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Review Article

OVERVIEW OF THE RESEARCH ON ROLL FORGING PROCESSES

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ABSTRACT

The paper overviews the research on roll forging processes in the last two decades. Given the broad scope of this problem, the overview focuses on processes in forging plants, omitting those performed in metallurgical plants. Three rolling processes are discussed in detail: longitudinal rolling, cross rolling and helical rolling. Each of the three techniques is discussed in terms of the main research problems and potential directions of future development.

Keywords: cross rolling, longitudinal rolling, helical rolling.

INTRODUCTION

Roll forging processes are usually performed under hot forming conditions. Depending on the type of motion, shape and tool set-up, the following processes can be distinguished:

- longitudinal rolling (Fig. 1a): the workpiece performs a translational motion between the contrary rotating tools. The points of contact between the tools and the workpiece perform translational motion toward the length of the workpiece;
- cross rolling (Fig. 1b): the workpiece performs a rotary motion between the tools which are rotated in the same direction. The points of contact between the workpiece and the tools move along the perimeter of the workpiece in a plane that is perpendicular to the centre line of the workpiece;
- helical rolling (Fig. 1c): the workpiece performs a translational and rotary motion, and the rolls are askew to each other and rotated in the same direction. The points of contact between the workpiece and the tools perform a central motion.

In recent years, many studies have been conducted on roll forging processes, which are more and more widely used for producing finished products and preforms. This paper provides an overview of the results of the studies on roll forging processes.

LONGITUDINAL ROLLING

Longitudinal rolling is the most widely used roll forging technique and is predominantly used for forming preforms of elongated forgings which are then formed on forging presses (Fig. 2). The main advantages of this technique include:

- reduced material consumption (even by 1/3);
- improved conditions of the die forging process, due to the removal of forge scale during the rolling process;
- increased life of dies, due to optimized preform shape;
- processes for producing preforms are automated;
- it is possible to produce preforms with other than circular cross sections (e.g. square, rectangular and oval); such preforms are very hard to produce by cross and helical rolling.

In longitudinal rolling, preforms can be formed in one or several roll passes. One can distinguish several basic roll pass systems, schematically illustrated in Figure 3. The combinations shown in

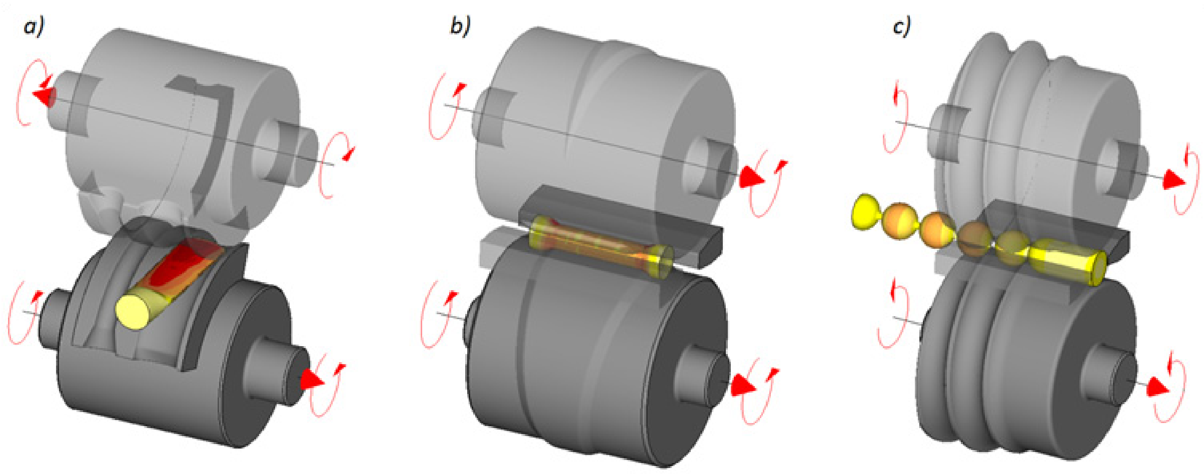

Fig. 1. Roll forging techniques: a) longitudinal rolling, b) cross rolling, c) helical rolling

