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Z. PATER*#

FEM ANALYSIS OF LOADS AND TORQUE IN A SKEW ROLLING PROCESS FOR PRODUCING AXISYMMETRIC PARTS

Skew rolling is a metal forming technique which can be used for producing stepped axles and shafts. This paper investigates seventeen cases of rolling at varying process parameters by the finite element method. As a result, it is possible to determine the effect of the forming angle α , skew angle Θ , linear velocity of the chuck, v , billet temperature, T , rotational speed of the rolls, n , reduction ratio, δ and friction factor, m , on axial load (acting on the chuck), radial load (acting on the roll in the radial direction) and torque. The results will be used when designing a laboratory stand for skew rolling which will be constructed at the Lublin University of Technology.

Keywords: FEM, skew rolling, load, torque

1. Introduction

Axisymmetric parts such as stepped axles and shafts are widely used in automotive, railway and machine-building industries. Nowadays these parts are produced by metal forming techniques such as open die forging, die forging, rotary forging and cross wedge rolling [1-3]. Nonetheless, new alternative methods for producing axisymmetric parts, particularly ones with large overall dimensions e.g. railway axles, are developed [4]. One of these methods is skew rolling by three tapered rolls, as shown in Fig. 1. In this process, the tools (rolls) are fixed (at an angle Θ) oblique to the workpiece axis and rotated in the same direction at the same speed. In addition, during the forming process, the rolls can travel linearly towards the workpiece axis, which enables adjusting the cross-sectional reduction of a shaft being formed. The linear motion of the rolls is synchronized with axial displacement of the chuck which holds the workpiece. If the motion of the rolls and chuck is set accurately, it is possible to manufacture products of various shapes using the same set of tools. It should be emphasized that the skew rolling process is performed at relatively low loads and torques, which means reduced energy consumption of this manufacturing process [5-7].

The present paper investigates the effect of basic parameters of skew rolling on loads (axial load acting on the chuck and radial load acting on the roll) and torque. The investigation consists in performing numerical simulations of several cases of skew rolling by the finite element method.

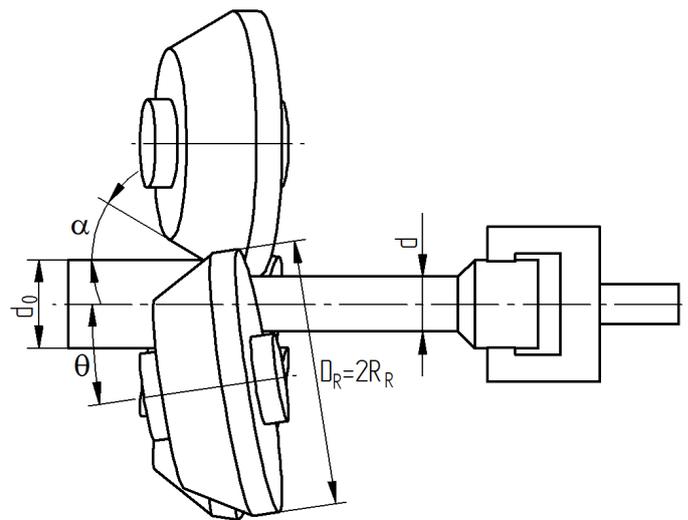


Fig. 1. Schematic design of the skew rolling process for producing a stepped shaft by three rolls

2. Model of the skew rolling process

To determine the effect of basic parameters of skew rolling on loads and torque, different cases of the skew rolling process for a stepped shaft were modelled numerically. The investigated stepped shaft is shown in Fig. 2, while Fig. 3 presents the numerical model of skew rolling at the start and end of the process. The model comprises three identical rolls and a billet with a diameter of 50 mm. The model does not include a chuck. Instead, the

* LUBLIN UNIVERSITY OF TECHNOLOGY, 36 NADBYSTRZYCKA STR., 20-618 LUBLIN, POLAND

Corresponding author: z.pater@pollub.pl

workpiece is fastened in fixed plane, while the axial motion of the chuck is replaced with axial feed of the rolls, which does not affect the kinematics of this process and facilitates the numerical simulation (axial load on the chuck is defined by a sum of axial loads acting on the rolls). This model of skew rolling was previously used by the author to investigate the skew rolling process for a axle [6] and a stepped shaft used in light trucks [8].

