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Tool profile stationarity while simulating surface plastic deformation by rolling as a process of flat periodically reproducible deformation

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ABSTRACT

Introduction. Surface plastic deformation is an effective way to improve the operating performance of machine parts. One of the promising approaches to the design of surface hardening technological processes is the technological inheritance mechanics. To calculate the hereditary parameters characterizing the accumulated deformation and damage to the metal, it is possible to simulate spinning as a process of plane fractional deformation, which significantly reduces the time required for modeling the process. However, upon rotation of the plane in which the stress-strain state is considered, the roller profile changes. **The aim of the work** is to assess the magnitude of the change in the roller profile in the deformation plane during deformation as an important factor ensuring the accuracy of the solution obtained. **Research methods**. The roll profile in the warp plane is defined by the intersection line of the roll surface and this plane. The paper presents the procedure for calculating the coordinates of the points of intersection lines, which are curves of the fourth order, depending on the geometric dimensions of the roller and the part, as well as the angle of inclination of the deformation plane. **Results and discussion.** To estimate the value of the roller profile change, the coordinates of the points of the intersection lines of the roller surface and the deformation plane are determined for the rolling modes corresponding to a sufficiently developed plastic deformation, the obtained lines are approximated in the coordinate system associated with the deformation plane, and the relative change in the coordinates of the intersection lines when the plane was rotated are estimated. As a result of the conducted analytical studies, it is found that even with developed plastic deformation, the relative change in the coordinates of the points of intersection lines does not exceed 0.1%. This indicates the possibility of using a stationary roller profile when simulating rolling using the plane fractional deformation model.

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Introduction

One of the most effective methods of improving the performance properties of machine parts is deep rolling, especially for increasing the fatigue strength. The surface layer hardening, the roughness reduction, and the formation of favorable compressive residual stresses can significantly increase the endurance limit and fatigue crack life of parts [1–7].

Deep rolling is used to treat both surfaces with relatively simple shapes (for example, external and internal cylindrical surfaces) and complex curved surfaces (for example, the surfaces of jet engine blades) [8].

The surface layer hardening and its depth, the surface roughness, and the distribution of residual stresses after deep rolling depend on the process parameters and the material physical and mechanical properties

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[9-10]. Improper process parameters lead to the fact that the increase in fatigue strength and the surface roughness reduction is slight, and, in some cases, can lead to surface condition deterioration [11–13].

The problem of determining the surface layer properties during deep rolling is complex due to the properties final values are determined not only by the finishing parameters, but also by the history of the surface layer metal loading during previous processing operations [14-15]. This phenomenon is called technological inheritance.

There are a large number of works aimed to predict the processing result by simulation the deep rolling process nowadays, in this case, direct processing parameters or determined processing parameters (for example, contact pressure) can be used as initial data for simulation [16–19].

One of the promising approaches to the design of hardening technological processes by rolling, taking into account the loading history, is the mechanics of technological inheritance [20]. The main parameters of the surface layer state are the shear strain degree Λ, which characterize the surface layer hardening, the plasticity reserve exhaustion degree Ψ, which characterize the accumulated damage of the surface layer metal, and the residual stress tensor, in accordance with the key provisions of the technological inheritance mechanics.

The calculation of the stress and strain values required calculating the values of the accumulated degree of shear deformation and the degree of depletion of the plasticity reserve is possible by finite element simulation of the volumetric stress-strain state during contact interaction of the roller and the part. However, the nonlinear nature of this problem, the need to use elements of small size, which leads to a large number of it, leads to a significant increase in the complexity of creating a model and the calculation time. Therefore, the possibility of finite element simulation of the contact interaction of the roller and the workpiece in a flat setting is important.

It is shown in [21] that deformations in the tangential section of the workpiece (in the plane perpendicular to the sample axis) are small compared to the deformations in the axial section (in the plane on which the axis of the workpiece lies). This makes it possible to calculate the stress-strain state during rolling in a plane-deformed formulation, considering it as a process of plane fractional deformation. In this case, the displacement of material particles, the occurrence and change of stresses and deformations are considered in the plane of deformation (axial section of the part) when it rotates about the axis of the part during processing.

