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NUMERICAL ANALYSIS OF A SKEW ROLLING PROCESS FOR PRODUCING AXLE SHAFTS

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Abstract

The paper presents a numerical analysis of a skew rolling process for producing axle shafts for a motor truck. In this process, three forming tools (disc or conical rolls) located every 120° on the circumference of the workpiece are set askew relative to the axis of the workpiece and they are rotated in the same direction at identical speed. The rollers can converge or diverge (relative to the axis of the workpiece) depending on the applied cross sectional reduction of a shaft step. In addition, the spacing of the rolls is synchronized with axial displacement of the workpiece-holding chuck. An advantage of this process is its universality, because the same rolls can be used to form different products depending on the motion of the rolls and chuck. Based on the numerical results, we compared two skew rolling techniques, each using differently shaped tools. The results of effective strain, temperature, damage function as well as loads and torques demonstrate that skew rolling is an effective method for producing elongated parts such as stepped axles and shafts.

Key words: skew rolling, axle shafts, FEM, metal forming

1. INTRODUCTION

Stepped axles and shafts (including hollow shafts) are widely used in machine building, automotive and railway industries. Elements of this type are nowadays mainly produced by machining and metal forming methods such as die forging, rotary forging, extrusion and cross wedge rolling (Lange, 1985; Pater, 2014a).

Among the above methods, it is worth drawing particular attention to cross wedge rolling (CWR) which – due to its numerous advantages (high efficiency, relatively low material consumption, eco-friendliness) – is becoming more and more popular. Nonetheless, this method is also characterized by certain limitations resulting from, among others, the fact that long parts are difficult to form. In such a case, the length of the forming tools (wedges) is significantly increased, which means higher overall dimensions of the rolling mill and longer manufacturing times. This can be best illustrated by an example of forming a motor truck axle shaft shown in figure 1. According of research performed by (Zhao & Lu, 2012), a semi-finished product of this type can be produced by CWR based on the multi-wedge rolling method wherein a part is formed by a few pairs of wedges simultaneously (Zhao et al., 2011; Zhou et al., 2014; Sun et al., 2012; Shu et al., 2012; Pater, 2013). However, the production of such parts requires the use of large-size rolling mills. For instance, according to (Zhao & Lu, 2012), the axle shaft shown in figure 1 can be formed by a rolling mill which has 1000 mm diameter rolls and enables running the forming process at a radial load of up to 1 MN and a torque of up to 390 kNm. In addition, the reduced tooling length in CWR means a more complicated shape of the tools (the design of the extreme wedges must take account of the product's elongation resulting from action of the central wedges) and a significant increase in loads and torques, both of which often exceed acceptable ranges for

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machines operated under industrial conditions. Given the above aspects, it must be stressed that there are continuous attempts at developing new effective metal forming methods for producing long axles and shafts.

disc-shaped or conical. In this process, the rolls are mounted askew, at an angle θ (in the investigated case, the angle θ is 7°) relative to the axis of the workpiece. The rolls are rotated at identical speed in the same direction. In addition, they can converge