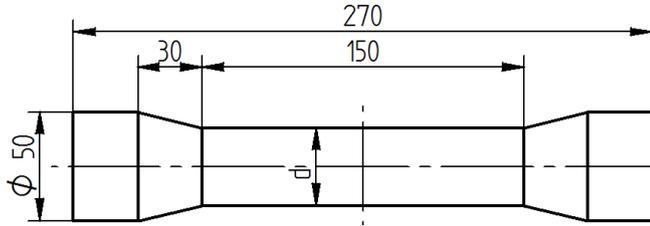


Fig. 2. Stepped shaft used in the analysis, where $d = 35.72$; 31.24 or 27.78 mm

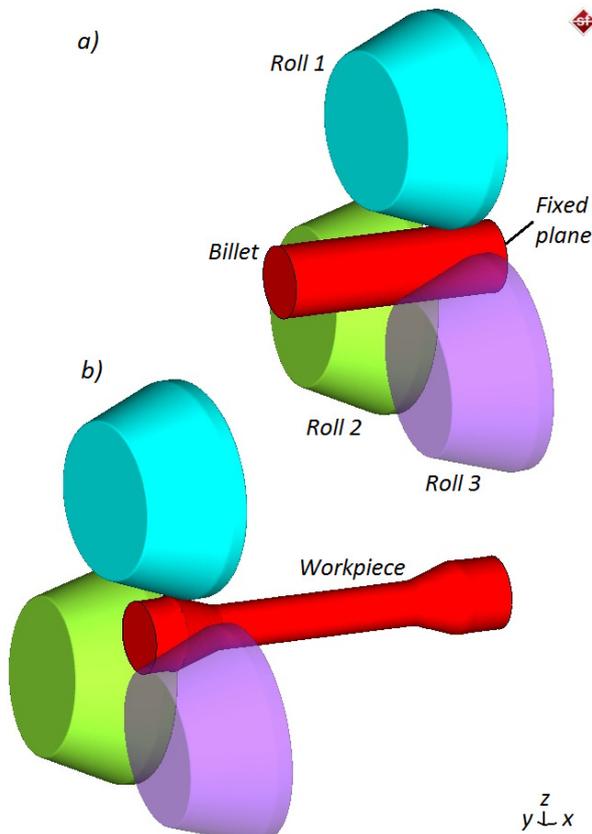


Fig. 3. Skew rolling process (Table 1; case 1) designed in Simufact. Forming: a) start of the process, b) end of the process

The shaft is described by a model of C45 steel expressed by:

$$\sigma_p = 4105e^{(-0.00355T)} \times \varphi^{(-0.00013T-0.00507)} \times e^{\left(\frac{-0.00002T-0.0281}{\varphi}\right)} \times \dot{\varphi}^{(0.00018T-0.02416)} \quad (1)$$

where σ_p is the yield stress [MPa], j is the effective strain, $\dot{\varphi}$ is the strain rate [1/s], T is the temperature [°C].

The skew rolling process is defined by the following variables (Fig. 1): the forming angle α , the roll radius R_R , the skew angle Θ , the reduction ratio δ (where $\delta = d_0/d$), the friction factor m , the velocity of the rolls (chuck) in the axial direction v , the billet temperature T and the rotational speed of the rolls n . There are only two constant parameters: the temperature of the tools (50°C) and the material-rolls heat transfer coefficient ($20 \text{ kW/m}^2\text{K}$). In total, 17 cases of skew rolling are investigated in this paper and their parameters are specified in Table 1.

The numerical model of skew rolling was designed using the commercial FEM-based simulation software suite Simufact. Forming v. 12. This software has been used by the author and the others researchers to investigate skew, cross and ring rolling processes [8-14], and the numerical results showed good agreement with experimental results. The results will be used when designing a laboratory stand for skew rolling which will be constructed at the Lublin University of Technology in the near future.

3. Numerical results

The numerical results demonstrate that in nearly all investigated rolling cases the produced stepped shaft has the desired axisymmetric shape (Fig. 3), with the exception of one case where the friction factor was low (Table 1; case 9). Here, the produced part is defective because its cross section is spirally twisted (Fig. 4). This results from the fact that the friction forces were too low to rotate the workpiece.