The roller profile at each time is defined as the intersection line of the roller surface and the strain plane. Obviously, the roller profile will change when the rotation angle of the strain plane changes.

In this regard, an important issue that determines the possibility of the rolling simulation as a plane-stain process using a constant profile roller model is the assessment of the change magnitude in the roller profile when the strain plane is rotated.

The work purpose is to estimate the change magnitude in the roller profile in the strain plane while rolling when this plane is rotated.

The work tasks are analytical description of the tool profile in the strain plane depending on the rotation angle of the strain plane of deformation, determination of the lines points coordinates of the tool profile when the strain plane is rotated, and determination of the relative change in the points coordinates of the roller profile when the strain plane is rotated.

Methods

In the process of rolling in the contact zone of the tool with the part, a deformation zone occurs – a local region of plastic deformation. A characteristic feature of the deformation zone in the part axial section of the part is the presence of a plastic wave in front of the roller. At each part turn, the roller is shifted relative to the deformation zone formed on the previous turn by the feed amount.

On the other hand, under the roller immobility assumption, each material point of the part moves in a spiral, shifting in the axial direction relative to the roller by the feed amount for each part turn. The trajectories of material particle movement in the deformation zone are called *flow lines*. When a material particle passes in the deformation zone along the flow line, the accumulation of deformation and damage to the metal occurs (Fig. 1).

The deformation zone dimensions depend on the process parameters: the rolling force P, the roller profile radius R_{pr}, the roller diameter D_r, the feed s, the part diameter D_p, and in the circumferential direction are characterized by the deformation angle φ_d.

The movement of a material particle in the deformation zone consists of its movement due to the rotation of the part (this value is the same for all material particles at the same depth) v_{rot} and displacement relative to other material particles v_d due to the contact interaction of the part surface with the tool (Fig. 2). The occurrence and change of stresses and strains is caused by successive movements of material particles v_d when the part is rotated.

When the roller and the part being processed interact, the section under consideration (strain plane) rotates sequentially relative to the axis of the part (Fig. 3), which causes the movement of the roller profile v_t and the movement of the material particles of the processed body v_d in the strain plane (Fig. 4).

The movement of the roller profile consists of a vertical movement v_{ty}, due to the sequential rotation of the strain plane in the direction of the roller central section, and a horizontal movement v_{tx}, which occurs due to the tool feed s. The v_{tx} value can be estimated as

