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Zbigniew Pater[1], Krzysztof Łukasik[1], Volodimir Ivanovič Stebliuk[2]
[1] Lublin University of Technology, [2] National Technical University of Ukraine

NUMERICAL SIMULATIONS OF SCREW SPIKE, WORM AND GEAR ROLLING

Cross wedge rolling (CWR) is a very efficient technological process which has a favourable effect on properties of rolled products. At the same time, however, this forming technique causes complex non-linear problems resulting from variable contact conditions in the deformation zone. During the rolling process either adhesion or surface slip on the rolling contact surface may occur. The situation is further complicated by complexly-shaped wedge tools with thread-forming grooves. Those problems notwithstanding, the cross wedge rolling process can be examined effectively with the aid of computer simulations which precede both laboratory and industrial tests. Lublin University of Technology has developed and implemented a novel method of screw spike rolling as well as it has conducted computer simulations and model tests of rolling semi-finished gears. Even though the rolling tests have been carried out on semi-finished gears, it is expected that significant material savings can be yielded in the process of producing finished products. Given the rolling tests conducted on other products, it can be assumed that the quality of produced gears thus can be also improved, in contrast to gears produced by means of metal machining methods. Apart from screw spikes, hot cross wedge rolling also allows to produce coarse-pitch gears, which is not possible in a cold cross wedge rolling operation.

Поперечно-клиновая прокатка (ПКП) является высокопроизводительным процессом получения изделий высокого качества. В то же время процесс формообразования является сложной нелинейной задачей вследствие различных условий на контактной зоне деформации. В течение процесса прокатки может происходить как прилипание, так и скольжение на контактной поверхности. Положение усложняется в дальнейшем сложной формой клиновидного инструмента для формовки винтового профиля. Несмотря на это процесс ПКП может быть эффективно осуществлен с использованием компьютерного моделирования, предшествующего как лабораторной, так и производственной проверке. В Люблинском технологическом университете разработан и осуществлен новый метод прокатки винтов для крепления рельс к шпалам согласно с результатами компьютерного моделирования, а также модельное тестирование прокатки заготовок шестерен. Полученные результаты позволят повысить качество изделий и сократить расход материала по сравнению с методами изготовления изделий механической обработкой. Горячая КПК позволит получать зубчатые колеса большого модуля, которые невозможно получить при холодной прокатке

Screw spike rolling

The screw spike thread is usually formed with three-high mills. Despite being highly efficient, this production technology has yet certain limitations, for instance a concavity may occur at the end of the threaded part.

A novel method of screw spike rolling in double configuration (described in detail in [1]) has been devised at the Faculty of Mechanical Engineering at Lublin University of Technology. Numerical modeling has been applied to develop this new method of forming screw spikes. The thread rolling process has been modelled with use of both the finite element method [2, 3] and the finite volume method [2, 4]. Despite a number of simplifications made in the simulations, the obtained results, however, have not been fully satisfactory.

The numerical model of the thread cross wedge rolling process

The numerical calculations of the cross wedge rolling process of screw spikes have been made by means of the commercial software DEFORM-3D v.6.0, which has already been successfully used by other researchers examining transverse and skew rolling [5-7].

Figure 1a shows the FEM model devised to calculate the cross wedge rolling process of screw spikes. The model consists of two flat wedges and the preform obtained in the process of flashless forging (See Fig. 1b). The geometric models of the tools have been first designed with CAD Solid Edge and then exported into DEFORM-3D.

In order to reduce the calculation time, it has been assumed that screw spikes are formed by means of symmetric tools. Such an assumption is true if one screw with a right-hand thread and one screw with a left-hand thread are formed simultaneously. As a result, the number of elements used has been reduced to the number necessary for modelling one preform only.

It has been assumed that the screw spike to be formed is made of St4S steel grade, whose material model is described by the following formula [1]:

$$\sigma_p = 395{,}1\varepsilon^{0.58} \exp\left(-0{,}35\varepsilon\right)\dot{\varepsilon}^{0{,}134} \exp\left(-0{,}00085T\right), \qquad (1)$$

where: σ_p is flow stress, ε is effective strain, $\dot{\varepsilon}$ is strain rate and T is temperature.

