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Arch. Metall. Mater., Vol. 61 (2016), No 2, p. 677–682

DOI: 10.1515/amm-2016-0115

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NUMERICAL ANALYSIS OF A SKEW ROLLING PROCESS FOR PRODUCING A STEPPED HOLLOW SHAFT MADE OF TITANIUM ALLOY Ti6Al4V

The paper describes a rolling process for a hollow Ti6Al4V alloy shaft used in driving systems of light trucks. The shaft is formed by skew rolling using three tapered rolls. The principle of this forming process was discussed stressing its universality due to the potential of applying it for forming various products by one set of rolls. The numerical analysis results (product shape progression in rolling, wall thickness distribution, effective strain, temperature and variations in loads and torques) confirm that the proposed technique can be used for producing hollow long shafts.

Keywords: skew rolling, hollow shaft, titanium alloy, numerical analysis

1. Introduction

Hollow axes and shafts are more and more widely used instead of their solid counterparts in order to reduce mass of structures [1]. These parts are mainly applied in the automotive and aircraft industries where fuel consumption and engine performance is strongly connected with structure mass [2, 3]. The use of hollow shafts in gears of cars reduces their mass by 15-30% [4]. Hollow axes and shafts are also applied in the automotive industry due to constructional reasons. For instance, they are used in dual clutches. These clutches have two coaxial output shafts. The output shaft of the first gear is placed inside the other output shaft, so the latter must be hollow.

Nowadays hollow parts are mainly produced by rotary forging [5]. They can also be manufactured by upset forging, extrusion or extrusion combined with welding or deep drilling [6-9]. In recent years, extensive research has been conducted to investigate the rotary compression method for producing hollow parts [10]. The costs of manufacturing hollow shafts are usually much higher than those of solid parts. The production cost of these parts can be reduced by lower material consumption and keeping machining to the minimum [11-13]. By eliminating the deep drilling of solid shafts in the production of hollow parts, the production cost can be reduced by approx. 20%. The mass of a hollow shaft depends on its production technique. In stepped shafts with drilled holes, the hole diameter is constant over the length of the whole shaft, which leads to variations in wall thickness of the shaft. In shafts produced by rotary forging, the distribution of wall thickness over the length of the shaft is approximately constant, so the shaft's mass is lower compared to drilled shafts which have varying wall thicknesses.

The concept of skew rolling by three rolls originated in the former Soviet Union [14, 15]. This process can be employed to produce both solid and hollow parts [16, 17]. The process is highly universal, as one set of tools can be used to form parts of different shapes [18]. To change production profile, one must only programme the motion of the forming rolls and chuck in a desired way. This paper reports the results of a numerical analysis of the rolling process by three rolls for producing a stepped hollow shaft made of titanium alloy Ti6Al4V. The objective of the analysis was to determine whether the skew rolling process by three rolls is suitable for producing hollow parts.

2. Geometrical model of skew rolling by three rolls

A schematic design of the analyzed process of skew rolling by three rolls is illustrated in Fig. 1. The process is performed using three tapered rolls located every 120° on the perimeter of the workpiece. In addition, the rolls are inclined relative to the axis of the workpiece at an angle θ. The rolls rotate in the same direction with a constant velocity n set to 90 revolutions per minute. Depending on cross sectional reduction of the workpiece, the rolls can travel radial towards or from the centreline of the workpiece during the process. The velocity of the rolls depends on the deformation ratio set for individual steps of the shaft. The chuck moves in an axial direction at constant velocity v_z = 40 mm/s and can rotate freely relative to the axis of the workpiece. The numerical modelling of the skew rolling process by the finite element method using the Simufact.Forming software involved making a series of assumptions. They are as follows: first of all, the workpiece is assumed to be a rigid plastic object described by the material properties of the Ti6Al4V alloy taken from the material library database of the applied software. Other objects in the numerical model are assumed to be ideally rigid. The rolling process is performed under hot forming conditions, and the initial temperature of the billet was 980°C. The temperature