$$v_{tx} = \frac{\varphi_d}{4\pi} s . \tag{1}$$

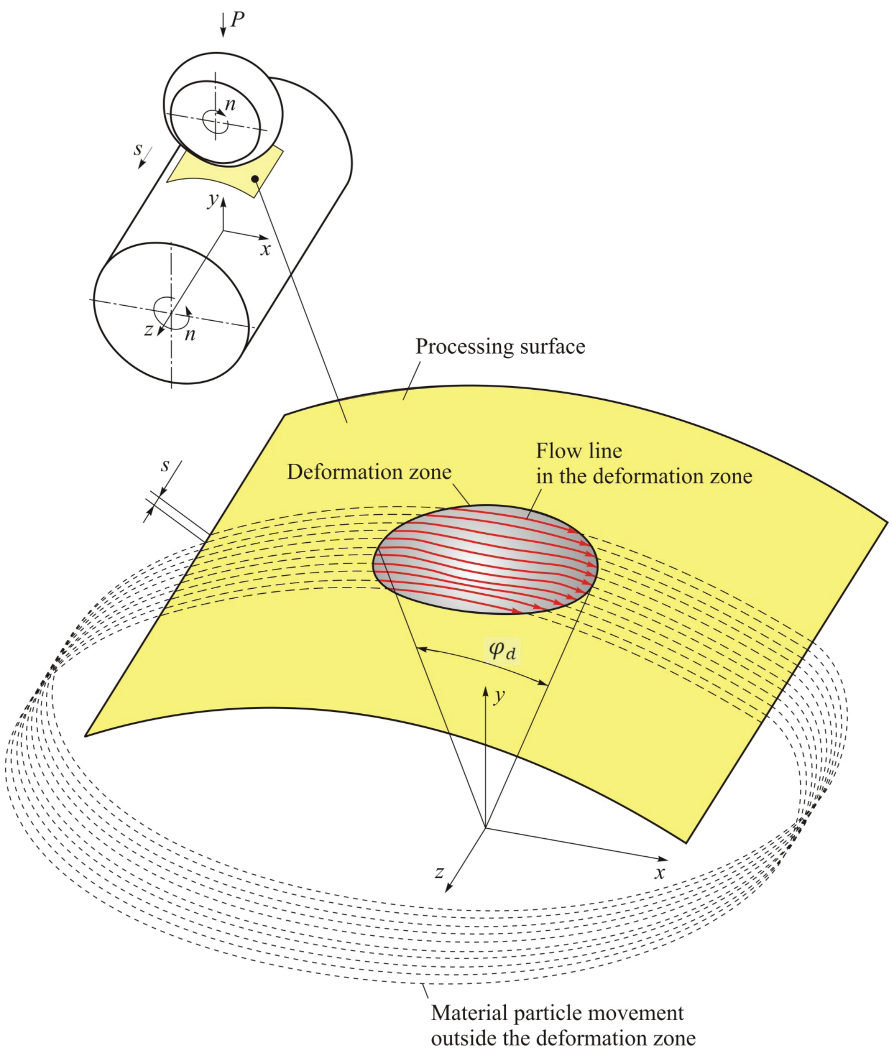

Fig. 1. The flow line while the material particle movement in the deformation area

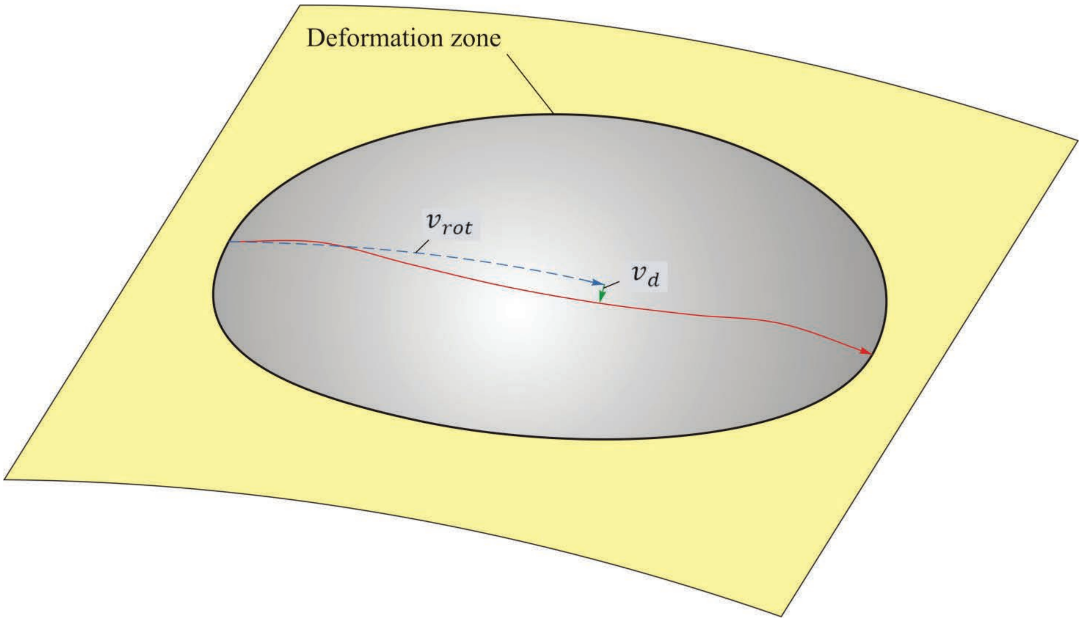

Fig. 2. Material particle displacement while moving along the *flow line* in the deformation zone

The roller profile changes when the strain plane is rotated, and in each time it is defined as the intersection line of the roller surface and the strain plane. At the time corresponding to the position of the strain plane 3 in Fig. 3, the tool profile is an arc of a circle. At the time corresponding to the positions of the strain plane 1 and 2, the intersection line is a fourth-order curve, the points coordinates of which are determined by the solution of a system of equations. One of it describes the equation of the roller surface, and the second – the strain plane.