Other calculation parameters included the friction factor on material-tool surface (m=1), wedge movement speed (v=0.25m/s), the preform temperature (1150˚C), tool temperature (150˚C), a heat exchange factor between the material and the tools (10000 W/m²K), and a heat exchange factor between the material and the environment (200W/ m²K).

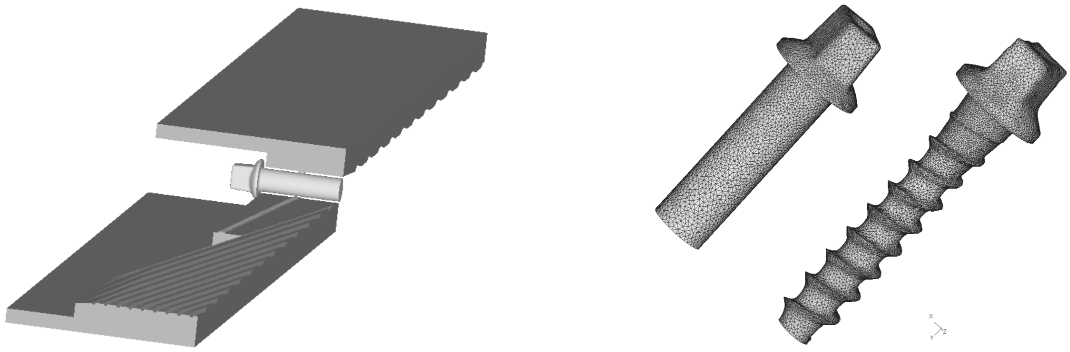

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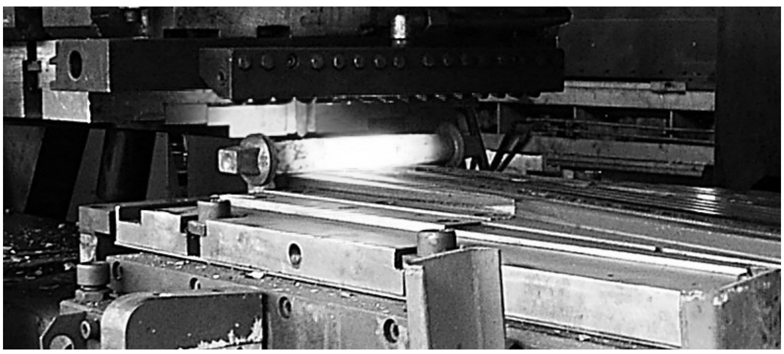
Fig. 1. The FEM computational model of the cross wedge rolling CWR process of screw spikes (a); the billet material (preform) and the rolled screw spike with a clear division into elements (b)



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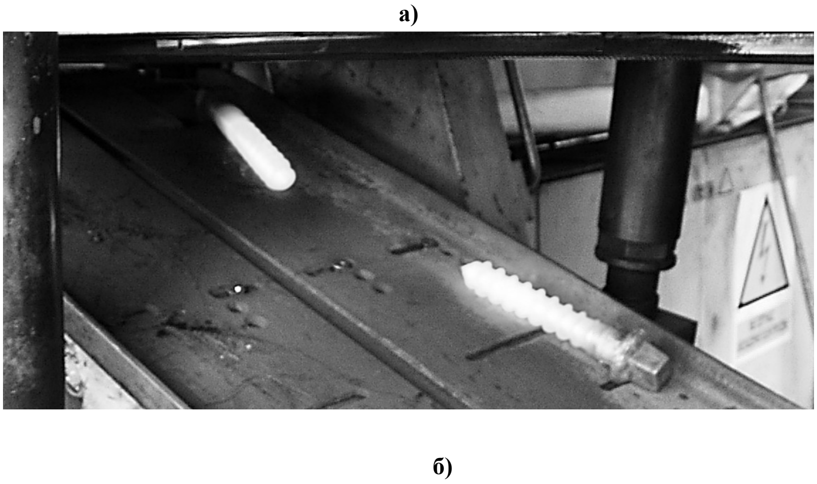