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of the tools was maintained constant throughout the process at 100°C. The contact between the workpiece and the forming rolls is described by a constant friction model with the friction factor *m* set to 0.9. The contact conditions of the chuck are defined by adhesion. Additionally, the workpiece-tools contact is assumed to generate heat flow described by the heat transfer coefficient α set to 20 kW/m^{2}K. The workpiece was tube which had an outer diameter of 50 mm, a wall thickness of 8 mm and a length of 200 mm. The shape of the stepped hollow shaft investigated in the present paper is shown in Fig. 2

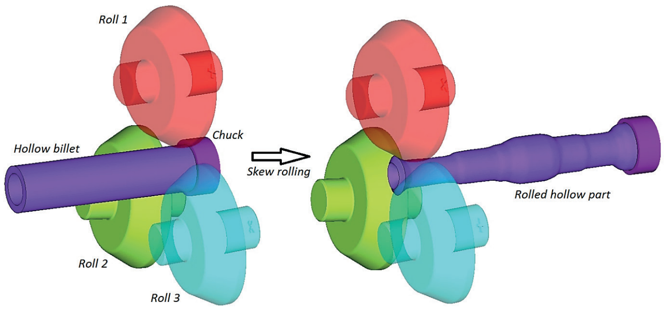

Fig. 1. Geometrical model of the skew rolling process for a hollow shaft made of titanium alloy Ti6Al4V

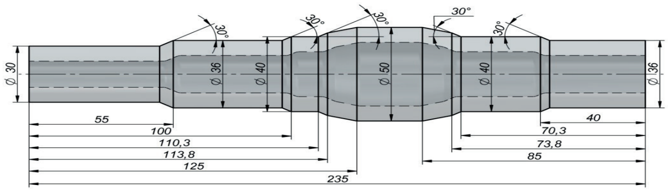

Fig. 2. Analyzed hollow shaft with a wall thickness of 8 mm

3. Results and discussion

The results of the numerical simulation performed in a three-dimensional state of strain, including a full thermal analysis, helped determine changes in shape of the workpiece during the rolling process, the distribution of wall thickness, the maps of effective strain and temperature as well as the variations in loads and torques. Initially it was predicted the occurrence of phenomena that could interrupt the process stability and thus hinder the production of correctly shaped parts. In addition to this, the distribution of an integral for the Cockroft-Latham ductile fracture criterion was calculated.

The changes in shape of a stepped hollow shaft depending on the progress of the rolling process are illustrated in Fig. 3. The tools revolving in the same direction make the billet material rotate. At the same time, the radially moving rolls cause a controlled cross sectional reduction in individual steps of the shaft. The axial motion of the chuck is correlated with the radial motion of the forming rolls, which enables producing shaft steps of the required length. Individual steps of the shaft are formed gradually, one by one. On its ends, the shaft has machining allowance which will be removed mechanically. The allowance on one end is used for mounting the workpiece in the chuck, while that on the other end serves as a rundown for the rolls. As can be seen from the data given in the figure, the rolling process proceeds in a correct way. One can observe no alarming phenomena such as slipping, cross sectional ovalization, workpiece collapse or twisting.

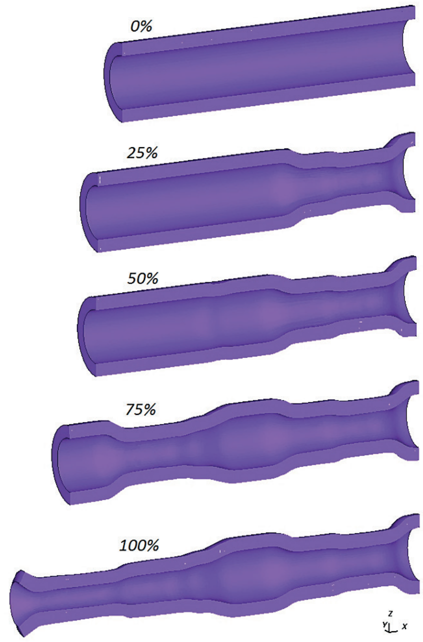

Fig. 3. Changes in workpiece shape (in longitudinal section) in skew rolling process