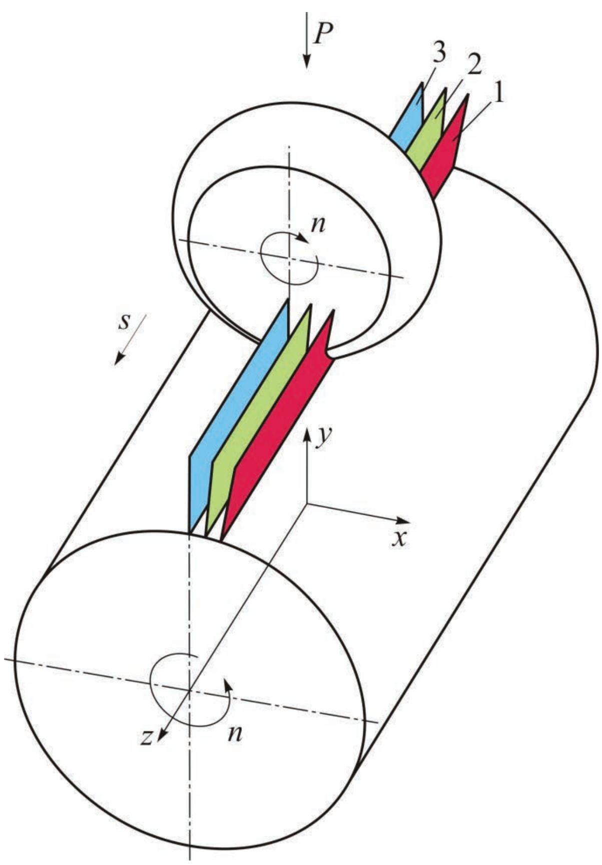

Fig. 3. Strain plane positions when the piece is rotated

The surface of the roller under consideration is a torus. If choosing a coordinate system in which the z axis coincides with the axis of generating circle rotation (Fig. 5), the equation of the surface will have the following form

$$\left(x^2 + y^2 + z^2 + R_r^2 - R_{pr}^2\right)^2 - 4R_r^2(x^2 + y^2) = 0, \quad (2)$$

where R_r is the rotation radius of the generating circle; R_{pr} is the roller profile radius (and the generating circle radius).

The part axis is parallel to the *z* axis and lies in the *yoz* plane, the strain plane passes through the part axis and is located at a certain angle α relative to the *yoz* plane. Then the strain plane equation for the x coordinate will have the following form

$$x = \tan\alpha(\Sigma R - y), \quad (3)$$

where ΣR is the distance from the axis of roller generating circle rotation to the part axis, determined by the sum of all radii

$$\Sigma R = R_r + R_{pr} + R_p, \quad (4)$$

where R_p is the part radius.

