THE THEORETICAL AND EXPERIMENTAL RESEARCH OF ROLLING - EXTRUSION PROCESS

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Contents

INDEX OF MARKINGS

α – rolls forming angle
Γ – ovality
δ – diameter reduction ratio
Δ – ovalization parameter
ν – pusher axial velocity
ω – rolls rotary velocity
D – billet neck diameter
D_F – billet reduced step diameter
D_{max} – maximal diameter of billet
D_{min} – minimal diameter of billet
D_{nom} – nominal diameter of billet
D_R – rolls diameter
D_W – billet diameter
g – billet wall thickness
L – length of rolls calibrating zone
p – feed rate
Q_C – squeezing (axial) force
r – billet reduced step radius
R_a – roughness parameter
R_W – rolls radius

BADANIA TEORETYCZNO - DOŚWIADCZALNE PROCESU PRZEPYCHANIA OBROTOWEGO

Jarosław Bartnicki

Streszczenie: Jedną z nowych technologii kształtowania stopniowanych wyrobów pełnych i drążonych, obok walcowania poprzeczno-klinowego, jest przepychanie obrotowe. W procesie tym materiał jest kształtowany za pośrednictwem trzech obracających się narzędzi rolkowych. Wsad wprowadzany jest do przestrzeni roboczej pomiędzy rolkami za pomocą popychacza wykonującego równocześnie ruch postępowy i obrotowy. W przedstawionych w pracy badaniach numerycznych określono wpływ kształtu narzędzi oraz podstawowych parametrów kinematycznych procesu na jego przebieg. W obliczeniach stosowano komercyjny pakiet oprogramowania MSC.SuperForm 2005 oraz Deform – 3D oparty na metodzie elementów skończonych. Na podstawie przeprowadzonych badań numerycznych stwierdzono, że stabilność procesu przepychania obrotowego jest uzależniona od doboru właściwego kształtu i prędkości obrotowej rolek profilowych oraz ustawienia prędkości liniowej popychacza wprowadzającego materiał do przestrzeni roboczej pomiędzy rolkami. Wyniki badań numerycznych stały się podstawą do opracowania założeń agregatu do przepychania obrotowego. Na podstawie obliczeń numerycznych przebiegu procesu przepychania obrotowego oraz analiz wytrzymałościowych z zakresu sztywności konstrukcji zaprojektowano i wykonano prototypowy agregat do przepychania obrotowego nazwany PO-1. Maszyna ta umożliwiła przeprowadzenie badań doświadczalnych o charakterze weryfikacyjnym w stosunku do wcześniejszego etapu symulacji numerycznych kształtowania wyrobów pełnych i drążonych. Uwzględnienie płynących z tych badań wniosków pozwoliło na zaprojektowanie procesu technologicznego procesu przepychania obrotowego stopniowanego wałka drążonego, co przedstawiono w przedostatnim rozdziale pracy. Pomyślne rezultaty prób doświadczalnych pozwoliły sprawdzić w praktyce wnioski płynące z opisanych we wcześniejszych rozdziałach prac. Innym efektem prowadzonych analiz było ustalenie dalszego kierunku rozwoju technologii przepychania obrotowego, do czego konieczna będzie dalsza modernizacja agregatu.

THE THEORETICAL AND EXPERIMENTAL RESEARCH OF ROLLING-EXTRUSION PROCESS

Jarosław Bartnicki

Abstract: One of the newest technologies of forming of stepped full and hollowed products, apart from cross-wedge rolling, is rolling extrusion . In this process material is formed by means of three rotating tools rolls. Billet is put into workspace between rolls by means of a pusher, which moves in translational motion and rotates at the same time. Influence of tools shape and basic kinematics parameters of the process on its course is presented in numerical research discussed in this work. Commercial softwares MSC.SuperForm 2005 and Deform 3D, based on finite element method, were used in calculations. On the basis of conducted numerical research, it was stated that rolling extrusion process stability depends on choice of proper shape and rotary velocity of profiled rolls and on linear velocity of the pusher placing the material into workspace between rolls. Results of numerical research were the basis for working out assumptions of aggregate for rolling extrusion. Numerical calculations of rolling extrusion process course and strength analyses within the range of construction stiffness allowed for designing and manufacturing of a prototype aggregate for rolling extrusion, called PO-1. This machine allows to conduct experimental research of verifying character in comparison with the former stage of numerical simulations of full and hollowed products. Considering results of this research, it was possible to design technological process of rolling extrusion of stepped hollowed shaft, which was presented in the last chapter of the book. Satisfactory results of experimental tests allowed to check in practice conclusions drawn from works described in earlier chapters. Another effect of conducted analyses was determining further direction of rolling extrusion technology development, in which modernization of aggregate will be needed.

1. Introduction

The XX century brought a very dynamic development of various life spheres. A new branches of science appeared together with it and a global technological development resulted in fast expansion of different manufacturing techniques.

Manufacturing companies around the world, after not thoroughly thought over from an economical point of view investments, began to reduce the prime costs. This tendency has been restricted recently by not favorable market conditions and the necessity of rivalry in order to maintain at the market. The victims of these manufacturing costs reductions were, at the beginning, small unknown brands, which could not face challenge. Because of that, in UE countries numerous financial programs have appeared, aiming at activating of this type of companies in order to maintain their market position and keep job positions. The necessary conditions for obtaining financial support included e.g innovative technologies and machines implementation guaranteeing relatively high quality of products and services. The further UE programs connect these solutions together with research and development, creating possibility of direct cooperation between industrial and scientific world. In that way, the role of new technologies development and the improvement of present solutions in economy were highlighted.

In the field of mechanical and machine construction a rapid development of manufacturing technologies belongs to the past. At present, research works aim rather to optimize parameters of conducted processes, their full automation and to obtain relatively high operating parameters of finished products at possibly the lowest costs. Hence, in the case of piece production and small lot production of mechanical metal parts, leading role, due to costs and manufacturing flexibility, have technologies connected with machining.

Considering products manufactured on a larger scale, casting and various methods of metal forming have been chosen so far. At present, due to ecology and not satisfying mechanical characteristics of products cast in a traditional way, this technology is being withdrawn. Constantly developing technologies of metal forming, guaranteeing continuous metal fibres structure and relatively the largest mechanical properties of products, are chosen as an alternative. One of the aims of modern techniques of metal forming is limiting manufacturing costs, in which production of specialist tooling is extremely important. This position (tooling) in cost calculation considerably increases financial costs and makes products series of a few- a dozen or so thousands pieces more cost effective.

Aviation production seems to be exception. In this production, due to very restrictive norms, single forgings of critical element status are sometimes made by means of die forging methods. Parts such as stepped shafts and axes are widely applied in industry. These parts are used by automotive concerns in engine sets and power transmission (drive) transfer. We can talk here about mass production of these products. In shorter production series, stepped axes and shafts are applied in engineering, aviation, agriculture etc industries.

Limiting the length of manufacturing series and the application of various mechanical solutions result in a considerable increase of metal forming costs. Because of that, the industrial interest in metal forming technology is lower in favor of increasing machining application.

This work presents one of the alternative possibilities of widening of scope of metal forming technology application on shorter series of stepped axi – symmetrical products of shafts and axes type. The discussed rotary forming method derives from the preceding research on cross – wedge rolling (CWR) conducted at Department of Computer Modelling and Metal Forming at Lublin University of Technology and supervised by prof. Zbigniew Pater. Theoretical analysis and experimental research of cross rolling processes were the basis for further works on improving metal forming technologies which use a similar forming schema. It is assumed that rotary forging technology allows for forming of stepped shafts and axes in full and hollowed versions without lengths limits, which, in CWR technologies, results directly from wedge tools width. Moreover, the possibility of change of three working tools –

rolls spacing applied in rotary forging process allows for accorded with planned earlier research schedule regulation of formed products diameters. Apart from design problems with transmitting the drive on three tools–rolls an a pusher placing a billet into workspace, this technology requires precisely determined billet guiding. Laboratory tests show that it is not an easy task and that billet positioning mistakes influence dimension tolerances of finished products. Hence, rotary forging, apart from advantages (in comparison with CWR), has also certain limitations, the most serious of which include guaranteeing relatively high repeatability of production.

At present, the conducted research show the possibility of the new forming method implementation in industrial conditions. One of the possibly realized applications is manufacturing of shafts for agriculture machines. Due to an easy regulation of formed products step diameter, it is possible to apply this solution for machine renovation, where shafts and axes of various dimensions are often used. Implementation of metal forming allows for increasing of durability and strength of these parts. The application, if necessary, in a design of machine for rotary forging inductive heating allows for limiting energy consumption to heating of the forming zone only and for minimizing the area of structural changes in a product.

Working out of theoretical part with numerical calculations and of experimental research realized in laboratory required a wide experience of the whole staff of Computer Modelling and Metal Forming Department, whom I would like to thank for help and support. I am most grateful to prof. W.S. Weroński, prof. Z. Pater and prof. J. Kazanecki (who as a reviewer proposed precious remarks) for their constant inspiration for research conducting

Author

2. General analysis

2.1. S tepped a xi – symmetrical p roducts – types an d application

Stepped axi – symmetrical elements of axes and shafts type are applied in various branches of industry, from the first made machines or tools to manufactured at present most advanced technically aviation constructions. Manufacturing technologies of these products have been gradually improved for many years, the most rapid development took place in last century.

As it was mentioned in the previous chapter, stepped axes and shafts are manufactured by means of various methods depending on manufacturer's conditions, production scale, ready market stability or manufacturing costs, which are at present one of the main decisive factors.

In order to demonstrate how large ready market is considered, it is sufficient to analyze data from GKN Automotive A.G. from Germany, which state that cars manufacturing on global scale in 2007 reached number 60 millions [20]. Considering that every car has at least two semi axles and extremely popular cars with four – wheel drive have four semi axles, automotive market demand is 130 millions of parts of this type. Additionally, in cars with four-wheel drive it is necessary to transmit drive to the second axle shaft by means of drive shaft, which also increases demand for these elements. An example of four – wheel drive is a car shown in Fig. 2.1, and axi – symmetrical products applied in different industrial branches are presented in Fig. 2.2.

In automotive industry the most widely applied so far semi-axles of full cross section are being replaced by hollowed products, made by means of various manufacturing and assembling technologies. The simplest of them is through feed drilling of full shafts, made in order to lower their weight and moment of inertia – Fig. 2.3.

Fig. 2.1. *Four – wheel drive vw passat [65]*

Fig. 2.2. *Examples of axi – symmetrical elements [61-64, 66, 69]*

Another possible to apply technology is hollowed shafts manufacturing from two or three semi-finished products connected later in one whole (part). In that case, components can be made mainly in machining and co – extrusion processes. An example of such a solution is shown in Fig. 2.4.

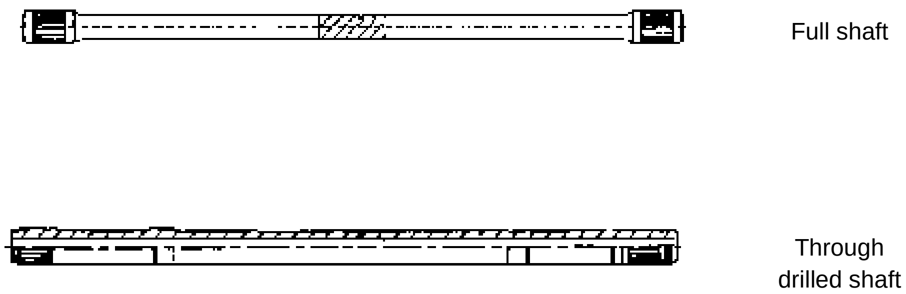


Fig. 2.3 *Full shaft and through drilled shaft [1, 2]*

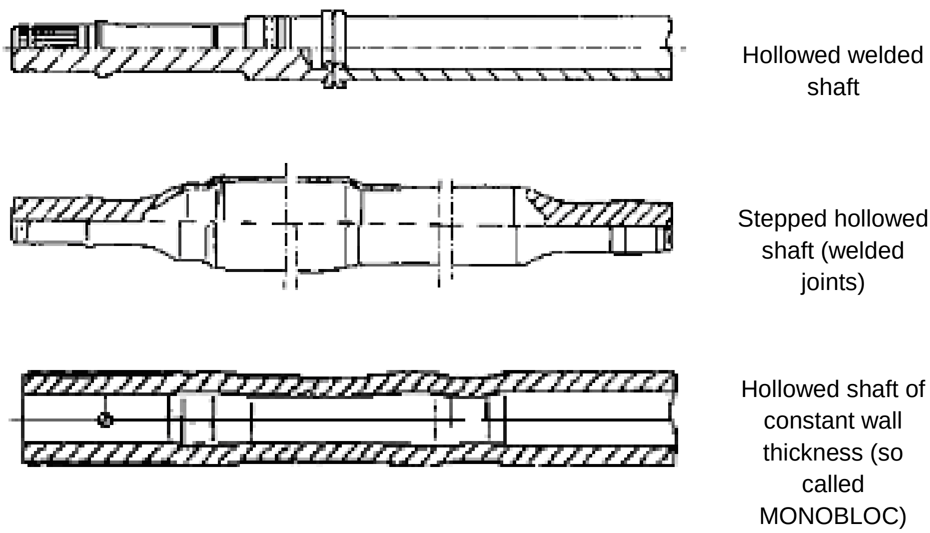


Fig. 2.4. *Design examples of hollowed shafts made from semi-finished products [1, 2]*

2.2 Manufacturing methods

2.2.1 Machining

One of the most popular methods of axles or shafts manufacturing is still machining method, based on removing of material upper layers from round bar used as a billet for the further machining operations. This technology is successfully applied even by small companies and workshops, where turning lathe is more often replaced by numerically controlled machine CNC, allowing for a considerable enlarging of scope of machining operations. This solution allows also for reaching high level of precision and production repeatability. It should be, however, remembered that during choosing machining it is necessary to consider material loss on technological allowance at manufacturing stages, as well as, on finishing operation in order to obtain required product dimensions. For example, for rough turning the allowance size is within the range from 2 to 6 mm, yet, allowances for forming operations are within the range from 0.7÷1.5 mm. These allowances are within these ranges due to the fact that they are chosen for specified ranges of diameters and semi–finished product lengths.

2.2.2 Metal forming

Searching for innovative solutions in the process of machine parts forming, special attention is paid to metal forming as elements manufactured by means of this technology have continuous fibers system. Moreover, comparing material which undergoes metal forming with material after machining it can be easily noticed that material external layers structure is strengthened by cold work (Fig. 2.5). This strengthening is also connected with larger material durability, especially at the formed profile base.

Among manufacturing methods of axi – symmetrical elements, basing on metal forming, the following should be considered:

- drawing;
- rolling extrusion;
- traditional forging;
- rotary forging;
- swaging;
- extrusion in cold conditions;
- forming of sintered materials;

Fig. 2.5. *Material fibres distribution after machining (at the left) and after metal forming process (at the right) [5]*

The choice of mentioned above technologies for specified needs depends on economical aspect connected with scale and stability of order. Each of these manufacturing methods have certain limitations and advantages destining them for specified application. A decisive role have manufacturing costs, in which all financial expenses bear by a potential manufacturer are considered. Another important aspect that should be considered is manufacturing repeatability. Permissible tolerances of thin tubes walls thickness together with limited shape dimensional tolerances are extremely difficult to preserve. If a considered full or hollowed element is to be used as high – speed machine shaft, the assumed (high) permissible rotary velocity corresponds with small dimensional tolerance of a finished product. Parts that fulfill these requirements can be obtained by means of drawing technology, which is characterized by high quality of external surface, compared with polished surfaces, and small dimensional tolerances. Moreover, due to appropriate heat treatment of metal before drawing process, it is possible to obtain products of high durability and fatigue properties at retaining good plastic properties [33]. Drawing process is based on product elongation by means of drawing dies (Fig. 2.6 and Fig. 2.7), however, the force acts on not formed piece of material.

The change of dimensions or shapes takes place on a part of formed product length. Billet used during this process is squeezed, which results in considerable limitations of acting force value. This force cannot be larger than force needed for reaching yield point of not formed part of semi-finished product, as after exceeding this limiting value the semi-finished product can be deformed.

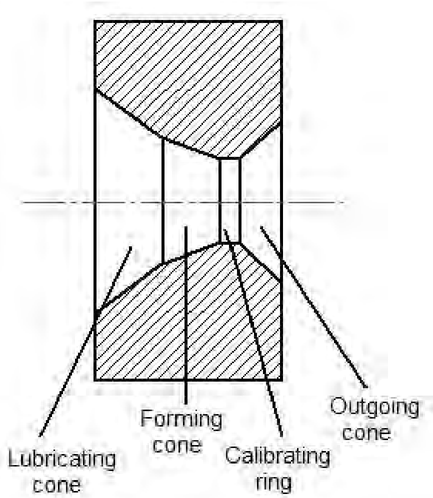


Fig. 2.6. *Schema of drawing die*

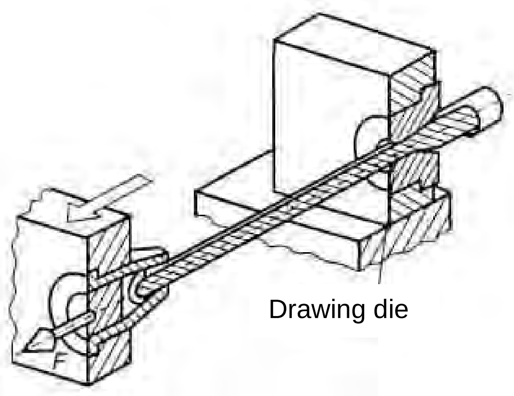
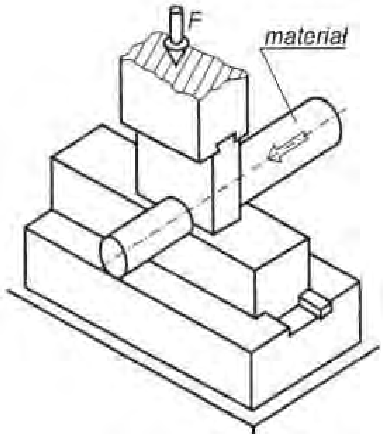


Fig. 2.7. *Drawing process schema [21]*

Drawing technology limitations are, by no means, small and connected with process characteristics manufacturing possibilities within the range of manufactured products shape. Products obtained in drawing process must have not very complicated shape, limited, if necessary, to one flange in the product external part. Considering the necessity to preserve constant diameter and wall thickness (hollowed elements) of formed products, more purposeful seems to be application of such obtained semi finished products for connecting with other elements. Another destination of semi finished products obtained by means of drawing can be their further forming with application of various metal forming methods in order to give the manufactured product a final shape. Hence, drawing method allows for ready manufacturing of hollowed elements within limited range. However, semi-finished products obtained by means of this technology are later often formed by various methods.
Among disadvantages of drawing process are: non – metallic impurities, scaling caused by overlapping and residue of contraction cavity.

