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NUMERICAL ANALYSIS OF THE CROSS WEDGE ROLLING PROCESS (CWR) FOR A STEPPED SHAFT

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The paper presents the results of numerical modeling of a complex CWR process for producing a stepped shaft. The modeling was performed using the Finite Element Method (FEM) based commercial software Simufact.Forming. The numerical analysis enabled the determination of changes in shape of the workpiece, strain and temperature distributions, as well as variations in the forces acting on the tool. The numerical results demonstrate that personal computers can today be used to model even most difficult cases of the CWR process, where complex shapes of tools and thermal phenomena occurring during forming are taken into consideration.

Key words: forming, cross wedge rolling, stepped shaft, numerical modeling, FEM

INTRODUCTION

Cross wedge rolling (CWR) is a manufacturing technique in which products are formed by the action of wedge-shaped tools. The tools are mounted either on rolls or on flat or concave rolling machine plates. The CWR technology is used to produce axisymmetric parts, mainly stepped axles and shafts, as well as preforms for elongated press forged products.

Cross wedge rolling offers a number of benefits, including high production yield, effective material utilization, high strength properties of products, eco-friendliness of the process, low energy consumption and automatibility [1, 2]. Despite the above advantages, the CWR process does not, however, find due application in the production of machinery parts. This results from the fact that it is difficult to design a tool that would ensure that the process is correct, as changing angles of the tool to even a small degree can lead to uncontrolled slipping, necking (rupture) or material cracking. For this reason, the design of new CWR-based technologies is only undertaken by research teams affiliated with manufacturers of rolling mills. When it comes to complex-shaped products, however, even such teams arrive at final solutions via successive approximations, by the trail-and-error method. Hence, the design of tools that would ensure the production of required quality products is a time-consuming and expensive process, which is not, obviously, without effect on the number of new implemented technologies. As early as in 1993 Fu and Dean [3] predicted that the interest in the CWR technology would increase with the development of numerical techniques that enable the modeling of complex metal forming processes under a three-dimensional state of strain. Under such conditions, the correctness of the solution applied can be verified in the virtual space of a computer via numerical simulations. In the case of a failure, appropriate adjustments can be made to the design of the tools used in the simulation; the process is then simulated again until the desired result has been achieved.

The CWR process is one of the metal forming technologies that are very difficult to model numerically due to complex shapes of products, very high tool pitches (several times higher than product dimensions), problematic tool-material contact (slipping and material sticking may occur) and nonlinearities. This given, it is no wonder that the CWR process was not successfully modeled numerically by the finite element method (FEM) until the end of the twentieth century. The specialist literature on the subject offers a number of studies in which the CWR process was numerically simulated using commercial programs such as Ansys/LS-DYNA, DEFORM-3D, Forge3, MSC.SuperForm and MARC.AutoForge [4, 5].

NUMERICAL MODEL OF THE CWR PROCESS FOR STEPPED SHAFTS

Figure 1 shows the numerically simulated CWR process for producing a stepped shaft. It is assumed that the shaft will be formed by two rolls, each roll having a weight of 1 kilogram and a diameter of 700 mm. In the simulated process, end steps of the shaft are formed at the deformation ratio δ (i.e. the measurement of deformation in CWR, where $\delta = d_0 / d$; d_0 is the diameter of the billet, d is the diameter of the step being rolled) set equal to 2,45. Such a high value of diameter reduction cannot be achieved in one roll pass, so the forming process must be run in two operations: an intermediate-

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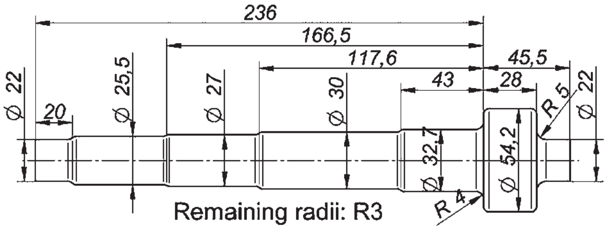

Figure 1 Stepped shaft produced by the CWR method

stage diameter must be formed prior to producing an intended final diameter.