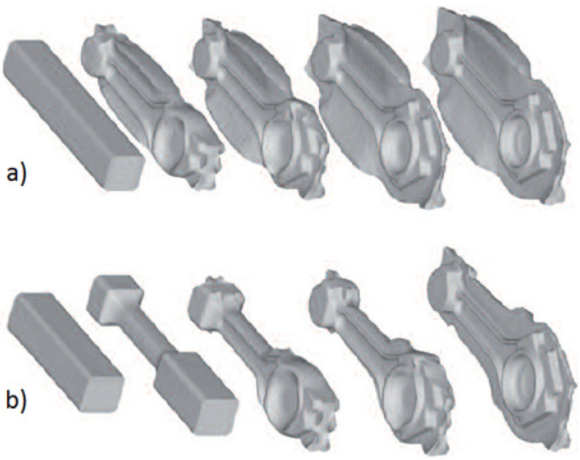

Fig. 2. Comparison of die forging processes for producing a connecting rod for trucks: a) from billet (bar) with a square cross section – material consumption: 100%, b) from preform produced by longitudinal rolling – material consumption: 67%; created based on [12]

this figure can be repeated a required number of times. The dimensions of a given roll pass can be established using different roll sizing methods, e.g. those developed by Spiess, Holler, Bachtinov-Shtiernov, Smirnov, Attoshenko, Kaufman, Martynov. These methods are described in detail in the monograph [45].

Despite a wide use of longitudinal rolling in industrial practice, the number of new research works devoted to this forming technique is relatively small.

Previous research works on longitudinal rolling are based on experimental tests and engineering analysis. One example of such a research is the study [165] reporting the experimental findings concerning the relationship between the size of widening and the cross-sectional reduction applied in the rolling of leaf springs. In turn, the work [167] describes a rolling process for alu-

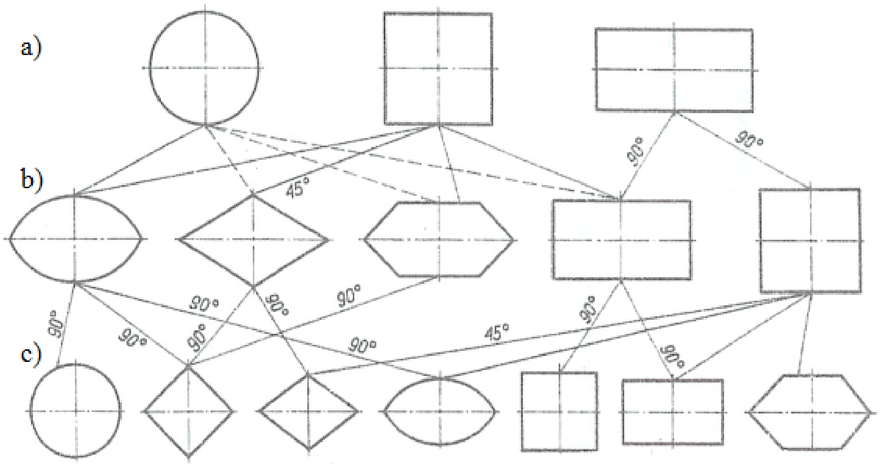

Fig. 3. Systems of stretching roll passes: a) starting material, b) first pass, c) second pass [88]

