Z. PATER*, A. GONTARZ*, G. SAMOŁYK*, J. BARTNICKI*

ANALYSIS OF CROSS ROLLING PROCESS OF TOOTHED TITANIUM SHAFTS

ANALIZA WALCOWANIA POPRZECZNEGO TYTANOWYCH WAŁKÓW UZĘBIONYCH

This paper presents the results of thermo-mechanical analysis of two stepped shafts. One of them has a step with toothed wheel rim (with skew teeth) and the second one has a step with worm winding (in the shape of trapezoidal screw). The shape of tools for toothing forming is similar to the shape used in a well-known Roto-Flo method (the basic differences include: rolling of whole shaft in hot rolling conditions, lack of mounts for stabilization of workpiece placement during rolling). Calculations were made in software DEFORM-3D, assuming that the shafts are rolled from titanium alloy Ti6Al4V. In the results of calculations, it was stated with high probability that the application of cross-wedge rolling allows for forming of stepped shafts with toothed steps in one working cycle. Moreover, temperature, strain and damage criterion distributions in the rolled product were analyzed and information concerning forces necessary for the rolling process realization was obtained.
Keywords: cross – wedge rolling, toothed shaft, FEM

W artykule przedstawiono wyniki analizy termomechanicznej dwóch wałków stopniowanych. Jeden z nich ma stopień z wieńcem zębatym (o zębach skośnych), zaś drugi uzwojenia ślimaka (w kształcie śruby trapezowej). Kształt narzędzi stosowanych do walcowania uzębień jest zbliżony do wykorzystywanego w znanej metodzie Roto-Flo (podstawowe różnice to walcowanie na gorąco całego wałka oraz nie stosowanie kłów do stabilizacji położenia odkuwki w trakcie kształtowania). Obliczenia wykonano w programie DEFORM-3D, zakładając że wałki walcowane są ze stopu tytanu Ti6Al4V. W efekcie wykonanych obliczeń, z dużym prawdopodobieństwem, stwierdzono, że stosując metodę walcowania poprzeczno-klinowego można kształtować w jednym przejściu wałki stopniowane ze stopniami uzębionymi. Ponadto, prześledzono rozkłady temperatury, odkształcenia i kryterium zniszczenia w wyrobie odwalcowanym oraz uzyskano informacje na temat sił niezbędnych do realizacji procesu walcowania.

1. Introduction

Stepped shafts are widely applied in machine and automotive industry. A lot of these steps have toothed wheel rims or worm windings. Products of this kind are mainly manufactured by means of machining from semi-products obtained in metal forming processes (e.g. forging, extrusion, rolling).

Toothed wheel rims can be also effectively manufactured by means of metal forming methods. Forging and rolling are the most important methods of metal forming of teeth [1, 2]. It should be, however, noticed that teeth forming is a separate forging operation and it requires the usage of special machines and units. Limiting the number of operations leads to the increase of effectiveness of manufacturing, which results in reduction of manufacturing time, number of machines and costs of production.

Modernization of production of toothed stepped shafts can take place by combining together metal forming processes of shaft and teeth. In order to do this, the cross-wedge rolling method (CWR), successfully used in manufacturing of stepped axes and shafts, can be applied [3, 4]. Wedge tools should be then equipped with special pads for teeth forming.

Jaws (pads) for teeth rolling should be placed at the end of tools, behind the sizing zone. They have a shape similar to the shape applied in a well-known teeth rolling method in cold working conditions by means of flat toothed tools (Roto-Flo method). Yet, in comparison with this method, the proposed rolling process takes place in hot working conditions, the used tools are shorter and the workpiece is not supported at both sides in mounts.

This paper presents the results of numerical analysis aiming at confirming the possibility of toothed shafts

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

rolling in hot conditions. Such a solution is optimal from implementation costs point of view and results from relatively wide application in wedge rolling mills industry with flat tools.

The calculations were made with the assumption that the rolled shafts will be made of titanium alloy Ti6Al4V. Presently, this material and other titanium alloys are widely applied in aviation and automotive industries. It is caused mainly by low density and excellent mechanical properties. Increased scope of applications of titanium alloys is connected with a large number of research works devoted to the new methods of fabrication including metal forming [5-7].

2. Stepped shaft with skew toothing

In order to verify the possibility of forming of toothed shaft by means of the planned method, the process of rolling of a shaft shown in Figure 1 was analyzed. This shaft has a skew toothing at the central step with the largest diameter, characterized by module 1,5 mm, number of teeth-18 and tooth line inclination angle 30°.