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Fig. 2. The tools used for screw spike rolling in double configuration: (a) a preform inserted between the rolling tools (the preform's middle part has been heated); (b) the formed screw spikes after cutting

The results of the computer simulations have allowed the industrial implementation of the screw spike rolling process in double configuration. Figure 2a presents the initial rolling phase, whereas Figure 2b shows the formed screw spikes after they have been cut.

Thanks to applying the finite element method FEM to numerical calculations of the cross wedge rolling CWR process, it is possible to thoroughly examine how the shape of the rolled material changes during the rolling process. The calculation results have demonstrated that the material in the formed thread zone is uniformly worked. In effect of the calculations, it has also been observed that the tangent force constitutes approximately 26.2% of the thrust force value. This observation is consistent with the research results of the cross wedge rolling process described in [8].

Worm rolling

At present, worms are predominantly produced with use of machining methods, yet it is possible to manufacture them in cold rolling. The cold rolling process usually makes use of two or three powered rolls which rotate in the same direction, thus forming the worm winding. During rolling, the charge is placed in the centre, while one of the rotating rolls moves in the radial direction (the radial rolling method). It can be claimed that worms, similarly to toothed gears, can be produced in cross wedge rolling operations. Figure 3 presents the examined scheme of forming worms.

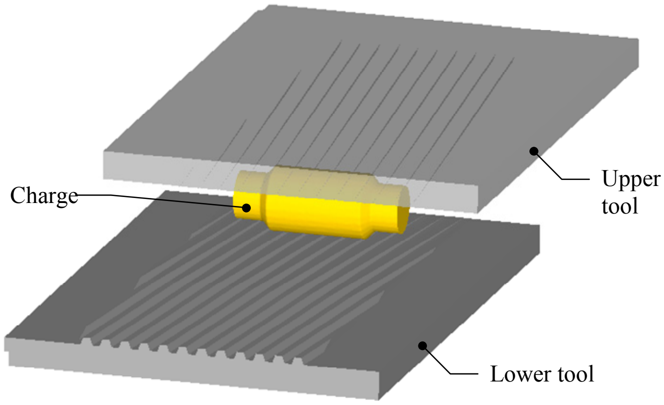

Fig. 3. The examined scheme of worm rolling with use of two flat tools

Rolling is done by means of two flat tools which move at the same speed in the opposite directions. The tools are equipped with splines of increasing height which penetrate the charge and form the worm's spiral grooves. The workpiece material displaced from the grooves flows into the worm's coils and increases their height. It is simultaneously assumed that the rolling process does not cause the workpiece to elongate axially.

The numerical analysis of worm rolling has been conducted in accordance with the same conditions as in the case of screw spike rolling. The conducted analysis examined the process of single-thread worm forming, which is illustrated in Fig. 4.

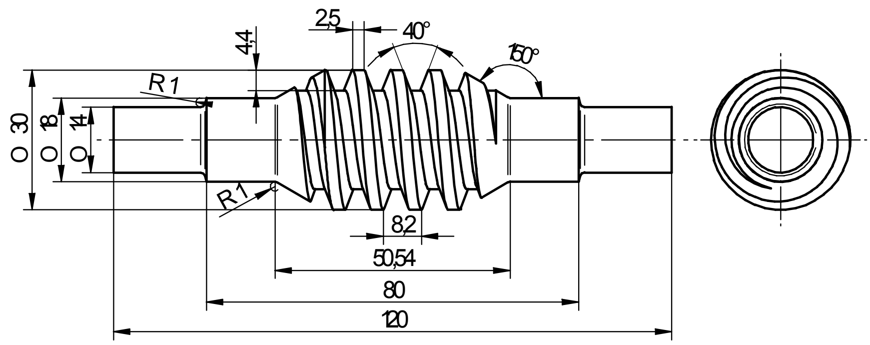

Fig. 4. The analysed worm used to verify the devised rolling method

It has been assumed that the rolled material's diameter is equal to the pitch diameter of the worm winding made at the largest (central) angle of the workpiece.