TABLE 1

Parameters applied in the numerical analysis of skew rolling by three tapered rolls

| No | α | R_R | Θ | δ | m | v | T | n |
|----|------------|--------|-----------|----------|-----|---------|----------------------|--------|
| 1 | 20° | 75 mm | 5° | 1.6 | 1.0 | 20 mm/s | 1150°C | 60 rpm |
| 2 | 15° | 75 mm | 5° | 1.6 | 1.0 | 20 mm/s | 1150°C | 60 rpm |
| 3 | 30° | 75 mm | 5° | 1.6 | 1.0 | 20 mm/s | 1150°C | 60 rpm |
| 4 | 20° | 75 mm | 3° | 1.6 | 1.0 | 20 mm/s | 1150°C | 60 rpm |
| 5 | 20° | 75 mm | 7° | 1.6 | 1.0 | 20 mm/s | 1150°C | 60 rpm |
| 6 | 20° | 75 mm | 5° | 1.4 | 1.0 | 20 mm/s | 1150°C | 60 rpm |
| 7 | 20° | 75 mm | 5° | 1.8 | 1.0 | 20 mm/s | 1150°C | 60 rpm |
| 8 | 20° | 75 mm | 5° | 1.6 | 0.8 | 20 mm/s | 1150°C | 60 rpm |
| 9 | 20° | 75 mm | 5° | 1.6 | 0.6 | 20 mm/s | 1150°C | 60 rpm |
| 10 | 20° | 75 mm | 5° | 1.6 | 1.0 | 10 mm/s | 1150°C | 60 rpm |
| 11 | 20° | 75 mm | 5° | 1.6 | 1.0 | 30 mm/s | 1150°C | 60 rpm |
| 12 | 20° | 75 mm | 5° | 1.6 | 1.0 | 20 mm/s | 1000°C | 60 rpm |
| 13 | 20° | 75 mm | 5° | 1.6 | 1.0 | 20 mm/s | 1100°C | 60 rpm |
| 14 | 20° | 75 mm | 5° | 1.6 | 1.0 | 20 mm/s | 1150°C | 30 rpm |
| 15 | 20° | 75 mm | 5° | 1.6 | 1.0 | 20 mm/s | 1150°C | 90 rpm |
| 16 | 20° | 100 mm | 5° | 1.6 | 1.0 | 20 mm/s | 1150°C | 60 rpm |
| 17 | 20° | 75 mm | 5° | 1.6 | 1.0 | 20 mm/s | 1150°C | 60 rpm |

Parts produced by skew rolling are characterized by a ring-like distribution of strains (Fig. 5). The highest strains occur on the workpiece surface (due to a rapid metal flow in the tangential direction caused by friction forces), while the lowest strains can

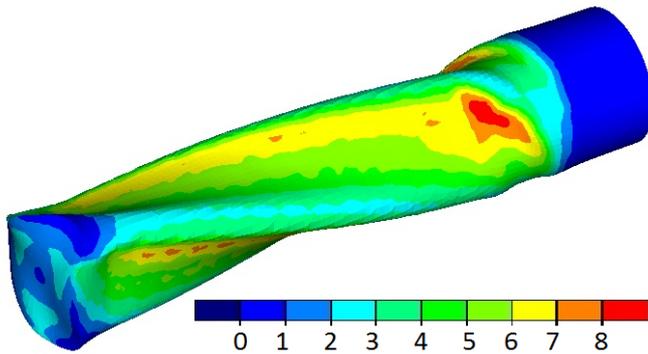


Fig. 4. Workpiece defect (and the distribution of effective strain) in skew rolling when $m = 0.6$ (Table 1; case 9)

be found in the axial (central) region of the part. The numerical results also reveal that the surface strains increase with increasing the reduction ratio δ , the friction factor m , the roll radius R_R and the rotational speed n . In contrast, with increasing the billet temperature T , the chuck velocity v and the forming angle α – the strains in the produced part decrease. The primary aim of the numerical analysis was to determine the effect of basic parameters of the skew rolling process on loads and torque. Figs. 6-8 show variations in the axial load (which acts on the chuck), radial load (which acts on the roll in the radial direction) and torque. The results demonstrate that in the initial stage of rolling, when the roll sinks in the material, the axial load is negative, which is caused by model simplification and replacing the chuck with fixed plane. As a result of axial compression of the material, the radial load on the roll increases and reaches its maximum value. Since this phenomenon will not take place in a real process, the analysis focuses on comparing loads and torque at steady state when these parameters are constant (e.g. the distributions shown in Figs. 6-8 for the forming time $t = 4-8$ s). The values of loads and torque are listed in Tables 2-9. Based on these results, the following observations can be made:

- The forming angle α (Table 2) has a visible effect on loads and torque in skew rolling. With increasing α from 15° to 30° the radial load decreased by 37.4%, while the torque decreased by 26.5%. At the same time, however, this led to increasing the chuck's drawing load by 183%.