As a result of non properly conducted process, material cracking may appear, which is caused by excessive stress presence. Another disadvantage may be material brittleness caused by excessive rolling reduction ratio in cold conditions and surface scratches appearing in the result of drawing die damage.

Technology of traditional forging (Fig. 2.8) is applied only in the case of shafts forming for the heaviest machines. This method ,due to the necessity of using considerably high technological allowances for final machining, is gradually replaced by more modern and more favorable, from economic and qualitative point of view, rotary forging and swaging technologies.



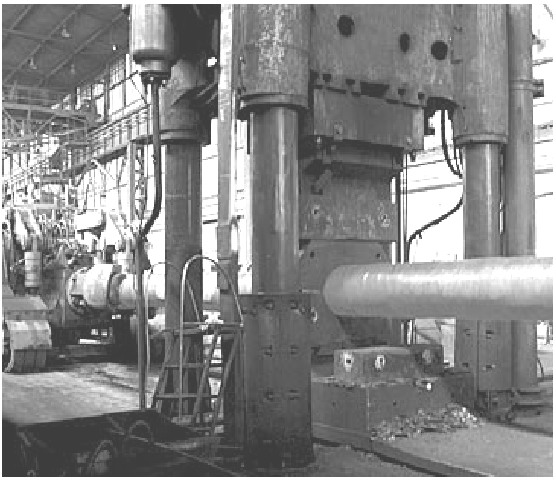


Fig. 2.8. *Forging schema and the process realized in forge plant HSW-Poland [21, 71]*

In the case of thick walled and relatively short products, punching technology is often used as more effective than forging [37]. The schema of punching of thick walled sleeve is shown in Fig. 2.9.

Punching method allows for obtaining very favorable material structure. Unfortunately, wall thickness tolerances (both in cross section and in longitudinal section) of product are relatively large. Together with the increase of forming force the tendency to punch buckling increases. When the punch goes into metal the unevenness of product wall thickness distribution becomes larger. In order to make easier removal of product from the die, the external surface of formed element can have certain technological convergence, allowing for trouble-free pushing out of finished product by the pusher. It, of course, increases size of allowances for the further machining of element unless designing solutions allow for application of such a formed part. In order to give this part final, cylindrical shape it is necessary to apply machining or further metal forming e.g in elongating skew rolling mill, so called elongator [29].

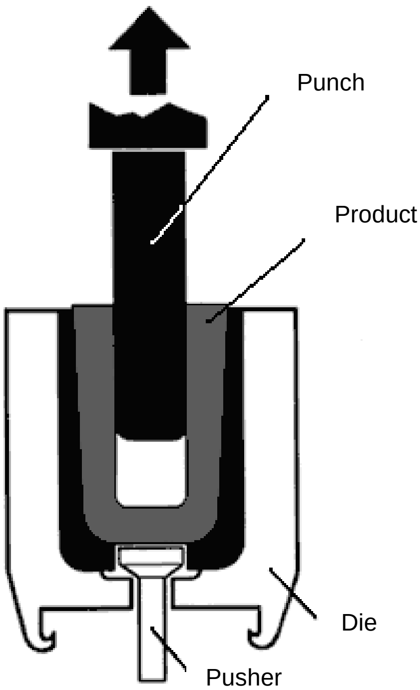


Fig. 2.9. *Schema of thick walled sleeve punching [56]*

Decrease of wall thickness unevenness, which is the aim of such an operation, can be linked with obtaining desired diameter of product. The problem of changeable wall thickness in longitudinal section is also eliminated by application of extrusion technology of sleeve by means of Ehrhard's system [29]. It enables to eliminate designing convergence of tools and leads to obtaining a target product of cylindrical shape. Schema of sleeve extrusion process by means of Ehrhard's system is shown in Fig. 2.10.

Extrusion is at present used also for manufacturing of screws or pins (bolts), as a part of product length undergoes this operation in order to gradiate diameters (Fig. 2.11). The element after extrusion operation has a considerably larger durability on the formed part than on the rest of the product. The disadvantage of extrusion process is the lack of possibility of obtaining long stepped elements. Because of that, this method is not widely applied in automotive industry.

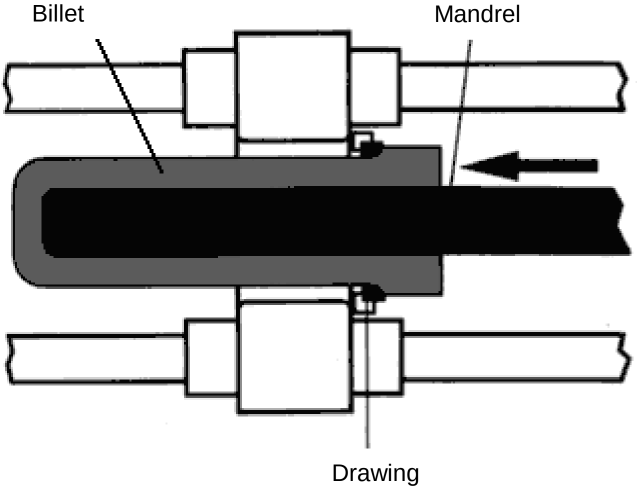


Fig. 2.10. *Schema of extrusion process of a sleeve by means of Ehrhard's system [56]*

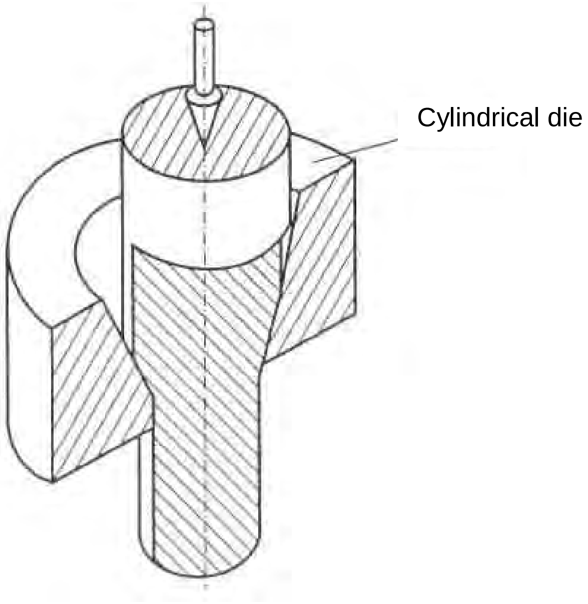


Fig. 2.11. *Extrusion process [21]*

Swaging allows for reduction of tubes and bars diameter and for obtaining large values of inclinations. Due to machining in cold conditions exact dimensional tolerances and advantageous material layers flow can be preserved. This favors material mechanical properties increase by hardening of its upper layer. The possibility of internal profiling of the product (very precise cylindrical and conical holes) are possible to obtain by this method. Process is realized in cold or in hot forming conditions [49] – Fig. 2.12.

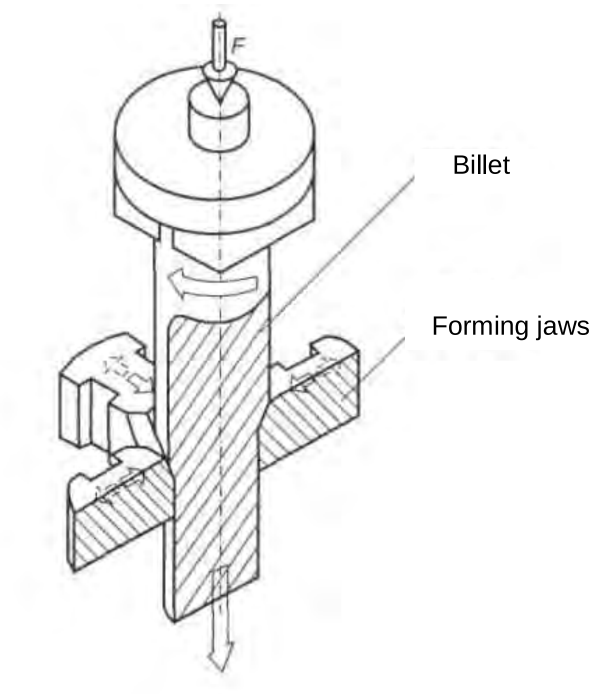


Fig. 2.12. *Schema of forging in swaging machine [21]*

Rotary forging is based on forming of axi-symmetrical products by means of two tools – Fig. 2.13. It is applied mainly for ring shaped elements (usually for steel ring of a automotive rims and rail wheels). The main difference between swaging and rotary forging is the fact that formed material, not tools, rotates. Dimensional tolerances are calculated very close to nominal. It is possible to adjust to that method majority of crank presses available at market [51,57].

Extrusion in cold conditions is a process in which material flow from the die appears due to punch load force influence. During this process large increase of length (even 1000 % for aluminum) can be obtained. A few types of extrusion depending on the material flow direction in comparison with punch movement can be distinguished: co-extrusion, indirect extrusion, two directional (or combined forward and backward extrusion). This method is applied in manufacturing of both hollowed and full products – Fig. 2.14.

In order to reduce material loss, full shafts are replaced by hollowed shafts made by a chosen method connected with friction welding, which increases manufacturing costs. The costs decrease can be obtained by connecting with deep drilling.

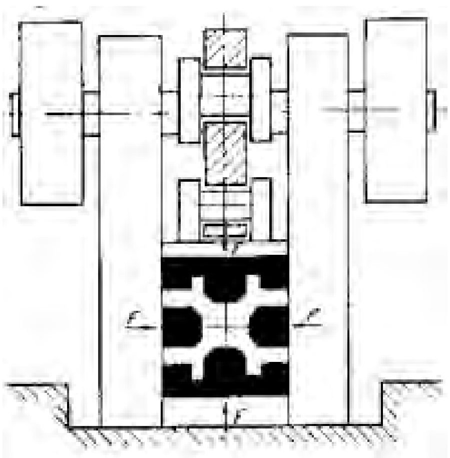


Fig. 2.13. *Idea schema of rotary forging process [1]*

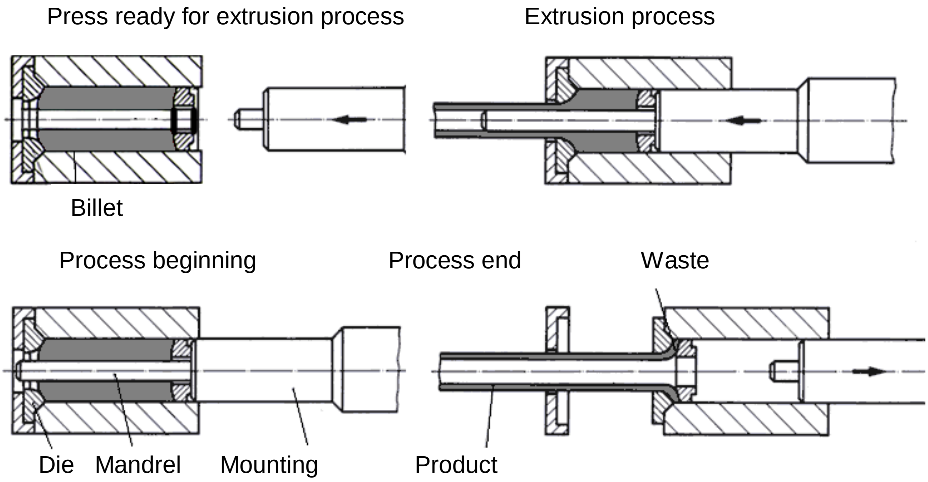


***Fig. 2.14**. Idea schema of extrusion process in cold of tube product [56]*

***Fig. 2.15.** Examples of elements made by means of extrusion process in cold conditions [54]*

Another method of manufacturing of axi – symmetrical elements is technology using powder metallurgy processes in connection with metal forming processes (e.g precise die forging) or extrusion. Powder metallurgy methods allow for producing new materials formed from materials with specified physical properties.

Forming in hot conditions of sinters becomes an alternative technique of forgings manufacturing for automotive industry in the USA and Japan to forging processes from rolled semi-finished products. By introducing strengthening phase during powder mixture preparing, it is possible to obtain materials with additionally determined functional properties, e.g. destined for work in increased temperatures in combustion engines and with increased resistance to abrasive wear.

During deforming of rough materials, the material density changes, which differs this process from forming processes of rolled semi-finished products where density does not change. Giving shape to sintered materials in metal forming processes takes place mainly by forging in close dies or by extruding. Forging of sintered materials is called densification, with presence or without it of yield stress, rough die stamping from metallic materials, metallic composites strengthened by ceramic fibers or ceramic powder metallurgy and precise die forging. Limited flexibility of powders to densification causes that obtaining small roughness of products by cold moulding is impossible from technical and economical point of view.

Gradual departure from traditional casting technologies as manufacturing methods was the result of drastic ecological requirements connected with the necessity of considerable capital expenditure. At present, concerning manufacturing of products for machine or automotive industry this technology is strongly displaced by thixoforming, that is connecting of casting with metal forming in semi-liquid state. The beginnings of this method are dated in 1970's and they concern limited range of application for particularly difficult forgings with complex shape, which, due to qualitative reasons, could not be made by means of pressure die casting.

Present development of thixoforming technology allows for obtaining products of spheroid structure and isotropic properties in the forging whole volume. In comparison with die forging methods, durability of dies applied in this technology is larger because there is no presence in this case of such large load. This method is more widely used for metal and difficult to form alloys, where dies durability for traditional forging is the most limited. Precision obtained in thixoforming technology allows for eliminating of machining (sometimes grinding is necessary), which is one of the aims of this manufacturing method usage.

The basic technical problem, determining proper implementation of thixoforming method in industry, is the necessity of application of high pressures of billet placement into dies and connected with this folding and die sealing problems. An example of thixoforming process schema is shown in Fig. 2.16.

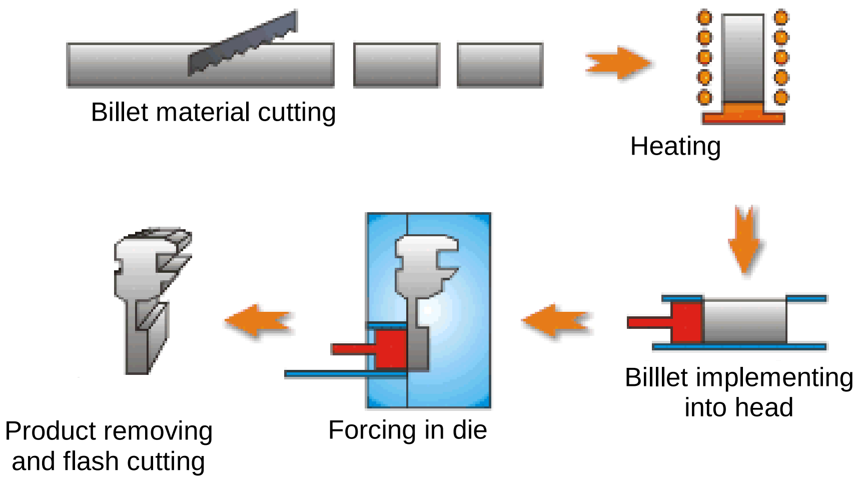


Fig. 2.16. *Thixoforming process schema [51]*

Issues connected with guaranteeing proper level of manufactured products quality are the most important, apart from unchangeable basic manufacturing costs, problems with which all manufacturers have to deal.

Application of complex solutions in quality field comprising implementation of systems guaranteeing quality and delivery control and staff training allows for considerable limitation of percentage of faulty products manufacturing and increasing the products quality. This concerns both improvement of mechanical properties and limitation of dimensional tolerances area leading to decrease of role (or complete elimination) of final machining, which is especially desired.

The outlook of formed element external surface is closely connected with its quality, determined later by factors such as: roughness of surface, hardness distribution, structural changes and internal stresses. Among the above parameters, distribution of internal stresses is one of the main factors deciding about a given element fatigue strength and its dimensional stability. Tensile stresses on the external surface can lead to cracking appearance and their further propagation causing product damage. In the reverse case, the presence of micro – cracks opens way to corrosion [72, 73].

In manufacturing of shafts and axes as machine parts, especially hollowed elements, which function as drive transfer elements, fatigue strength is of large importance. These parts, being critical for machine and vehicles functioning, have to perform their function as well as traditional elements of full section. Within this range, process of extrusion in cold conditions should be highly evaluated, in the result of which final shape of manufactured product, often without additional operations, is obtained. Extrusion with application of internal mandrel allows for obtaining products of high quality of internal and external surfaces.

Additionally, dimensional precision of such obtained finished products or tube preforms destined for further forming is very high.

New solutions within the scope of forming of stepped axi – symmetrical products are, developed at the Computer Modelling and Technology of Metal Forming Department at Lublin University of Technology, technologies of cross – wedge rolling (CWR) and wedge – rolls rolling (WRR).

Cross- wedge rolling is a technology which has established its position in world wide industry [14,15, 38, 40, 47]. In that way, at present, are made: axi – symmetrical preforms of various types (semi – finished products for forging of connecting rod, bearing bush (constructional spanners, forks, levers etc) [14], finished products (non-conductor cores, pins bolts, shafts) and forgings destined for further machining (stepped axles, cars suspension and steering systems) [25, 26]. CWR technology allows for obtaining high quality and precision of formed products. At permissible tolerances deviations of product diameter measured in parts of millimeter and surface roughness R_a = 5 μm, increase of fatigue strength is obtained from 1.5 to 2 times and product resistance to abrasive wear increases from 20 to 40% [34]. Application of CWR in place of other manufacturing technologies e.g. die forging, elongated rolling or machining allows for material savings from 20 to 60% (depending on the substituted method) [34]. Examples of CWR technology application are given in Fig. 2.17, showing a choice of products offered by Bellarussian company Beltechnology & M, specializing in metal forming area. CWR technology after automatization was used in grand series and mass production, finding buyers mainly in automotive sector. This was because of large costs of buying appropriate machine set and of wedge tools manufacturing [14]. Various CWR forming methods are shown in Fig. 2.18.