In skew rolling by three rolls, the longitudinal section becomes deformed; it is twisted due to shear stresses acting in the circumferential direction. The twisting of the shaft is shown in Fig. 4. Prior to rolling the initial profile of the billet section (marked in Fig. 4 by thick line) is parallel to the axis of the workpiece. During the process it becomes twisted relative to the direction of the rotating workpiece. However, the angle of twisting of individual material layers is not constant over the length of the shaft. The highest twisting of the plane (marked by thick line) is located in the region of the end step where the deformation ratio is the highest.

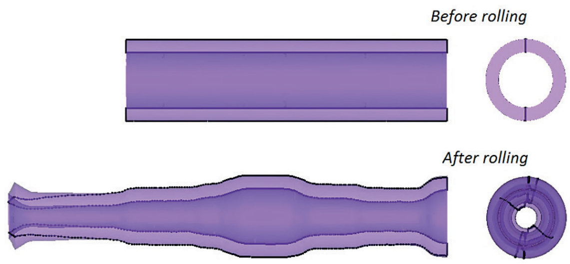

Fig. 4. Twisting of workpiece longitudinal section caused by skew rolling

In skew rolling by three rolls, the thickness of the workpiece wall changes. The variations in wall thickness of the shaft are shown in Fig. 5. The part is characterized by a relatively high uniformity of wall thickness. Compared to the initial thickness, the change in wall thickness does not exceed 10%. One can observe that the wall thickness increases in most of the shaft, which is favorable due to strength reasons. The local decrease in wall thickness occurred only in the vicinity of the smallest diameter step of the shaft.

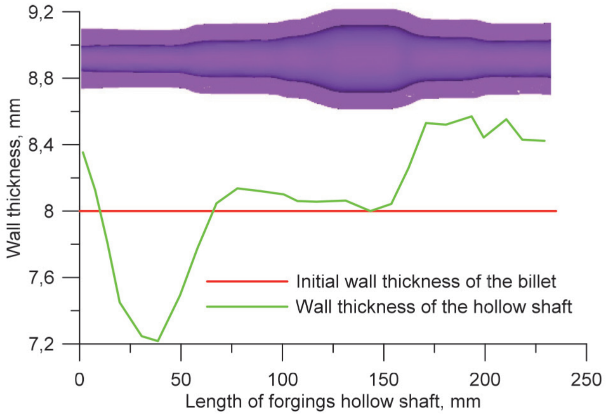

Fig. 5. Variation of wall thickness in a produced hollow shaft

The maps of effective strain determined by the finite element method reveal that the produced shaft is characterized by non-uniform strains (Fig. 6). The non-uniformity of the strains results from cross sectional variations in the shaft. In the analyzed case, the highest strains are located at the surface of the shaft, and they gradually decrease the closer it is to the axis of the product.

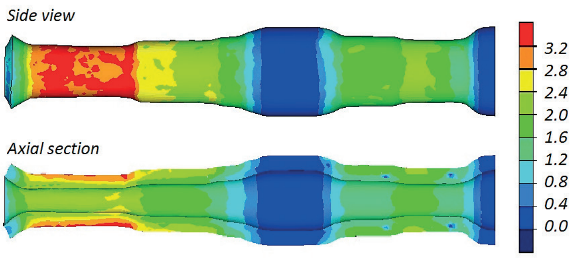

Fig. 6. Distribution of effective strain in a hollow shaft produced by skew rolling

The highest effective strain is approximately 3.2 and occurs at the surface of the shaft step with the smallest diameter. In the highest diameter step and the chuck allowance, the strains does not exceed 0.4 and can only result from workpiece tension during the forming process.