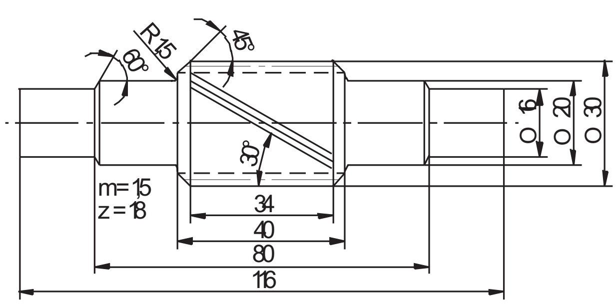

Fig. 1. Stepped ahaft with skew teeth

In Figure 2 is shown the tool guaranteeing the rolling process of the analyzed toothed shaft together with the most important dimensions. This tool consists of three main parts:

- wedge L_w, where shaft steps are formed in a way characteristic for CWR process;
- forming L_F, where teeth are rolled at the assumption that material does not move in axial direction;
- cutting L_C, where final waste with formed (in the result of metal flow at the external zones) cavities at part extremities is cut.

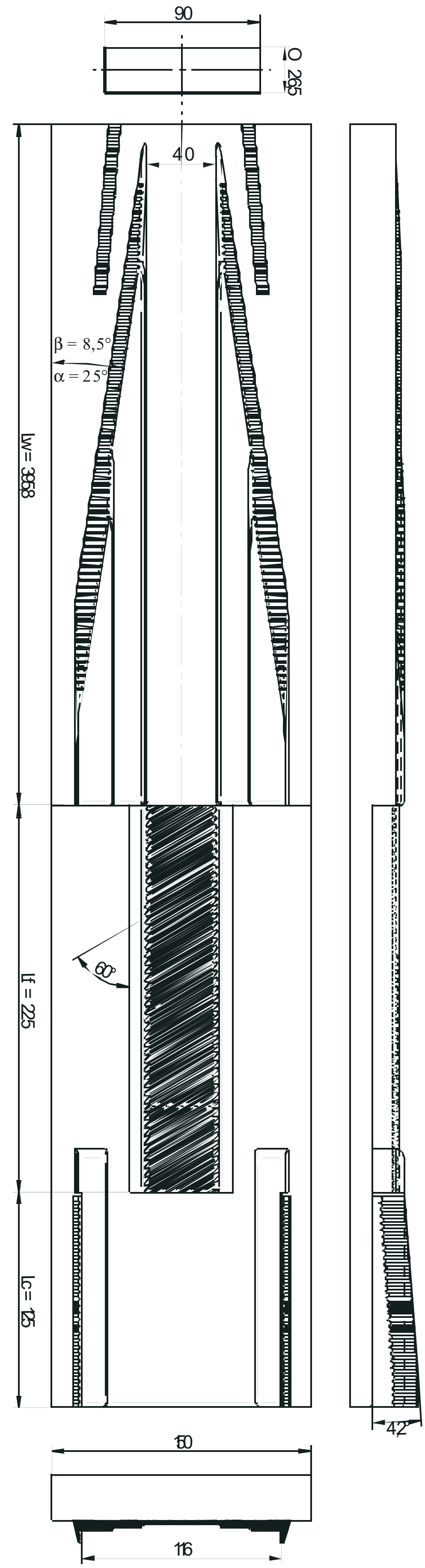

Fig. 2. Billet and tool segment applied in toothed stepped shaft forming

Technological serrations, which aim is to contract uncontrolled slip of workpiece during rolling, are made on side surfaces of forming wedges and cutting knives.

Numerical calculations of the rolling process of toothed shaft were made in software DEFORM-3D. It was assumed, that the billet for rolling was: cylindrical-with dimensions Ø26,5×90 mm (Fig. 2), made from titanium alloy Ti6Al4V and heated to the temperature 960 °C. The model of the formed material was taken from the applied software library. The chosen flow curves of this alloy are shown in Fig. 3. The rest of the parameters assumed in calculations are as follow: tools temperature 150 °C, coefficient of heat exchange between material and the environment 0.2 kW/m^{2}K, tools velocity 0.15 m/s. It was also assumed that friction factor on the contact surface between material and tool reach the limiting value m=1. This assumption is caused by the fact that the tools have special serrations which significantly decrease risk of slipping during rolling. In CWR technologies this solution is applied very often [3, 8].