Figure 2 shows the tool used in the CWR process for producing a stepped shaft. The figure also gives the overall dimensions of the tools as well as the forming angle α and spreading angle β. Owing to the shape of the shaft, it was necessary to leave an area of excess material for concavities (frontal funnels) that would form there in the course of rolling. The excess material would then be removed by cutting. On their flanks, the wedges had serrations, spaced by 3 mm at a depth of 0,4 mm, in order to increase the tangential forces that rotate the workpiece.

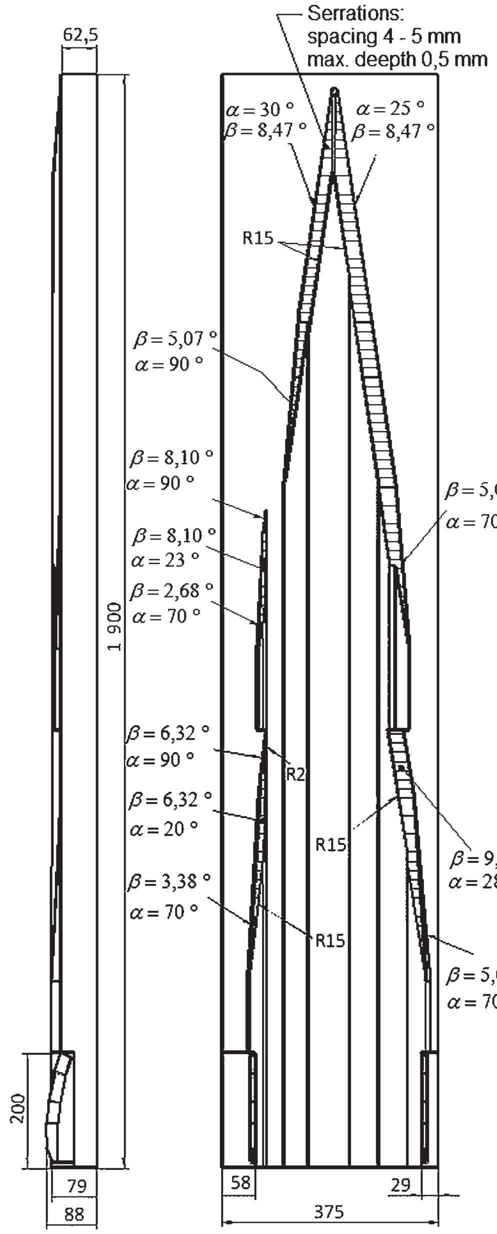

Figure 2 Developed view of the wedge tool used to roll a stepped shaft; linear dimensions are given in mm, while angular dimensions are given in degrees

Figure 3 shows the designed FEM model of the CWR process for producing a stepped shaft. The model consists of two wedge tools, two linear guides and one cylindrical billet with a diameter of 54 mm and a length of 134 mm.

The shaft was assigned the properties of C45 steel, whose material model and parameters were obtained from the database library of the Simufact software. The friction on the material-tool contact surface was described by the friction factor *m* that was set equal to 1.The rolls were rotated at a velocity of 9,55 rotations per minute, the billet was heated to a temperature of 1 170 °C, while the tools had a temperature of 250 °C. The material-tool heat exchange coefficient was set to 10 kW/m^{2}K, while the material-environment heat exchange coefficient was 0,2 kW/m^{2}K.