TABLE 2

Effect of the forming angle α on load parameters at steady state when: $R_R = 75$ mm, $\Theta = 5^\circ$, $\delta = 1.6$, $m = 1.0$, $v = 20$ mm/s, $T = 1150^\circ\text{C}$, $n = 60$ rpm

| Load parameter | Forming angle α | | |
|-----------------|------------------------|---------------------|---------------------|
| | $\alpha = 15^\circ$ | $\alpha = 20^\circ$ | $\alpha = 30^\circ$ |
| Torque, Nm | 594.55 \pm 12.36 | 514.52 \pm 13.04 | 436.98 \pm 6.96 |
| Radial load, kN | 44.72 \pm 0.79 | 36.41 \pm 0.73 | 28.01 \pm 0.37 |
| Axial load, kN | 8.59 \pm 0.15 | 15.33 \pm 0.29 | 24.33 \pm 0.26 |

- The roll radius R_R (Table 3) is an important parameter due to its effect on torque, which is obvious given that the radius increases under the action of the forming force. A two-fold increase in R_R from 50 to 100 mm made the torque increase

by 43.2%, while the axial load decreased by 25.5%. At the same time, it was found that the radial load does not change if this parameter is changed.

TABLE 3

Effect of the roll radius R_R on load parameters at steady state when: $\alpha = 20^\circ$, $\Theta = 5^\circ$, $\delta = 1.6$, $m = 1.0$, $v = 20$ mm/s, $T = 1150^\circ\text{C}$, $n = 60$ rpm

| Load parameter | Roll radius R_R | | |
|-----------------|-------------------|--------------------|-------------------|
| | $R_R = 50$ mm | $R_R = 75$ mm | $R_R = 100$ mm |
| Torque, Nm | 406.60 \pm 6.16 | 514.52 \pm 13.04 | 582.33 \pm 8.45 |
| Radial load, kN | 36.14 \pm 0.60 | 36.41 \pm 0.73 | 34.45 \pm 0.48 |
| Axial load, kN | 18.15 \pm 0.29 | 15.33 \pm 0.29 | 13.53 \pm 0.16 |

- The skew angle Θ (Table 4) has a significant effect on torque and axial load, yet its impact on radial load is insignificant. With increasing the Θ angle from 3° to 7° , the torque increased by 10.5%, while the axial load decreased by 39.1%.

TABLE 4

Effect of the skew angle Θ on load parameters at steady state when: $\alpha = 20^\circ$, $R_R = 75$ mm, $\delta = 1.6$, $m = 1.0$, $v = 20$ mm/s, $T = 1150^\circ\text{C}$, $n = 60$ rpm

| Load parameter | Skew angle Θ | | |
|-----------------|---------------------|--------------------|--------------------|
| | $\Theta = 3^\circ$ | $\Theta = 5^\circ$ | $\Theta = 7^\circ$ |
| Torque, Nm | 478.89 \pm 9.65 | 514.52 \pm 13.04 | 529.35 \pm 7.29 |
| Radial load, kN | 35.07 \pm 0.69 | 36.41 \pm 0.73 | 36.17 \pm 0.45 |
| Axial load, kN | 19.53 \pm 0.35 | 15.33 \pm 0.29 | 11.90 \pm 0.10 |

- The reduction ratio δ (Table 5) plays a significant role in skew rolling with respect to load parameters. In general, with increasing δ the investigated load parameters increased too, which was undoubtedly caused by a higher material processing rate. When δ was increased from 1.4 to 1.8, the axial load increased by 47.4%, the radial load increased by 14.0%, and the torque increased by 8.6%.