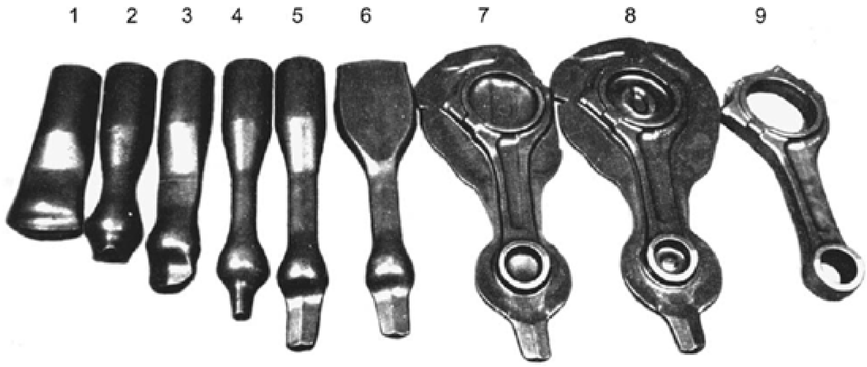

Fig. 4. Changes in the shape of the semi-finished connection rod, where: 1÷5 - successive roll passes in longitudinal rolling, 6 – flattening, 7 and 8 – die forging, 9 – flash trimming [24]

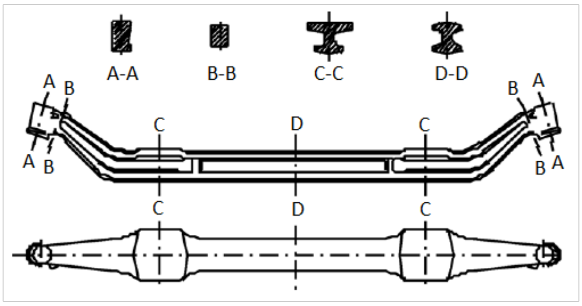

Fig. 5. Schematic design of a standard front axle beam for trucks [9]

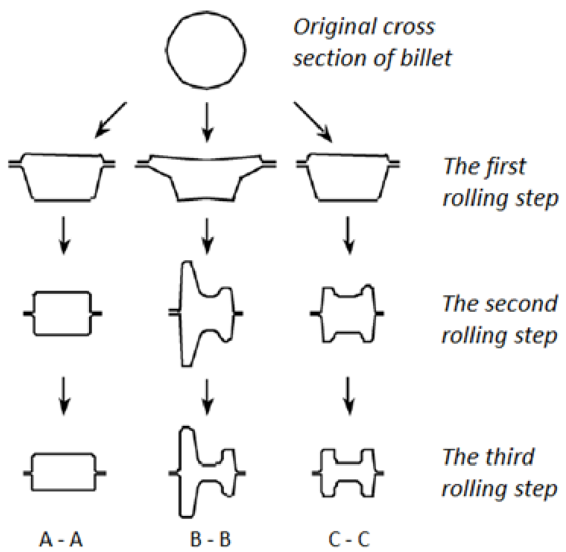

Fig. 6. System of roll pass sizing used in the rolling of a front axle beam; cross sections denoted in compliance with Fig. 5 [9]

minium alloy preforms for connection rods (after rolling, the preforms are heated again and subjected to forging on a forging press).

After the year 2000, the research on roll forging processes was more and more often performed by means of FEM-based numerical analysis. The analyses were performed using commercial simulation software such as MSC.AutoForge, MSC. SuperForm, QForm, Deform-3D. The objectives of the numerical analyses included:

- reducing material consumption via optimized shape of the preform [129];
- determination of metal flow kinematics, microstructure development and the distribution of local strength properties during five roll passes when the preform is being formed into a connection rod (Fig. 4) [23, 24];
- design of new types of roll pass including oval-flat and oval-rhombic [33, 53, 172], the use of which will ensure that effective strains are uniform on the cross section of the strip being elongated.

A series of publications [9, 40, 42, 43, 152] were devoted to the problem of the longitudinal rolling of front axle beams for trucks (Fig. 5). The study [9] describes a method for accurate determination of the roll pass design used for forming this part, which then served as a basis for developing a roll pass sizing system shown in Figure 6. According to this solution, the front axle beam is flash-rolled in three roll passes and then subjected to bending and press forging in order to obtain the required shape. The studies [40÷42, 152, 175, 176] report the results of numerical simulations which were performed to verify the above solution. The following were examined during each roll pass: changes in the workpiece shape (Fig. 7), force parameters, the distributions of temperatures, effective strains and stresses. As a result of development works conducted in China, 30 production lines for manufacturing front axle beams (Fig. 8), comprising longitudinal rolling mills and screw presses exerting loads of 25÷40 MN.