Fig. 7 shows the distribution of the temperature in the produced shaft. Despite the long forming time (about 6 s), no significant temperature drop can be observed in the produced part. The minimum temperature in the deformed region of the workpiece does not exceed 880°C. It must however be noted that the regions with this temperature are already cooled down, as they were either the first to undergo deformation or did not undergo deformation at all. The lowest temperature drop can be observed in the shaft steps with the smallest diameter. The low temperature drop in this region results from intensive heat release generated by plastic deformation. In compliance with the assumptions made at the design of the numerical model, as much as 90 % of deformation work is converted into heat. The maintaining of correct temperature in the metal forming of titanium alloys is very important due to phase transitions that occur in these materials due to temperature. According to literature data, the Ti6Al4V alloy should be formed in the α+β phase, which corresponds to a temperature range between 925 and 980°C [19]. The machining performed at a temperature over 995°C can lead to grain growth and limited deformation.

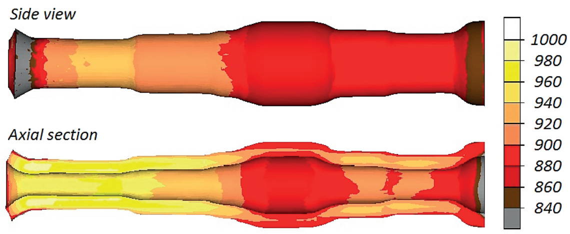

Fig. 7. Distribution of temperature (in °C) in a hollow shaft produced by skew rolling

When run in a correct way, the process will produce a product that is free from shape defects, undesired mechanical properties or cracks. The cracking of titanium alloys in metal forming can be caused by selecting a wrong temperature of the process, which will lead to changes in material structure. Material cracking can also result from incorrect states of stress and strain. This problem can however be solved using empirical criteria for predicting the moment of material cohesion loss. One of the criteria frequently used in metal forming for predicting crack occurrence is the Cockroft-Latham ductile fracture criterion. The distribution pattern of the Cockroft-Latham integral in the produced shaft is illustrated in Fig. 8.

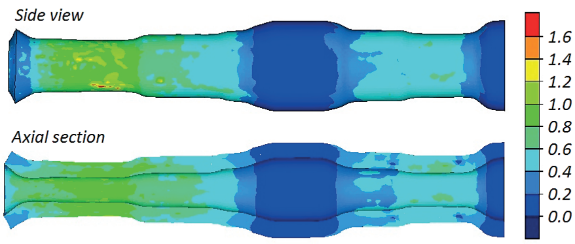

Fig. 8. Distribution of the ductile fracture function (according to the Cockroft-Latham criterion) in a hollow shaft produced by skew rolling

The maximum values of the fracture criterion was located in the region where the material has undergone the highest strains. The value of the Cockroft-Latham criterion in this region does not exceed 1.2. In other regions subjected to plastic deformation, the criterion is nearly twice lower. The value and distribution of the fracture criterion largely depends on the distribution and values of effective strain. The two distribution patters are very much similar.

One of the main advantages of numerical modelling is that it allows us to estimate loads with high accuracy. The knowledge of force and energy parameters at the stage of technique development is vital, as it enables selection of a machine that is appropriate for performing the developed process. Variations in the loads acting on a single roll during the rolling process are illustrated in Fig. 9. As can be seen in the diagram, the radial load acting on the roll is nearly five times higher than the axial load. The highest loads can be observed at the end of the process when the deformation ratio is the highest. Between 2 and 3 seconds of the process, the rolls are unaffected by any loads. During this period, the rolls have no contact with the workpiece and travel a distance corresponding to the length of the highest diameter step of the shaft. When the rolls take the radial position, the deformation ratio changes, which entails changes in deformation resistance. As can be seen in the diagram, the moment of change in deformation ratio value takes form of characteristic peaks.