TABLE 5

Effect of the reduction ratio δ on load parameters at steady state when: $\alpha = 20^\circ$, $R_R = 75$ mm, $\Theta = 5^\circ$, $m = 1.0$, $v = 20$ mm/s, $T = 1150^\circ\text{C}$, $n = 60$ rpm

| Load parameter | Reduction ratio δ | | |
|-----------------|--------------------------|--------------------|--------------------|
| | $\delta = 1.4$ | $\delta = 1.6$ | $\delta = 1.8$ |
| Torque, Nm | 480.91 \pm 4.65 | 514.52 \pm 13.04 | 522.45 \pm 14.73 |
| Radial load, kN | 33.24 \pm 0.31 | 36.41 \pm 0.73 | 37.89 \pm 0.92 |
| Axial load, kN | 11.71 \pm 0.12 | 15.33 \pm 0.29 | 17.26 \pm 0.34 |

- The rotational speed n (Table 6) is an important variable with respect to the loads and torques in skew rolling. On increasing the n parameter, all loads and torques clearly decreased. To give an example, when the rotational speed n was increased three-fold (from 30 rpm to 90 rpm), the torque decreased by 35.5%, the radial load decreased by 9.9%, while the axial load decreased by 19.1%.

TABLE 6

Effect of the rotational speed n on load parameters at steady state when: $\alpha = 20^\circ$, $R_R = 75$ mm, $\Theta = 5^\circ$, $\delta = 1.4$, $m = 1.0$, $v = 20$ mm/s, $T = 1150^\circ\text{C}$

| Load parameter | Rotational speed n | | |
|-----------------|----------------------|--------------------|-------------------|
| | $n = 30$ rpm | $n = 60$ rpm | $n = 90$ rpm |
| Torque, Nm | 665.03 \pm 10.82 | 514.52 \pm 13.04 | 429.21 \pm 7.13 |
| Radial load, kN | 37.61 \pm 0.31 | 36.41 \pm 0.73 | 33.90 \pm 0.61 |
| Axial load, kN | 18.40 \pm 0.12 | 15.33 \pm 0.29 | 14.89 \pm 0.12 |

- The friction factor m (Table 7) ensures that the skew rolling process runs correctly. If the friction factor is set too low, the rotational motion of the workpiece can be disrupted. Moreover, this phenomenon can be accompanied by a sudden increase (even by several times) in loads and torques (Table 1; case 9). In contrast, when the forming process runs stable, an increase in the friction factor makes the torque and radial load increase, while the axial load on the chuck decreases.

TABLE 7

Effect of the friction factor m on load parameters at steady state when: $\alpha = 20^\circ$, $R_R = 75$ mm, $\Theta = 5^\circ$, $\delta = 1.4$, $v = 20$ mm/s, $T = 1150^\circ\text{C}$, $n = 60$ rpm

| Load parameter | Friction factor m | | |
|-----------------|---------------------|-------------------|--------------------|
| | $m = 0.6$ | $m = 0.8$ | $m = 1.0$ |
| Torque, Nm | 1545.06 \pm 15.04 | 459.08 \pm 8.23 | 514.52 \pm 13.04 |
| Radial load, kN | 55.14 \pm 0.63 | 35.61 \pm 0.60 | 36.41 \pm 0.73 |
| Axial load, kN | 44.29 \pm 0.70 | 20.11 \pm 0.33 | 15.33 \pm 0.29 |

- The billet temperature T (Table 8) is a crucial variable which affects loads and torques in the skew rolling process. With increasing the temperature T the above parameters decrease, which is undoubtedly related with a higher plasticity of the material. The numerical results reveal that when the temperature T was increased from 1000°C to 1150°C , the torque decreased by 33.1%, the radial load decreased by 32.9%, while the axial load decreased by 35.2%.

TABLE 8

Effect of the temperature T on load parameters at steady state when: $\alpha = 20^\circ$, $R_R = 75$ mm, $\Theta = 5^\circ$, $\delta = 1.4$, $v = 20$ mm/s, $m = 1.0$, $n = 60$ rpm

| Load parameter | Temperature T | | |
|-----------------|--------------------------|--------------------------|--------------------------|
| | $T = 1000^\circ\text{C}$ | $T = 1100^\circ\text{C}$ | $T = 1150^\circ\text{C}$ |
| Torque, Nm | 768.86 \pm 8.07 | 585.14 \pm 8.66 | 514.52 \pm 13.04 |
| Radial load, kN | 54.25 \pm 0.51 | 41.32 \pm 0.57 | 36.41 \pm 0.73 |
| Axial load, kN | 23.65 \pm 0.24 | 17.57 \pm 0.18 | 15.33 \pm 0.29 |

- The chuck velocity v (Tab. 9) has a directly proportional effect on part production time. A three-fold increase in this variable shortened the time of forming by three times, thus undoubtedly increasing efficiency of the process. This did

not change the load parameters to any significant extent: the axial load increased only by 11.6% and the radial load decreased by 4.0%, while the torque increased by as much as 28.7%.