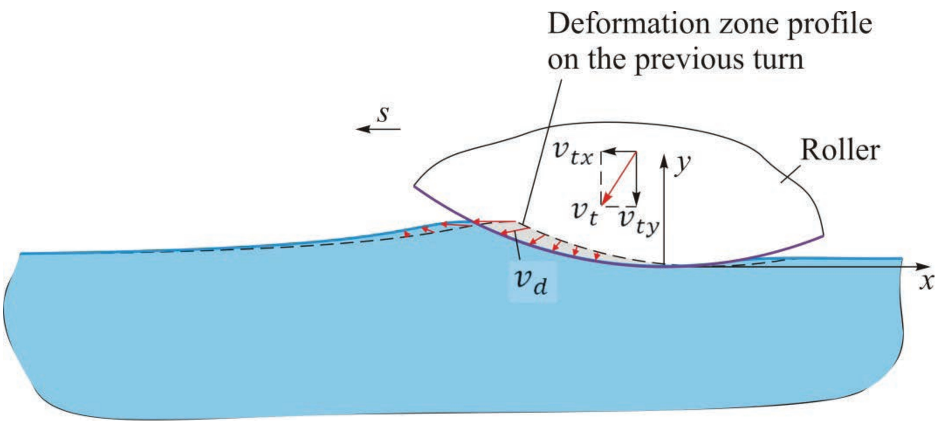

Fig. 4. Displacements in the strain plane while it is rotated

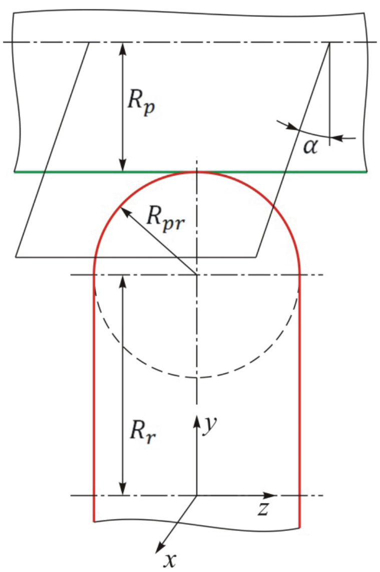

Fig. 5. Coordinate system for determining the intersection line of the roller surface and the strain plane

Substituting the deformation plane equation (3) into the roller surface equation (2) and introducing the notation will give

$$(z^2 + B)^2 - C = 0\,, \quad (5)$$

where

$$B = A + R_r^2 - R_{pr}^2, \quad (6)$$

$$C = 4AR_r^2, \quad (7)$$

$$A = y^2(1 + \tan^2 \alpha) + \Sigma R(\Sigma R - 2y)\tan^2 \alpha. \quad (8)$$

Assuming $\zeta = z^2$, from (5) we obtain the quadratic equation

$$\zeta^2 + 2B\zeta + (B^2 - C) = 0. \quad (9)$$

By solving this equation, we can define z as $\sqrt{\zeta}$.

Thus, the x and z coordinates of each intersection line point of the roller surface and the strain plane rotated by an angle α can be determined from the given value of the y coordinate using expressions (3) and (9).

To calculate the intersection line points coordinates in the coordinate system associated with the strain plane, the following expressions can be used:

$$x_{cp} = 0; \quad (10)$$

$$y_{cp} = y\cos\alpha; \quad (11)$$

$$z_{cp} = z. \quad (12)$$

Result and Discussion

To estimate the tool profile change during the strain plane rotation, the intersection lines points coordinates of the roller surface and the strain plane were calculated at R_{pr} =7 mm, R_r =8 mm, R_p =20 mm, ΣR=35 mm for the inclination angle of the strain plane α 0°, 2°, 4° and 6° (Fig. 6, Table 1).