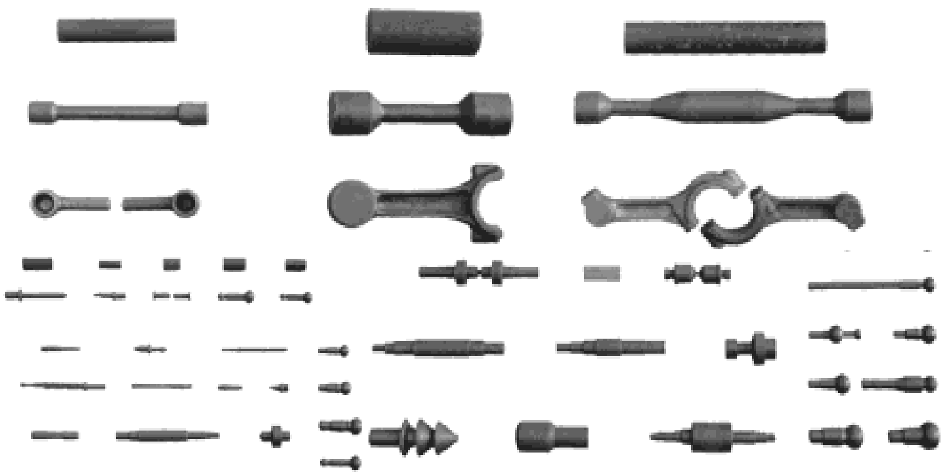


Fig. 2.17.*Examples of products made in CWR technology by company Beltechnology & M [52]*

Development of numerical techniques and specialist computer software allowed for widening of narrow group of buyers of this rolling method on new consumers.

Modern softwares destined for tools designing and numerical modelling of processes allowed for a considerable decrease of implementation costs of this manufacturing technology. At present, using FEM, it is possible to simulate cross – wedge rolling processes on

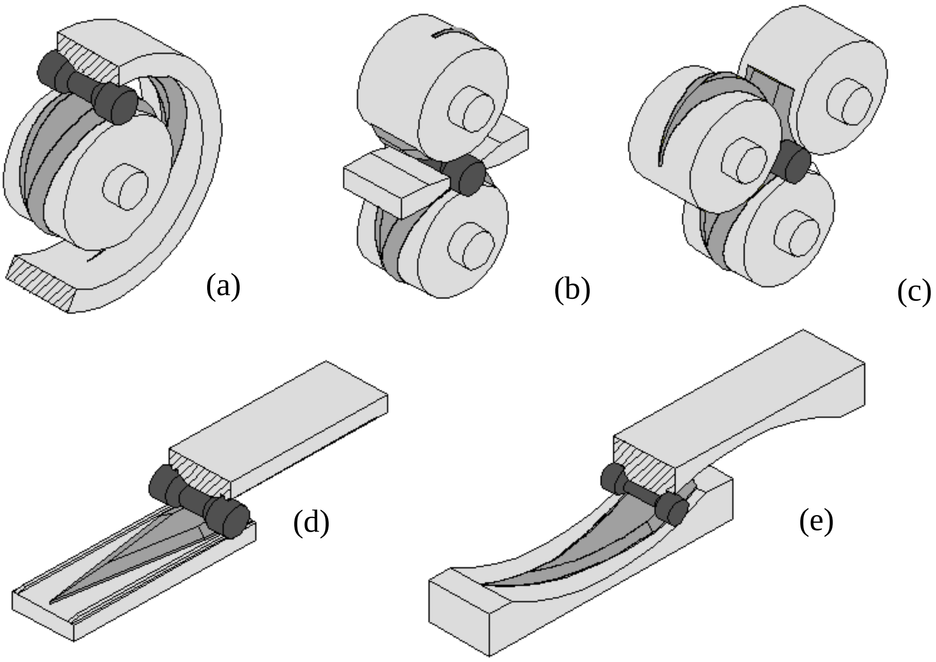


Fig. 2.18. *CWR methods classifications due to tools construction: a) cross rolling in segment-cylindrical tool set b) cross rolling in double cylindrical tools configuration c) cross rolling by means of three cylindrical tools d) cross rolling by means of two flat tools e) cross rolling by means of two concave tool segments [23]*

personal computers. In the result of these calculations, the user can verify the correctness of designed tools and assumed process parameters. In that way, lack of process engineers' experience is compensated. Works, in which various technological aspects of this technology are presented, are available [39 – 41, 43, 48].

Among close geographically companies dealing with rolling mills manufacturing and CWR technology implementation, the following companies should be mentioned: Beltechnology&M (Bellarussia) and Šmeral (Czech Republic). In Beltechnology&M company flat wedge rolling mills are produced, one of them is shown in Fig. 2.19. This machine is connected with cooperating inductive heating equipment and feeder. This complete assembly line needs only mounting on slides wedge tools, determining billets size and range of temperatures to which billets will be heated. Such a solution, due to outline compactness and relatively the smallest (from the presented CWR methods) cost of tools manufacturing, seems to be one of the most beneficial offers from economical point of view. The disadvantage of flat wedge method is low effectiveness of work, caused by tools retrace lost motion.

Fig. 2.19. *Flat wedged rolling mill of Beltechnologia & M (Bellarussia) [52]*

Czech company Šmeral manufactures rolling mills with two working rolls of diameters 700 mm or 1000 mm – Fig. 2.20. These machines, due to a more difficult and complex process of tools designing and manufacturing, are more expensive at the production start. Their, by no means, advantage is the lack of tools lost motion, resulting in increase of machine output and possibility of rolling in continuous way from a bar (of length to 6m). The photo of rolling stand of two rolls rolling mill during forming process of a product is shown in Fig. 2.21.

A method allowing for the further improvement of CWR output is application of forming in double system, in which in one tools working cycle two products are formed. The limitation here is only maximal width of wedge tools mounting determining maximal length of formed products. A large advantage of this system is presence of favorable, due to process stability, symmetrical distribution of axial forces acting on forgings. An example of products rolled in double system is shown in Fig. 2.22.

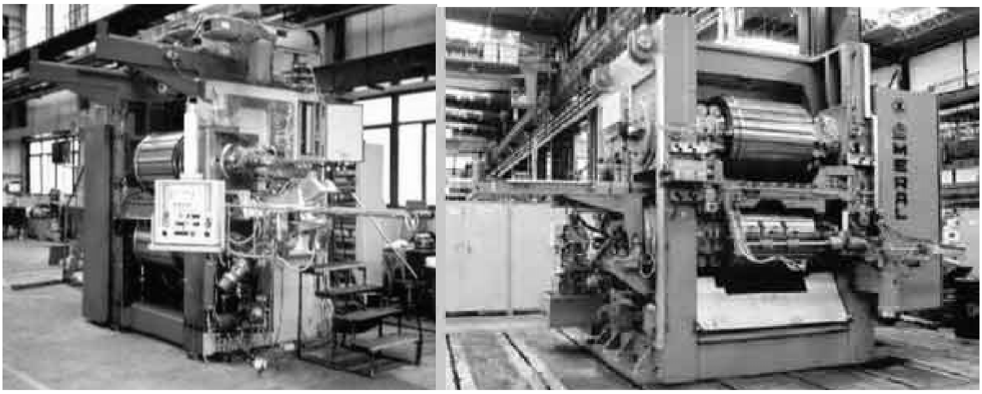


Fig. 2.20.*Two-rolls cross- wedge rolling mills (Šmeral - Czech Republic) [67]*

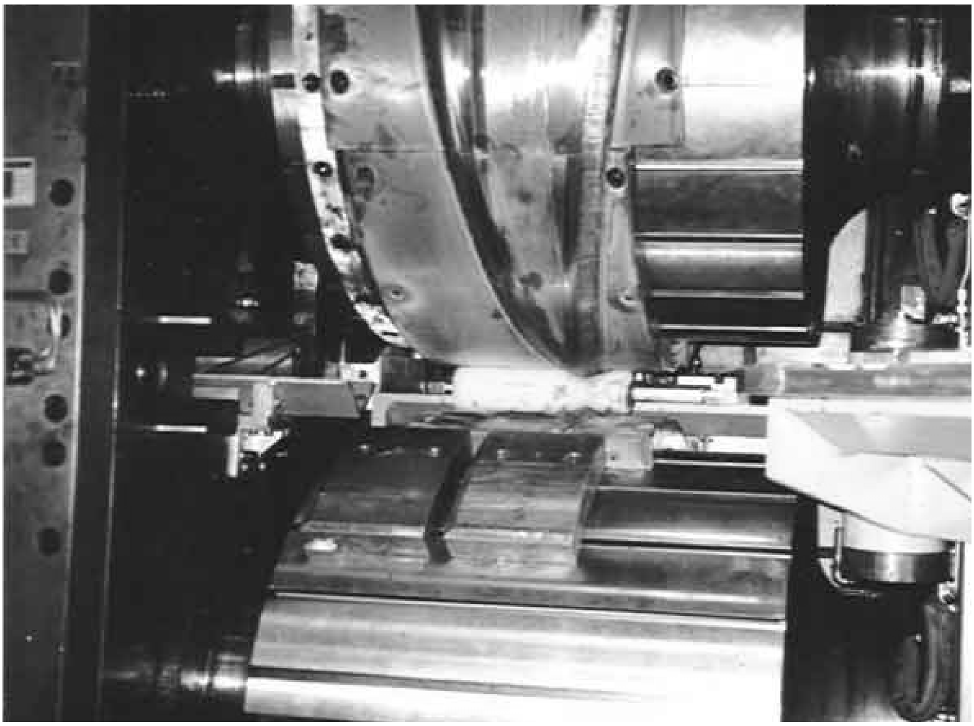
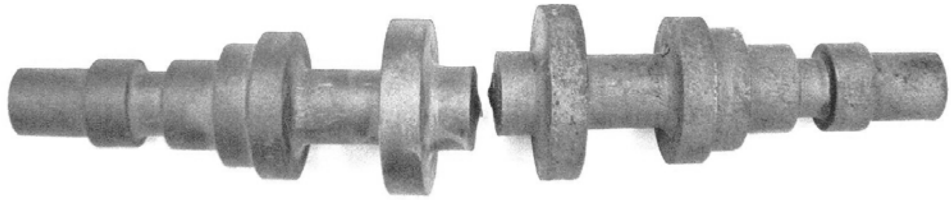


Fig 2.21*. Product forming in two-rolls rolling mill ULS (Šmeral - Czech Republic) [67]*

CWR processes are accompanied by intensive surface material flow. It increases proportionally to degree of metal forming of formed billet. In the result of strong axial flow of material upper layers, at the edges of formed forging characteristic funnels appear. Because of that, this creates the necessity of side knives application or introducing additional cutting operations after forming. Knives mounted on tools segments can be used also for splitting of products made in double system. An example of a product formed in CWR technology with head waste cutting, with characteristic funnels, is shown in Fig. 2.23.



Rys 2.22. *Products made in double configuration (CWR) [67]*

Fig. 2.23. *Forging of mean shaft together with final waste cut during CWR process [40]*

Very important limitation of CWR technology application in forming of hollowed products are problems of shape disturbances in the form of rolled products cross sections ovalization [1]. A solution allowing for reducing ovalization present in CWR processes with two wedges is rolling of hollowed products by means of three tools. Due to the fact that experimental research on these processes need expensive new research posts, in analysis conducted in Computer Modelling and Technology of Metal Forming Department conditions [1–7] only numerical calculations on the basis of FEM were considered.

In industrial practice by means of CWR with three rolls on which wedges are mounted [16 – 18, 32, 42, 43] a marginal part of production is made. The advantages of this method include: elimination of guiding devices guaranteeing proper position of forging between rolls during forming and decrease of internal cracks presence probability in formed full products [19]. The basic disadvantage of this method is forming wedges length limitation, resulting from the following dependency [40]:

$$R_w < \frac{\sqrt{3}}{2-\sqrt{3}} r, \tag{2.1}$$

determining limiting value of roll radius R_w depending on radius r of forging rolled step.

High costs of three wedge rolls manufacturing and wedges length limitations resulting from condition (2.1) force to search for alternative forming method characterized by similar stresses schema. Wedge – rolls rolling method, which conception was worked out at Computer Modelling and Technology of Metal Forming Department of Lublin University of Technology can be regarded as such a promising method.

Wedge – rolls rolling is based on forming of axi – symmetrical products using one forming wedge and two rolls (forming or supporting only – Fig. 2.24). The rolled product is placed on rolls which are driven and rotate with the same velocity, opposite to the direction of wedge movement. These rolls can be made as smooth or profiled rolls. The wedge moving in plane motion cuts into material and forms a necking of assumed dimensions on its circuit. In comparison with applied so far CWR methods, wedge – rolls rolling has many advantages which include e.g.:

- smaller implementation costs due to application of one flat wedge only;

– decrease of material axial cracking probability, which is very characteristic for CWR processes with two tools;
– increase of output by WRR schema (Fig. 2.25) application allowing for simultaneous forming of a few or more products.

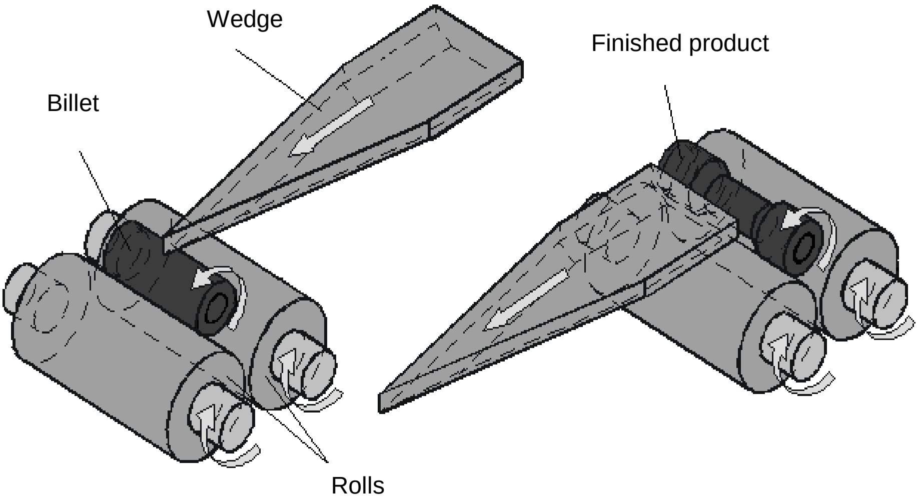


Fig. 2.24. *Idea schema of wedge – rolls rolling method (WRR) [70]*

It should be noticed that WRR process is not thoroughly analyzed and its analyzing requires e.g. numerous experimental research (also with application of hollowed billets). After that, directions for probable further application of this forming technology of axi – symmetrical products can be provided.

Analysis of forming processes of axes or full shafts and hollowed shafts forming and determining economical and technological aspects explaining choice of proper manufacturing technology was the subject of many works, both of theoretical and experimental character, supported by industrial practice.

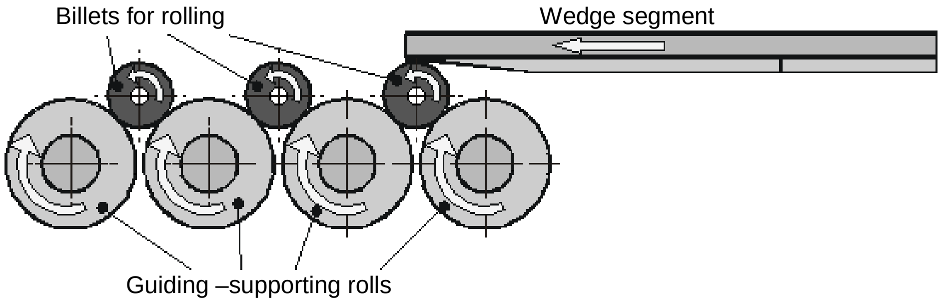


Fig. 2.25. *Schema of wedge – rolls rolling of a few products [12, 42]*

Presented in literature solutions from field of manufacturing of these type of structural elements show possibilities of obtaining new solutions, which allow for considerable material savings. The fact that new technologies are proecological and by costs reduction also more profitable is of great importance.

Application of innovative hollowed parts in machines and vehicles required introduction of additional technological operations allowing for obtaining assumed external shapes (stepped shafts, elements extruded in hydrostatic way) and diversification of walls thickness of manufactured products. These requirements are fulfilled by presented in this chapter manufacturing technologies. It should be, however, noticed that there are numerous limitations of these technologies, resulting mainly from their technological and design character. It is connected with high qualitative requirements which all products have to fulfill and narrow scope of manufacturing technologies accepted by potential buyers of these parts. The most favorable techniques of hollowed shafts manufacturing include: swaging and extrusion in cold conditions connected with friction welding or deep drilling [1, 2, 22, 30, 31]

In comparison with presented manufacturing methods, cross – wedge rolling technology appears to be very advantageous. This method good points include high effectiveness and series repeatability. Instead of a few operations necessary for hollowed element manufacturing (as it takes place in case of swaging, extrusion in cold) in CWR method one wedge segments transition is used. Moreover, rolling in double system not only increases process effectiveness but also allows for obtaining, favorable for process stability, symmetrical distribution of axial forces acting on a forging. Unfortunately, as it was proved in works [3, 4, 11, 35, 36], design rules used for designing of cross-wedge rolling technologies of full products cannot be used for designing of hollowed products CWR processes.

3. Numerical analysis of rolling extrusion process

One of the attempts to solve at least partially the problem of cross – rolling workspace width and to determine maximal length of formed products are the discussed research works on rolling extrusion, a new technology of metal forming.

Implementation of this technology is not connected, as it is assumed, with limitation of product length and allows for free arrangement of forming cycle, within the range of relation of rolls rotary movement and linear movement of a pusher putting forward the formed material. Hence, depending on size of billet feeder, it is possible to form products of larger length-diameter ratio, which is present e.g. in axle shafts and transmission shafts and gear box components such as first motion shaft. This solution connects in itself advantages of cross-wedge rolling by means of three working tools with additional possibilities offered by application of a pusher placing billet into workspace. In that way, the length of the obtained in this method product is limited by pusher stroke and stiffness of rotating billet, which can undergo buckling. In order to determine the practical scope of rolling extrusion technology implementation numerous numerical research and experimental tests were conducted, changing kinematics parameters and analyzing their influence on products forming.

Due to a complex character of metal flow during forming and constantly changing contact surfaces between the formed product and rotating tools, it was foreseen that a proper analysis of the process by means of finite element method would require long and arduous simulations. In order to limit time consuming analyses, it was decided to make engineering calculations, which aimed at giving direction to further research. Hence, theoretical research on rolling extrusion process were divided into two phases:

– estimated calculations with application of chosen methods of engineering analysis
– numerical calculations with application of finite element method (FEM)

3.1 Estimated calculations

The aim of the research was to determine flow curves for large strains and strain rates in plastometric test; theoretical and experimental research are given in works [23, 44, 45].