Fig. 7. FEM-simulated shape of a semi-finished front axle beam produced by longitudinal rolling: a) after first roll pass, b) after second roll pass, c) after third roll pass [176]

Fig. 8. Production line for manufacturing front axle beams and a selection of finished parts [110]

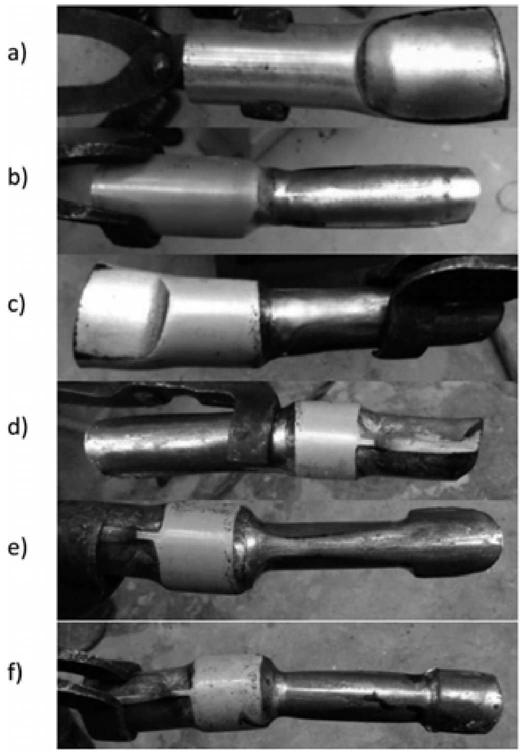

Fig. 9. Successive stages of the forming of an AZ31 alloy preform by longitudinal rolling in the following roll impressions: a) oval I, b) circle I, c) oval II, d) circle II, e) oval III, f) circle III [8]

The annual throughput of such lines ranges from 50.000 to 1.000.000 beams (depending on their overall dimensions); the yield of material in this forming process amounts to 85%÷92%. The lifetime of the roll segments is 8÷15 thousand pieces (preforms), which is twice higher than the lifetime of forging dies in which beams are formed by bending and additional forging [110].

Specialist literature also provides some information about the longitudinal rolling of semi-finished products made of non-ferrous metal alloys. For instance, the study [135] reports the numerical results of the rolling process for producing a preform of lever made of magnesium alloy AZ31. The numerical simulations described in the study were performed for two different rolling methods, i.e., longitudinal and cross-wedge rolling. The results reveal that, due to the risk of workpiece cracking, lever preforms should be produced by longitudinal rolling. This observation was confirmed by findings of the experimental tests (Fig.

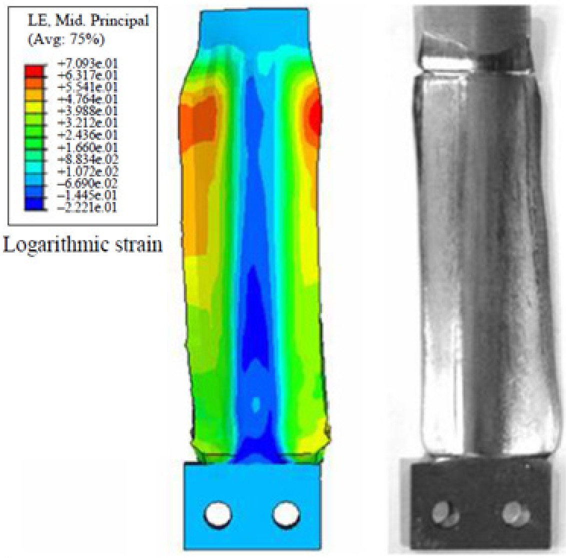

Fig. 10. Comparison of the FEM and experimental results of the shape of an Inconel 718 alloy compressor blade formed by cold rolling [120]

9) which are described in detail in [8]. The publication [7] reports the experimental results of the longitudinal rolling process for producing a lever preform made of aluminium alloy 2014. The experiments were performed at Lublin University of Technology using a laboratory rolling mill provided with the rolls which are 320 mm in diameter. In turn, the study [120] reports numerical and experimental results of the longitudinal cold rolling of a compressor blade made of Inconel 718 alloy (Fig. 10). The research was aimed at investigating the possibility of increasing rolling accuracy by taking account of elastic strains which occur between tools and rolling mill.