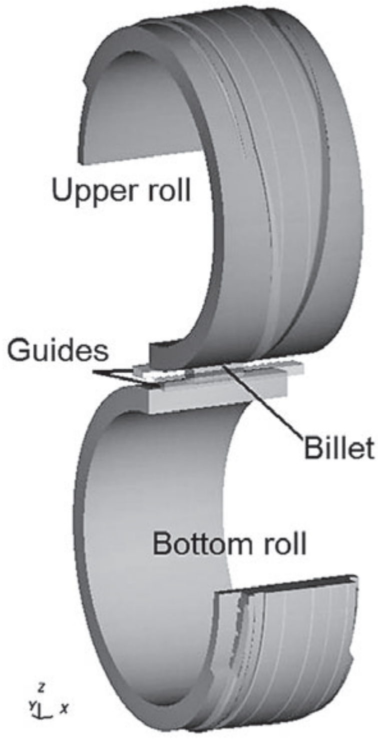

Figure 3 Geometrical model of the analyzed CWR process

SELECTED FEM ANALYSIS RESULTS

Thanks to the application of the FEM, it was possible to examine how the workpiece shape would change in the course of rolling the stepped shaft. The changes are illustrated in Figure 4. In the initial stage of the process, the wedge tools cut into the central part of the workpiece, thus reducing its diameter. After the forming of three steps of the shaft (the ones to the right of the shaft head), an intermediate-stage diameter (30 mm) of the shaft located to the left of the shaft head is rolled

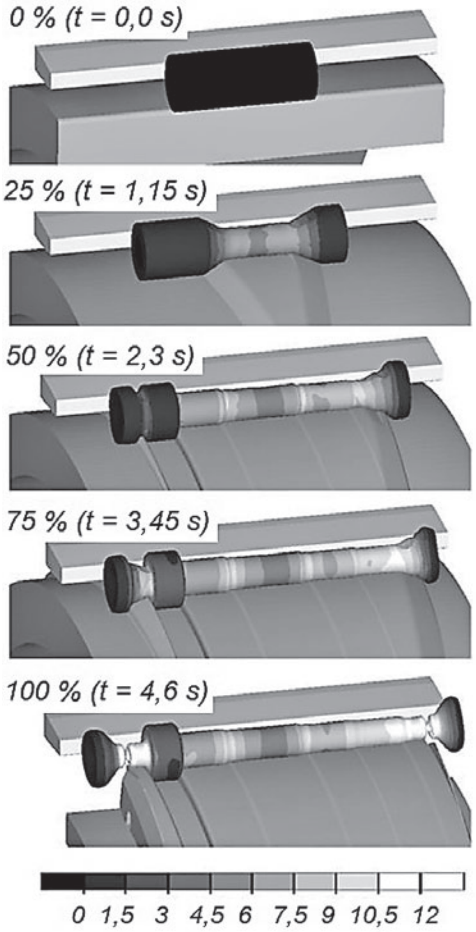

Figure 4 Changes in shape of the stepped shaft during the CWR process, along with the indicated effective strain versus time

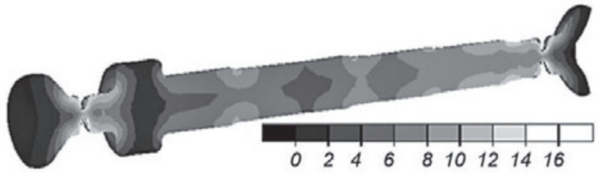

Figure 5 Effective strain distribution in the axial section of the produced stepped shaft

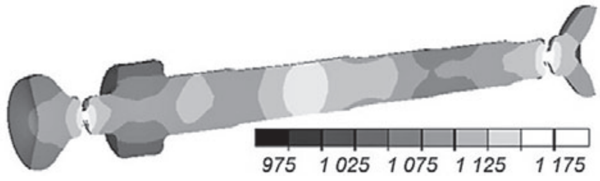

Figure 6 Temperature distribution (in °C) in the axial section of the produced stepped shaft