TABLE 9

Effect of the chuck velocity v on load parameters at steady state when: $\alpha = 20^\circ$, $R_R = 75$ mm, $\Theta = 5^\circ$, $\delta = 1.4$, $m = 1.0$, $T = 1150^\circ\text{C}$, $n = 60$ rpm

| Load parameters | Chuck velocity v | | |
|-----------------|--------------------|--------------------|-------------------|
| | $v = 10$ mm/s | $v = 20$ mm/s | $v = 30$ mm/s |
| Torque, Nm | 422.92 \pm 20.27 | 514.52 \pm 13.04 | 544.44 \pm 8.07 |
| Radial load, kN | 36.88 \pm 1.52 | 36.41 \pm 0.73 | 35.42 \pm 0.44 |
| Axial load, kN | 15.89 \pm 0.53 | 15.33 \pm 0.29 | 17.73 \pm 0.22 |

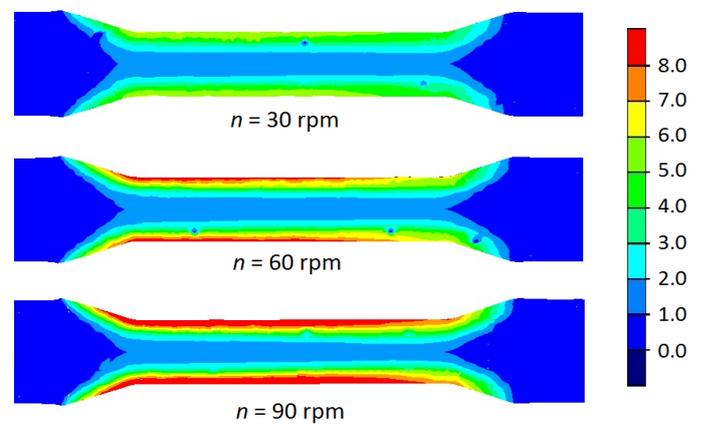


Fig. 5. Effective strains in longitudinal (axial) sections of shafts produced at different rotational speeds