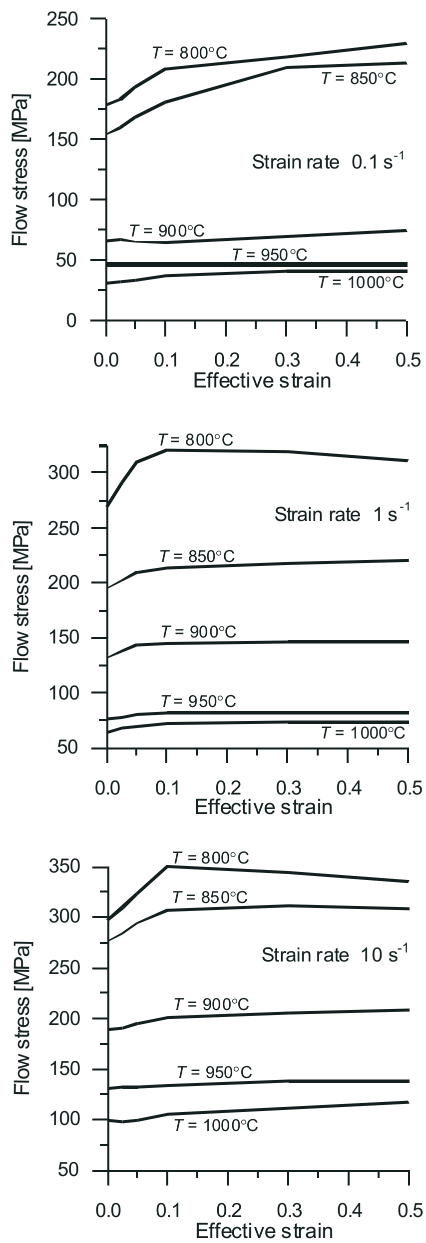

Fig. 3. Flow curves of Ti6Al4V titanium alloy

Figure 4 shows how the toothed shaft forging shape changes in the rolling process. From this Figure results that the workpiece during forming rotates undisturbed and there are no limits of rolling process stability. Hence, it can be stated that the application of the proposed forming method allows for forming of stepped shafts with cylindrical toothed wheel rims.

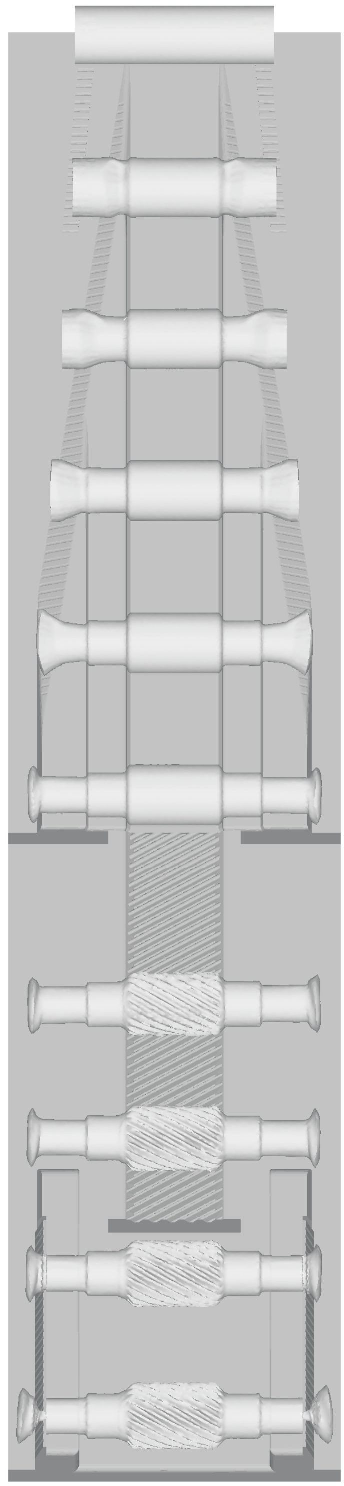

Fig. 4. The shape progression of toothed shaft rolled by means of tools shown in Fig. 2

Figure 5 shows distributions of temperature, strain intensity and Cockroft-Latham damage criterion on the surface and in cross section of the obtained forging of toothed shaft. Considering the temperature it can be stated that, although the forming time is relatively long (5s), the temperature remains within the range proper for metal forming in hot conditions of titanium alloy Ti6Al4V. It can be assumed, that material temperature drop caused by heat abstraction to tools is effectively compensated by heat generating in the result of deformation work and friction work.