Given the wide use of the roll forging technique, Eratz Engineering developed commercial forging software to aid the design of tool segments for roll forging. This software, known as VeraCAD [142], generates, based on a three-dimensional model of a forging, the following: a schematic of the cross section of the workpiece (including flash allowance), 3D models of the workpiece (with circular, square and oval cross sections), a schematic design of roll sizing. After that, the programme simulates the way in which the rolls should be sized and shows preform shape after every roll pass, producing a 3D model of the tool segment (it is possible to generate a code for CNC machine tools) and their technical documentation in 2D. VeraCAD significantly facilitates the design of a required longitudinal rolling process, and information about its applications can be found in the specialist literature, e.g. in [146].

CROSS ROLLING

Among the many cross rolling processes, cross wedge rolling (CWR) is a technique which is the most widely used in the forging industry. The CWR technique consists in the metal forming of axisymmetric parts by wedge-shaped tools which are mounted either on the rolls or on flat or concave rolling mill plates. The CWR method is widely used to produce such parts as stepped axes and shafts as well as to produce preforms for press forging.

The state of the art in the theory and technology of CWR before 1992 was exhaustively described in [18]. However, this interesting forming technique was the subject of numerous research works published in the last two decades, the results of which seem worth highlighting.

Initially, CWR processes were investigated exclusively by engineering analysis methods. Those methods enabled the determination of basic force parameters. Next, a new method of layer modelling was developed [59, 87, 89, 92]. The method was based on the similarity between the patterns of metal flow in the cross section of the workpiece in CWR and rotary compression. The solution consisted in the modelling of a deformation zone by means of adjacent layers (Fig. 11) described by a two-dimensional state of strain. The layer method enables determining not only basic force parameters at every stage of the process but forecasting stability of the rolling process. Moreover, this method was used for the multi-criteria optimization of basic parameters in CWR [102].

CWR processes can be best investigated by modelling with the finite element method (FEM). Given the complexity of the deformation process, the tool pitch which is many times higher than

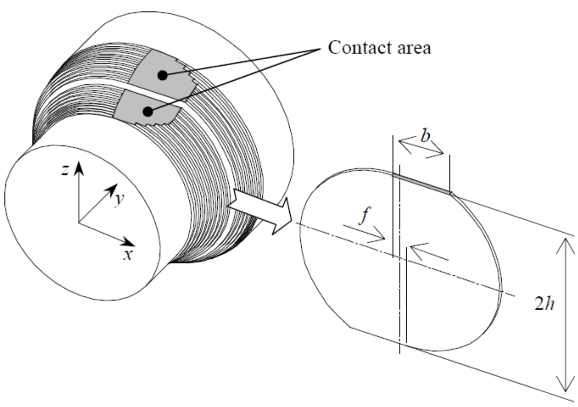

Fig. 11. Layer model of the deformation zone in CWR introduced by Pater

the dimensions of the workpiece and the type of metal-tool contact, the modelling of CWR processes was not successful until the twenty-first century. Numerous studies published so far report the results of numerical simulations. The simulations were performed using the following simulation software: ANSYS/LS-DYNA [11, 13÷16, 34, 38, 39, 47, 48, 106, 107, 126, 128, 139, 140, 149, 153, 156, 162, 170], Deform 3D [17, 19, 21, 26, 28÷32, 35, 44, 49, 50, 54, 74, 75, 81, 86, 104, 108, 112, 113, 121, 124, 125, 127, 130, 143÷145, 148, 150, 154, 155, 157, 159÷161, 163, 166, 169, 171, 173, 174], Forge 3 [37, 51, 52, 56, 109], MSC.SuperForm, MARC.AutoForge and Simufact.Forming [3, 5, 27, 66, 67, 69, 71, 77, 90, 91, 95, 111]. A vast number of the numerical analyses and experimental tests [5, 13÷16, 29, 39, 46, 47, 54, 56, 57, 61, 90, 113, 139, 148, 162, 173, 174] were focused on the modelling of failure modes which may occur in CWR such as uncontrolled slipping, step necking, workpiece bending and material cracking. In addition, the FEM was used to investigate forces [4, 52, 107, 126] and the variations in workpiece temperature [42, 66, 112], microstructure [19, 28, 29, 34, 49, 145, 154], stresses [16, 17, 67, 90, 128, 148, 153, 162, 169], strains [26, 67, 91, 96, 113, 121, 153, 163], and tool wear [27].

