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Analysis of the Cross-Wedge Rolling Process of Toothed Shafts Made from 2618 Aluminium Alloy

*PATER Zbigniew**, *GONTARZ Andrzej*, *TOFIL Arkadiusz*
(Mechanical Department, Lublin University of Technology, Lublin 20-618, Poland)

Abstract: The paper presents the results of a thermo-mechanical analysis of the rolling two stepped shafts. One of the shafts has a toothed step with skew teeth, while the other has a worm winding in the shape of a trapezoidal screw. The shape of the rolling tools resembles that of the tools used in the Roto-Flo rolling method; yet unlike in Roto-Flo, the shafts are hot-rolled and no centres are used to stabilize the position of the workpiece during the forming process. For the calculations made with use of the DEFORM-3D process simulation system it has been assumed that the rolled shafts are made from 2618 aluminium alloy. As a result of the calculations made, it has been found that the toothed stepped shafts can be formed in one pass by means of the cross rolling process. Additionally, the temperature and strain distribution in the rolled product have been determined as well as some data concerning the forces which are necessary for the rolling process have been obtained.
Key words: cross rolling, toothed shafts, 2618 aluminium alloy, finite element method (FEM)
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0 Introduction

Stepped shafts are widely used in the machine-building and automotive industry. Many of them have toothed gears or worm windings. Products of that type are usually manufactured by means of machining semi-finished products obtained from such plastic forming processes as forging, extrusion or rolling.

Toothed gears can also be successfully produced by means of metal forming. The important methods of forming teeth include forging and rolling[1-3]. It should be observed that tooth forming is a separate forging operation which requires special machines and devices. The production process is more efficient if the number of operations is limited, which results in reducing the production time and cost as well as the number of machines and devices employed.

The production process of the toothed stepped shafts can be improved by combining the shaft and tooth forming processes. This could be done with use of the cross-wedge rolling (CWR) method, which has been successfully applied to manufacture products such as stepped axes or stepped shafts[4-8]. To make tooth forming possible, the wedge tools should be fitted with special pads.

The jaws, or the pads for rolling teeth should be placed at the end of the tools, and might be beyond the sizing zone. Their shape resembles that of the toothed jaws widely used in the process of forming teeth in cold rolling, also known as the Roto-Flo method. In contrast to Roto-Flo, the method suggested in the paper is based on a hot rolling operation, the tools used are shorter, and the billet is not supported on both sides in the centres.

The following study presents the results of a numerical analysis which demonstrates whether toothed shafts could be formed in hot rolling. Such a solution is optimal in terms of potential implementation costs; its adoption is also advisable due to the fact that flat wedge tools are widely used in many industrial fields.

1 Stepped Shaft with Skew Teeth

In order to verify the possibility of forming toothed shafts in cross rolling, the production process of this part shown in Fig. 1 has been analysed. Formed on the largest diameter of the step, the skew teeth of the produced stepped shaft are 2-mm module and they consist of 16 teeth with slope angle 30°. It has been assumed that the product is to be formed in a double

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***E-mail:** z.Pater@pollub.pl

configuration operation (2 pieces rolled at the same time), which is advantageous due to the equilibrium of axial forces occurring during the process.

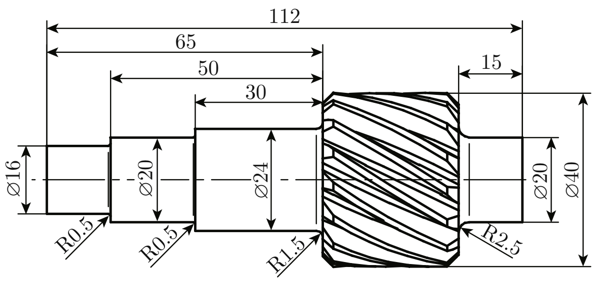

Fig. 1 Stepped shaft with skew teeth (mm)

The tools used for the rolling of the investigated toothed shaft are presented in Fig. 2, which shows a geometric process model. It should be observed that the simulation process has been limited to forming one shaft only. Three fundamental zones can be distinguished in the tools used to form the shaft: the wedging zone where the shaft steps are formed in a standard CWR operation; the tooth rolling zone where the teeth are formed on the assumption that the workpiece is not displaced in the axial direction; the cutting zone where the shafts are cut.