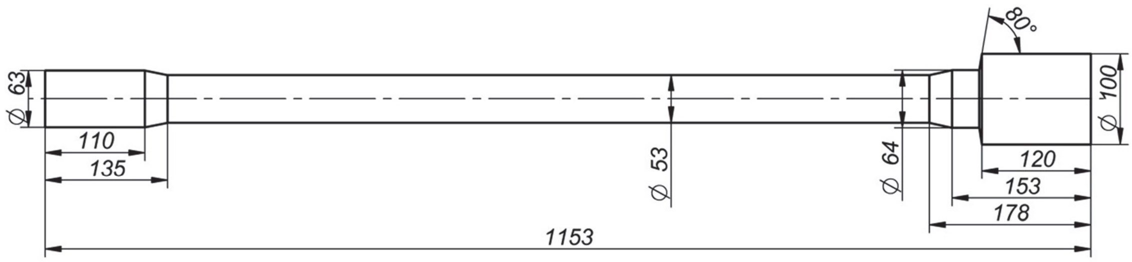

Fig. 1. *Schematic of a motor truck's axle shaft used for numerical analysis.*

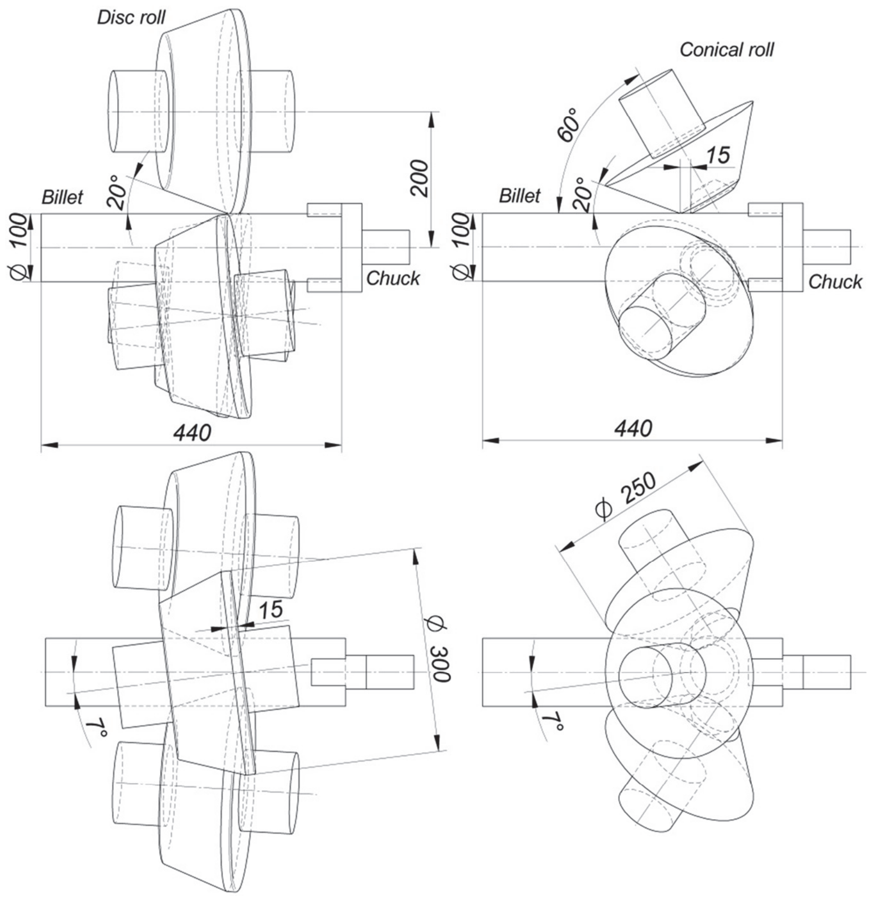

Fig. 2. *Schematic designs of the investigated skew rolling processes based on the use of three rolls; the figure also shows the most important dimensions.*

This paper focuses on a skew rolling method performed by means of three forming rolls. The rolls can be disc-shaped or conical, as shown in figure 2. It seems that this forming method is suitable for effective production of long axi-symmetric parts.

2. PRINCIPLE OF SKEW ROLLING WITH THREE ROLLS

Figure 2 shows a schematic design of the skew rolling process by three rolls which can be either

and diverge (towards the axis of the billet) depending on the desired cross sectional reduction of the shaft step. The spacing of the rolls is synchronized with axial displacement of the chuck in which the workpiece is mounted. The end face of the conical rolls has grooves enabling the rolls to cut into the material during forming. Moreover, both types of rolls are equipped with sizing surfaces (15 mm in width) to ensure that the cylindrical regions of the part have higher manufacturing accuracy.

The above method for forming axles and long shafts was described by (Sor, 1960). The spacing of the rolls was controlled by means of a template. However, due to the developments in control and automatics, the motion of the rolls and the chuck can now be synchronized numerically. It must be stressed that one pair of rolls can be used to form different parts, as their shape will only depend on the way in which the motion of the rolls and chuck is programmed.