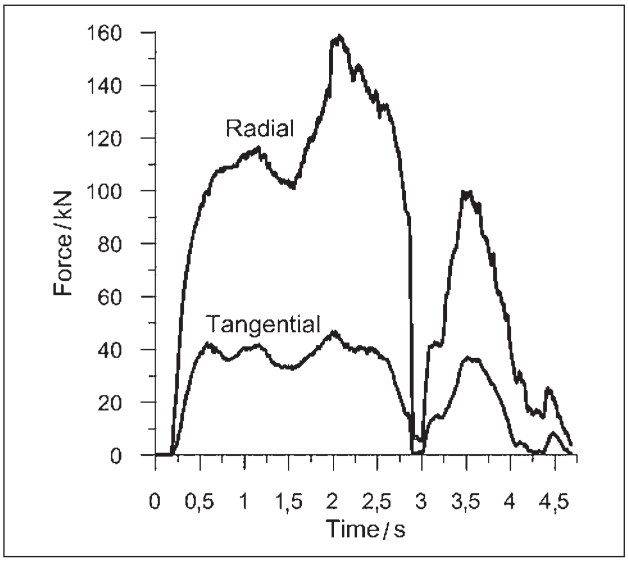

Figure 7 Forces acting on the tool in the process for forming a stepped shaft versus time

(for $t \approx 2,0$ s). The first operation takes 2,5 s; after that, the workpiece undergoes sizing over a short length of the tools ($t \approx 2,5 \div 2,9$ s). Next, the second operation begins where end steps of the shaft are formed; the minimum diameter of these steps is 22 mm. This operation takes $t \approx 3,8$ s. After that, the workpiece is subjected to sizing again ($t \approx 3,8 \div 4,2$ s) in order to remove all shape defects produced in the previous rolling operations. In the final stage of the CWR process ($t > 4,2$ s), areas of excess metal are removed by cutting.

Figure 5 illustrates the distribution of temperature in the shaft produced by the CWR process. Despite a relatively long forming time ($t \approx 4,5$ s) when the workpiece is in contact with the much colder tools ($T = 250$ °C), the temperature of the metal does not drop below the lower limit of the hot working temperature. The temperature is the lowest in the head of the shaft; this is due to the fact that this part of the workpiece gives up the heat to the rolls as it is rolled freely over their surface. In contrast, no significant decrease in temperature was observed for the steps formed. It can therefore be expected that in CWR the heat carried away to the tools is fully compensated for by the heat generated by deformation work and frictional work.

Figure 6 shows the distribution of effective strain in the produced stepped shaft. As can be seen from the data given in the figure, the strains increase as the diameter is being reduced and their values are relatively constant in particular steps of the shaft. At the same time, however, it can be observed that the effective strain is higher in the shaft head (the diameter of the head was not subjected to reduction). This results from rapid tangential flow of the metal (mainly due to torsion), a characteristic of the CWR process that generates redundant strain in the material.

Figure 7 illustrates the FEM-determined distributions of the radial force (perpendicular to the tool surface) and tangential force (parallel to the direction of rolling). Comparing the data given in Figures 4 and 7, it can be observed that the forces in CWR sharply decrease in the sizing stage, where their values are several times lower than the values observed during the forming of shaft steps or cutting excess material. The numerical results demonstrate that the tangential force is approximately 31,2 % of the radial force. This observation is consistent with the results of the research on forces in the CWR process given in the study [2].

CONCLUSION

The paper presented a thermo-mechanical model of cross wedge rolling for producing a stepped shaft. Using the model and commercial software Simufact Forming, the rolling process for the shaft was simulated numerically. As a result, changes in shape of the shaft as well as distributions of temperatures and strains in the shaft were determined. Also, variations in the forces acting on the wedge tool during the rolling process were determined. It has been found that the use of the Simufact Forming software and a personal computer is a viable way to model such complex metal forming processes as cross wedge rolling. Taking advantage of the potential offered by numerical modeling, it is hence demonstrated that new CWR-based manufacturing processes can be designed in a simpler manner, which can particularly be helpful for technologists who deal with the CWR process for the first time.

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Note: The professional translator for the English language is Magdalena Jung, Poland