In the process of rolling, two flat tools move at the same speed in the opposite directions. The tools should be located at the end of the rolling tool – that is, beyond the cutting or sizing zone, provided that no cutting tools are used. When rolling occurs at extreme angles, a charge with specially prepared ends should be used.

Figure 5 illustrates the changes in the shape of the examined single-thread worm which occurred in the hot rolling process.

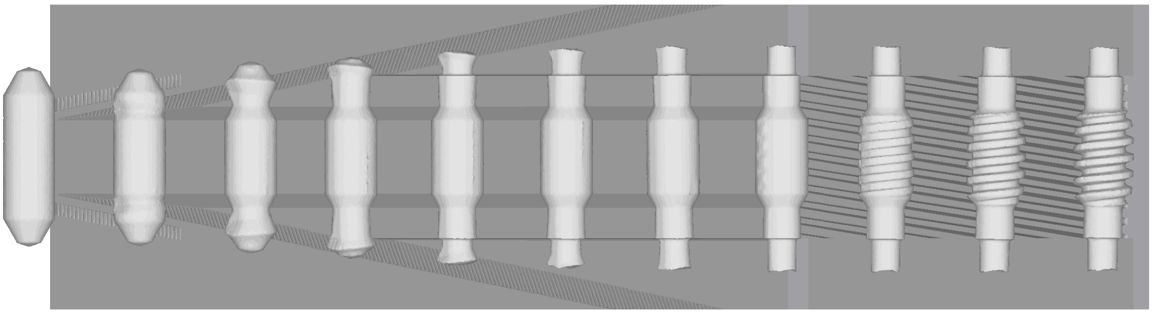

Fig. 5. The changes in the shape of a worm formed by cross-wedge rolling

The numerical calculations have shown that the elongation of the forming zone intensifies material processing within the angle where the winding is rolled. In effect, the differences between the strain rate of the surface and axial areas are reduced. Consequently, it should be stressed that the forming zone needs to be elongated because it decreases the imbalance between the strength properties of the obtained material.

The calculation results have shown that changing of the length of the forming zone does not considerably affect the value of rolling force components. It has been simultaneously observed that the tangent force (which presses the tool) and the thrust force (which determines the rolling precision) increase gradually in the forming zone, they take the maximal values on the boundary of the forming and sizing zones to successively decrease further on. Additionally, it has been noticed that unlike in cross rolling of other products, worm rolling involves an additional axial force, which assumes relatively lowest values out of the three mentioned forces. The axial force is at its highest during the sizing of the worm winding. This rolling force component may have an undesirable effect on the rolled material and displace it axially.

Laboratory tests.

Novel methods of rolling worms and other products described in the present paper have been tested under laboratory conditions with use of the LUW-2 rolling mill in the Department of Computer Modelling and Metal Forming Technologies at Lublin University of Technology. After the process of rolling, the worms are first cooled and then cleaned of scale and examined. It has been observed that the worms have an accurate shape, which demonstrates that the employed method of worm rolling can be successfully used under industrial conditions. Figure 6 presents a number of sample worms produced during the rolling tests.

The shape of the formed coils is accurate; it is only in the external coils that small undercuts can be noticed. The depth of those undercuts is insignificant and does not exceed the machining allowance which depends on the rolled material's overall dimensions and – as the conducted tests have shown – may range from 1 to 1.5 mm.