3. NUMERICAL MODEL OF THE SKEW ROLLING PROCESS FOR AN AXLE SHAFT

To investigate technological potential of skew rolling, we performed a numerical analysis of the skew rolling process for an axle shaft illustrated in figure 1. This type of shaft is used in motor trucks and its length is about 11 times larger than its maximum diameters, while the diameter of the basic step is about two times smaller than its maximum diameter.

el does not include a chuck; instead, the surface end of the billet is fixed while the chuck's axial motion is replaced by axial feed of the rolls (this does not change the kinematics of this process yet it facilitates the numerical simulation). During the forming process, the rolls are rotated in the same direction at the identical rotational speed set to 60 rev/min (disc rolls) or 90 rev/min (conical rolls), and they move linearly in an axial direction (with the speed v_x) and relative to the axis of the billet (with the speed v_r). The variations in the rotational speed of the rolls resulted from their different dimensions. As can be seen in figure 2, the disc rolls have a higher diameter which additionally does not change as radically as is the case with the conical rolls. Furthermore, the shaft is made of C45 steel, the material model of which is described by the following equation:

$$\sigma_p = 4105 e^{(-0.003355T)} \varphi^{(-0.00013T-0.00507)} e^{\left(\frac{-0.00002T-0.0281}{\varphi}\right)} \dot{\varphi}^{(0.00018T-0.02416)}, \quad (1)$$

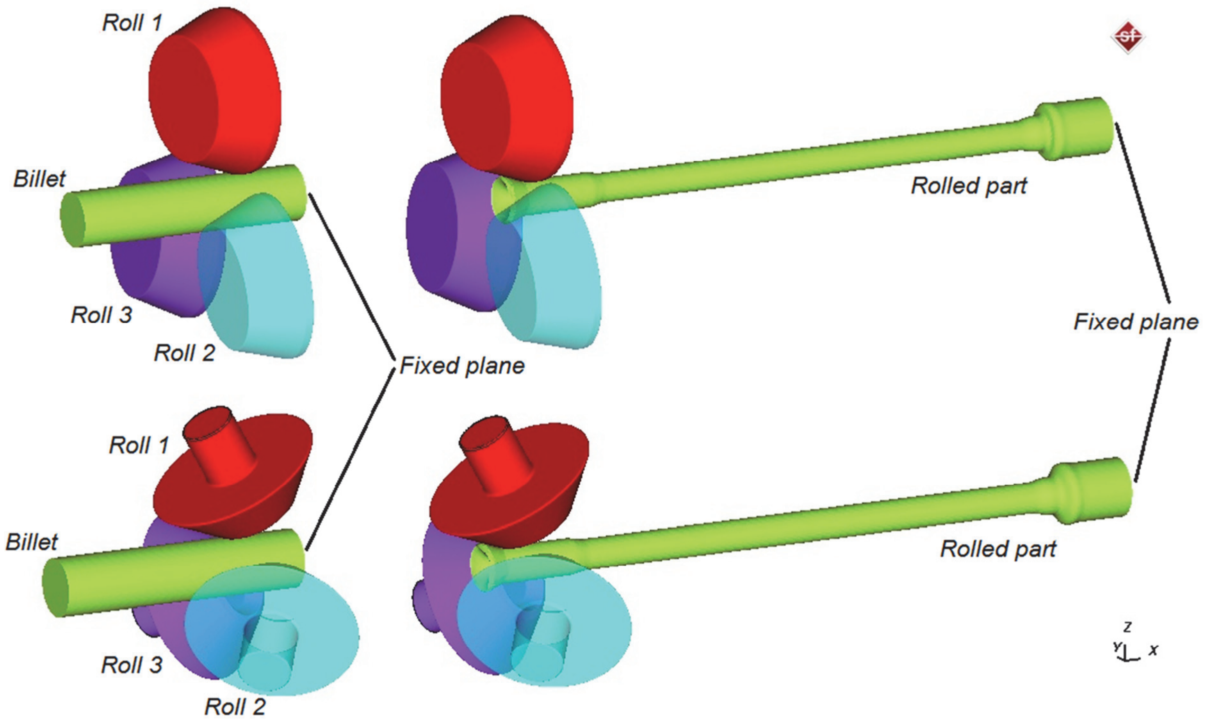

Fig. 3. Geometrical models of the investigated skew rolling processes based on the use of 3 disc rolls (top) or conical rolls (bottom); the start of the process is shown on the left and the end of the processes is illustrated on the right.

