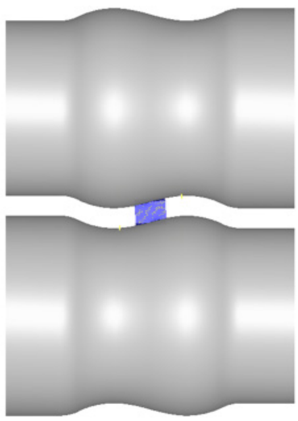


Fig. 14. Profile of a S-profile roll barrel, and also the pattern of rolling

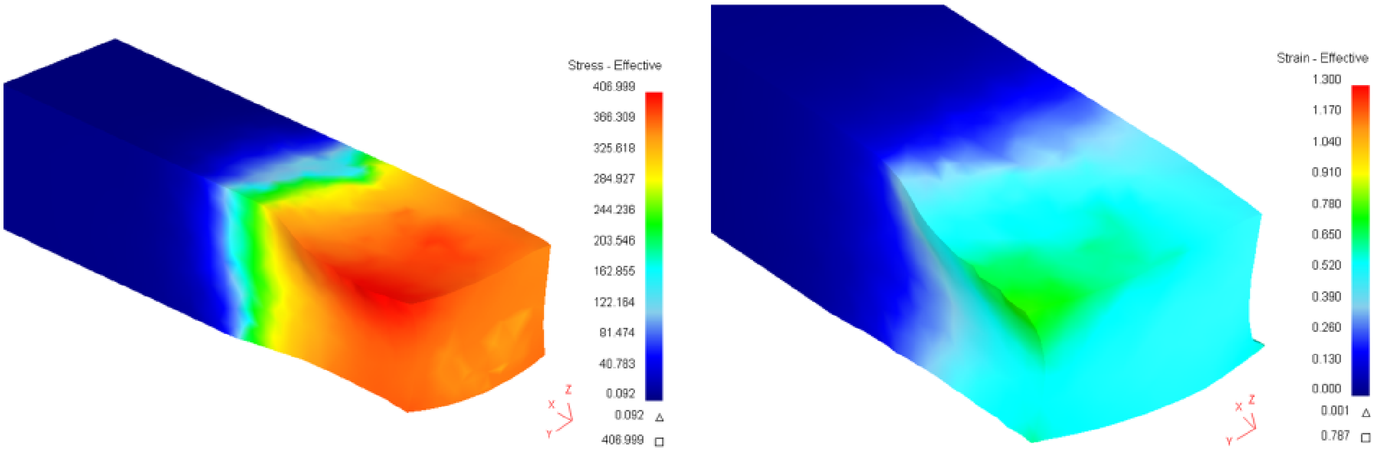


Fig. 15. Distribution intensity of stresses σ_i and deformations ε_i in the cross-section of the band rolled with the application of the MEFASS method. Rolls having S-profile roll barrels

4. The results of the analysis and conclusions

The values of intensity of stress σ_i and deformation ε_i in a band rolled in the MEFASS system, determined for simulated cases of a different shapes of roll barrels, were collated in Table 1.

TABLE 1

Values of the intensity of stress σ_i and deformation ε_i in the MEFASS process

Shape of roll barrel surfaces	Intensity of stress σ_i			
	$\sigma_{i\,\max}$ MPa	$\sigma^*_{i\,\max}$ MPa	$\frac{\sigma_{i\,\max}}{\sigma_{i\,\min}}$	$\frac{\sigma_{i\,\max}\ \text{(MEFASS)}}{\sigma_{i\,\min}\ \text{(walc.klas.)}}$
Conventional rolling	348	285	1.22	—
MEFASS process				
Smooth roll barrel surface	slip	slip	—	—
Barrel having sharp-profile furrows	441	295	1.49	1.27
Barrel having rounded-profile furrows	558	288	2.04	1.60
Barrel having a positive curvature	584	344	1.70	1.68
S-profile barrel	406	340	1.19	1.17