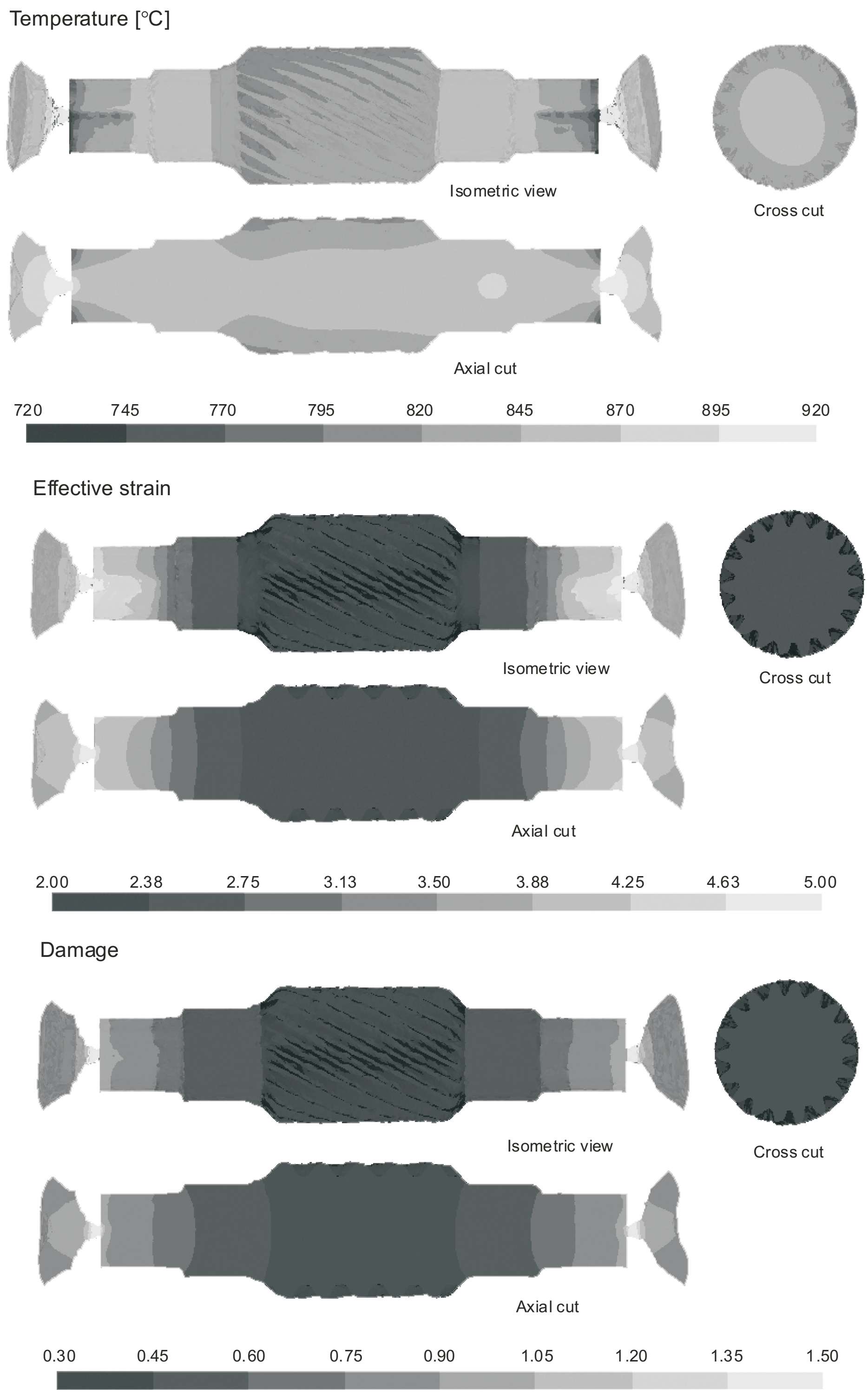

Fig. 5. The temperature, effective strain and Cockroft-Latham damage criterion distributions in stepped shaft with skew teeth

The analysis of strain intensity distributions shows that strains increase together with the reduction of cross section and assume the largest values for shaft steps with the smallest diameter. It is stated, at the same time, that material in external steps of the rolled part was formed at all its volume. However, during teeth forming at shaft central step, metal flow had parts external zones character. This was connected with strains distribution, which in this part of the shaft had circular character and were the largest in external surface layers, and the smallest in the axis area.

Distribution of damage criterion (according to Cockroft – Latham) is worth noticing. From this distribution results that in the zone of the formed teeth the value of damage does not exceed level 0.5. It means that during workpiece rolling there should not appear metal cracking. At the same time, it was noticed that bigger damage values (above 2.0) were present in layers connecting final waste with the workpiece. Hence, in these layers the metal should crack, leading to separating of final waste from the rolled shaft.

Considering calculated distributions of tangent force (wedge tool squeezing force) and radial force (perpendicular to tools sizing surface), shown in Fig. 6, it can be stated that the largest values they assume at the end of forming stage of stepped shaft. Next, during teeth rolling, these forces lower a few times in order to reach almost zero at the final waste cutting stage.