Figure 3 shows a numerical model of the skew rolling process performed with disc and conical rolls. The model consists of three identical rolls and a cylindrical billet that has an outside diameter of 100 mm and a length of 440 mm. This process mod-

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

The simulation takes into account the thermal effects: heat exchange between the billet and the tools (which the temperature was constant), the heat exchange between the billet and the environment, and it was assumed that 90% of the work of plastic deformation is converted into heat. As for other parameters used in the simulation, the friction factor on the material-tool contact surface was set to 0.95, the temperature of the rolls was 100 °C, the temperature of the billet was 1120 °C and the material-tools heat transfer coefficient was set to 20 kW/m^{2}K.

The numerical model was designed using the finite element method-based commercial simulation software Simufact.Forming v. 12. This program was previously used by (Pater & Tofil, 2007; Pater, 2005; Tomczak et al., 2013; Pater et al., 2013a; Pater et al., 2013b; Pater, 2014b; Pater, 2014c) for analysis of helical rolling and cross wedge rolling processes, the numerical results of which showed good agreement with the findings of experimental tests performed to verify the numerical results.

4. NUMERICAL RESULTS

The numerical results demonstrate that axle shafts can be produced by skew rolling with three rolls, both disc and conical ones. Figure 3 also illustrates changes in the part's shape after rolling. Individual steps of the shaft are formed one by one; the shaft's ends have allowance which must be removed (e.g. during machining). The allowance for removing the rolls from the forming zone (shown on the left side of the shaft - figure 3) can be decreased by reducing the billet's length. It is vital here that the shaft - despite its significant slenderness - does not undergo bending, which undoubtedly is caused by axial tensile stresses which occur in the region between the rolls and the chuck (fixing).

strains are evenly distributed in the section of the workpiece and that they increase with the distance from the axis of rotation of the workpiece. In addition to this, one can observe a clear dependence between the magnitude of strains and the reduction in diameter of the shaft step (an increase in the diameter reduction leads to an increase in strains). Higher strains occur in rolling by conical rolls, which should be attributed to a higher linear speed of the tools (rolls) resulting from the application of a higher rotational speed, which, in turn, leads to a more rapid tangent flow of the material.

The forming time for an axle shaft is relatively long as it is set to 35 s. Nonetheless, during the forming process, the tools are in local contact with the workpiece, which means that the temperature of the workpiece does not significantly decrease but remains within the range that is suitable for hot forming. This is proven by the distribution of temperature shown in figure 5. It must be stressed that the heat losses resulting from the fact that heat is carried away to the tools and environment are compensated for by the heat generated due to the exchange of friction work into work of deformation. In terms of the effect of the applied rolling methods, it must be observed that rolling by three disc rolls is better because in this process less heat is carried away from the workpiece. It should however be emphasized that irrespective of the rolling method applied, the temperature of the workpiece during the entire rolling process was suitable for hot forming.

Figure 6 shows the distribution of the damage function according to the Cockroft-Latham criterion. It can be seen that material cracking is more probable to occur in the surface region of the material

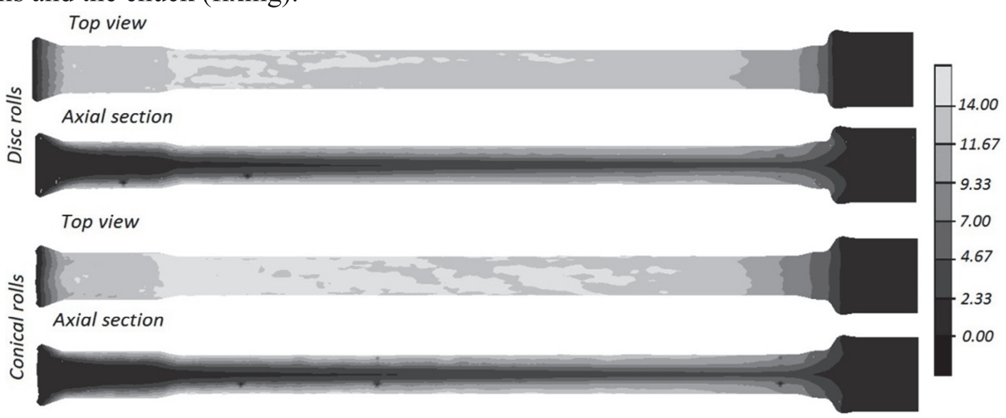

Fig. 4. *Distribution of effective strain in semi-finished products obtained from the investigated skew rolling processes.*