Mentioned earlier, long time of calculations for a simple forming case resulted in the necessity of creation of specialist program for quick estimation of values of forces and moments present in the process. Screenshot of software “Force calculator” [44] and results of exemplatory, estimated analyses realized by means of this software are shown in Fig. 3.1 and Fig. 3.2. After giving basic process technological parameters and writing down parameters characterizing tools size, software, by means of one of the chosen engineering analysis methods (energetic, equilibrium differential equation, upper bound method), makes estimated calculations- according to pressure schema shown in Fig. 3.1. Due to the possibility of contact surfaces changes, depending on the shape of applied tools (forming angle α), in the program option of this parameter percentage correction was predicted.

In estimated calculations values of angle α were changed every 5° which led to obtaining calculation results of force parameters given in Fig. 3.3. This Figure presents also comparison of force values, showing that together with the increase of working rolls forming angle α, values of radial force Pr acting on a rolling tool gradually decrease. At the same time decrease of necessary values for squeezing force Q_c application is observed. However, this happens during increasing angle α values until reaching value α = 45°. After reaching minimum, the further enlarging of rolls working surfaces inclination leads to a gradual increase of squeezing force value until maximum at α = 90°.

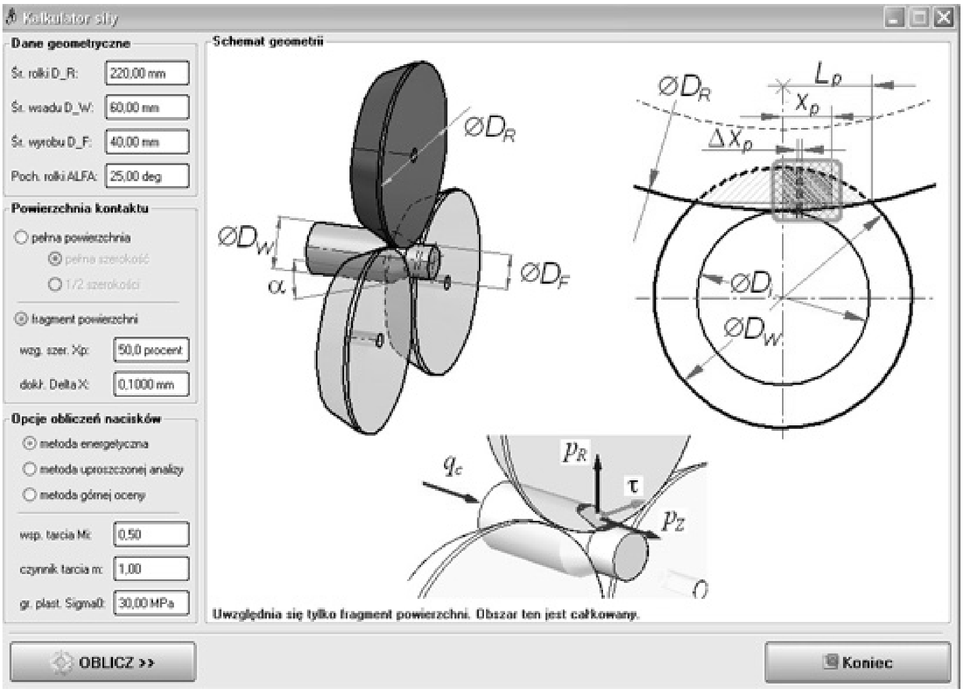


Fig. 3.1. *Screen shot of program starting procedure „Force calculator" [44]*

The obtained, by means of software "Force calculator", results allowed for initial determining process limits in the form of forming angle α value. It was stated that above $\alpha = 45°$ forming forces values increase (Fig. 3.3), which results in intensive billet buckling before forming zone between rolls and decrease of desired axial metal flow. Because of that, the above limitation was introduced into assumptions of numerical research FEM. This software, written for research needs, allowed also for determining values of forces and pressures depending on cross section area reduction ratio δ coefficient described as billet diameter to product formed step diameter ratio ($\delta = D_W/D_F$ - Fig. 3.1.).

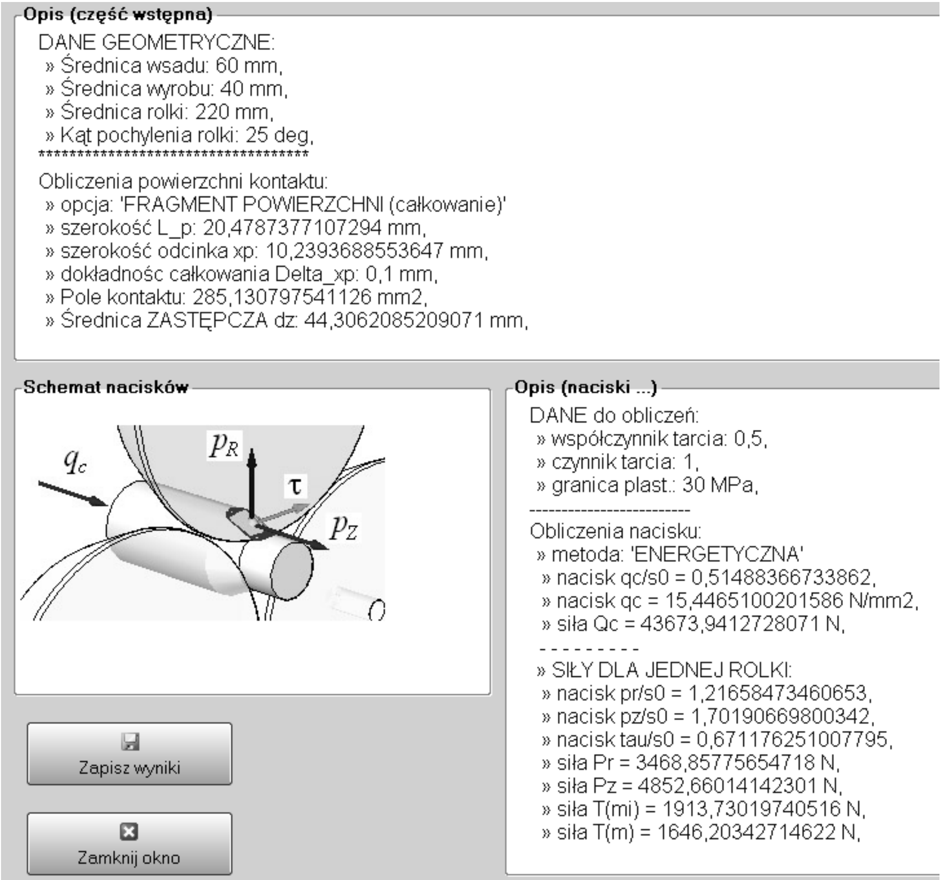


Fig. 3.2. *Screen shot of results „Force calculator”*

In further theoretical calculations mean value δ = 1.5 was assumed (at assumed maximal value δ = 2.0). Application of rolls with forming angle α of value smaller than $\alpha = 20^{\circ}$ during research was considered as purposeless and without technological justification for further usage of this forming method. In that way the scope of conducted analyses was limited to working rolls forming angles within the range of $\alpha = (20 \div 45)^{\circ}$.

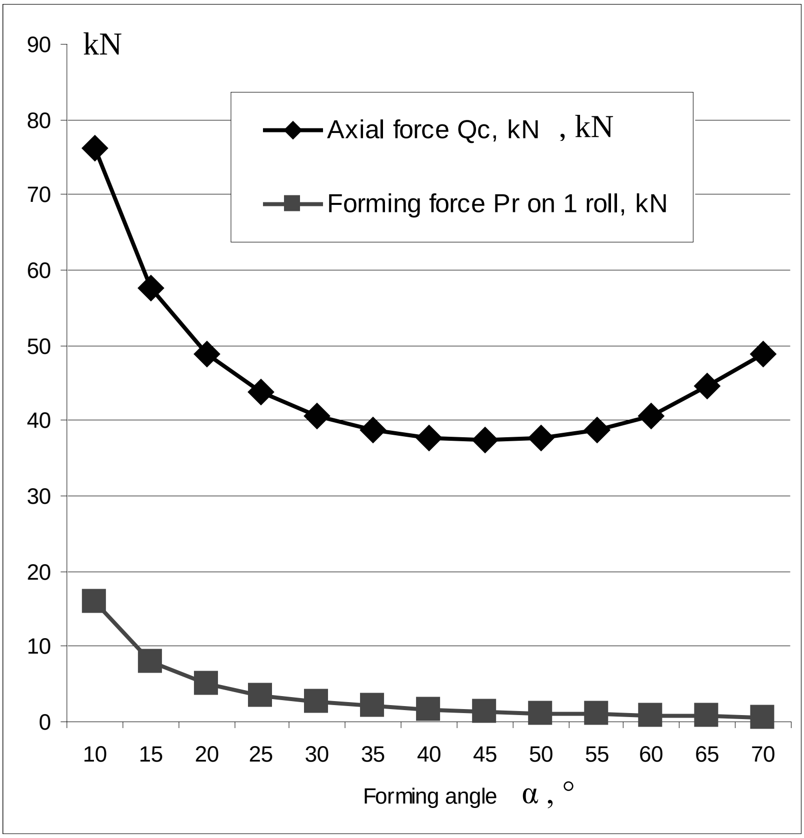


Fig. 3.3. *Comparison of squeezing force and forming force values acting on one roll at various values of forming angle (D_W = 60 mm reduced to D_F = 40 mm)*

3.2 Numerical research by means of finite element method (FEM)

Within the frame of assumed numerical research FEM, a simulation of rolling extrusion process of full and hollowed products was made. In research on rotary tools geometrical parameters influence on rolling extrusion process course, a case was analyzed of forming of billet cross section central necking within the range of technological and geometrical parameters shown in Fig. 3.4. In order to guarantee proper billet guiding in workspace between profiled rolls, a pusher moving in linear motion was modeled. This tool had a possibility of free rotation forced by movement of the formed billet. Due to a complex character of metal flow, during numerical modelling of rolling extrusion process, calculations were made only in 3D state of strain. A specialist commercial software MSC.SuperForm 2005 and Deform 3D were used. Realized calculations considered thermal phenomena present during forming-in all conducted simulations assumed temperature of billet was 1150ºC and tools temperature 50ºC for profiled rolls and the pusher. Moreover, it was assumed that heat exchange coefficient between tools and billet was 5000W/m^{2}K and between billet and the environment 200 W/m^{2}K. Relatively long time of simulation (about 7-10 days) resulted from difficulties in finite element method remeshing and from problems of numerical character connected with constantly changing contact surfaces.

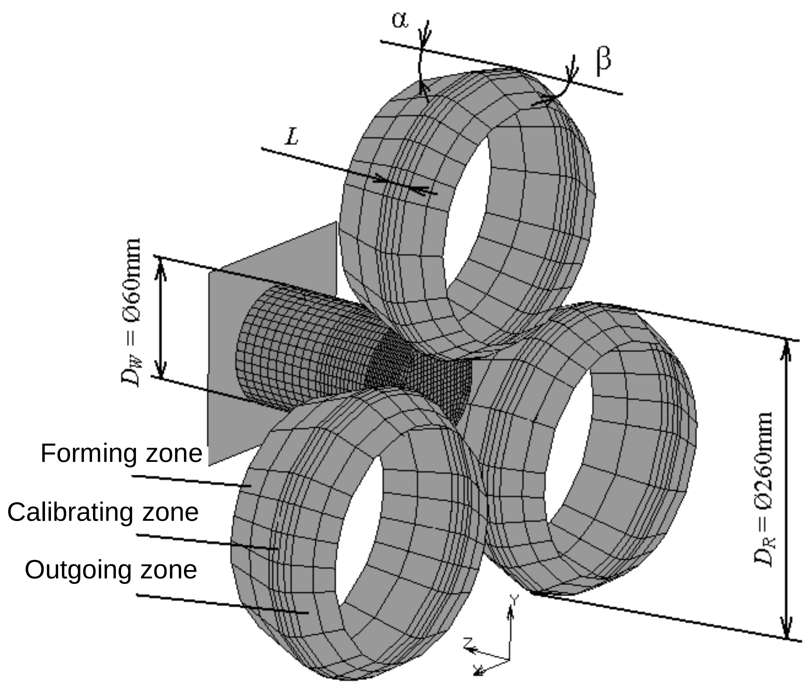


Fig. 3.4. *Made for calculations needs model of rolling extrusion process with description of basic parameters and tools zones*

In further simulations forming angle α was changed within the range $\alpha = (20 \div 45)^{o}$, profiled rolls velocity was ω = 2 or 3 rot/s. These values were linked to pusher linear velocity v being within range of $v = (2.5 \div 15)$ mm/s and in that way changeable values of feed rate on rotation $p = (0.83 \div 7.50)$ mm/rot. were obtained. Billets for the process in the form of full bars or thick-walled tubes made from C45 steel had external diameter D_w = 60 mm and internal D_F = 40 mm for hollowed billets.

Billets external diameter D_w = 60 mm during simulation of rolling extrusion process was reduced to value D_F = 40 mm, which allowed for obtaining diameter reduction coefficient δ = 1.5. An example of rolling extrusion process course of hollowed product together with strain intensity distribution is shown in Fig. 3.5.

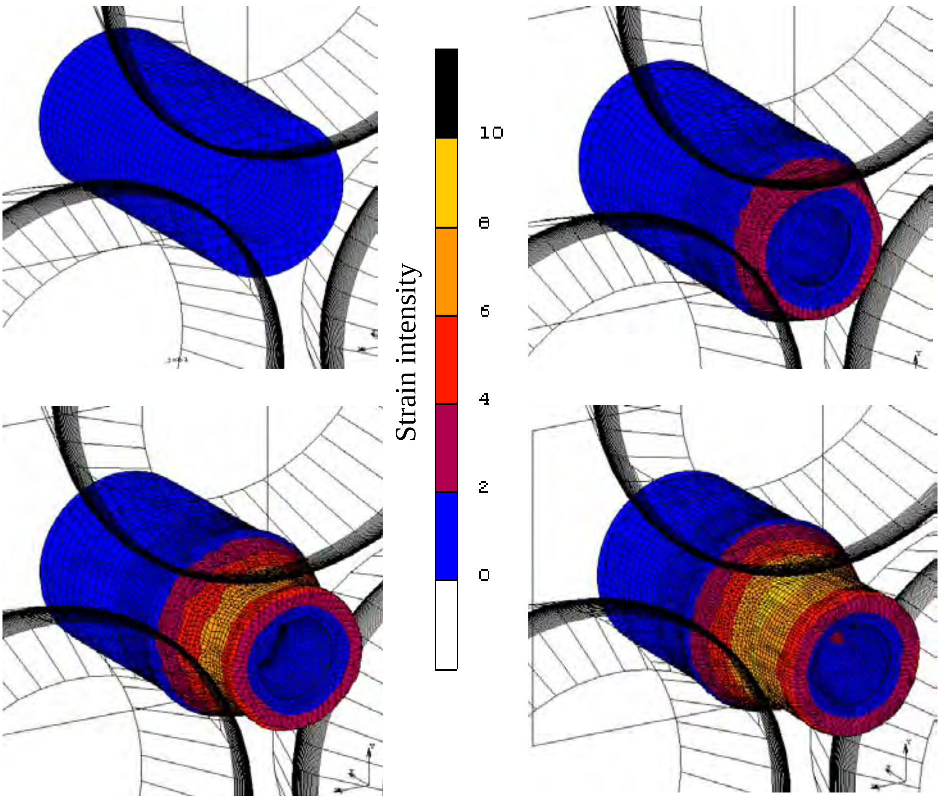


Fig. 3.5. *Progression of shape of hollowed product and strain intensity distributions in rolling extrusion process at inclination angle of forming surface α=30° (Fig. 3.4) and p =5 mm/rot.*

In the initial phase of rolling extrusion, beveling of billet contacting with forming rolls was present. As this stage of the process did not bring much into research, causing additional difficulties instead, it was decided to model billets with already formed initially chamfering. Its angle corresponded to forming angle of chosen profiled rolls set. It allowed for, in the phase of rolls and billet coming into contact, contact on a larger surface. Considering high time consumption of calculations (MSC.SuperForm2005), this solution considerably shortened their time.

An example of earlier chamfering was shown in Fig. 3.6. Comparing strain intensity of hollowed product (Fig. 3.5) and full product (Fig 3.6), a large disproportion of this parameter value in the end of the process is well visible. These differences are probably caused by larger, for forming of full billet, participation of redundant strain, not acting on the shape change of obtained product.

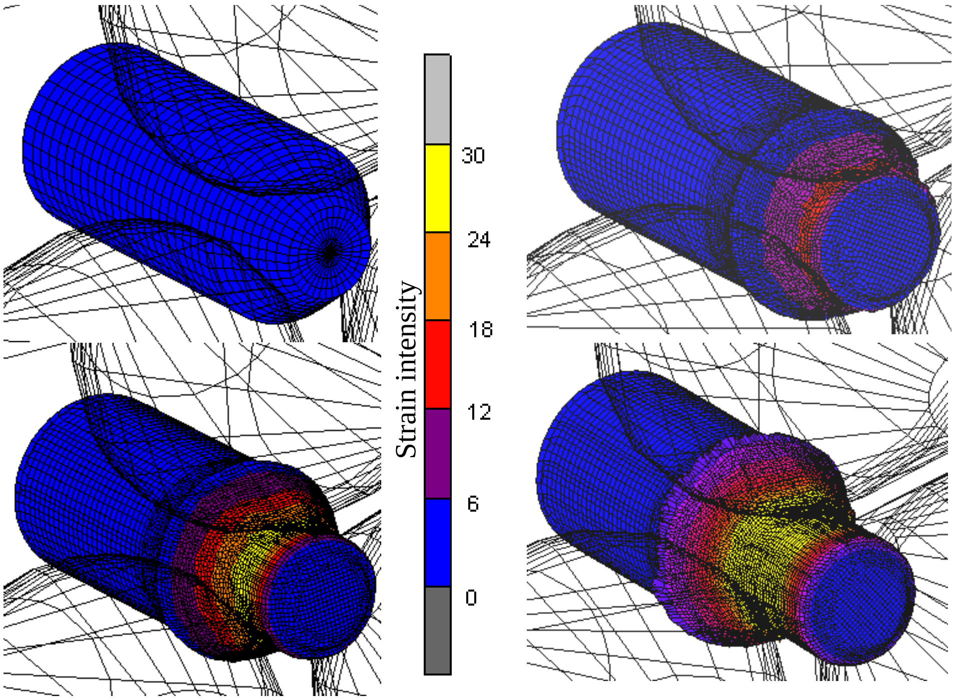


Fig. 3.6. *Progression of shape of full product and strain intensity distributions in rolling extrusion process at inclination angle of forming surface α=30° (Fig. 3.4) and feed rate p = 5 mm/rot.*

3.3 Shape disturbances

During manufacturing of both full and hollowed elements, it is impossible to avoid shape precision disturbances, that is such disturbances which to a some extent deform obtained element in comparison with its assumed theoretical outline.