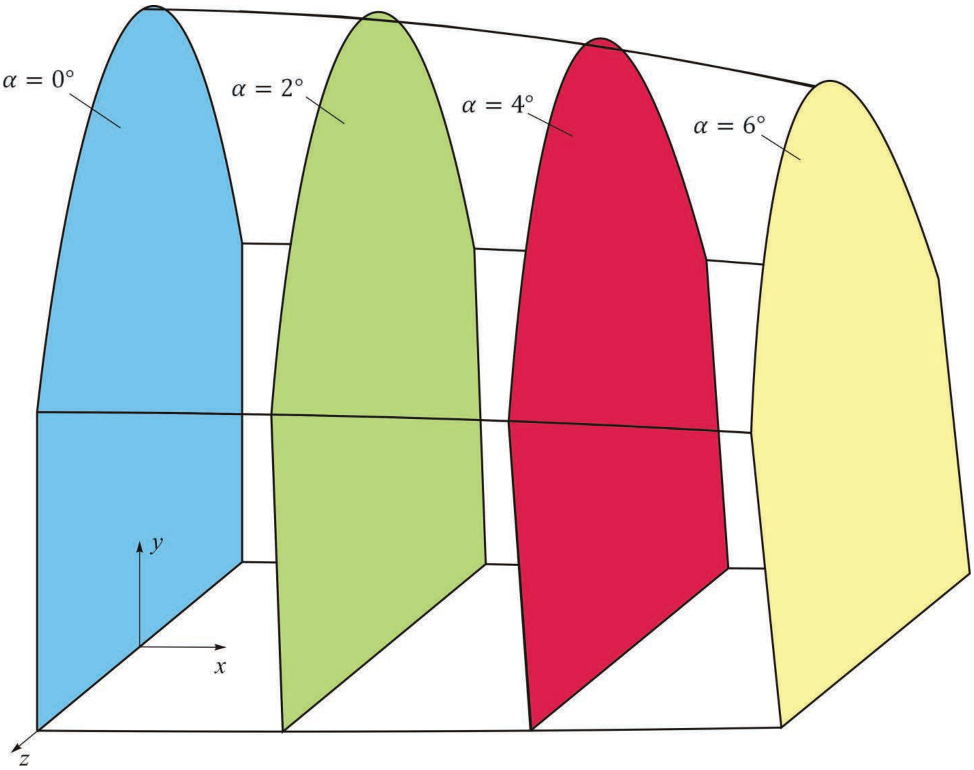

Fig. 6. The intersection lines of the roller surface and the strain plane while this plane is rotated

Table 1

Coordinates of the intersection lines points in the global coordinate system, mm

α = 0°			α = 2°			α = 4°			α = 6°		
x	*y*	*z*	*x*	*y*	*z*	*x*	*y*	*z*	*x*	*y*	*z*
0.00	14.00	3.61	0.73	13.99	3.57	1.47	13.97	3.47	2.22	13.92	3.30
0.00	14.10	3.43	0.73	14.09	3.40	1.46	14.07	3.30	2.20	14.02	3.11
0.00	14.20	3.25	0.73	14.19	3.21	1.46	14.17	3.10	2.19	14.12	2.91
0.00	14.30	3.05	0.72	14.29	3.01	1.45	14.27	2.90	2.18	14.22	2.69
0.00	14.40	2.84	0.72	14.39	2.79	1.44	14.36	2.67	2.17	14.32	2.44
0.00	14.50	2.60	0.72	14.49	2.55	1.44	14.46	2.41	2.16	14.42	2.16
0.00	14.60	2.33	0.71	14.59	2.28	1.43	14.56	2.13	2.15	14.52	1.83
0.00	14.70	2.03	0.71	14.69	1.97	1.42	14.66	1.79	2.14	14.62	1.42
0.00	14.80	1.66	0.71	14.79	1.59	1.42	14.76	1.36	2.13	14.72	0.82
0.00	14.90	1.18	0.70	14.89	1.08	1.41	14.86	0.69	2.13	14.74	0.64
0.00	15.00	0.00	0.70	14.97	0.00	1.41	14.90	0.00	2.13	14.77	0.00

The value of the deformation angle φ_d in this case is 12°, which is obviously greater than the actual values of φ_d during processing. Further, the coordinates of the points of the intersection lines were converted into the coordinate system of the deformation plane according to formulas (10)–(12) and reduced to the common coordinate y_{cp} for the upper point of the intersection line (Table 2). The intersection lines for the angles of inclination of the plane of deformation 0 ° and 6 ° are shown in Fig. 7.

Table 2

Coordinates of the intersection lines points in the coordinate system of the deformation plane, mm

$\alpha = 0°$		$\alpha = 2°$		$\alpha = 4°$		$\alpha = 6°$	
z_{cp}	y_{cp}	z_{cp}	y_{cp}	z_{cp}	y_{cp}	z_{cp}	y_{cp}
3.606	14.000	3.573	14.017	3.475	14.068	3.301	14.155
3.434	14.100	3.400	14.117	3.296	14.168	3.112	14.254
3.250	14.200	3.214	14.217	3.104	14.268	2.908	14.354
3.051	14.300	3.013	14.317	2.896	14.367	2.685	14.453
2.835	14.400	2.795	14.417	2.667	14.467	2.438	14.553
2.598	14.500	2.553	14.517	2.414	14.567	2.158	14.652
2.332	14.600	2.283	14.617	2.125	14.667	1.830	14.752
2.027	14.700	1.970	14.716	1.786	14.766	1.422	14.851
1.661	14.800	1.591	14.816	1.357	14.866	0.823	14.951
1.179	14.900	1.078	14.916	0.688	14.966	0.636	14.970
0.000	15.000	0.000	15.000	0.000	15.000	0.000	15.000