The distribution of the effective strain both on the surface and in the axial section of the shaft is illustrated in figure 4. It can be observed that the

rather than in its axial region. Such a distribution of the damage function undoubtedly results from rapid metal flow in a tangent direction. The flow increases with the distance from the axis of the workpiece and, similarly to the damage function, has the highest values on the workpiece surface. It must be noted that the damage function has higher values in rolling by conical rolls which are rotated at a higher speed. Given the results of material damage, it is probable that material scaling will occur on the surface of the axle shaft; however, this phenomenon should remain within the limits of allowance for mechanical working.

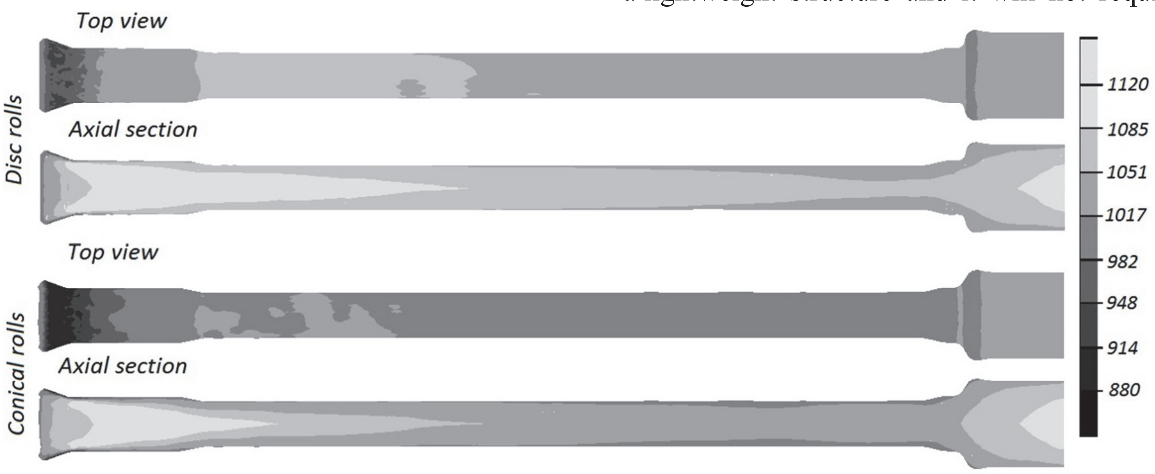

Fig. 5. Distribution of temperature (in °C) in semi-finished products obtained from the investigated skew rolling processes.

Fig. 6. Damage function (according to the Cockroft-Latham criterion) in semi-finished products obtained from the investigated skew rolling processes.

Interesting observations can be made with regard to force parameters in the rolling process, the distributions of which are given in figure 7. It can be observed that the chuck load (which is three times higher than the axial load on the roll) and the load on the rolls (radial load), as well as the torque strongly depend on cross sectional reduction. The higher the cross sectional reduction is, the higher the above parameters are. In this context, it is worth emphasizing that the maximum values of the chuck load (below 55 kN), radial load (below 160 kN) and torque (below 5000 Nm) are lower compared to the overall dimensions of the part being rolled. As for the effect of roll shape on force parameters, it can be observed that in this range a mean torque during forming was 3700 Nm for the disc roll and 1839 Nm for the conical roll. This means that the rolls must be driven by a power of 70 kW and 52 kW for the roll mill with disc rolls and conical rolls, respectively. Therefore, the rolling mill used in skew rolling can have a lightweight structure and it will not require high power as is the case with standard machines used in CWR processes.