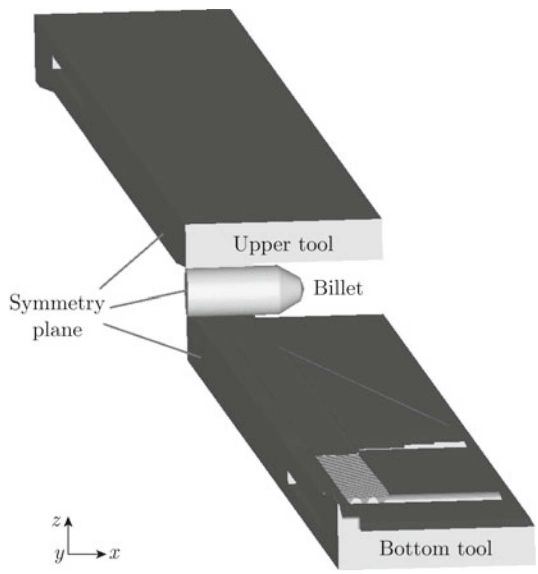

Fig. 2 Model of rolling a shaft with skew teeth as based on process symmetry

Some serrations have been made on the flanks of the forming wedges and knives to prevent the workpiece from an uncontrolled slip during the rolling process.

The numerical calculations of rolling the toothed shaft have been made by using the DEFORM-3D process simulation system. It has been assumed that the rolled billet has a diameter of 32 mm, it is made of 2618 aluminium alloy and is heated to the temperature of 480 °C. Also, it has been assumed that the rolled billet has specially made cone ends (Fig. 2). Thanks to the use of the cone-shaped billet it is possible to eliminate the process of cutting the final waste material. Consequently, the material consumption can be reduced, the forming tool can be shortened, and the rolling process can be made more efficient. The workpiece model has been taken from the template library of the applied software. The other calculation parameters include: the tool temperature of 150 °C, the heat exchange factor between the material and the tools of 12 kW/(m^2·K), the heat exchange factor between the material and the environment of 0.2 kW/(m^2·K), the tool movement speed of 0.15 m/s, and the friction factor on the contact surface of 1.0.

The rolled product is formed by means of tetrahedral elements (Fig. 3), whose number is increased in the course of the process. The complicated shape of the shaft has required a frequent mesh rebuilding during the calculations.

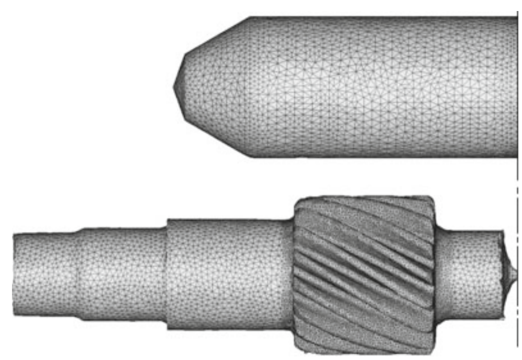

Fig. 3 Billet and a formed shaft with a clear division into elements

Figure 4 shows how the shape of the workpiece changes in the course of rolling. The figure also demonstrates that the rolled material rotates steadily and the stability of the rolling process is not constrained in any other way. It can therefore be claimed that the suggested forming method can be used to roll-stepped shafts with toothed gears.

Having analyzed the distribution of the tangential force which presses the tool and the radial force which is perpendicular to the tool sizing surface (Fig. 5), it can be claimed that the two forces assume their maximal values at the end of the stepped shaft forming phase. Next, in the course of rolling teeth, these forces decrease considerably and, finally, they virtually drop down to zero during the cutting operation.

Figure 6 presents the temperature distribution on the surface of the toothed shaft obtained from rolling. It can be observed that the temperature is within the

