NUMERICAL MODELLING OF THE ROLLING PROCESS OF INTERNAL TOOTHING OF TOOTHED WHEEL RIMS

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Abstract

This paper presents results of numerical analysis of rolling process of internal toothing. Numerical simulations of the rolling process were made basing on finite element method (FEM), using commercial software DEFORM-3D in version 10.0. Geometrical models applied in FEM calculations were discussed in details. Calculations were made in three dimensional state of strain with consideration of thermal phenomena. During research works, geometrical parameters of obtained parts were analyzed, distributions of effective strain, effective stress and temperatures as well as the process force parameters were given. Next, the influence of particular process parameters on tools durability and the possibility of presence of phenomena disturbing the process stability were discussed. Described results of numerical research confirm the possibility of forming of internal toothing by means of rolling methods and constitute the introduction for a more complex analysis of metal forming processes of internal toothing.

1 Introduction

Toothed wheels, which mainly constitute elements of drive transmission, are widely applied in machines design [1-5]. Torque transmission takes place in the result of two co-operating wheels meshing and teeth side surfaces interaction. Because of that, the toothed wheels toothing undergoes large loads, often much bigger than loads of other elements. Hence, durability and resistance of the toothed wheels toothing have a crucial influence on machines and devices durability and, in many cases, these elements durability decides about the people safety [6]. Hence, the requirements are very high. The improvement of toothed wheels resistance can be realized in a few ways, for example by application of better materials and appropriate thermo-mechanical treatment. However, the easiest and cheapest way is appropriate forming of the product internal structure due to the application of semi-finished metal forming.

At present, a widely applied way of toothed wheels toothing manufacturing is machining, in which obtaining of a tooth outline is the result of removing of particular material layers [7-10]. Apart from long tradition, machining processes are relatively expensive and time consuming and they, additionally, lead to weakening of teeth resistance due to material structure rupture. This phenomenon has imposed a search for other unconventional methods of toothing forming. Numerous methods of metal forming of toothed wheels toothing have been worked out, among

which the largest importance have forging, rolling extrusion and rolling [11]. Due to the application of toothing metal forming techniques, material and energy consumption considerably decreases, the process efficiency increases and resistance properties improve as the structure continuity is preserved [12-14]. However, these processes are rarely used, although they have many advantages. This situation is caused by many factors; the largest importance have here small tools durability, which often wear too fast, and their complicated shape, difficult to obtain by means of conventional methods. Modern tool materials of higher resistance than resistance of tool materials used so far and the application of machines guided numerically and allowing for manufacturing of tools of complex shape become the solution for this problem [15, 16].

Among many methods of toothing manufacturing, rolling processes should be considered, in which the outline of the formed toothing is the envelope of particular profile points of teeth of rotating tools. Due to this the forming process gradually takes place on the rim circumference and forces values are a few times lower than in forging processes. Depending on material resistance properties and the size of the formed rims modules, toothing rolling can be realized in cold or hot conditions. However, in majority of cases, these are processes used for external toothing forming [17-21]. Techniques of internal toothing rolling are not popular, which is reflected in the lack of literature concerning this subject. Dynamic development of industry, especially automotive and aviation industries, leads to a larger requirement for toothed wheels with internal toothing. Hence, it is justified to search for new manufacturing methods of this type of products, guaranteeing obtaining high qualitative and resistance parameters and limiting material and energy consumption at the same time. In order to meet the industrial requirements, numerous methods of toothed wheels metal forming, which are to a large extent connected with rolling techniques [22, 23], have been worked out at Lublin University of Technology.

2   Experimental materials and methods

Rolling of internal toothing can be regarded as envelope method of metal forming, in which tools in the form of toothed working rolls rotate during plunging into material. In the result, tools cooperate with a semi-finished product and toothing internal outline is formed. Depending on the diameter of the formed toothed rim, the tooth line shape and the module size, the rolling process can be realized according to two schemata. The first method is based on radial movement of rotating tools into the semi- finished product, which gradually form the toothing outline on the whole tooth line length, yet, these tools have the width almost equal the width of the rolled rim. The second method is based on axial movement of rotating tools in the semi-finished product hole, due to which they gradually form teeth outline, plunging into material on the tooth whole height.