One of the most popular shape disturbances in round profiles is roundness disturbance, which is present in both full and hollowed elements. A characteristic feature of this kind of disturbance is lack of dimensional uniformity in cross section and it is the measure of unconformity of product real outline with geometrical shape of circle. This is the largest distance of real outline from circle adherent to this outline, measured along this circle radius. The most frequent roundness disturbances are ovality and lobing.

Ovality (Fig. 3.7) is a disturbance of roundness Γ, which value changes in such a way that real outline constitutes a figure close to ellipse, which diameters – the largest and the smallest – are in mutually perpendicular directions [28].

$$\Gamma = \frac{d_{\max} - d_{\min}}{2} \tag{3.1}$$

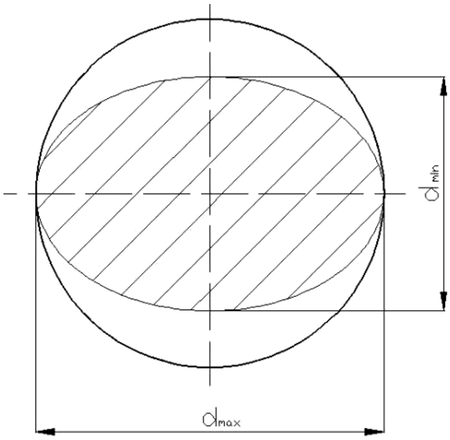


Fig. 3.7. *Ovality [28]*

Lobing (Fig. 3.8) is a disturbance of roundness Δ, which values change in such a way that real outline constitutes a figure close to regular polygon with rounded sides and tops. Lobing is differentiated depending on the number of real outline tops. In a special case of outline with uneven number of tops, lobing is characterized by constant values of diameters determined at various directions [28].

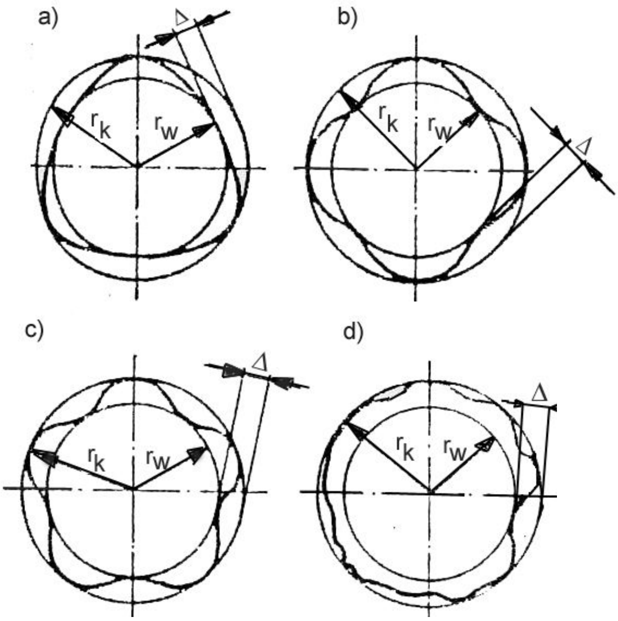


Fig. 3.8. *Lobing: a) triangle (n=3), b) square (n=4), c) pentagonal (n=5), d)irregular of regular polygon with rounded sides and tops [28]*

Other types of disturbances present in axi – symmetrical elements machining include e.g.: cylindrical disturbances which can de divided into:

- conicity;
- crowning (barrel shape);
- saddle back distortion;
- rectilinearity.

They are disturbances measured along a given element axis of rotation. Parameter which changes in further cross-sections is product diameter that can change in a linear way (proportionally),as in the case of conicity or irregularly, as in e.g crowning or saddleback distortion.

According to various sources, disturbances which are present during axi – symmetrical materials forming, especially during metal forming, are triangularization disturbances described by J. Kazanecki [29]. The author discusses this case of disturbance on the example of tubes machining in Assel's rolling mills. Examples of parameters deciding about this phenomenon presence are: chamfer angle, strain intensity (reduction ratio on diameter and wall thickness) and rolling velocity. One of the ways to prevent this disturbance appearance is lowering of chamfer angle, yet it is connected also with decrease of rolling productivity. However, application of sufficiently small chamfer angles results, to a large extent, in appearance of complex strain schema. Increasing diameter and ratio d/g of preform and finished product leads to increase of transverse strain. Intensive transverse strain causes enlarging of distance of metal-cylinder contact surface, which disturbs rotation conditions; and tube cross section under squeezing forces influence loses its stability and assumes a shape of a bell in the form of trihedron at the tube's end, which is shown in Fig. 3.9 [29]. This makes removing of product from the rolling mill difficult and does not allow for its sizing at the same time.

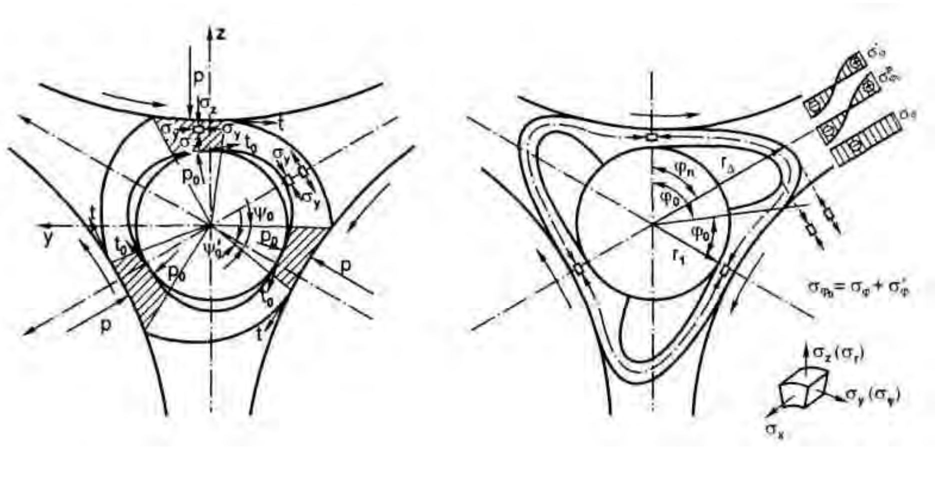


Fig. 3.9. *Cross section of trihedron appearing at tube's end together with schema of stresses [29]: a) initial stage; b) final stage*

Among various shape disturbances that can be observed, those responsible for dimensional precision of a given element should be taken into consideration. They mainly include rectilinearity, roundness, cylindrical, coaxiality disturbances. Another group of shape disturbances are non-uniform distributions of rolled products wall thickness. From the further application in technique point of view, axi – symmetrical hollowed products of stepped axes and shafts type with no possibility of mass balancing, have limited scope of application. A potential market in this case can only be agriculture sector with machines equipped in slow-speed drive transmission mechanism. In typical automotive applications, hence at larger assumed scopes of operating velocities, it is necessary to obtain even walls thickness distributions, especially in cross sections of formed products. The former research within this range for cross – wedge rolling technologies of hollowed products are given in works [5, 13].

3.4 Results of calculations

In order to limit the presence of mentioned earlier disturbances of hollowed and full products shape, forming parameters such as: movement velocity, tools shape and process temperature, should be chosen in an optimal way. The further part of the work discusses results of research on shape disturbances of products obtained by means of rolling extrusion [6-10]. In the conducted analysis analogy to mentioned above works on CWR technology development was searched for.

In next simulations forming angles $\alpha = 30^{\circ}$ and $\alpha = 35^{\circ}$, guaranteeing a certain degree of equilibrium between axial and radial material flow during process, were applied. Profiled rolls velocity was $\omega = 2$ or 3 rot./s. These values were connected with pusher's linear velocity $v = (2.5 \div 15)$ mm/s and changeable values of feed rate on rotation $p = (0.83 \div 7.50)$ mm/rot. were obtained. Examples of results of numerical simulation of hollowed product rolling extrusion process are shown in Fig 3.10.

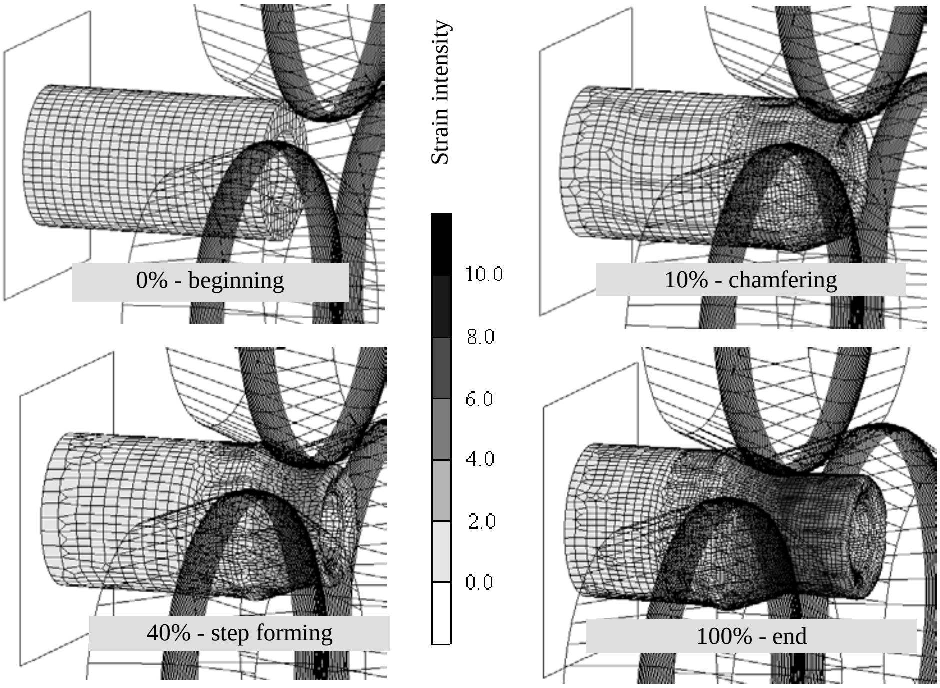


Fig. 3.10. *Shape progression of hollowed product during rolling extrusion process at: α=30° and p=5mm/rot.*

It was assumed that tool forming zone changes fluently into outgoing zone, considering relatively large transition radius. However, in the case of further research it was stated that feed rate was equal p=5 mm/rot., the lack of sizing zone resulted in disturbances of hollowed products formed profile. After implementing a separate sizing zone of length L=10 mm in tools, a considerable improvement of dimensional stability of products was observed, which can be seen in Fig. 3.11 and is described in details in works [2,3].

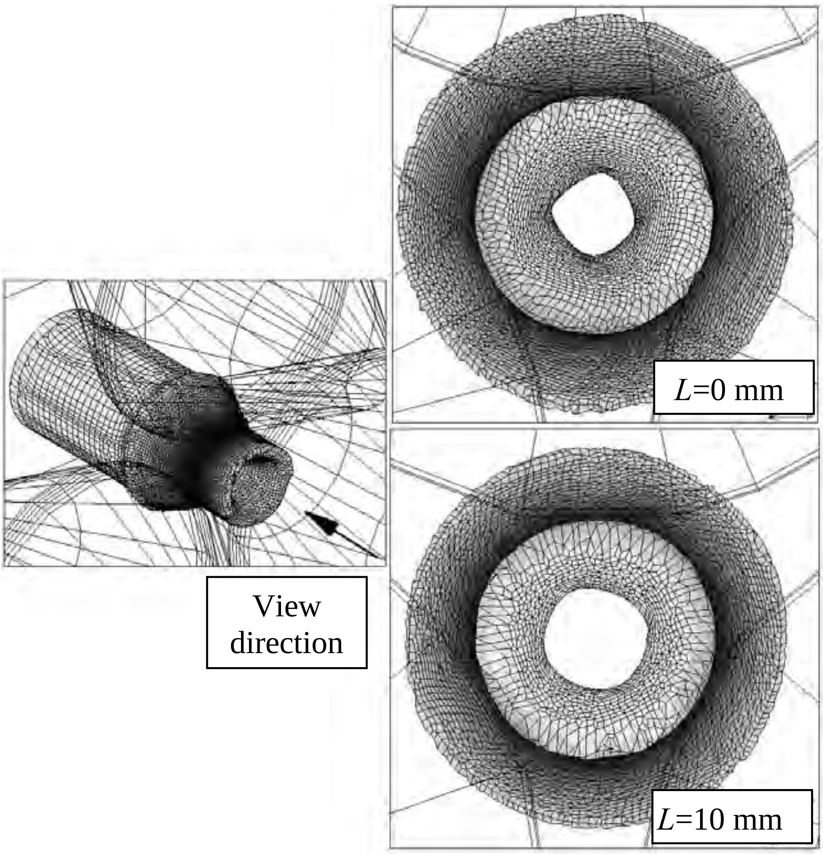


Fig. 3.11. *Comparison of hollowed products in rolling extrusion process without distinguished sizing zone and in rolling extrusion process by means of tools equipped with this zone of length L=10 mm (p=5 mm/rot.)*

Billet for the process in the form of thick walled tubes made from steel C45 had external diameter D_W = 60 mm and internal D_F = 40 mm. External diameter D_W = 60 mm during simulation of rolling extrusion process was reduced to value D_F = 40 mm, allowing for obtaining coefficient of diameter reduction $\delta = 1.5$.

However, in the result of billet diameter reduction, billet upsetting before working rolls forming zone appeared. This phenomenon increased together with the increase of linear velocity of the pusher responsible for placing billet into workspace between tools. Because creating during this process characteristic cone noticeably increased full billet diameter in extreme case (at feed rate value p = 7.5mm/rot.), it was decided to conduct additional numerical analyses with application of tools with modified shape. Figure 3.12 shows results of example of comparison of full products forming process by means of tools designed initially and after modification.

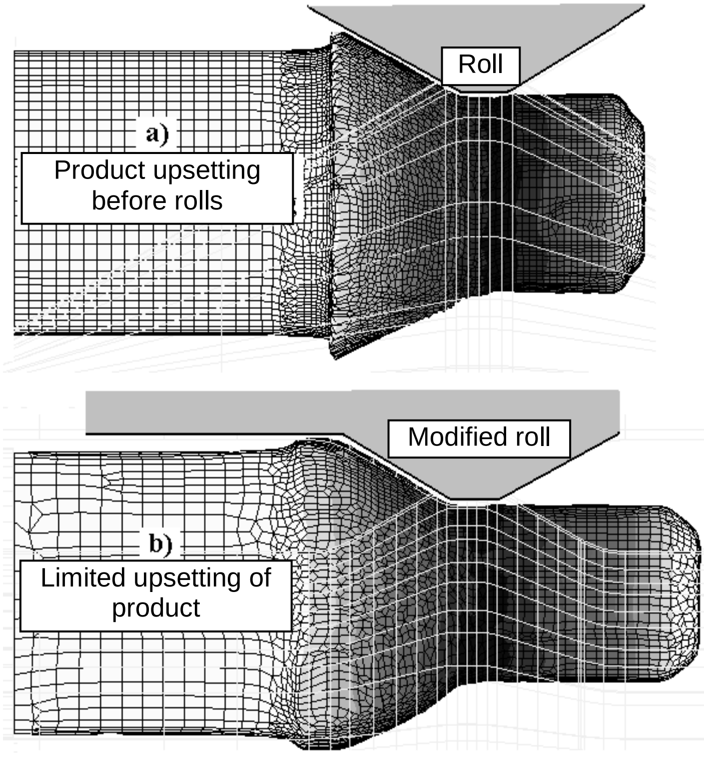


Fig. 3.12. *Comparison of material upsetting in a product formed by means of rolls of assumed initially outline(a) and by means of rolls of modified shape limiting material radial flow (b)*

For the given in Fig. 3.12 full product forming example with application of rolls of modified shape, in Fig. 3.13 is presented a progression of shape and strain intensity distribution of a shaft in rolling extrusion.

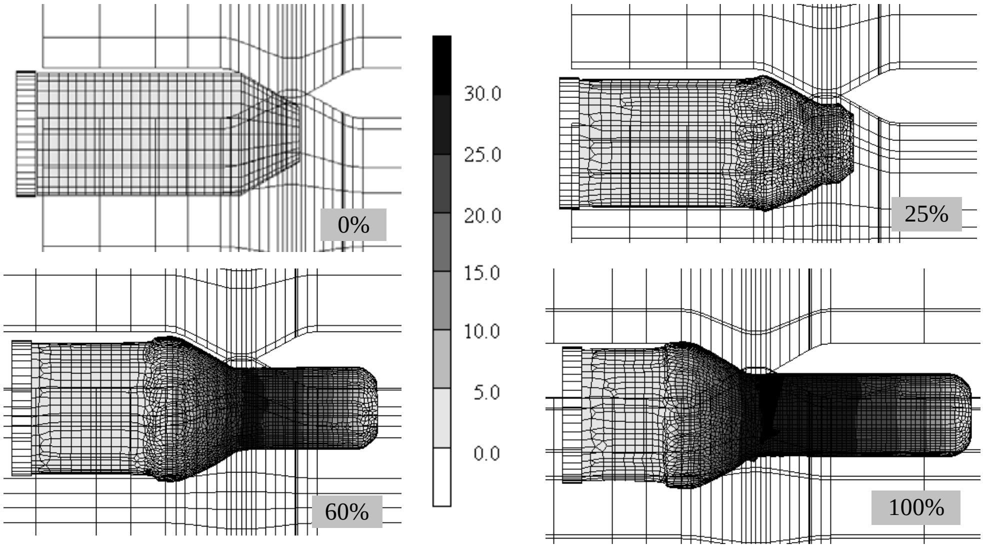


Fig. 3.13. *Shape progression and strain intensity distribution of full product in rolling extrusion process by means of two tools of modified shape (α=30°, p=7,5 mm/rot.)*

Obtaining favorable outline, from the further machining point of view of e.g conical toothing, of full product reduced diameter degree was connected ,however, with radical increase of lobing disturbances in cross sections of shaft conical part – Fig. 3.14.