As a result of both the development of computer software for modelling metal forming processes and enhanced computational possibilities of digital machines, it is possible to model even the most complex CWR processes using personal computers [80]. For instance, a PC can be used to model the rolling process for producing a drive shaft which is shown in Fig. 12. In this process, the shaft is formed by two flat wedges from a billet, the diameter of which is equal to the largest step to be formed on the shaft. The end steps of the shaft are formed here at the reduction ratios δ (where: $\delta = d_0/d$; d_0 – billet diameter, d – diameter of the rolled step) which are equal up to 3.33. In order to make such a high cross-sectional reduction possible, the rolling process must be performed in two stages: first, the intermediate diameter of the step is formed, and then the final diameter is produced.

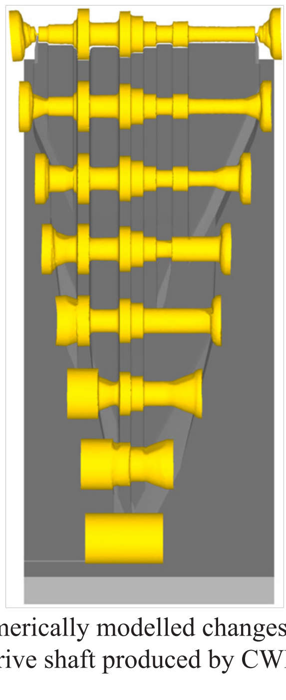

Fig. 12. Numerically modelled changes in the shape of a drive shaft produced by CWR [80]

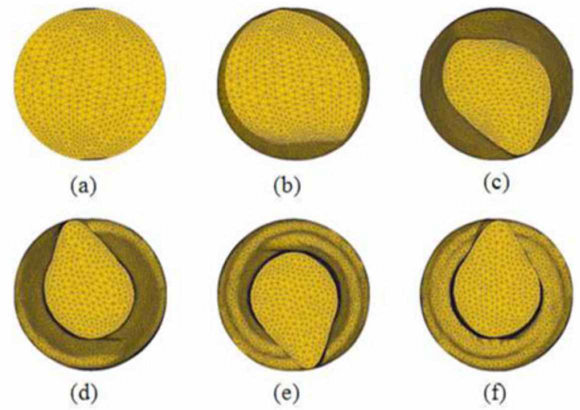

Fig. 13. Changes in shape of the cross section of a cam produced by CWR: a) – f) successive stages of the forming process [50]

To increase the technological potential of cross wedge rolling, a number of theoretical and experimental studies were conducted. Some of them focused on CWR processes for producing parts with steps with other than circular cross sections (e.g. square, oval, hexagonal). Such steps can be produced using tools which have specially formed sizing surfaces. Numerical results and experimental findings [1, 25, 50, 76, 80, 103, 171] demonstrate that the CWR technique can be applied to produce non-axisymmetric products. Such forming processes are characterized by oscillatory variations in forces resulting from the cyclically changing rolling reduction. One example of such a process is the forming of cams on a stepped shaft, described in [1, 25, 171]. Figure 13 illustrates the successive stages of forming the cam, as determined with Deform-3D.