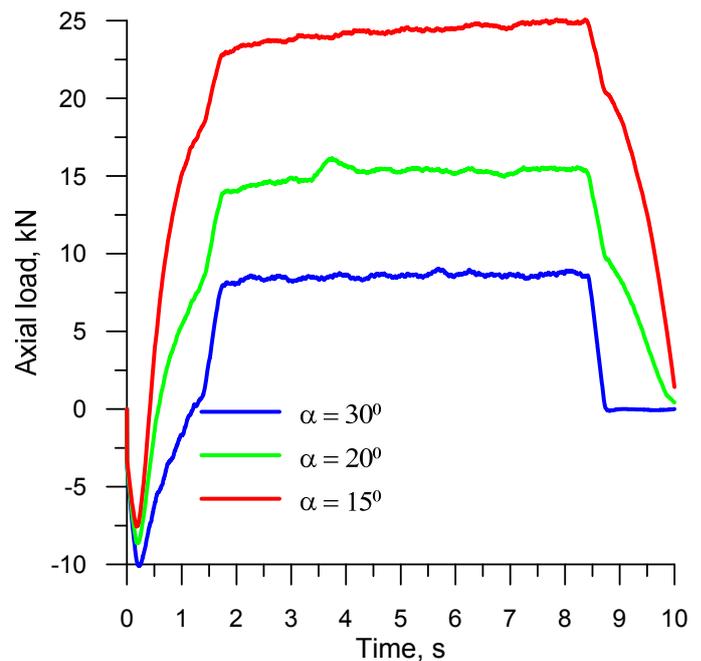


Fig. 6. Effect of the forming angle α on axial load in skew rolling processes

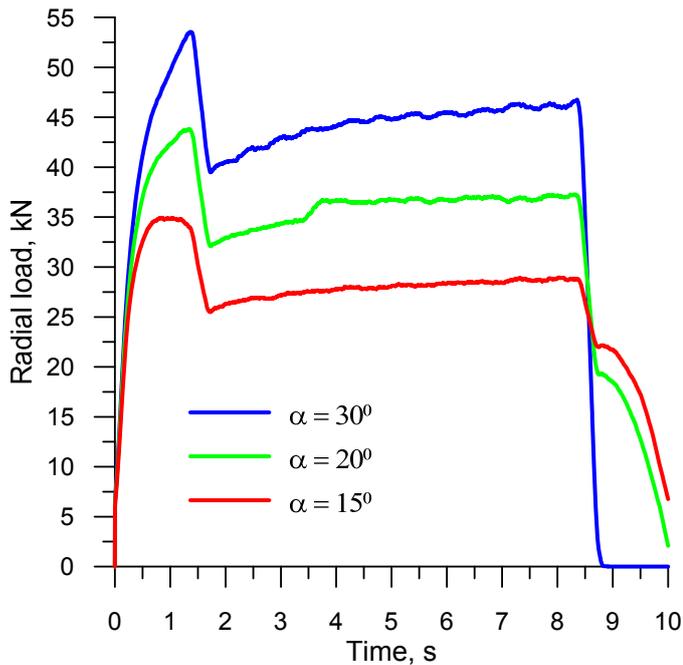


Fig. 7. Effect of the forming angle α on radial load in skew rolling processes

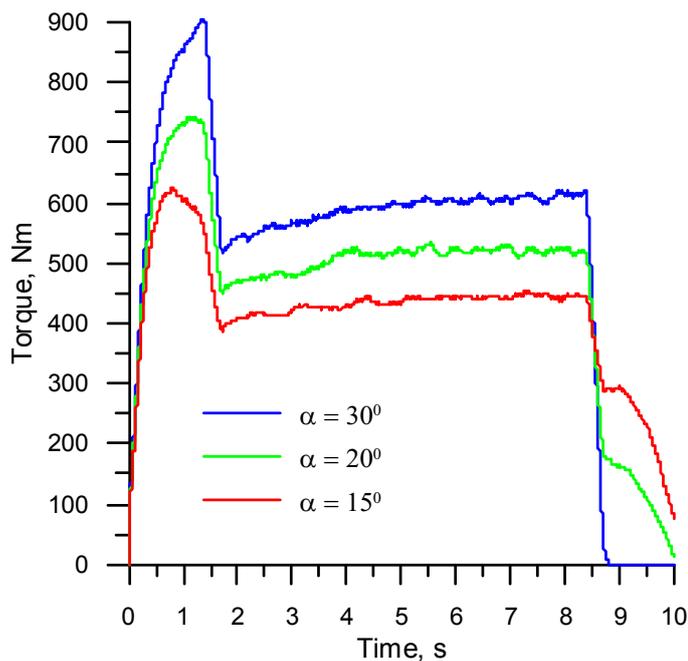


Fig. 8. Effect of the forming angle α on torque in skew rolling processes

4. Conclusions

Based on the numerical results for seventeen cases of the skew rolling process, the following conclusions have been drawn:

- skew rolling can be used to produce stepped axles and shafts;
- if the applied friction factor is too low, the skew rolling process can be disrupted by slipping, which causes product defect;

- parts produced by skew rolling are characterized by a ring-like distribution of strains; the highest strains occur on the surface of these parts, while the lowest ones can be found in the axial (central) zone;
- loads and torques in skew rolling strongly depend on parameters of the forming process;
- on increasing the axial load on the chuck in skew rolling, the forming angle α , the reduction ratio δ and the chuck velocity v increase, while the roll radius R_R , the skew angle Θ , the rotational speed of the rolls n , the friction factor m and the billet temperature T decrease;
- with increasing the radial load in skew rolling, the reduction ratio δ and the friction factor m increase, whereas the forming angle α , the rotational speed of the rolls n and the billet temperature T decrease (changes in the roll radius R_R , the skew angle Θ and the chuck velocity v have practically no effect on the radial load);
- with increasing the torque on the roll, the roll radius R_R , the skew angle Θ , the reduction ratio δ , the friction factor m and the chuck velocity v increase, while the forming angle α , the rotational speed n and the billet temperature T decrease.
- the results should be taken into consideration when designing a laboratory stand for skew rolling which will be constructed at the Lublin University of Technology.

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