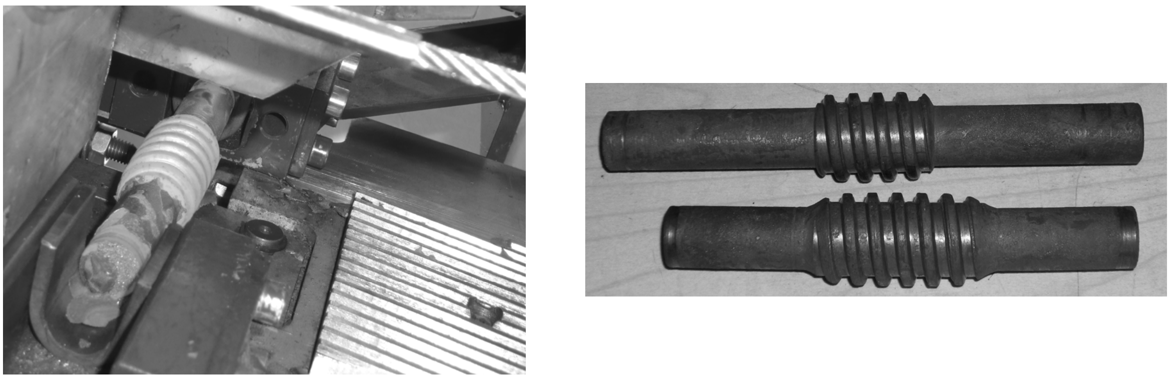

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Fig. 6. The formed worm just after its winding has been rolled (a), sample worms produced by cross-wedge rolling with use of flat tools (b)

Frequently used in many fields of motor industry, toothed stepped shafts are produced by machine forging. They can be forged by means of cross wedge rolling (CWR), which is successfully used to produce both stepped axes and stepped shafts. A numerical analysis of hot rolling of normal gear teeth, skew gear teeth, curved gear teeth and herringbone gear teeth using toothed racks has been conducted. Such a technique is optimal in terms of implementation costs (which include the manufacturing of necessary tools) and the fact that flat wedge tools are widely used in many industrial fields. Toothed racks can be assembled in the tools used for the cross wedge rolling process (the racks should be assembled beyond the sizing area), which allows the toothed gear to be rolled in one pass.

Gear rolling

The conducted 3D numerical analysis involved straight gear teeth, curved gear teeth, helical gear teeth and herringbone gear teeth rolling. All of the examined gear types had the same module (*m*=1.5) and the number of teeth (*z*=18). The workpieces used for the rolling tests had the same shape and their diameter (*ø* = 27 mm) was equal to the reference diameter of a gear.

It has been assumed that to form teeth pads will be used (toothed racks) whose longitudinal section shape is presented in Figure 7.