The schema of the rolling process of internal toothing with tools axial movement is shown in **Fig.1**. The process is realized by means of a special head-1, on which three tools are mounted- 3, 4, 5 in the form of toothed rolls driven by a common toothed wheel - 2. The semi-finished product in the form of a bush is mounted between two rings - 6, 7 which can rotate aroundtheir axis. The toothing forming process is realized due to axial movement of the head in the semi-finished product direction and tools rotation, which by plunging into material make it rotate and cause gradual teeth embossing. To make tools plunging into material easier and to lower forming resistance, the toothed rolls profile in the initial and exit areas have the cone shape (**Fig. 2**), in which the sizes of forming angles γ_1 and γ_2 depend on the type of rolled material. Additionally, toothing on the initial cone and exit cone has the form of wedges (with angles β_1

and β_2 of spreading in longitudinal direction to tools axis and angles α_1 and α_2 of teeth inclination in the direction normal to the outline), which fluently pass into involute outline in the tools central sizing part.
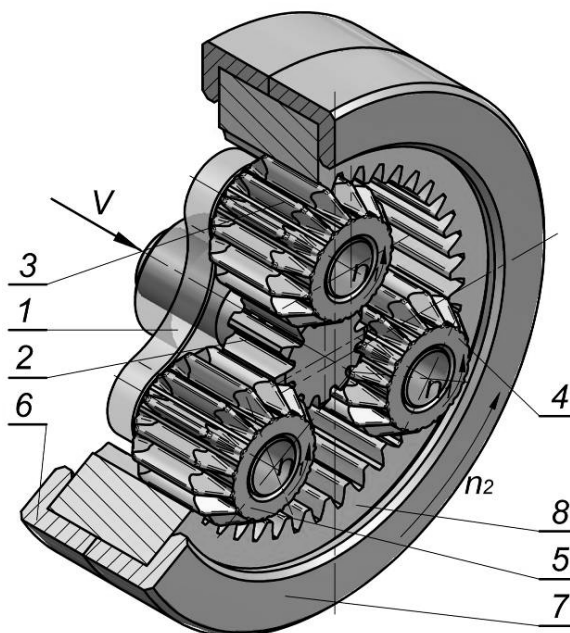

Fig. 1 Schema of the internal toothing rolling process with axial tools movement
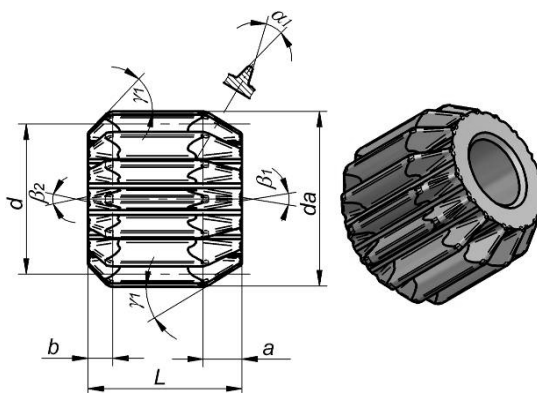

Fig. 2 Schema of the internal toothing rolling process with axial tools movement

3   Results and discussion

In order to confirm the rightness of assumed metal forming conception, numerous simulations of internal toothing rolling process were made. Shape and dimensions of the analyzed internal