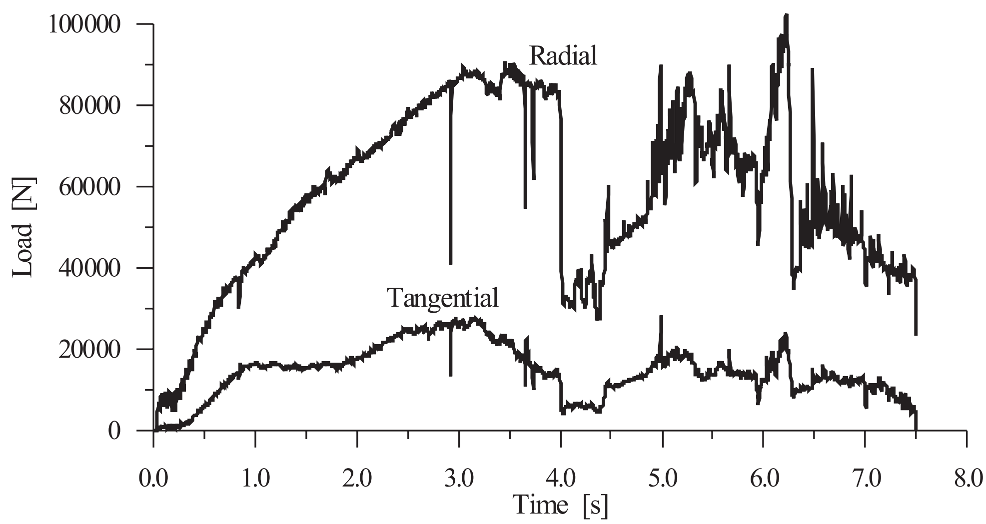

Fig. 6. The loads distributions in CWR process of toothed shaft shown in Fig. 1

3. Stepped shaft with worm

The second of the analyzed processes concerned the possibility of CWR method forming of stepped shaft with worm (in the shape of trapezoidal screw), shown in Figure 7. In that case, it was assumed that the billet for rolling had specially prepared edges, in shape of cones (fig. 8). The application of the billet of this shape should eliminate the operation of final waste cutting, and thanks to that: reduce material consumption, shorten the forming tool and increase the rolling effectiveness.