5. CONCLUSIONS

The numerical results led to formulation of the following conclusions:

– the skew rolling method can be used to produce long parts such as stepped axes and shafts using both disc and conical rolls;

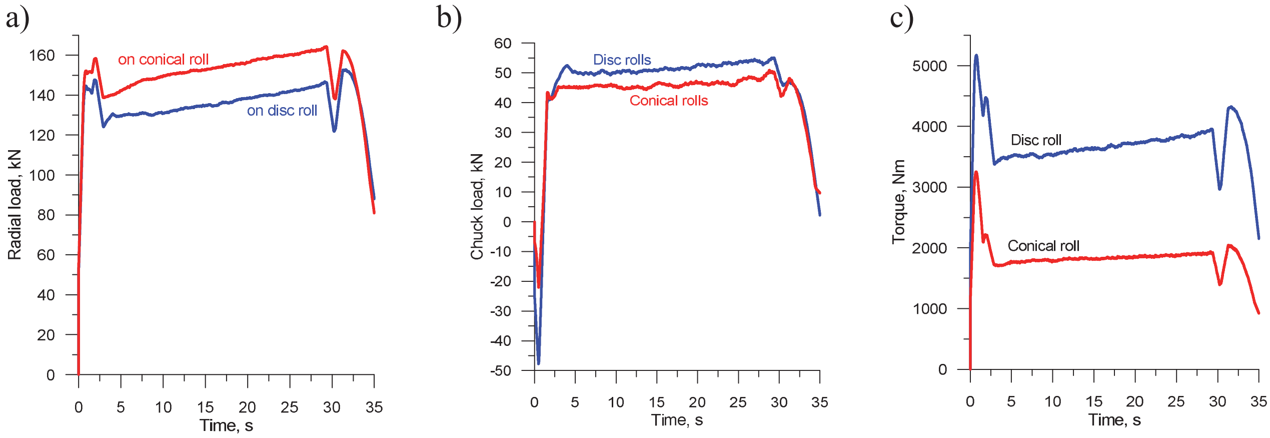

Fig. 7. *Force parameters in the rolling process: a) radial load acting on the roll in the investigated skew rolling processes for an axle shaft, b) chuck load in the investigated skew rolling processes for an axle shaft, c) torque acting on the roll in the investigated skew rolling processes for an axle shaft.*

– the skew rolling method is highly universal because it enables formation of parts with different shapes using one set of rolls;
– strains in the rolled part are distributed in layers (ring-shaped) and – typically of cross rolling processes - they have the highest values in the surface layers;
– despite a relatively long forming time, the material does not undergo excessive cooling which could hamper the forming process;
– force parameters (loads and torque) in skew rolling have small values compared to the dimensions of parts being formed;
– the research on formation of long axi-symmetric parts by skew rolling should be continued and expanded to include experimental tests.

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ANALIZA NUMERYCZNA PROCESU WALCOWANIA SKOŚNEGO PÓŁOSI SAMOCHODOWEJ

Streszczenie

W artykule przedstawiono analizę numeryczną procesu walcowania skośnego półosi samochodu ciężarowego. W proponowanym procesie walcowania skośnego trzy narzędzia kształtujące (rolki zbieżne lub stożkowe), rozmieszczone na obwodzie przedmiotu obrabianego co 120°, ustawione są skośnie względem osi wyrobu i obracają się z jednakową prędkością w tę samą stronę. Rolki mają możliwość zsuwania i rozsuwania się (w kierunku osi wsadu), w zależności od zastosowanej redukcji przekroju poprzecznego kształtowanego stopnia wałka. Przy tym rozstaw rolek

zsynchronizowany jest z przemieszczeniem osiowym uchwytu, w którym zamocowany jest koniec wyrobu kształtowanego. Zaletą omawianego procesu jest jego uniwersalność, objawiająca się tym, że korzystając z tych samych rolek można kształtować różne wyroby, których kształt wynikać będzie z odpowiednio zaprogramowanego ruchu rolek i uchwytu. Bazując na wynikach symulacji porównano dwie metody walcowania skośnego, w których zastosowano narzędzia o różnym kształcie. Bazując na wyznaczonych rozkładach intensywności odkształcenia, temperatury, funkcji zniszczenia oraz sił i momentów walcowania stwierdzono, że proces walcowania skośnego jest efektywna metodą wytwarzania odkuwek wydłużonych, w szczególności typu stopniowanych osi i wałów.

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