There have also been studies investigating CWR processes for producing shafts with toothed coiling or worms. The design of such processes consists in the use of special inserts for forming

Fig. 14. Shaft with straight teeth (number of teeth: 18; module: 1.5) produced by cross rolling [76]

Fig. 15. Worm shafts (with single coiling, coil height: 3 mm) produced by cross rolling [76]

coils; the inserts are mounted at the end of the tool segment, beyond the sizing zone. The results of preliminary research on the rolling of toothed shafts with normal teeth (Fig. 14) and helical teeth [35, 58, 73, 76, 133, 166] as well as worm shafts (Fig. 15) [62, 72, 76, 79, 157÷159] are promising. The results demonstrate that the CWR method can be used to produce teeth and worms, the shape of which can later be slightly corrected by means of accurate milling or grinding.

It should also be mentioned that the CWR process was successfully implemented to produce

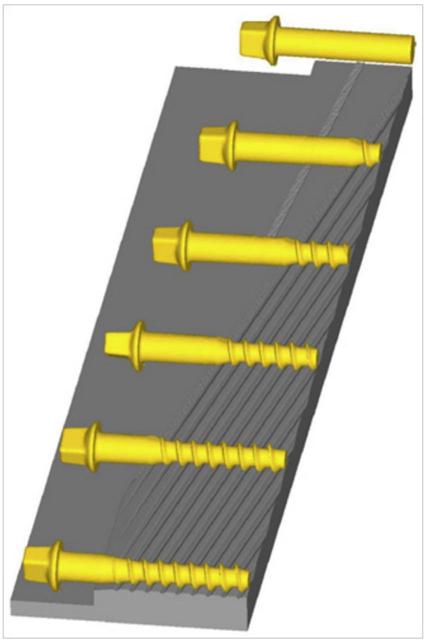

Fig. 16. Numerical model of a rolling process for producing screw spikes (axial symmetry of the forming process is assumed) [81]

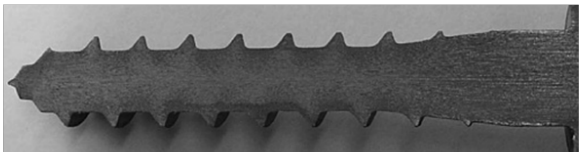

Fig. 17. Longitudinal section of the screw spike thread produced by cross wedge rolling [20]

screw spikes, including those formed in a double configuration [20, 22, 70, 78, 81, 141, 151]. The new method for producing screws designed and developed at Lublin University of Technology [20, 22, 70, 78, 81, 151] consists in the use of two forging operations. The first operation involves the flashless forging of screw heads in a double configuration, i.e., screw heads are formed on both ends of a cylindrical bar. The second operation consists in forming a thread on two screws by cross wedge rolling (as shown in Fig. 16); the screws are separated in the final stage of the forming process. Thereby, the produced screw spikes have a good quality, the required grain pattern and the desired tapered ends (Fig. 17).

Given a growing demand for hollow parts in machine design, studies have also been conducted on the possibility of producing such parts by CWR methods. The results of the extensive research [2÷5, 26, 30, 32, 49, 94, 98, 105, 108, 130, 131, 139, 140, 160, 161, 163] demonstrate that:

- the cross rolling technique can be used to form parts, the accuracy of which is similar to that of solid parts produced by rolling; potential failure modes which may occur during the forming process include collapse of a workpiece, workpiece necking and considerable defects of its internal surface;
- the angles of tools (wedges) should differ from those applied in the rolling of solid parts; the principles of selecting these angles are formulated in [2, 3, 5];
- due to increased cross-sectional ovalization, the sizing zone should be elongated such that the workpiece can be rotated approx. 3 times.

The findings of the survey of the specialist literature reveal that previous developments in the CWR technique focused on the production of steel parts, and little attention was put on the production of parts made of non-ferrous metals and their alloys. There have been attempts to form parts made of titanium alloys [6, 55, 69, 75, 98], aluminium alloys [75, 94, 137], magnesium alloys [104] and nickel-based superalloys [54], copper balls [117] and zinc alloy shafts used in nuclear reactors [118]. It seems that the research on CWR for non-ferrous materials will become one of the research trends in the future.