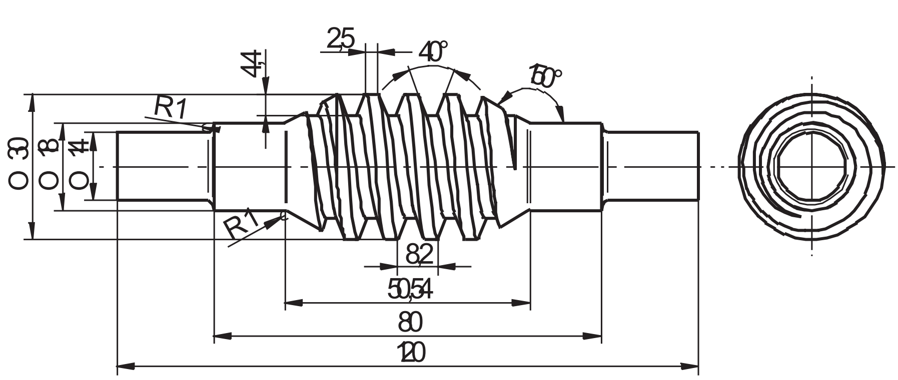

Fig. 7. Stepped shaft with worm

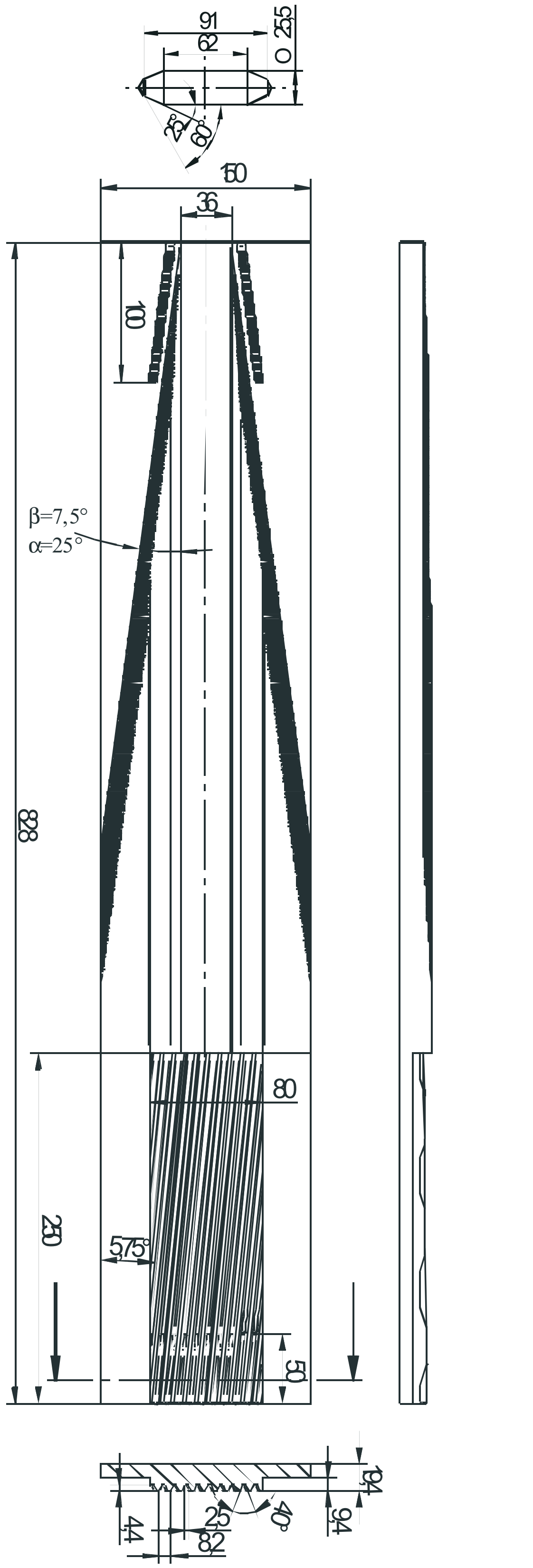

Fig. 8. The billet and wedge tool applied in rolling process of shaft shown in Fig. 6

Wedge tool for manufacturing of shafts of the shape shown in Fig. 7 is presented in Figure 8. This tool consists of two parts. The first part is a typical wedge tool (characterized by angles α = 25° and β = 7,5°), which acts on the billet by reducing its diameter-in the result of this cylindrical, external steps of the shaft appear. The second part of the tool is a placed centrally jaw forming the worm winding. The inclination angle of notches in the jaw is accorded with the inclination angle of the screw line of worm winding.

3D model of wedge tools (made in CAD software) was used for designing of geometrical model of the analyzed rolling process. Apart from tools, geometrical model of the process (Fig. 9) consists also from the billet.

Numerical simulation of the rolling process of stepped shaft with worm was made in software DEFORM-3D. In calculations, the model of the process shown in Figure 9 was used. Forming parameters were assumed the same as during rolling of the toothed shaft described in the second chapter. The results obtained in numerical calculations confirmed the possibility of the CWR method application for forming of shafts with worm in the shape of trapezoidal screw. Figure 10 presents how the workpiece shape changes during rolling: from the billet to the shaft with worm. It can be stated that the rolling process is stable (the lack of uncontrolled slip), both during forming of shaft cylindrical steps and worm winding. The shape of the obtained part is proper.

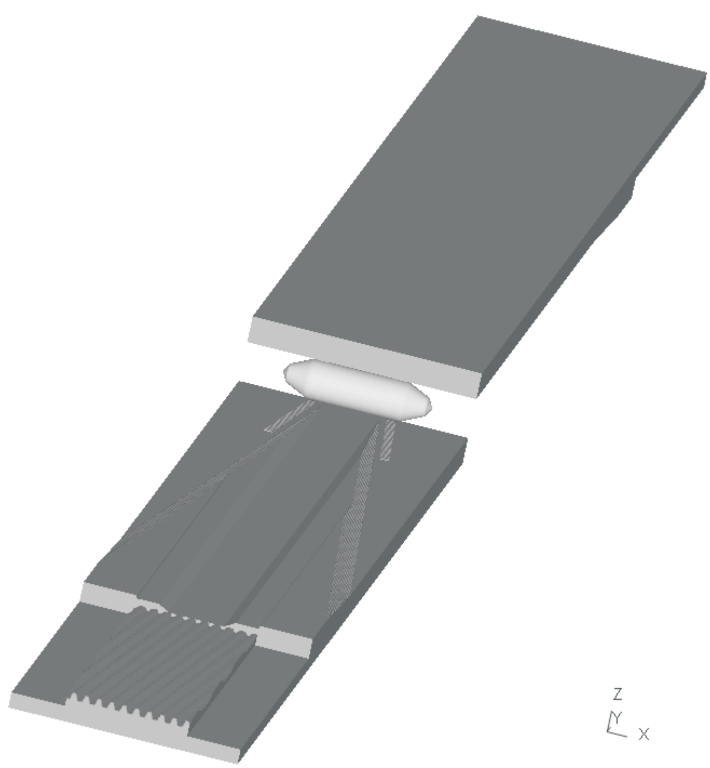

Fig. 9. The geometrical model of CWR process of shaft with worn built in DEFORM-3D software