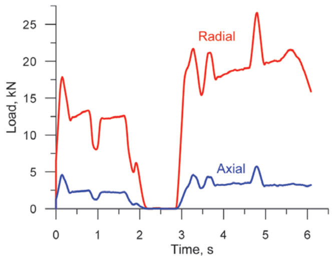

Fig. 9. Variations in the loads acting on a single roll in the skew rolling process for a hollow shaft

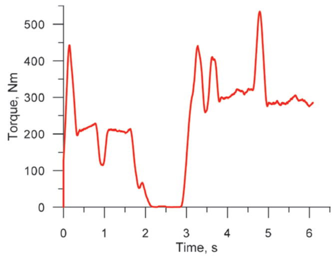

Fig. 10. Variation of the torque acting on the roll in the skew rolling process for a hollow shaft

The recorded variations in the torque acting on one of the rolls are shown in Fig. 10. The maximum recorded value of the torque is approx. 500 Nm. The pattern of torque variations is similar to that of the loads. The variations in the torque have exactly the same cause as in the case of the radial and axial loads. With respect to the size of the part being formed, the maximum values of the force parameters in the rolling process are relatively low, which ensures low energy consumption of the proposed method for rolling hollow parts.

The axial load, the variations in which are illustrated in Fig. 11, also depends on an instantaneous value of the deformation ratio. The highest axial load does not exceed 20 kN and can be observed at the final stage of the process. The characteristic variations in the axial load also result from changes in the deformation ratio during the process. During the rolling process, the turn of the axial load acting on the chuck varies, as shown by negative and positive values. The axial load takes negative values at the beginning of the process when the rolls sink in the material and at the start of forming the shaft region located beyond the highest diameter step. This stems from the fact that, one, in both cases the axial load is close to zero, and, two, the material between the rolls and the chuck is under compression when the rolls are sinking in it. The material remains under compression until the desired deformation ratio is achieved (the rolls are in a suitable position), the load increases and the turn becomes tensile. Every change in the deformation ratio is accompanied by a local decrease in the axial load on the chuck.

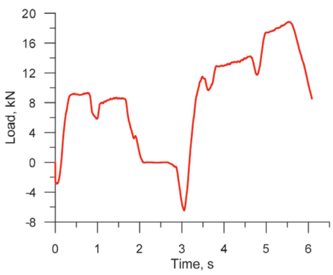

Fig. 11. Variation of the axial load acting on the chuck in the skew rolling process for a hollow shaft

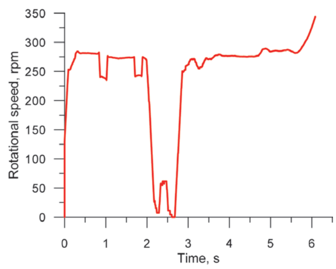

Fig. 12. Variation of rotational speed of the chuck in the analyzed skew rolling process for a hollow shaft

Fig. 12 illustrates variations in the rotational speed of the chuck in rolling. Owing to small differences in diameters of successive shaft steps, the rotational speed of the chuck during the process is approx. 275 rev/min. The observed variations in the chuck's rotational speed occur the moment the deformation ratio is changed. Between 2 and 3 second of process duration the rotational speed of the chuck decreases because the rolls do not contact the workpiece. However, at 2.5 s, the speed slightly increases due to a temporary contact between the rolls and the workpiece. As can be seen in Figs. 9 and 10, the load and torque slightly increase at 2.5 s of the process. This contact can result from a potential twisting of the workpiece caused during the forming of the first two steps of the shaft.

4. Conclusion

The following conclusions have been drawn from the FEM analysis results:

- skew rolling by three rolls is a highly stable process for forming hollow stepped shafts,
- this forming process is highly universal due to the fact that one set of tools can be used to form a wide spectrum of products such as stepped axles and shafts of various dimensions,
- hollow parts produced by the analyzed method exhibit a high uniformity of wall thickness, compared to its initial value, wall thickness does not change significantly; in the analyzed case, the wall thickness does not change more than by 10%,
- an increase in deformation ratio leads to a higher non-uniformity of strains,
- the small contact area between the workpiece and the tools ensures maintaining a suitable treatment temperature,
- skew rolling by three rolls exhibits a favourable ratio of energy consumption to workpiece overall dimensions.

Acknowledgement

Financial support of Structural Funds in the Operational Programme - Innovative Economy (IE OP) financed from the European Regional Development Fund - Project "Modern material technologies in aerospace industry", No POIG.01.01.02-00-015/08-00 is gratefully acknowledged

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