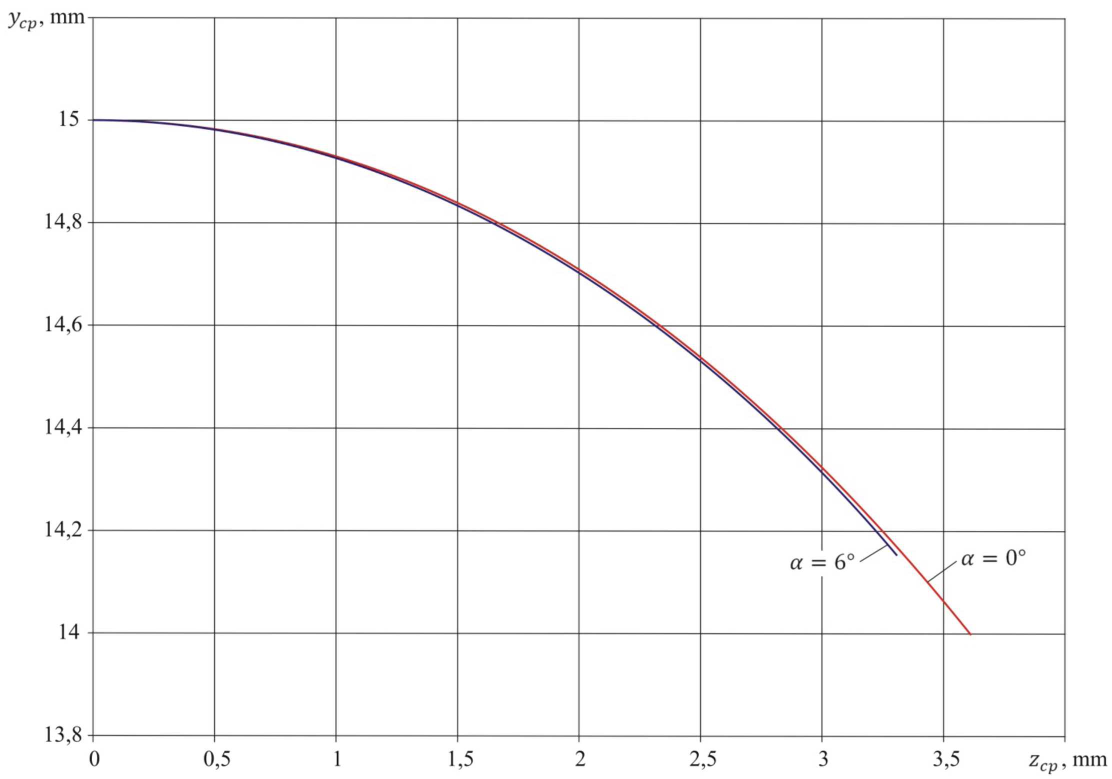

Fig. 7. The intersection lines of the roller surface and the deformation plane

The intersection lines of the roller surface and the strain plane are generally fourth-order curves, the coefficients of approximation of these lines by fourth-order polynomials of the form

$$y_{cp} = a_0 + a_1 z_{cp} + a_2 z_{cp}^2 + a_3 z_{cp}^3 + a_4 z_{cp}^4, \quad (13)$$

are shown in Table 3.

Table 3

Coefficients of intersection lines approximation of the roller surface and the strain plane by fourth-order polynomials

Coefficient	$\alpha = 0°$	$\alpha = 6°$
a_0	15	15
a_1	0.0009	0.0005
a_2	–0.0731	–0.0741
a_3	0.0011	0.001
a_4	–0.0006	–0.0006

Table 4 shows the calculated y_{cp} values by the specified z_{cp} values for the strain plane inclination angles of 0° and 6°, the deviation of the profile for 6° relative to the profile for 0°

$$\Delta_{cp} = \frac{y_{cp0^O} - y_{cp6^O}}{y_{cp0^O}}, \tag{14}$$

as well as the deviation of the profile for 0° from the forming part,

$$h = R_p - y_{cp0^O}, \tag{15}$$

this value characterizes the vertical size of the plastic wave, if the contact of the tool and the part begins at this value of z_{cp}.