In recent years, considerable research has been conducted on the multi-wedge rolling technique wherein the workpiece is formed by more than one pair of wedges (tools) at the same time. Although this solution leads to a considerable shortening of the tool length, it results in increasing the forming forces. The design of tool segments is more complicated, too, because the shape of the side wedges must allow for the elongation of the workpiece caused by the impact of the central wedges [83, 125, 168]. The multi-wedge rolling technique can be used for producing:

- very long shafts and axes, e.g. for cars and trains [108, 128, 153, 170];
- several (or more) short parts at the same time, including balls for ball mills and bearings (Fig. 18) [83, 84, 97].

Fig. 18. Multi-wedge tools and 22 mm diameter steel balls formed by these tools; based on [83]

HELICAL ROLLING

Helical rolling processes are seldom used in industrial practice. This results from the fact that the tools (rolls) used in this process have helical grooves on their perimeter; the grooves are of a varying shape and pitch (due to the constancy-of-volume relationship of the workpiece constrained in a roll pass formed by two or three grooves on the mating rolls), which makes it significantly difficult to design and build these tools. For this reason, the helical roll forging technique is only used for producing parts with relatively simple shapes, for example bearing rings or balls for bearings or ball mills.

As a result of a small range of applications for helical wedge rolling in industrial process, there are only a few recent studies devoted to this technique. The studies mainly concerned the FEM-based numerical modelling of rolling processes for rings [36, 116] and balls [10, 114, 115, 123, 132, 138] as well as the design of tools used for these processes [10, 100, 122, 147, 164].

In recent years, Lublin University of Technology has run an extensive research programme aimed at designing a new rolling method for forming steel balls from heads of scrap railway rails [101]. The project led to the development of a new rolling technique called helical wedge rolling (HWR). The technique is based on the use of wedges with helical grooves which are mounted on the rolls to ensure that parts are formed in a continuous manner. The numerical results and experimental findings demonstrate that helical wedge rolling is a viable technique for forming balls [60, 63, 68, 85, 99, 101, 134, 136]. Figure 19 shows the tools used in the HWR for balls and semi-finished balls. Parts formed with these tools exhibit high quality and manufacturing accuracy.

Fig. 19. Rolls used in helical-wedge rolling (top) and 33 mm diameter balls formed by these tools (down) [68]

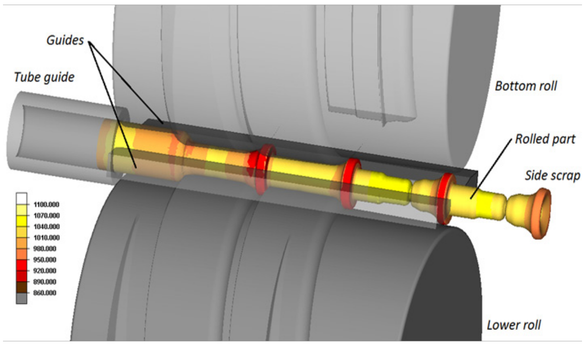

Fig. 20. Numerically simulated distribution of the temperature (in °C) in a helical rolling process for producing a rotary cutter body

The satisfactory results of the helical wedge rolling technique for producing balls led a team of researchers from Lublin University of Technology to investigate if this new manufacturing technique could be used for manufacturing some other parts. The results of the FEM numerical analyses described in detail in [64, 65, 93] demonstrate that the helical rolling method can be used to produce fixings, stepped shafts and bodies of rotary cutters (Fig. 20). At the same time, the authors underline the need for further experimental investigations of the helical wedge rolling technique to expand its application to the production of other products, including hollow parts.

CONCLUSIONS

The survey of the literature led to the formulation of the following conclusions:

- roll forging processes are more and more widely used in industrial practice, predominantly for forming preforms and axisymmetric parts;
- the research on the above processes is predominantly conducted using numerical techniques, particularly those based on the finite element method;
- the development of longitudinal rolling predominantly involves the design of new roll passes and a new technique for forming front axle beams;
- cross wedge rolling processes were greatly developed in the last twenty years; in particular, one can observe a growing popularity of the cross wedge rolling technique;
- helical rolling is seldom used in industrial practice due to the complex design of the tools ensuring the formation of parts with the required quality.

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