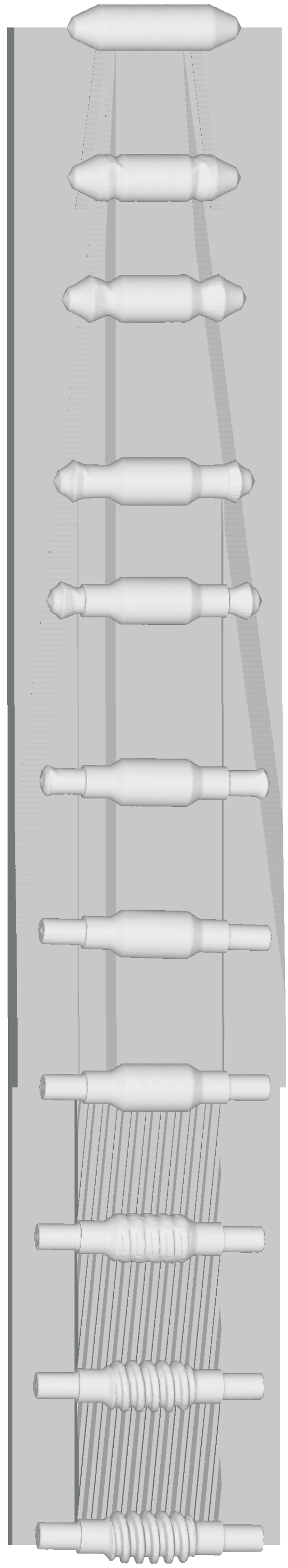

Fig. 10. The shape progression of stepped shaft with worm in analysed process

Figure 11 shows the distributions of temperature, effective strain and damage (according to Cockroft-Latham) in the rolled shaft, obtained in the analyzed rolling process. The analysis of the data from this Figure confirms the observations for the discussed earlier (in the second chapter) toothed shaft forging.

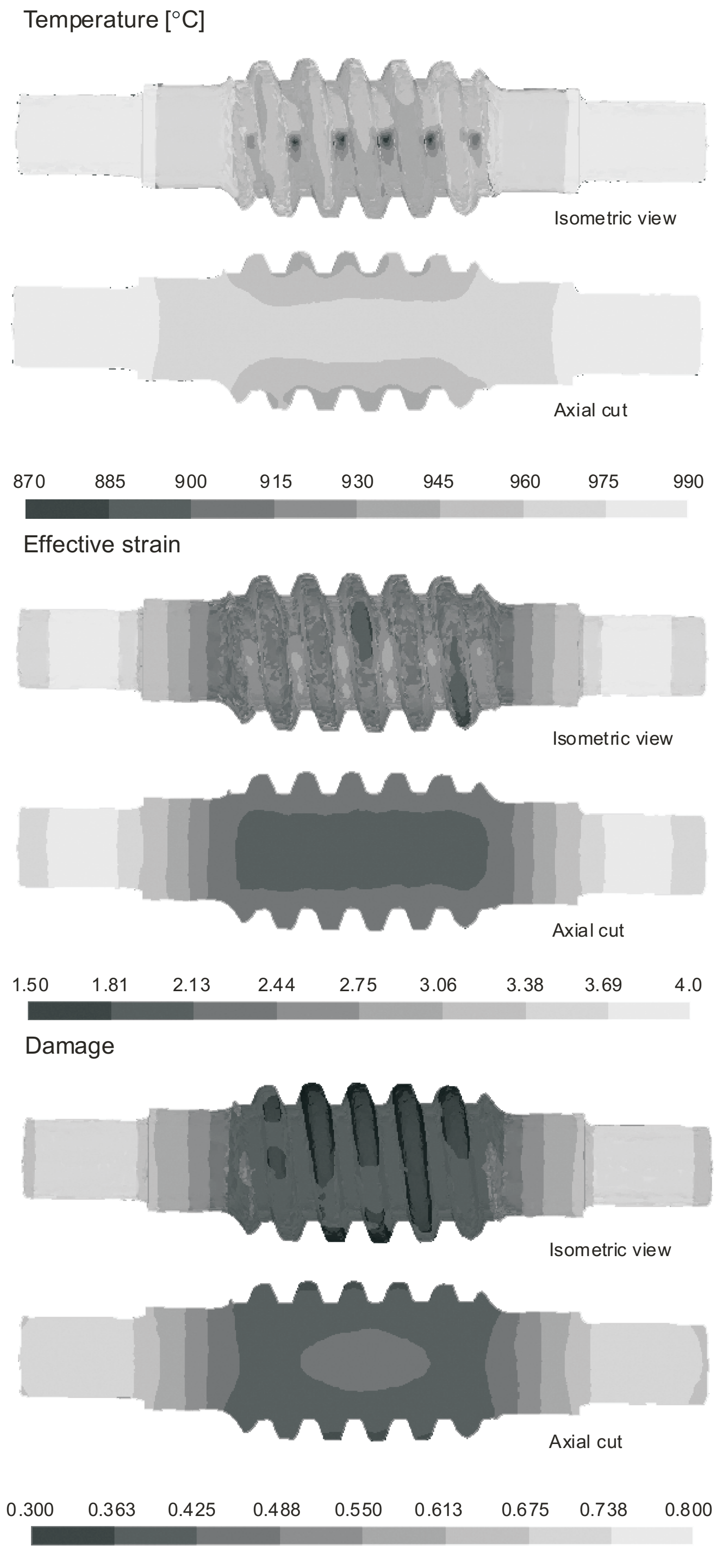

Fig. 11. The temperature, effective strain and Cockroft-Latham damage criterion distributions in stepped shaft with worm