wheel are shown in **Fig.3**. The number of teeth of the formed wheel equal z = 42, module m = 2, tooth outline angle α = 20°, angle of the tooth inclination β = 0°.
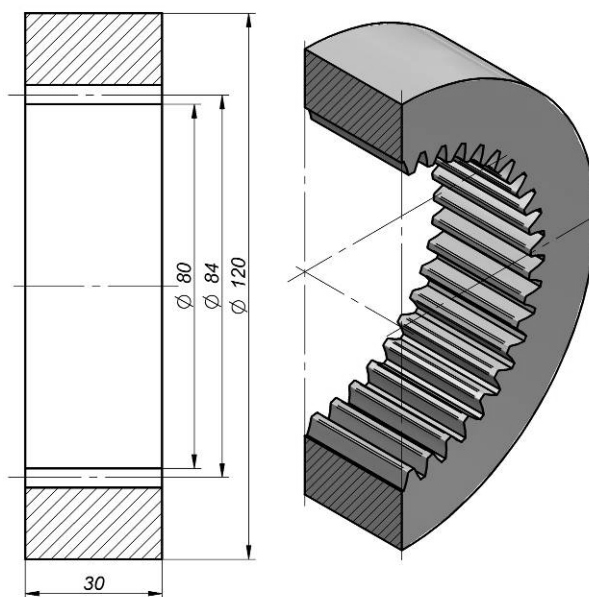

Fig. 3 Shape and dimensions of internaltoothed wheel

The analysis of the rolling process of internal toothing was made by means of finite element method (FEM), using commercial software DEFORM-3D in version 10.0. Because of the complex character of material flow, calculations were made in three-dimensional state of strain with consideration of thermal phenomena. In simulations geometrical parameters of the obtained products were analyzed. Geometrical model of the process of internal toothing rolling, which was used in calculations, is shown in **Fig.4**. This model consists of three the same tools-toothed rolls - 1 and wokrpiece - 2 mounted between two rings - 3. Tools rotate with constant velocity $n_1 = 90$ rot/min in the same direction and move along the wokrpiece axis with constant velocity v = 0.005 m/s. The ring of diameters: external 120 mm, internal 83 mm and the length l = 30 mm, modelled by means of four-nodes tetragonal elements was used as wokrpiece. Due to large changes of the product shape during simulations a remeshing is often used. It was assumed in the numerical analysis of the process that material from which internal toothed wheels will be made is steel C45 type. This material is widely applied for manufacturing of various toothed wheels, shafts, axes, toothed shafts, crank shafts, etc. Material model of C45 steel from the data base of DEFORM-3D was used in calculations. It was assumed in simulations that wokrpiece was heated to the temperature 1000°C, tools temperature during the process was constant and equal 250°C. The size of the base element was assumed 1.5 mm, which, in the result, allowed for wokrpiece splitting at the initial stage of calculations into 150000 elements, the number of which at the end of simulations increased to about 260000, due to systematic remeshing. Additionally, in the area of toothed rim, the mesh was refined in order to represent teeth shape (the base element size was assumed here equal 0.5 mm). Other parameters assumed in

calculations include: friction factor on tool-metal surface of contact m = 0.3, heat exchange coefficient between the tool and material - 10 kW/m^{2}K and between material and the environment - 0.2 kW/m^{2}K.
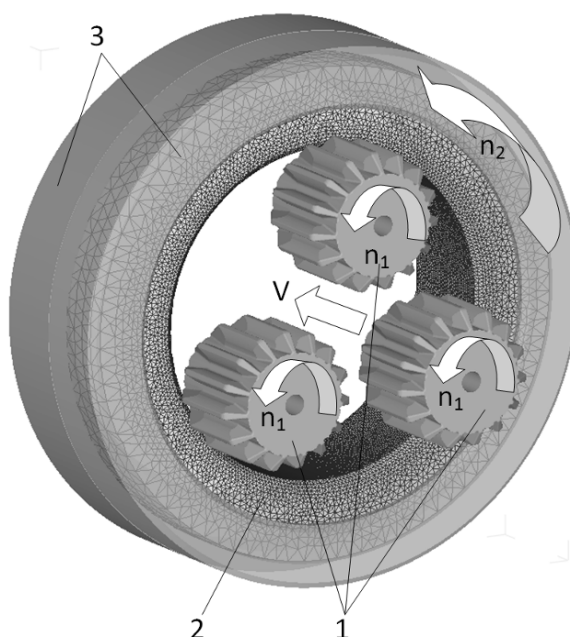

Fig. 4 Geometrical model of the internal toothing rolling process

The shape of the internal toothed rim determined numerically in the simulations of the rolling process by means of three rolls is shown in **Fig.5**. Due to the fact that the process was realized in hot conditions, on the teeth surface small allowance was left for machining.