Shape of roll barrel surfaces	Intensity of deformation ε_i			
	$\varepsilon_{i\,\max}$	$\varepsilon_{i\,\max}^*$	$\frac{\varepsilon_{i\,\max}}{\varepsilon_{i\,\min}}$	$\frac{\varepsilon_{i\,\max}\ \text{(MEFASS)}}{\varepsilon_{i\,\min}\ \text{(walc.klas.)}}$
Conventional rolling	0.40	0.23	1.74	—
MEFASS process				
Smooth roll barrel surface	slip	slip		
Barrel having furrows having a sharp profile	1.27	0.19	6.68	3.17
Barrel having rounded-profile furrows	1.30	0.20	6.50	3.25
Barrel having a positive curvature	1.90	0.28	6.78	4.75
S-profile barrel	0.89	0.53	1.68	2.22

* value in the axis of a band

They reflect, also observed in experimental research [9], the strong heterogeneousness of the distribution of stresses and deformations in the cross-section, with the strong concentration of those in the contact zone between the material and the surface of rolls, and also decrease in them towards the axis of a band. That is the result of the location of deformation brought about by a change in a deformation path in the course of the rolling process.

It makes it possible to set in one roll pass deformation several times larger than it would be possible to achieve in a conventional process. It is conducive to the formation of strongly disintegrated, advantageous from the point of view of strength, the crystal structure of the material.

The analysis of the distributions of the intensity of stress σ_i and the intensity of deformation ε_i in the band rolled in the MEFASS system indicates beyond doubt the essential aspects of the influence which is exerted upon those distributions by the shape of roll barrels. In this contexts, it is justifiable to ascertain that the most advantageous conditions are provided in this case by the application of rolls with rounded-profile furrows, or having a positive curvature of a barrel surface.

It is also possible to presume that the obtained values of the intensity of deformation ε_i at the level of 1.30-1.90, and, therefore, three to five times exceeding the values obtained for a conventional rolling; it will be possible to enlarge them even further after conducting – for both of those variants of the shape of rolls – procedure of optimizing accompanied by maximizing the intensity of deformation as the function of the goal.

Obtaining such an essential technological effect which is constituted by maximizing the values of deformation in a single roll pass is, however, connected with the necessity of providing an appropriate quantity of energy.

The values of work needed to deform a band in the MEFASS process, which is composed of the sum of works connected with the rotary motion of rolls W_R, and also with the axial movement transverse to the direction of rolling W_T were collated in Table 2 and compared with the values for a conventional rolling.

TABLE 2

Values of deformation working capacity determined upon the basis of the MES model (the MEFASS process for the following conditions: $\varepsilon_k = 20\%$, $v = 0.029$ m/s, $A = 1.4$ mm, $f = 3$ Hz)

Parameters of the process	W_R **MJ/m**	W_T **MJ/m**	ΣW **MJ/m**
Conventional rolling	26.2	0	26.2
MEFASS process, a roll having furrows with a rounded profile	27.3	150.6	177.9

It is revealed that the work is nearly seven times (6.79) larger than in the case of a conventional rolling. In the case of comparable values of works connected with the moment of rolling is the result of dominant influence exerted by the work of axial forces. Therefore, the MEFASS rolling process appears to be an energy-consuming one, as well as strongly dependent upon technological conditions, including the shape of roll barrels in which it takes place.

For the assessment of the industrial usefulness of the MEFASS process is the postulated that the shape of a band after roll pass make it possible to conduct the further plastic working of it, or machining. Therefore, one of the criteria of selection of the shape of rolls in the MEFASS process ought to be restricting the conditions resulting in band torsion.

The conducted simulations indicate as well strongly oscillatory character of force changeability F_y, F_z, and also the moments of rolling $M_{w1,2}$, the amplitude of which remain determined by the size of a rolling reduction in a roll pass, and also the kinematic parameters of movement. Those are, it should be remembered, closely correlated with the subsequent phases of the transverse location of rolls in relation to the axis of a rolling stand. Such a changeability of loads, also observed in the course of experimental research [7], certainly ought to be considered as a typical feature of the MEFASS process making it essentially different from the stable course of those loads in a conventional rolling process. The consequence of that is increasing the number of the cycles of changes in a load influencing the particular mechanisms of a roller, which may result in their wear breakdowns.

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