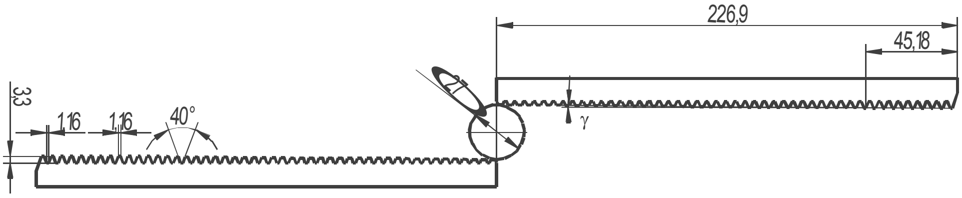

Fig. 7. The analysed scheme of cross wedge rolling of normal gear teeth

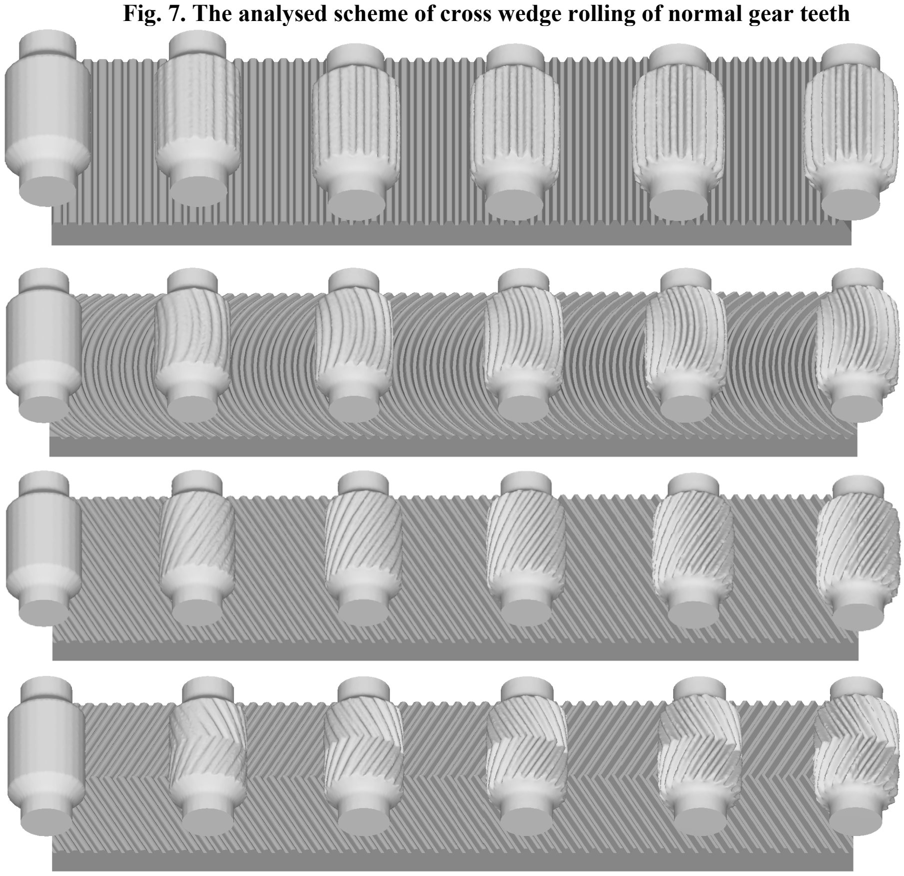

Fig. 8. The progression of shape changes in the teeth rolling process, *from above*: normal, curved, helical and herringbone gear teeth

Each of the applied pads had the same width of 60 mm. The way of forming teeth in the pads depended on the type of gear teeth being made. The teeth were cut in the pads in the following way:

- normal gear teeth were cut perpendicularly to the rolling direction,
- curved gear teeth were cut on the radius (R35),

- helical gear teeth were cut at an angle of 60˚ to the rolling direction,
- herringbone gear teeth were cut on both sides at an angle of 60˚ to the rolling direction.

The calculations were based on the same forming conditions as in the case of screw spike rolling. The workpiece's shape progression obtained as a result of the numerical simulation is illustrated in Figure 8. The following has been observed in all cases: (i) the tools gradually press the charge, which leads to metal extrusion from the tooth space to the teeth; (ii) the length of the sizing zone has been accurately estimated; (iii) the rolled material assumes the desired shape.

Taking the calculation analysis into account, it can be claimed that it is, in practice, easier to roll curved, helical and herringbone gear teeth rather than normal gear teeth. Normal teeth rolling is connected with substantial force variations resulting from temporary condition changes in the course of the process. It should, however, be stressed that the maximum values of the forces which occurred during the tests were comparable.

Conclusions

On the basis of the numerical calculations and conducted experimental tests, the following conclusions have been drawn:

- the hot cross-wedge rolling technique can be effectively used to form screw spikes, worms and toothed gear;
- the tools for rolling worm windings (i.e. flat tools) should have the possibly longest forming zones, which guarantees that the winding will be more uniformly formed;
- during the process of forming worms, the metal flows on the surface, which consequently deforms the external layers most, while less significant deformations occur in the central (axial) area;
- in contrast to other products, during worm rolling an additional axial force appears which may change the rolled material's position during the forming process;
- a drop in the metal temperature which occurs during rolling is insignificant and does not have a detrimental effect on the course of the process.

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