The precision of the toothed rim shape obtained in numerical simulations is connected with the size of the applied elements. Precise representation of the teeth outline is possible only at appropriately large refinement of elements mesh in the toothed area. This leads, however, to elongation of the calculation time. The outline obtained from numerical calculations is characterized by large convergence with the rim theoretical shape, which was worked out during the process designing. Faults in the form of teeth infilling or their bending were not observed. On the toothed rim side surfaces, which are not limited by rings during the process, deformation is observed in the form of upsetting and axial movement of the material outside the product. The present deformation is treated as allowance which does not influence the precision of the obtained products.

The application of numerical techniques in the analysis of metal forming processes of metals and their alloys allows for relatively correct foreseeing of phenomena present during forming, which are difficult or impossible to determine by means of other methods. During numerical simulations of the internal toothing rolling process, distributions of strain intensity (**Fig. 6**), reduced stresses (**Fig. 7**), temperature (**Fig. 8**) were analyzed; the possibility of cracks appearance was foreseen on the basis of damage criterion (calculated according to Cockroft-Latham criterion) (**Fig. 9**).
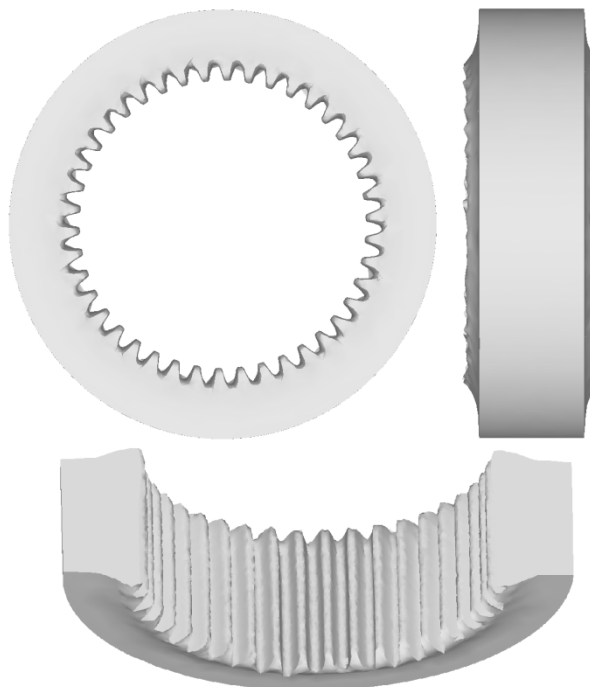
Fig. 5 The shape of the rim with internal toothing determined numerically during rolling simulations

The obtained strain intensity distribution (**Fig. 6**) confirms the assumption concerning the superficial character of deformation. The teeth of rotating and moving tools plunge gradually into the bush hole and extrude material from notches to the toothing heads. In the result, metal undergoes intensive plastic deformation in the surface layers in the area of the toothed rim, with the lack of deformation in the external area at the same time. Quite different character has the distribution of reduced stresses (**Fig. 7**). Maximal stresses concentrate in the superficial areas of the formed semi-finished product, directly contacting the tools, and their values do not exceed 180 MPa. However, in the other areas reduced stresses are considerably lower. Rotational forming process causes that the areas of the largest stresses move rotationally together with the formed toothing. Relatively small values of reduced stresses, determined during numerical simulations, allow assuming that during the process realization the premature tools wear should not take place due to their excessive load. A crucial influence on the rolling process course has the temperature value of wokrpiece and the formed part and its distribution in the semi-finished product (**Fig. 8**). A considerably low value of the heating temperature (1000°C) was assumed in calculations, which was connected with the necessity to reduce scale phenomenon. A characteristic feature of the determined temperature distribution (**Fig. 8**) is its relatively small decrease in the area of the formed toothing (to about 900°C).