Table 4

Changing the tool profile when the strain plane is rotated

z_p, mm	$y_{cp0°}$, mm	$y_{cp6°}$, mm	Δ_{cp}	h, mm
0.5	14.982	14.982	0.003 %	0.018
1.0	14.928	14.927	0.010 %	0.073
1.5	14.838	14.834	0.021 %	0.166
2.0	14.709	14.703	0.038 %	0.297
2.5	14.539	14.530	0.061 %	0.470
3.0	14.326	14.313	0.090 %	0.687

The dependence of the profile deviation on h is shown in Fig. 8. Analysis of the results obtained shows that even for $h = 0.6$ mm, which corresponds to the intense plastic flow of the metal during rolling, the change in the coordinates of the points of the roller profile when turning the deformation plane does not exceed 0.1 %.

With an increase in the diameter of the part, the diameter of the roller, as well as with a decrease in the wave height, the change in the roller profile decreases. This gives grounds to assert that modeling of rolling as a process of plane fractional deformation using a constant roller profile does not lead to any significant error.

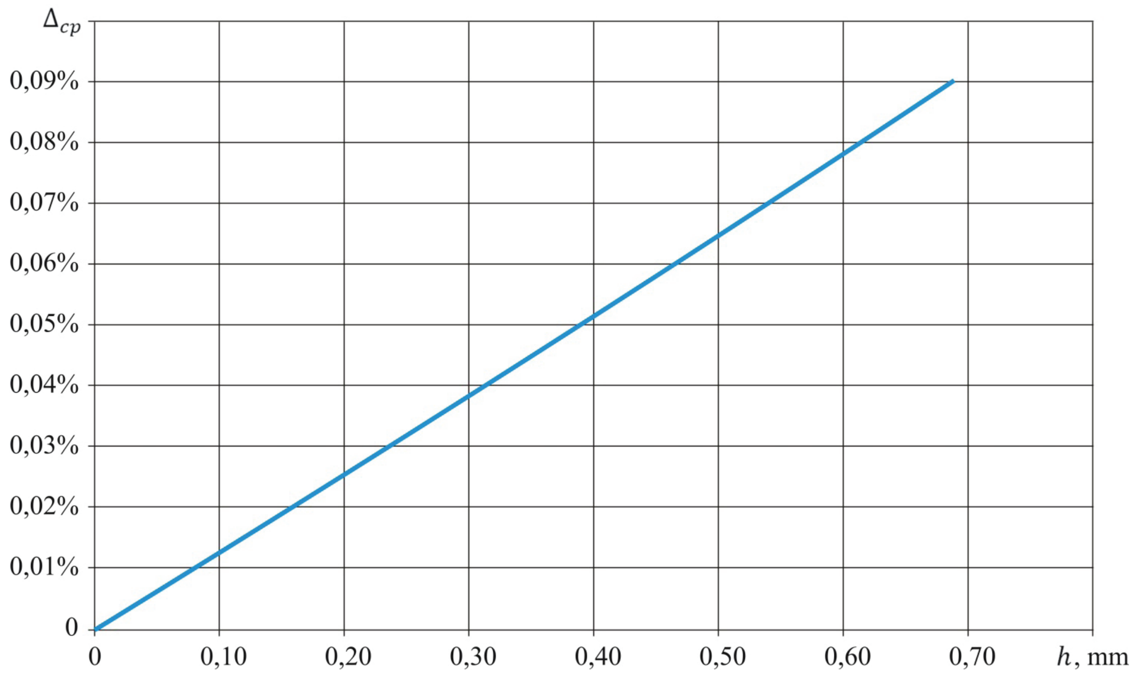

Fig. 8. Dependence of the profile deviation on the plastic wave height of the deformation zone

Conclusion

1. An analytical solution is obtained for determining the coordinates of the points of intersection of the roller surface and the deformation plane depending on the rotation angle of the deformation plane; the geometric dimensions of the part and the roller, as well as the angle of inclination of the deformation plane, are used as the initial data.

2. A relative change in the coordinates of the points of the profile lines in the plane of deformation during its rotation is obtained. It is shown that even in the rolling regimes accompanied by intense plastic flow, the change in coordinates does not exceed 0.1 %.

3. The results obtained show the possibility of using a constant roller profile when simulating rolling as a process of plane fractional deformation.

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Conflicts of Interest

The author declare no conflict of interest.