Hence, limitation of material radial flow before working rolls forming zone, causing billet upsetting, resulted in accumulating of its excess in spaces between rolls working surfaces. The next effect of this phenomenon was calculation instability of numerical character, which caused frequent stop of calculation procedure, apart from using option of often remeshing. In the further part of the realized research program, that is in experimental tests, it was stated that all uneven walls thickness distributions in cross sections (on product reduced diameter) influence directly pusher's set vibrations implementation. In the result of this process, radial run-out of pusher's rotating head appears and the product obtains characteristic wavy external surface. Hence, stability problems in conducted numerical simulations of this forming variant find confirmation in experimental research.

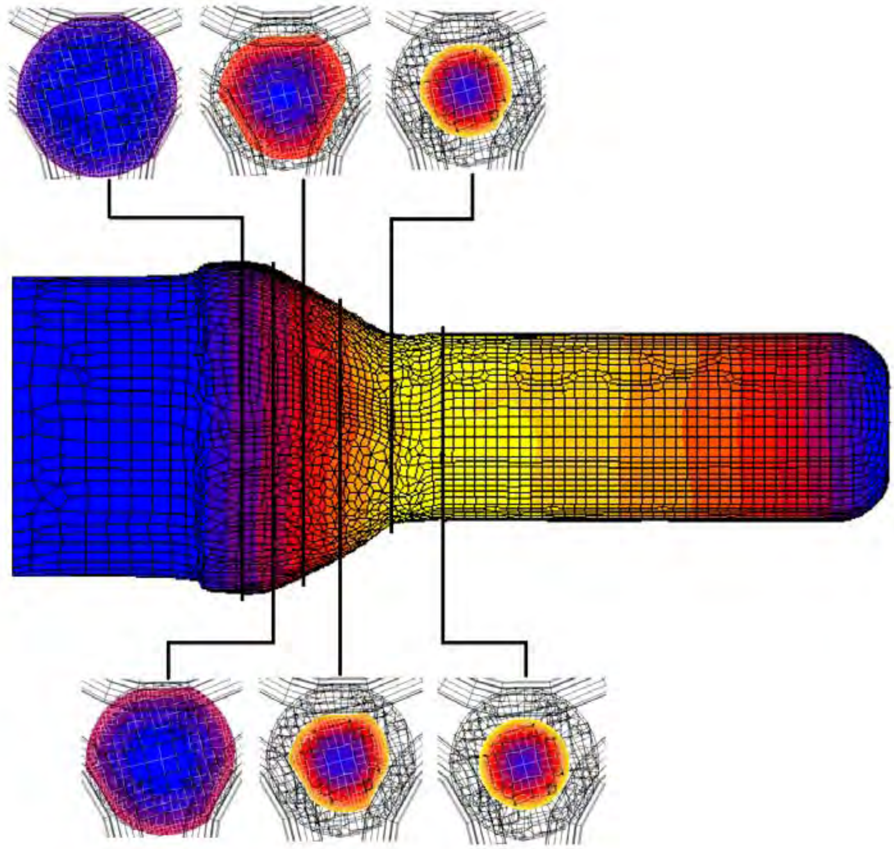


Fig. 3.14. *Shape disturbances in chosen cross sections of full product in rolling extrusion process by means of tools of modified shape (Fig. 3.12 and Fig. 3.13)*

In rolling extrusion process of hollowed products such a strong material upsetting before sizing zone was not observed. This can be explained by possibility of metal flow in radial direction also into the center of the formed product. For precise verification of this phenomenon, numerical calculations were made for hollowed billets rolling cases in analogical, as for full billets forming, scope of feed rate. In Figure 3.15 cumulative comparison of research results is shown.

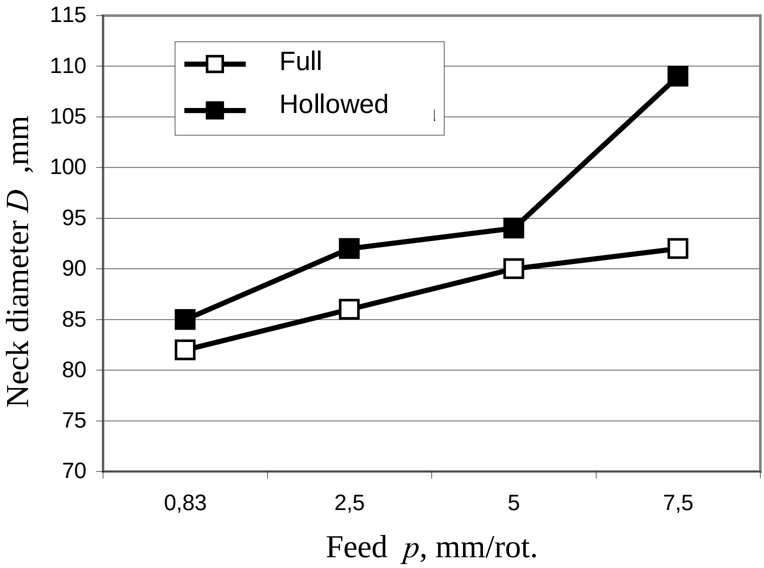


Fig. 3.15. *Comparison of diameters changes of flanges of full and hollowed products in rolling extrusion process at given values of feed on rotation*

As it was expected, it was stated that together with the increase of feed rate value diameters of products flanges also increase, yet, this dependency, for forming from full charges, assumes character close to linear. For analyzed cases of rolling extrusion from hollowed billets, a tendency for local billet upsetting at larger values of feed rate was observed, which was regarded as a favorable phenomenon for the further applications of manufactured in that way stepped hollowed shafts. Lower values of feed rate caused increase of product diameter at a certain distance before workspace between rolls– Fig. 3.15. Because of the mentioned above causes, for analyses of hollowed products walls thickness distributions, due to a local diameter upsetting, products formed at feed rate p = 5 and 7.5 mm/rot were chosen.

However, considering cross sections shapes disturbances of full products, analogous issues for rolling extrusion process of hollowed products were analyzed.

Figures 3.16 and 3.17 show results of research conducted in order to determine dependency between feed rate and ovalization disturbances Δ. These simulations gave results similar to earlier observations concerning flanges upsetting.

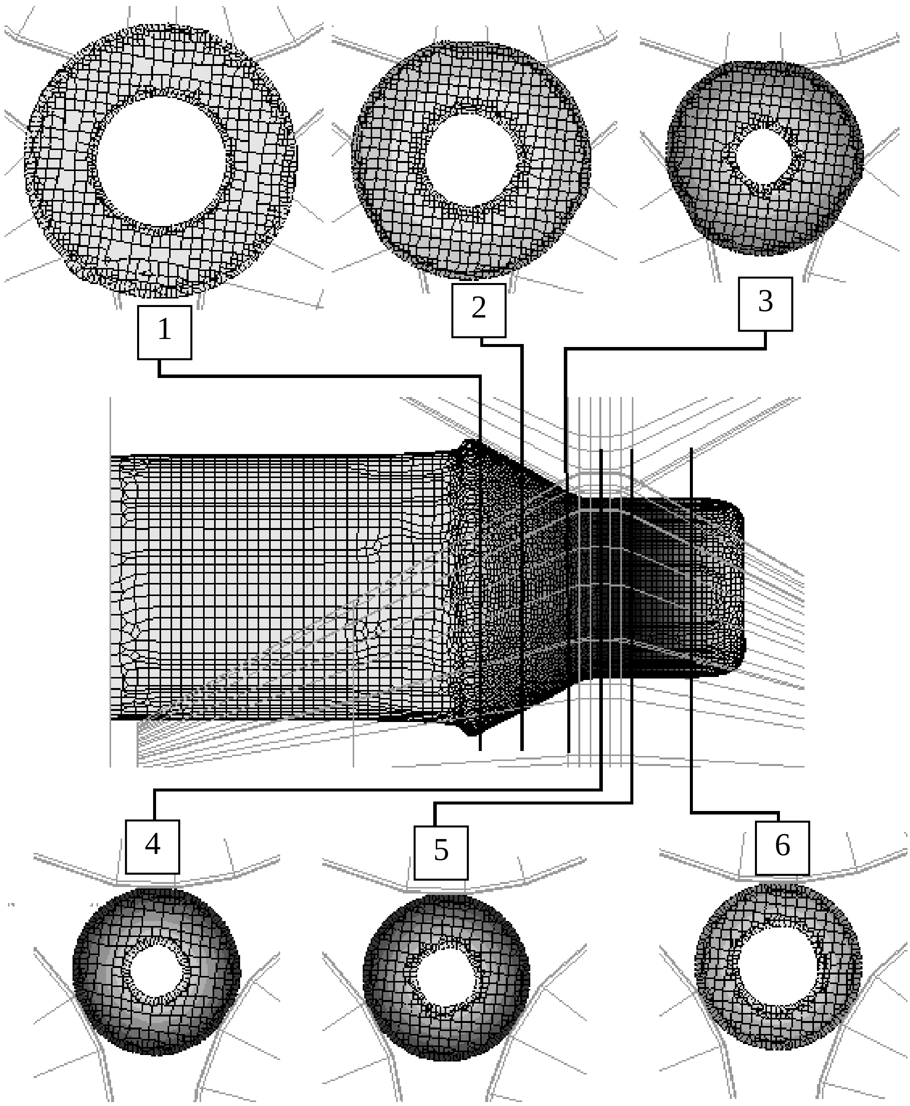


Fig. 3.16. *Disturbances of shape in chosen cross sections of hollowed product in rolling extrusion process at feed p = 2.5mm/rot.*

Visible in Fig.3.16, especially in cross section marked as number 3,clear disturbance of cross section should be considered as an undesired phenomenon. Additionally, shape changes of product internal surface presented in cross sections number 4 and 5 show probability of application in conducted simulation tools with too short sizing zones. Fortunately, according to diagram in Fig. 3.14, increasing feed rate value in a considerable way reduces size of technological allowance necessary in designing of this technology.

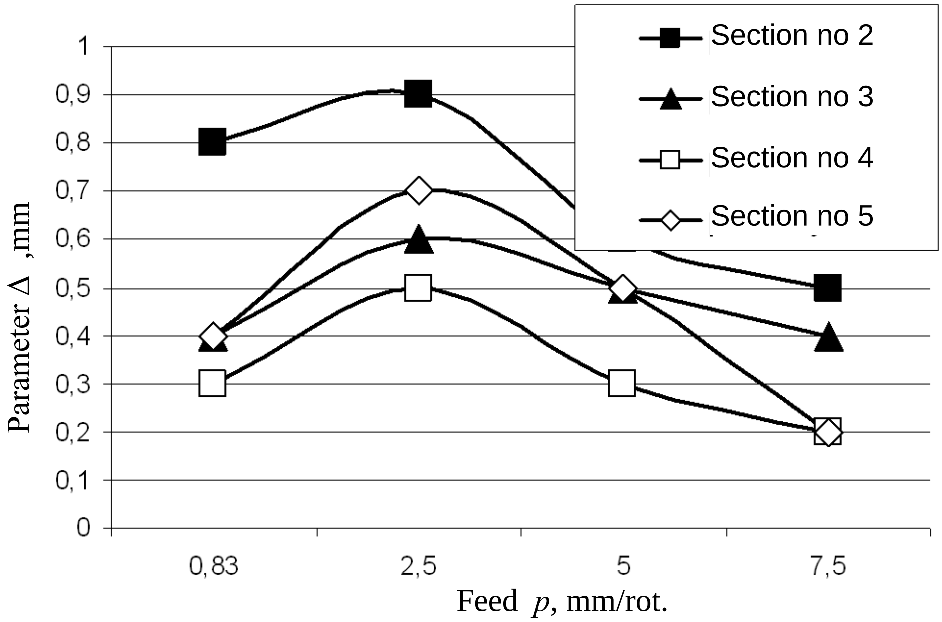


Fig. 3.17. *Distributions of parameter Δ depending on feed p values in chosen sections of hollowed (sections positions at Fig. 3.16)*

Examples of numerical calculations results for feed rate p = 5 mm/rot. and p = 7.5 mm/rot. are shown in Fig.3.18. Apart from easily noticed in this Figure small oscillation of wall thickness for product formed at feed rate p = 5 mm/rot., it was also stated that larger upsetting of material appeared before forming zone (conical zone). The area of this phenomenon presence spread in this case wider than in the case of rolling extrusion with larger value of feed rate. A possible explanation of this phenomenon was faster, than in the case of forming of full billet, material cooling leading to the increase of deformation resistance in the area of product diameter reduction. Due to upsetting of product before rolls (especially during forming from hollowed billets and at larger feed rate values) it was decided to make simulations with modified rolls shape - Fig.3. 19. Adding in rolls design a cylindrical guiding zone aimed at limiting radial metal flow outside .Conducted numerical research confirmed effectiveness of this solution (Fig. 3.19b), which, due to obtained product shape, destines this solution for preforms forming aimed at later cutting of e.g. conical toothing.

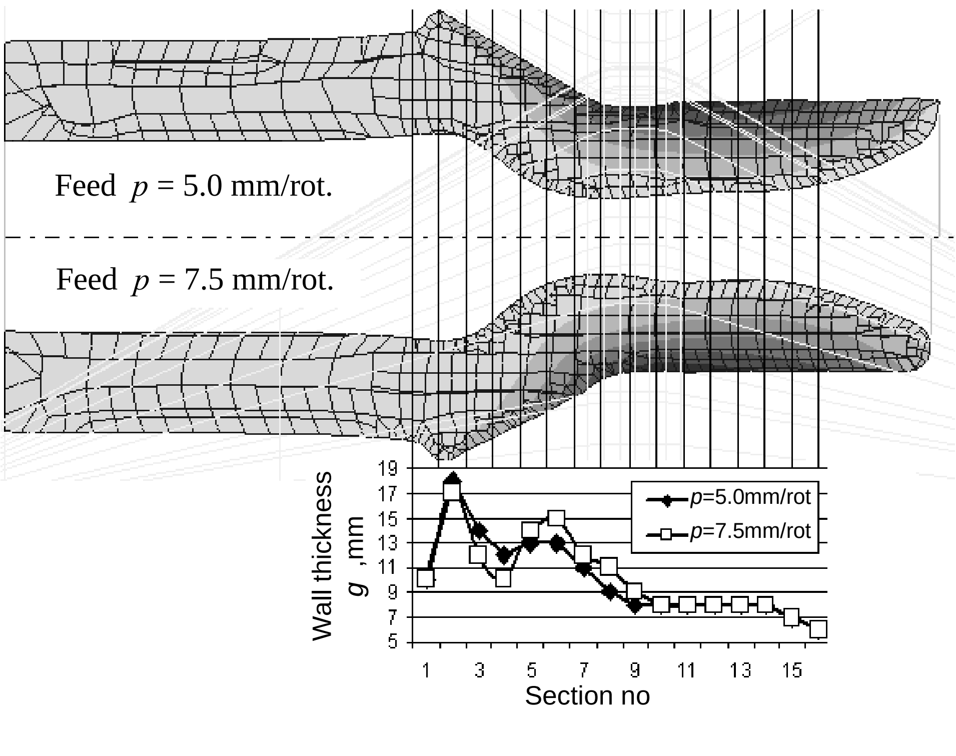


Fig. 3.18. *Distributions of walls thickness of hollowed products in rolling extrusion process at given values of feed rate p*

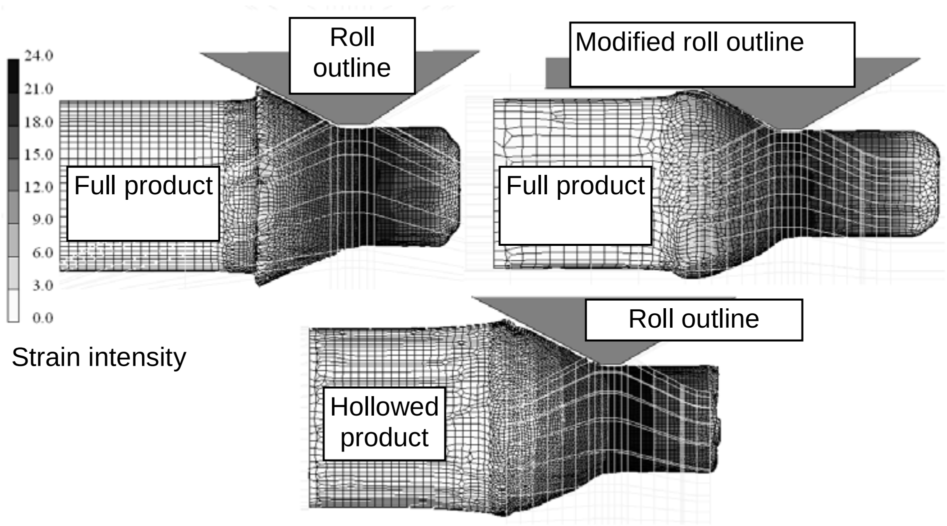


Fig. 3.19. *Full billet upsetting by means of rolls of initially chosen shape (a), rolls of modified shape (b) and forming of hollowed billet(c)*

Presented for comparison analysis of forming from hollowed billet (Fig.3.19 c) shows that such a product upsetting during rolling extrusion is reduced by metal flow towards product axis. It should be assumed that this phenomenon is obviously also dependant on chosen feed rate and walls thickness of applied hollowed billet.

Single forming tests with usage of profiled rolls with angles $\alpha = 20^\circ$ and $\alpha = 25^\circ$ showed that in the case of hollowed billets, considerable problems with numerical stability of the process are caused by strong material flow toward the axis of the formed part. In real conditions, this would probably lead to appearance of excessive ovalization of product or to its squeezing by back of stability.

The application of bigger values of feed rates resulting in different uncontrolled deformation of obtained parts. The results of single numerical research made with different feed rates are shown in Fig. 3.20.