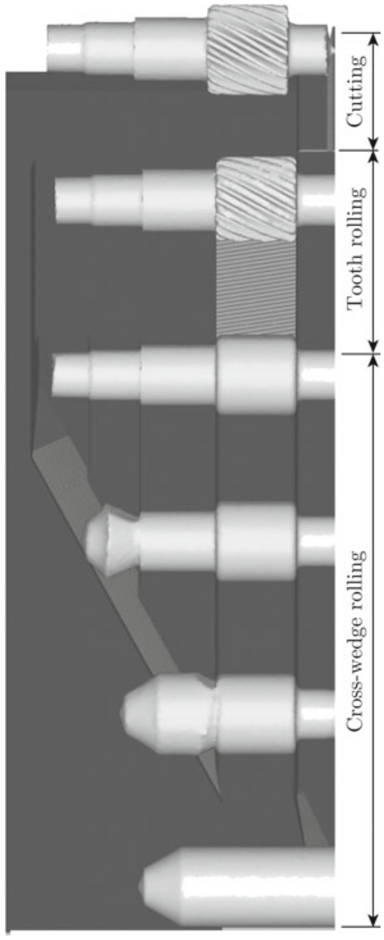

Fig. 4 Shape changes of a toothed shaft in cross rolling

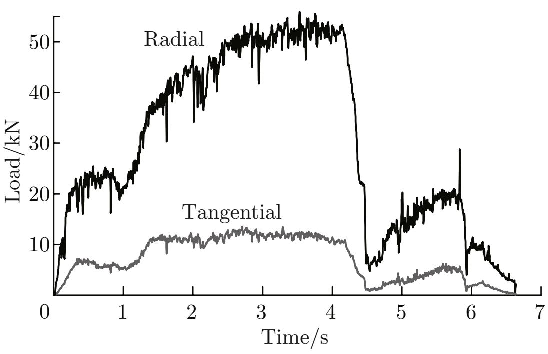

Fig. 5 Distribution of rolling force components in the process of toothed shaft forming

upper hot working range for 2618 aluminium alloy despite the considerable length of the forming process, which amounts to approximately 6.5 s. Any temperature drops that occur in the process due to heat being carried away to the tools are compensated for when plastic deformation and friction generate heat, which even lead to an increase in the material temperature.

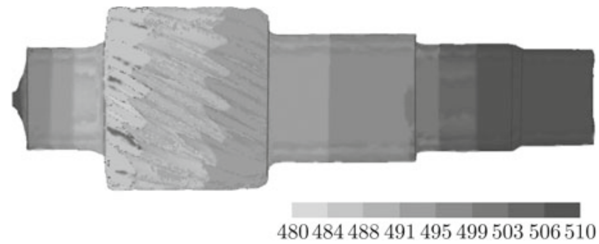

Fig. 6 Temperature distribution on the surface of a stepped shaft with skew teeth (℃)

2 Stepped Shaft with a Worm

The other investigation described in the present paper has been made to demonstrate the possibility of forming a stepped shaft with a worm in the shape of a trapezoidal screw (Fig. 7) by means of the CWR method. Similarly to the previous analysis case, it has been assumed that the billet has specially made cone ends to simplify the shaft production process (Fig. 8).

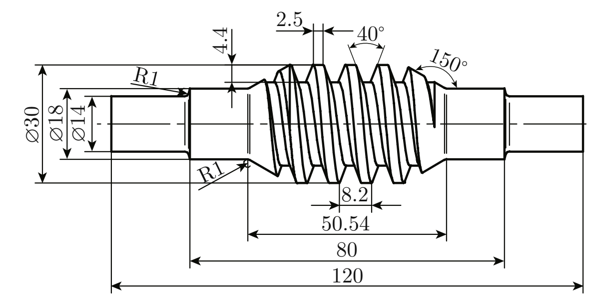

Fig. 7 Stepped shaft with a worm (mm)

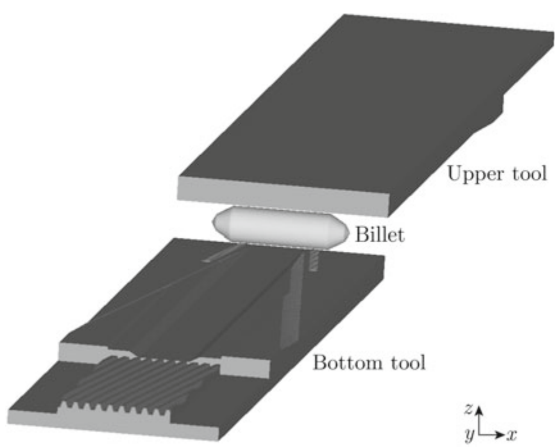

Fig. 8 Process model of rolling a stepped shaft with a worm

As illustrated in Fig. 7, the wedge tool used for producing the shaft consists of two elements. The first element is a standard wedge tool with two characteristic angles: forming angle $\alpha = 25°$ and spreading angle $\beta = 7.5°$. During the forming process the tool reduces the billet's diameter, which gives rise to cylindrical side steps of the shaft. The other tool element is a centrally placed jaw which forms the worm winding. The slope angle of the jaw grooves corresponds to the slope angle of the screw line.

Generated by the CAD system, a three-dimensional model of the wedge tools has been used to build a geometric model of the analysed rolling process. Apart from the tools, the geometric model of the rolling process also includes the billet (Fig. 8).

The numerical simulation of rolling the stepped shaft with a worm has been made in DEFORM-3D. The calculations are based on the process model shown in Fig. 8. Apart from the billet temperature which equals 440 ℃, the rest of the applied forming parameters are identical to the ones assumed for the process of the toothed shaft rolling.