This is especially important due to the process long duration and it allows supposing that the material at the end of forming should still have good plastic properties. Relatively high temperature in the area of the toothed rim is the effect of heat generation due to large metal plastic deformation. The largest decrease of temperature connected with heat transmission to

tools was observed in the areas of the rim external surface (under 800°C), where material contacts colder rings during the whole process. The observed metal cooling in this part of the rim should not be dangerous for the rolling process realization. During the conducted calculations, distributions of damage criterion in the rim section after the toothing rolling process were determined. The maximal values of this criterion are localized in the formed toothing (**Fig. 9**). However, the obtained values of this criterion (about 0.6) are considerably lower than critical values at which the metal cracking takes place.
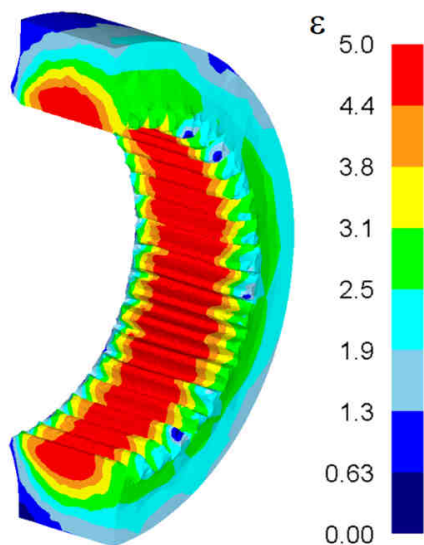

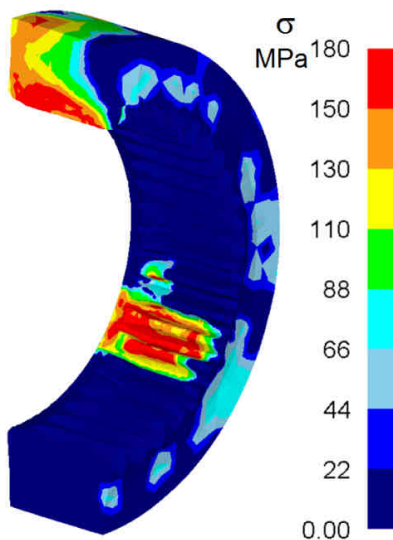**Fig. 6** Determined numerically distributions strain intensity

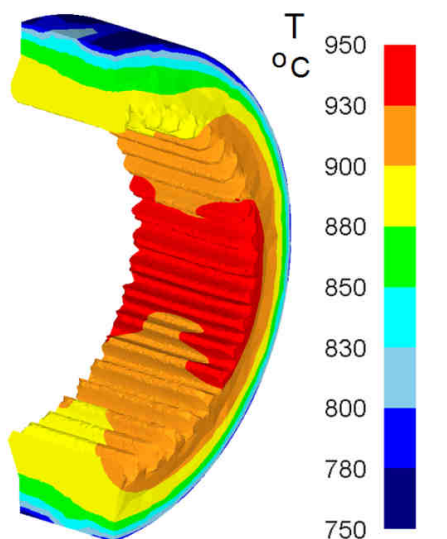**Fig. 7** Determined numerically distributions reduces stresses

Fig. 8 Determined numerically distributions temperature
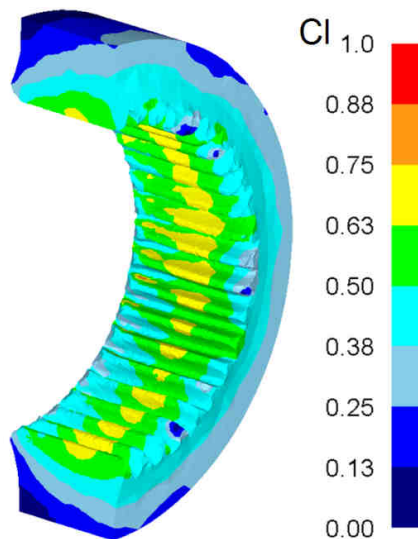