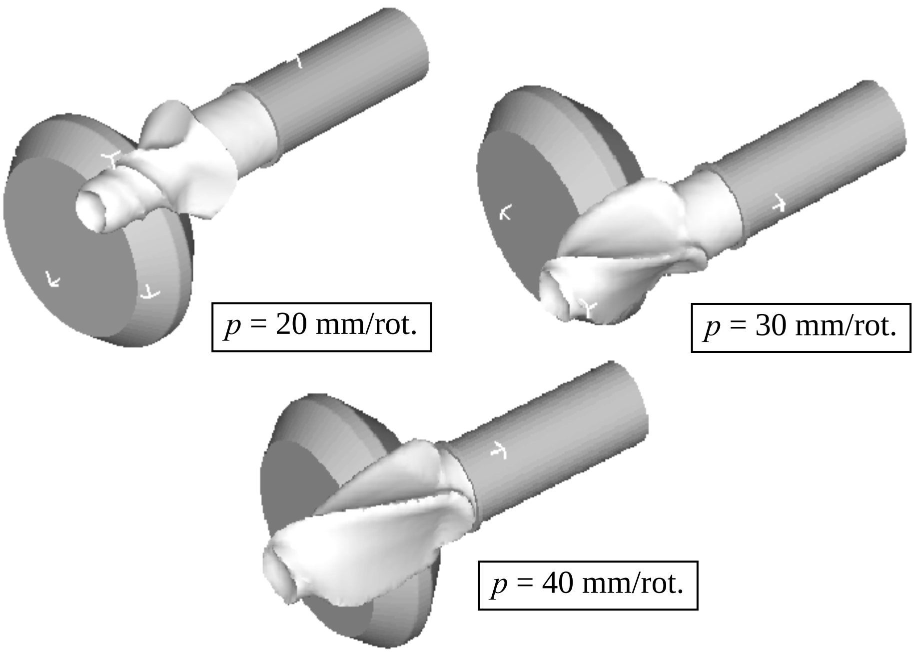


Fig. 3.20. *External shapes of full parts in rolling extrusion process at given values of feed rate p*

4. Designing, constructing and certification of a prototype aggregate for rolling extrusion PO-1

4.1. Assumptions

Constructing of research post for experiments on rolling - extrusion process was a natural continuation of presented in the previous chapter, results of theoretical research devoted to this new technology. Satisfactory results of initial theoretical analyses of forming of axi-symmetrical hollowed and full products were used for designing a prototype research post. Especially important at this stage of works, was the application of software ”Force calculator”, by means of which, in short time, values of forces and pressures for a wide range of analyzed designing and technological parameters were calculated.

Due to the possibility of easy assembling, design stiffness and possibility of the further modernization of the research post, it was decided to choose torsion-welding solution from rectangular closed profiles with application of ribs and stiffening plates.

In conducted calculations of the design, module FEMAP of Solid Edge ST software was used, which allowed for analyzing of strength of chosen parts by means of finite element method. Problematic, from dimensional precision point of view, was aggregate plate, to which mountings of rolls tools are fixed. Axes parallelism of rotating rolls depends on this element stiffness, which has a decisive influence on quality of products in rolling extrusion process. Chosen for the analysis element is presented in Fig. 4.1 and in Fig. 4.2 results of stiffness analysis of given plate are presented.

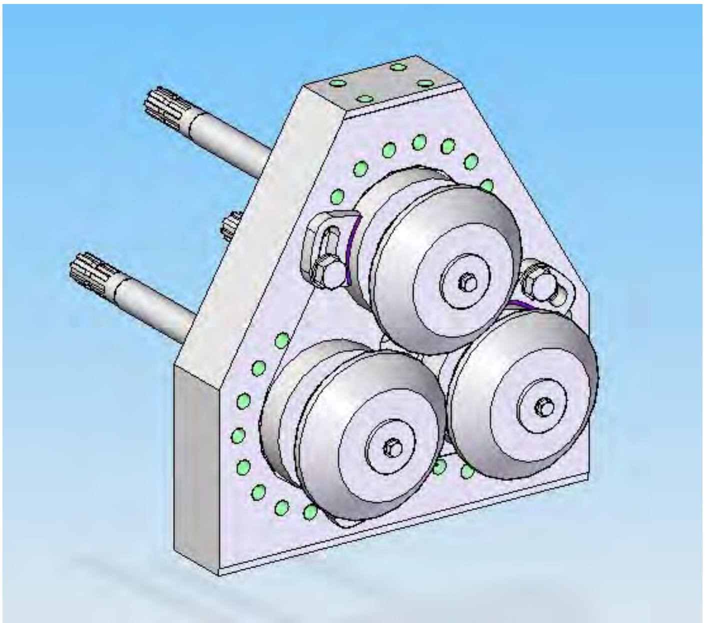


Fig. 4.1. *Model of supporting plate of rolling extrusion aggregate PO-1 with mounted rolls, mountings and drive shafts*

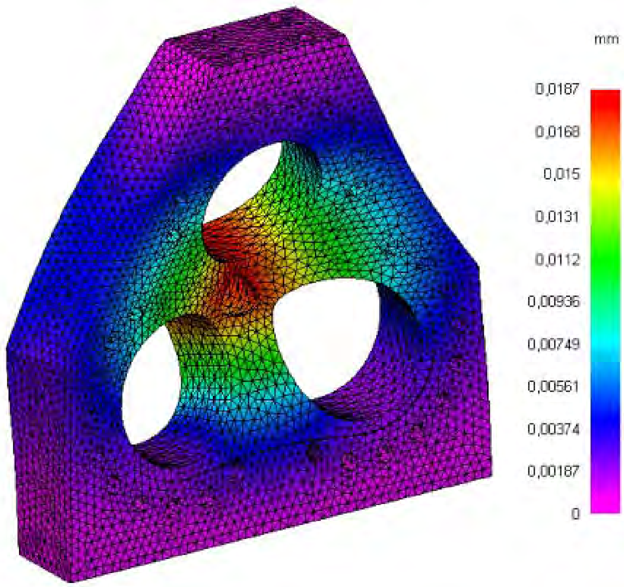


Fig. 4.2. *Analysis of stiffness of supporting plate of rolling extrusion aggregate PO-1 (force added centrally F=100kN)*

Due to necessity of guaranteeing identical rotary velocities of tools rolls within the wide range of velocities, coupled power transmission system was used, which is powered by electric motor equipped in system of additional cooling, stabilizing electric motor operating conditions at lower rotary velocities.

Regulation of tools rolls rotary velocity was foreseen to be obtained by means of vector inverter, the pusher set placing billet into workspace between rolls was planned to be equipped in a hydraulic drive. After assuming the above designing assumptions of the research post, proper designing works took place. Considered in theoretical works, diameters of working rolls and billets together with movement velocities of particular tools were transmitted into designing project of the research post in such a way, that planned for realization experimental research would verify obtained earlier theoretical results.

4.2. Design of virtual model of aggregate

The main components of the aggregate (Fig.4.3) include: frame body, drive set equipped with worm gear and reducer splitting torque into three jointed working shafts with fasteners, and forming set consisting of three, symmetrically placed on body plate, mandrels destined for driving rotary tools-forming rolls. On the machine second side, a hydraulic servo-motor, allowing for putting the formed billet into workspace between rolls, was designed.

Machine body [10] was designed as screwed – welded construction equipped with four body plates to which instrumentation and power transmission system equipped in worm gear and reduction gear which also splits torque into three shafts. In order to guarantee the proper stiffness of the design construction verifying calculations were made for fixing plate of forming set and drive unit transfer.

As a limiting value in calculations it was assumed that elastic strain of analyzed elements cannot exceed 0.1 mm, which guarantees obtaining assumed precision. This assumption for forming of products in hot forming conditions was only theoretical, as precision of forming of products in such a complex process depends on a considerably larger number of parameters which interaction was unknown. The further stiffening of machine design would lead to accumulation of unjustified costs, which were not considered at this stage of research.

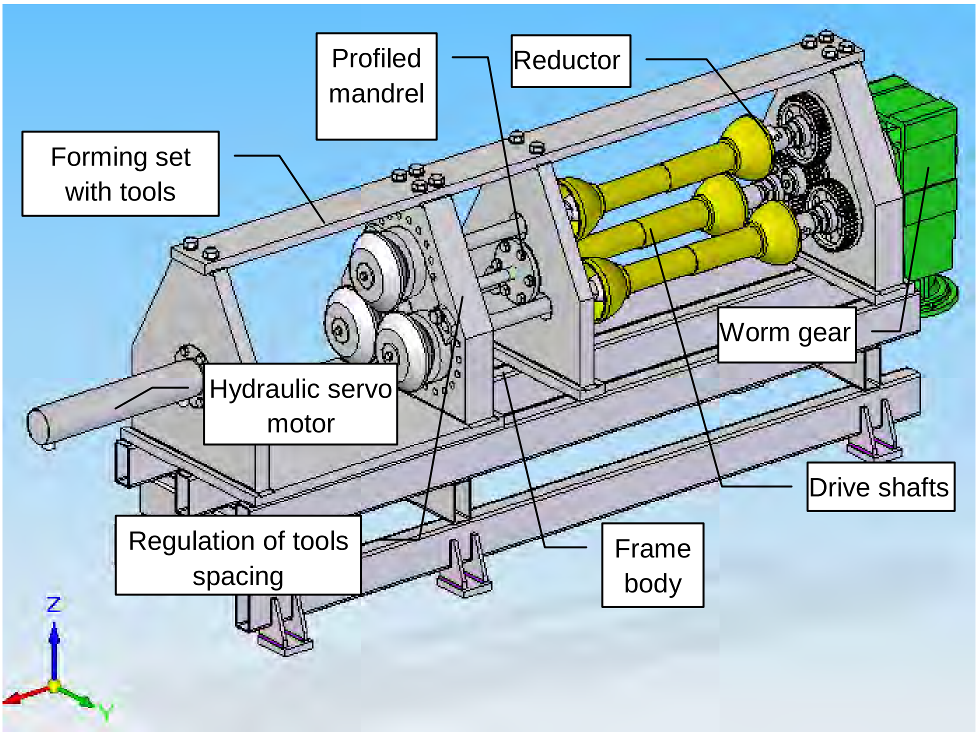


Fig. 4.3. *Virtual model of rolling extrusion aggregate PO-1 without shown electric motor*

After conducting analysis of a few solutions of rolls drive with application of motor engines with different rotary velocities equipped with reduction gears, it was decided to apply engine with power 18.5 kW, which in connection with worm gear reducer and vector inverter was to allow for obtaining tolls rotary velocities within the range from 0 to 3.0 rot./s, at maximal value of torque of 600 Nm on each roll. In order to make rolls spacing regulation possible, it was planned to apply eccentric mechanism equipped with stroke adjustment control. This solution was to allow for changing rolls spacing within the range of 15 mm (Fig. 4.1). In aggregate design it was assumed to apply a hydraulic servo-motor supplied from independent source of power, allowing for slide operating movement with the velocity regulated within the range from 0 to about 60mm/s, at assumed maximal force up to 100 kN. After considering maximal predicted value of forces and torques, elastic strains of structural plate, to which servo-motor flange was mounted, should not exceed assumed value 0.1 mm.

4.3. M anufacturing of a prototype a ggregate f or rolling extrusion PO-1

A prototype aggregate PO-1, destined for rolling extrusion process of full and hollowed products was based on design documentation. A ready finished research post was initially assembled at works contractor and, in that state, transported to the laboratory of Department of Computer Modelling and Technology of Metal Forming at Lublin University of Technology.

Here, the final assembly took place and hydraulic and electric power were connected. A photo of the finished research post is shown in Fig. 4.4 – 4.6.

Fig. 4.4. *General view of rolling extrusion aggregate PO-1 (without hydraulic feeder)*

***Fig. 4.5** .Steering unit with steering panel and vector inverter and hydraulic servo-motor equipped with steering valves*

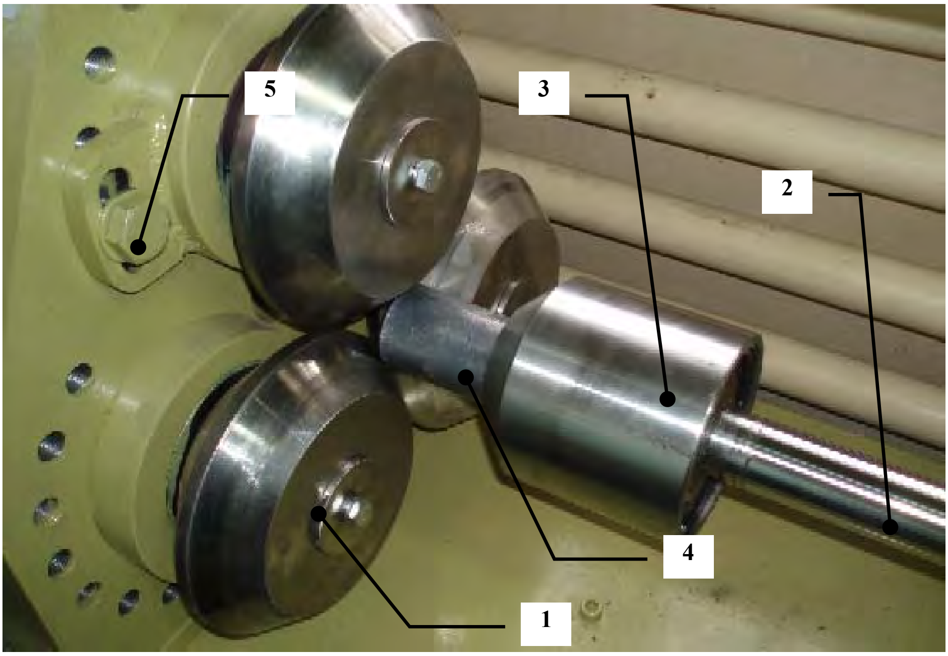


***Fig. 4.6.** Forming set with rotary tools (1), put forward hydraulic servo-motor (2) with rotary head(3), billet(4) at the position of start of forming and with eccentric mechanism (5) equipped with stroke regulation to regulate rolls spacing*

4.4. Certification procedure

After identifying legal acts which are used in the described case, it was stated that aggregate for rolling extrusion type PO-1, according to paragraph 1, point 2 is a machine and is subjected to main requirements Directive 98/37/WE "Machines". The mentioned above machine is not on the list annex of machine Directive no 4, and because of that the procedure of research type WE does not find application by notified verifying center. Hence, only module A was analyzed.

Mounted in aggregate hydraulic feeder with servo-motor of permissible pressure 160 bar and maximal volume of hydraulic unit 7.0 liters fulfils the requirements category article 3 point 3 (annex 2, table 4) Directive 97/23/WE "Hydraulic systems". According to article 3, point 3 Directive 97/23/WE, the mentioned above hydraulic system should be designed and manufactured with "Recognized engineering practice" in order to guarantee safe usage and should not be marked with CE sign for conformity with this Directive.

As the aggregate is powered by 400V voltage it is subjected to norms Directive 2006/95/WE "Electric equipment of low voltage (50-1000V)"- module A. Applied electric and electronic appliances are marked by CE sign and because of that there is no need of valuating conformity with Directive 2004/108/WE "Electromagnetic compatibility".

For risk estimation the following norms were used:

PN-EN ISO 12100-1:2005	Machines. Safety. Basic concepts, general designing rules. Part 1:Basic terminology, methodology
PN-EN ISO 12100-2:2005	Machines. Safety. Basic concepts, general designing rules. Part 2: Technical rules.
PN-EN 60204-1:2001	Machines Safety. Machines electric equipment. General requirements.

PN-84/N-01307	Noise. Permissible values of noise level at working posts and general requirements concerning measurements.
PN-EN 61310-1:2000	Machines safety. Indicating, notation and steering. Requirements concerning visual, audible tactual signals.
PN-EN 294:1994	Machines safety. Safe distances not allowing for touching by upper limbs dangerous areas.
PN-EN-982:1998	Machines safety. Requirements concerning hydraulic and pneumatic units and their elements safety. Applied hydraulics.

Within the scope of identification and dangers valuation for crucial dangerous and harmful, according to PN-EN ISO 12100-1:2005 and PN-EN ISO 12100-2:2005, factors which during aggregate usage can create a risk include:

- mechanical dangers;
- electric dangers;
- thermal dangers;
- noise risk;
- danger resulting from application of hydraulic equipment.

In estimating value “Probability of dangers appearance” a scale from 1 to 5 was assumed. As a limiting value grade 1 was chosen, for which it was assumed that risk presence is minimal and machine is safe due to design solution after using safety measures.

Determining acceptable risk “Danger degree” and recommendation concerning actions resulting from this risk evaluation was made according to PN-N-18002:2000 and given in table 4.1 at the end of the book.

Scale from 1 to 5 was assumed. Work risk minimizing was achieved by applying:

– technical solutions of safety appliances;
– protectives shields;
– individual protectives;
– risk minimizing by means of information for users.

According to PN-EN ISO 12100-1:2005 appropriate minimizing of risk can be regarded as achieved when the answer to each of the following questions will be positive:

– were all kinds of works and all ways of interference considered? – were considered;
– was dangers elimination or risk minimizing by usage of protectives applied? – was applied;
– were dangers eliminated or was risk caused by them minimize to the lowest possible level? – dangers were limited to the lowest possible level
– was it checked if applied means? did not create new dangerous situations? – it was checked if applied means did not create new dangerous situations
– were users informed and warned about the residual ? – were informed
– was it assured that operators working conditions were not threaten by applied protectives? – it was assured
– are applied protectives compatibile? – they are
– were effects resulting from application of machine designed for professional usage / industrial in non professional area / non industrial considered? – were considered
- was it assured if applied means did not considerably limit possibility to fulfill function? – it was assured

At this stage, the process of iterative risk lowering was finished. After conducting all procedures and research it was said that the proposed for verification aggregate for rolling extrusion type PO-1 fulfills main requirements Directive 98/37/WE and 2006/95/WE and article 3 point 3 Directive 97/23/WE.

On the basis of this, the aggregate manufacturer gave conformity declaration according to norm PN-EN 45014:2000 “General criteria of conformity declaration provided by supplier” and marked the product by CE conformity sign at rating plate.

5. Experimental research of forming process in aggregate PO – 1

5.1. Initial research – rotary head mounting

After finishing certification procedure the research stand was operated. The first stage of the research was conducting functional and movement tests in order to determine basic kinematics parameters of the process and to regulate the unit.

Measurements of pusher movement velocity were made and appropriate scopes of vector inverter responsible for working rolls rotary velocity were determined. After regulations concerning reciprocal association of working elements movement velocities, first tests of forming of stepped products took place. At this stage of work, it was decided to apply billets made from commercially pure lead, which allowed for process conducting without the necessity of billets heating and with minimal values of feed. In order to guarantee direct comparison, at this stage of research, hollowed and full billets were used. In both cases external diameters of billets were D_W = 60 mm, however, in the case of hollowed billets, internal diameters were D_F = 40 mm and D_F = 24 mm correspondingly. The same external diameter of billets D_W = 60 mm was reduced during the rolling extrusion process, analogically as in theoretical research, to the value D_F = 40 mm.