The results obtained from the numerical calculations have confirmed that it is fully legitimate to apply the CWR method to form shafts with worms which have the shape of a trapezoidal screw. Figure 9 shows the shape changes in which the workpiece undergoes during rolling before it is formed into the stepped shaft with a worm. It can be observed that the rolling process is stable, as no uncontrolled slip occurs in the course of forming either the cylindrical shaft steps or the worm winding. The shape of the obtained product is correct.

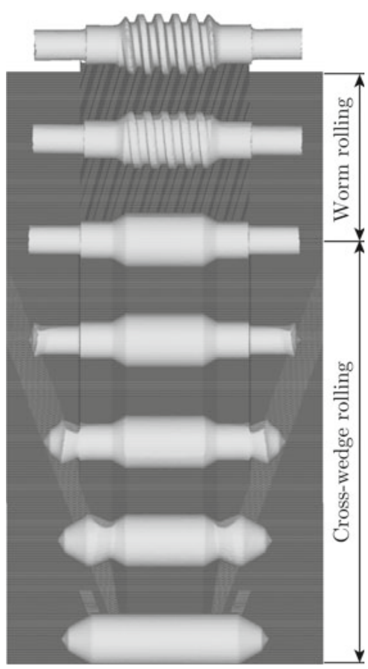

Fig. 9 Shape changes of a stepped shaft with a worm in cross rolling

Figure 10 shows the temperature and effective strain distribution in an axial cross-section of the shaft produced in rolling. The analysis of the data fully corresponds to the observations made in relation to the toothed shaft rolling operation.

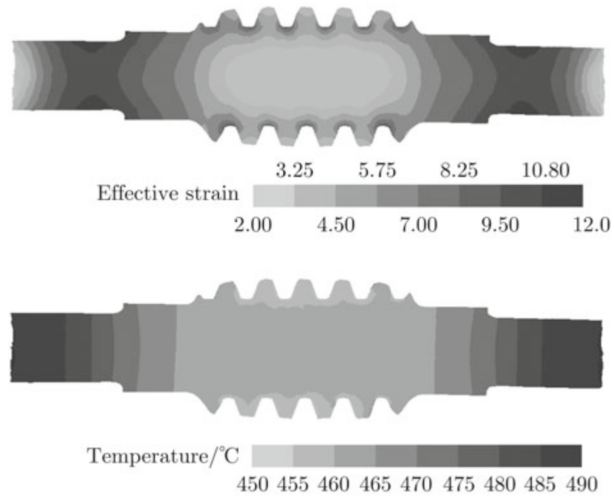

Fig. 10 Temperature and effective strain distribution in an axial cross-section of a stepped shaft with a worm

Figure 11 presents the distribution of the tangential, radial, and axial forces which occur during rolling. The calculation results have demonstrated that the forces appearing during the worm winding operation are approximately three times lower than the forces occurring in the process of rolling the side steps. It proves that cross wedge rolling mills have more power than it is required to form the worm winding. Such a situation probably results from limited material processing in the winding zone; it occurs only in the surface layers of the formed product. It should, however, be observed that during this rolling phase there occurs an additional axial force which may lead to undesirable workpiece displacement.

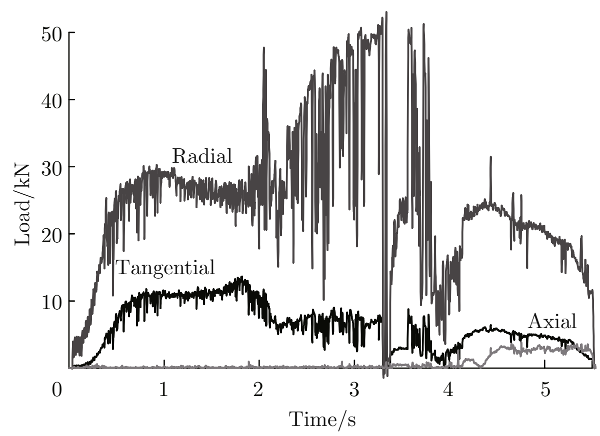

Fig. 11 Distribution of rolling force components in forming a stepped shaft with a worm

3 Conclusion

On the basis of the conducted numerical calculations, the following conclusions can be drawn. The CWR method can be used to form the stepped shafts with toothed gears and worms made from 2618 aluminium alloy. The shape of the tools employed for rolling teeth or worms is similar to that of the tools used in the popular Roto-Flo rolling method. The probability of disturbances which may occur during the process, such as uncontrolled slipping, metal cracking or workpiece necking, is very low and does not depend on the type of formed teeth. Despite the considerable length of the process, no drop in the material temperature occurs during the forming process. It is advisable to verify the above results by conducting laboratory or industrial tests.

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