Fig. 9 Determined numerically distributions damage criterion

During numerical simulations the process force parameters were also analyzed, the knowledge of which is crucial in the case of the technology proper description. Determined numerically distributions of axial and spreading forces and rolling moment on one of the toothed tools are shown in **Fig.10**. At the beginning of rolling, a conical- wedge toothing of tools gradually plunges into material making it rotate. This leads to fast increase of forces and rolling moment values, which lasts until the tools completely immerse in the semi-finished product. Next, the decrease of force parameters values connected with tools going out of material is observed. Additionally, in the case of the axial force and torque, a stage can be noticed at which their stabilization takes place at constant level. This is the result of the tools complete immersing into the formed material, which leads to the development of tools-metal area of contact on the whole rolls toothing. It should be noticed that the radial force acting on the tool is four times larger than the axial force pushing the tool into material. Hence, the precision of the obtained toothing will to a large extent depend on the tool head rigidness. Relatively small values of the axial force result directly from small tools movement velocities. A characteristic feature of the observed courses is oscillation of force and moment values, which result from cyclic forming of the toothing by rotating tools.
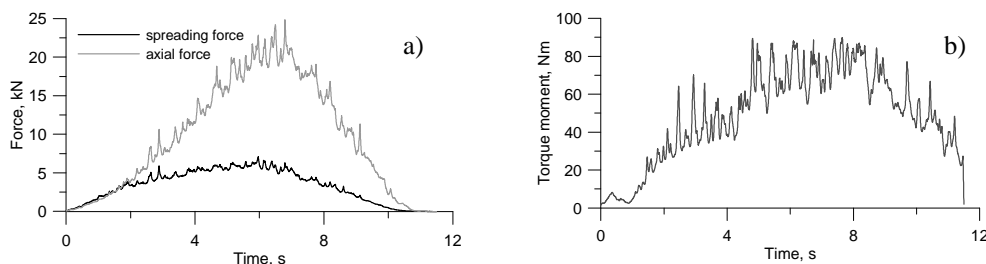

Fig. 10 Determined numerically courses of force parameters for one tool during toothing rolling simulation: a) spreading and axial force, b) rolling moment

4   Conclusions

The conducted numerical analysis confirms the possibility of internal toothing forming in the rolling processes. The main recipients of this type of products are automotive and aviation industries, which are characterized by mass production. Hence, even a small decrease of materials wear, energy and labour can bring financial profits. At present, in majority of cases, internal toothing is made in the machining processes. These technologies are, however, connected with large load of machines, relatively small efficiency and large material consumption, which in connection with more expensive materials is especially unfavourable and increases manufacturing costs.

Although metal forming techniques of elements have many advantages, including smaller material consumption and increase of resistance properties, they are used for toothing manufacturing only on a small scale. This is caused by numerous difficulties connected with these processes realization. However, due to large technical and economical advantages, it is purposeful to search for new methods allowing for manufacturing of elements with the application of metal forming techniques.

Based on the results obtained for the conducted numerical simulations, the following conclusions can be drawn:

- it is possible to form internal teeth by rolling processes,
- in the area of the teeth being formed, the metal flows on the surface,
- a local concentration of reduced stresses whose values do not exceed 180 MPa was observed in the area of the direct impact of the tools,
- in the area where the teeth were being formed, a relatively small temperature decrease from 1000 °C to approximately 900 °C was observed,
- in the initial stage when the tools would completely sink into the wokrpiece, the highest force parameters of the rolling process were observed (axial force was 6 kN, radial force was 24 kN and torque was 90 Nm).

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