The next Figure (Fig. 12) presents distributions of tangent and radial forces, determined for the CWR process of stepped shaft with worm. The results of calculations show that forces in the forming process of worm winding are about 3 times lower than forces present during rolling of external steps. It means that rolling mills for CWR are characterized by excessive power needed for worm winding making. It is possibly the result of lower metal total strain work in the area of winding forming, limited to the external layers of the rolled part.

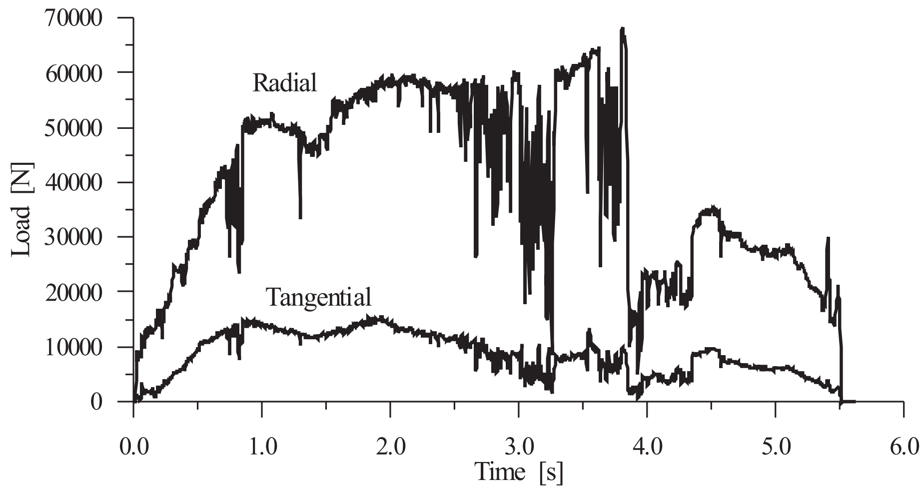

Fig. 12. The loads distribution (calculated by FEM) in rolling process of shaft shown in Fig. 6

4. Conclusions

The realized numerical calculations are the base for the following conclusions:

- □ The limitations which can disqualified CWR method in forming of stepped shafts from titanium alloys with toothed and wormed steps were not observed;
- □ The tools for tooth (worm) rolling have a shape close to the one used in the Roto-Flo method;
- □ During rolling of teeth (worms) the material flows at the surface, in the effect of this phenomenon the biggest strains in the external zones are present. The smallest are observed in axial area of formed parts;
- □ The probability of process stability disturbances (in form of uncontrolled slipping, material cracking, overlaping e.c.) is very small and it is not depended from the kind of teeth forming;
- □ The temperature diminution during rolling is very small and it is not dangerous in proper course of the process;
- □ It is recommended to verify the results of numerical calculations in laboratory or industrial tests.

Acknowledgements

Financial support of Structural Funds in the Operational Programme - Innovative Economy (IE OP) financed from the European Regional Development Fund – Project No POIG.0101.02-00-015/08 is gratefully acknowledged.

REFERENCES

[1] A. Turno, M. Romanowski, M. Olszewski, Obróbka plastyczna kół zębatych. WNT, Warszawa 1973.
[2] J. Sińczak, Kucie dokładne. Wyd. AGH, Kraków 2007.
[3] X. P. Fu, T. A. Dean, Past developments, current applications and trends in the cross wedge rolling process. International Journal of Machinery Tools Manufacture Design, Research and Application **33**, 367-400 (1993).
[4] Z. Pater, A. Gontarz, W. Weroński, Wybrane zagadnienia z teorii i technologii walcowania poprzeczno-klinowego. LTN, Lublin 2001.
[5] W. Pachla, M. Kulczyk, M. Sus-Ryszkowska, A. Mazur, K. J. Kurzydlowski, Nanocrystalline titanium produced by hydrostatic extrusion. Journal of Materials Processing Technology **205**, 173-182 (2008).
[6] X. Wu, Review of alloy and process development of TiAl alloys. Intermetallics **14**, 1114-1122 (2006).
[7] E. O. Ezugwu, J. Bonney, Y. Yamane An overview of the machinability of aeroengine alloys. Journal of Materials Processing Technology **134**, 233-253 (2003).
[8] Z. Pater, Walcowanie poprzeczno-klinowe. Wyd. Politechniki Lubelskiej, Lublin 2009

Received: 20 May 2009.