First laboratory tests showed proper functioning of all working mechanisms of the aggregate and confirmed the possibility of forming of axi – symmetrical stepped products by means of rolling extrusion method. These tests also confirmed earlier assumptions concerning disturbances caused by non axial billets guiding in this process. However, designing assumptions of rotary head were modified after first tests with the aggregate prototype. In these research, the lack of coaxial billet guiding led to the product destruction and reduce pusher servo-motor seals durability. In the result of conducted tests, products of strongly deformed external and internal surfaces and of characteristic, wavy surface quality of a part of reduced diameter were obtained. Examples of products obtained at this initial stage of functional-movement tests are shown in Fig. 5.1.

Fig. 5.1. *Rotary extruded products made from lead Pb1 during functional – movement tests of aggregate PO – 1 without the application of rotary head mounted on pusher*

In order to avoid this unfavorable phenomenon, the pusher unit was equipped with special rotary head mounted at the servo – motor's end – Fig.5.2. Designing solutions of the head were based on mounting of three bearings unit (one cross bearing and two longitudinal bearings) in the body equipped with the billets mounting seat. This solution allowed for simple positioning of billets with diameter correlated with ring – shaped reducing pads. The aim of a massive construction of the head was to adjust this unit to heat excess carrying away, produced during the foreseen at the further stage of works steel forming in hot conditions.

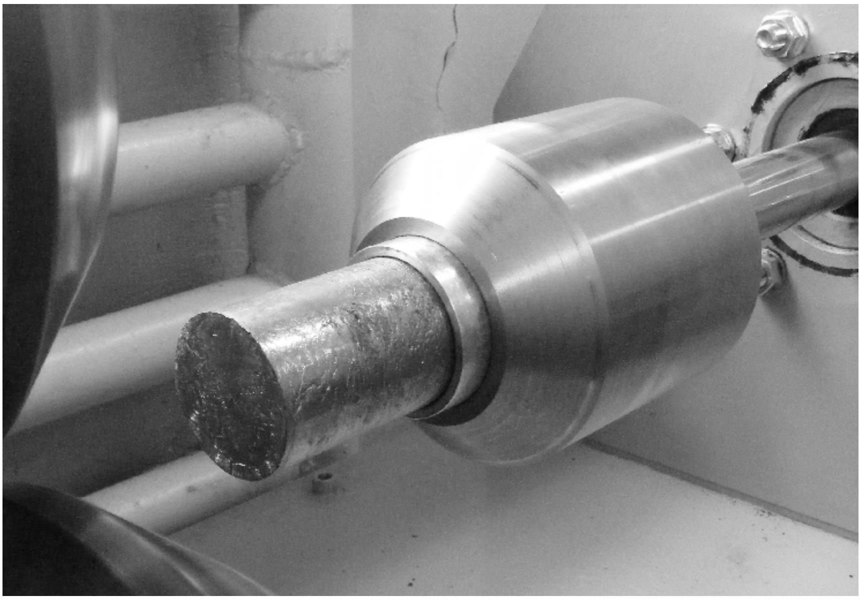


Fig. 5.2. *Rotary head with billet in tube during functional – movement tests of aggregate PO – 1*

5.2. Forming from full and hollowed billets made from commercially pure lead

After described change of aggregate PO – 1 construction, forming tests with modified billets guiding were made. An example of forming process of full product with the application of material model in the form of lead is shown in Fig. 5.3, where rotary head and ring-shaped reducing pad supporting billet in axial position to workspace between rolls tools are presented. Finished full and hollowed products, obtained in rolling extrusion process, are shown in Fig. 5.4.

In both cases of forming from full and hollowed billets, in the Figure the result of intensive surface metal flow, appearing as head cavity - funnel (in the case of full product) and material burring (hollowed product) is well visible. Presence of this phenomenon is also a characteristic feature of cross-wedge rolling processes, and means similar metal flow. Such solutions can be drawn from the analysis of conical area of product upsetting before rotary rolls, where characteristic material concentration appears. In both analyzed cases, this phenomenon, apart from products upsetting, leads to uncontrolled burring of material. This unfavorable phenomenon will be later present in the case of rolling extrusion processes from steel billets in hot conditions and it will be especially visible during forming from full billets. It was assumed that in forming of hollowed products, with smaller thermal capacity and cooling faster than full products, presented here characteristic flanging would be limited by cooling in air of surface metal layers.

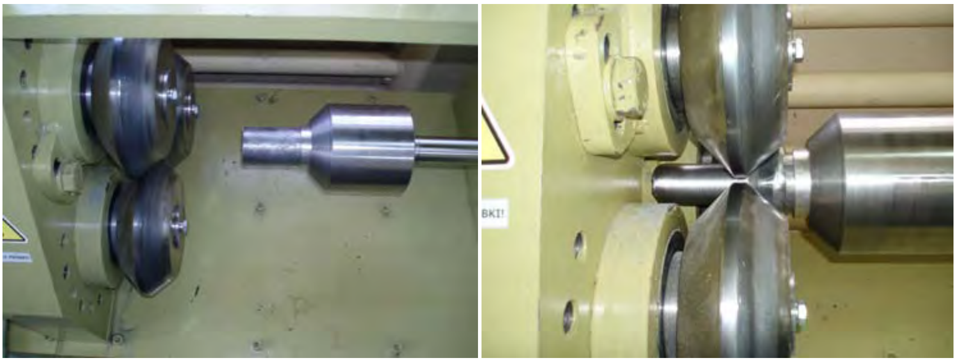


Fig. 5.3. *Rolling extrusion of full product made from commercially pure lead*

Fig. 5.4. *Full and hollowed products obtained in rolling extrusion process (material – commercially pure lead)*

Coaxial billets guiding disturbances and their influence on quality of obtained external surface of formed products became one of basic issues of experimental research. Due to the lack of this disturbance introduction in numerical analyses FEM, described in this chapter results determine tolerance areas of hollowed and full products obtained in rolling extrusion method. Moreover, additional disturbances of the process are introduced by manual placing billet to the pusher rotary head, which also constitutes a factor generating shape deviations of product obtained step.
Considering problems of shape disturbances, resulting directly in obtained tolerance areas, further research were aimed at determining connections between process basic parameters, shape of obtained products and necessary technological allowances .

The most important dimensional deviation, acting directly on next machining processes, was ovalization parameter of cross – section, described as:

$$\Delta = \frac{D_{max} - D_{nom}}{2} \tag{5.1}$$

where: D_{max} - maximal diameter of product in a given section, D_{nom} - adequate nominal diameter.

In conducted experimental research values of feed p were changed, during application of full and hollowed billets. Measuring of diameters of finished product formed part took place in three sections, shown in Fig. 5.5, and comparison of obtained results is given in table 5.1. A well visible in Fig. 5.5, characteristic wavy surface of the product is the direct cause of slight pusher radial run-out during forming with higher values of feed (in that case feed p= 5 mm/rot).

Analysis of data presented in table 5.1 shows strong connection between values of, applied in the process, feed and measured dimensional accuracy of full and hollowed products. The data obtained during research show that the decrease of feed value allows for narrowing dimensional tolerances area of finished products.

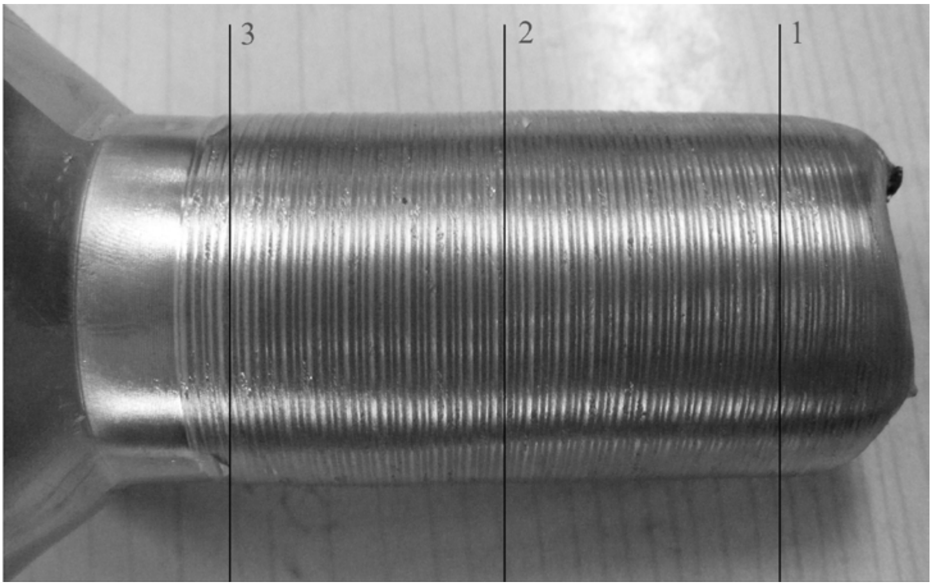


Fig. 5.5. *A view of measuring planes space positionig of analyzed full and hollowed products*

Tab. 5.1. *Comparison of ovalization deviations of full and hollowed products in rolling extrusion with values of feed given in the table*

Ovalization Δ, mm	Hollowed billets				Full billets	
Feed *p* , mm/rot.	7.5	5	2.5	1	2.5	1
Nr billet Measuring plane (Fig. 5.3)	I	II	III	IV	V	VI
1	0.8	0.9	0.3	0.1	0.6	0.4
2	0.7	0.6	0.3	0.2	0.5	0.4
3	1.3	0.5	0.2	0.2	0.3	0.2

However, due to a very complex character of metal flow in rolling extrusion process and due to using in research only one tools rolls set with two inclination angles of side walls (forming angle α = 30° and α = 35°), the further, detailed determining of particular parameters influence on obtained dimensional precision and stability requires experimental tests within the wider scope of applied tools.

Later research works concerning hollowed products made from commercially pure lead included products cutting in order to obtain possibility of analysis of walls thickness distributions in longitudinal sections. Unfortunately in this case, after cutting operation, large fluctuations of walls thickness distributions were observed, which eliminated further application of obtained in that way products. An example of hollowed product made from commercially pure lead after rolling extrusion process, at feed p = 5 mm/rot, is shown in Fig. 5.6.

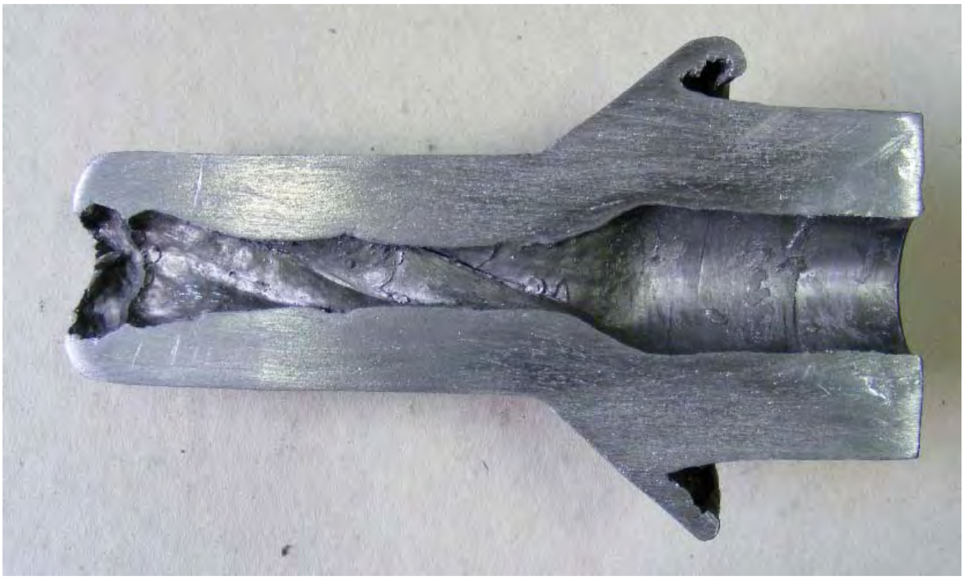


Fig. 5.6. *Longitudinal section of hollowed product made from commercially pure lead after rolling extrusion process (p=5 mm/rot.)*

Characteristic spiral metal flow causing waving of walls thickness and appearance of substitute of internal screwed outline pointed to unsatisfactory metal flow in transverse direction to pusher movement. In order to limit this unfavorable phenomenon, forming tests were made again with application of lowered values of feed on rotation p = 2.5 mm/rot. Results of the experiment did not bring a considerable improvement, leaving the internal surface of formed product impossible to accept without removing dimensional allowance of up to 3 mm. Such a wide tolerance area and disturbance of material coherence in the process of further machining in such a large scope would make this technology completely unprofitable and ineffective. Considering, however, results of similar research on forming of hollowed products in CWR processes, where considerable differences in steel and lead billets properties during research were observed, the conclusions were left to be drawn when tests with steel billets formed in hot conditions would be made.

5.3. Forming from full and hollowed billets made from steel C45

For chosen cases of forming of full and hollowed billets, rolling extrusion tests from steel billets formed in hot conditions were made. Billets made from steel C45, with dimensions analogical to dimensions in numerical simulations and heated in a furnace to temperature 1150°C, were used. Working rolls and rotary head of the pusher were, at the beginning, left in the environmental temperature, which led to fast cooling of the product formed between rolls. In the result of temperature lowering, fast increase of yield point causing slip phenomenon was present. An example of a product deformed by slip is shown in Fig. 5.7.

Fig. 5.7. *Example of product damaged in the result of slip phenomenon (p = 5 mm/rot.)*

After three or four working cycles of rolling extrusion, when tools had working temperature about 150°C, further forming took place according to the assumptions. In next research works, it was decided to heat working tools initially to temperature about 200°C.

Figure 5.8 presents a forming process of one of full billets and chosen finished products, full and hollowed. Similarly, as in the earlier forming from lead billets (Fig. 5.2), intensive, surface flow of metal is visible, resulting in head funnel appearance in the reduced step of full product. In this case, as for lead billets, characteristic burring of material, limiting time of the process to the appearance of this phenomenon, is also present.

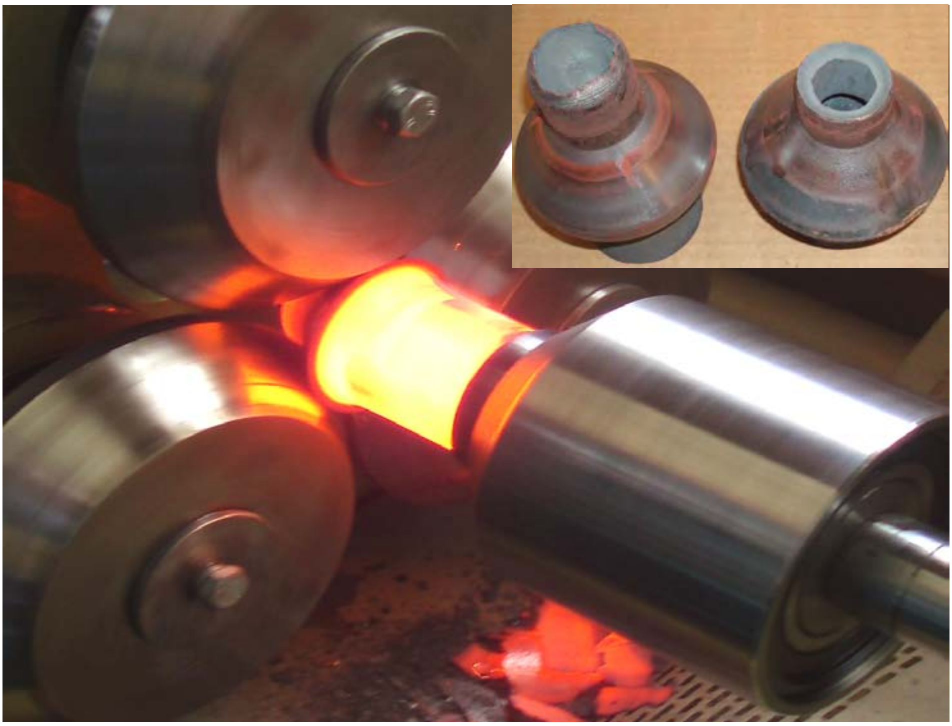


Fig. 5.8. *Rolling extrusion process of full product (p = 5mm/rot.) and obtained finished products (steel C45)*

An important difference, at forming from hollowed billets, is a practical lack of tendency to flanging. This phenomenon is replaced by change of length of upset product part before flange, that is before the area of diameter reduction.

On the basis of numerical data, experimental research were made of forming process from hollowed billets at feed p = 5 mm/rot. and p = 7.5 mm/rot. Results of these tests are shown in Fig.5.9, where photos of obtained hollowed products are presented.

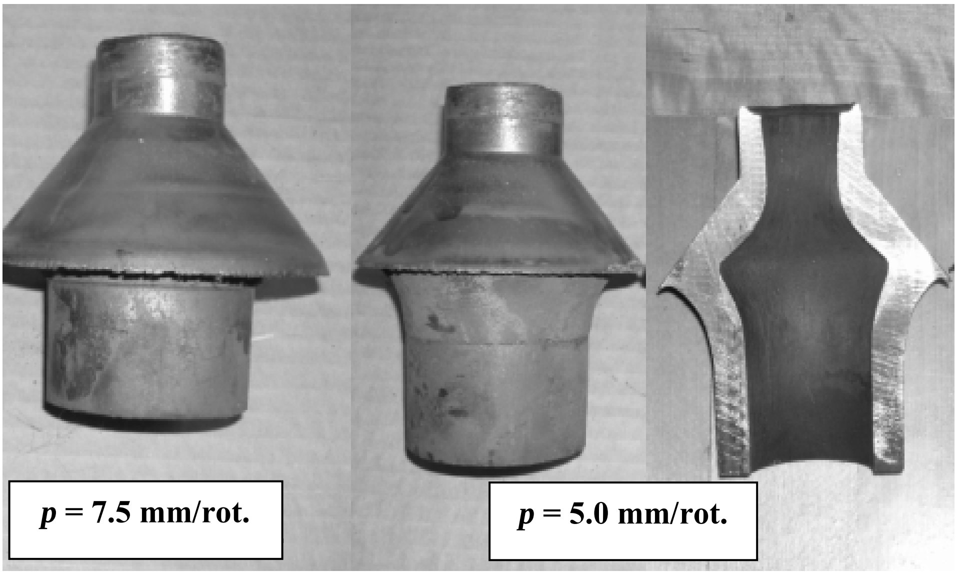


Fig. 5.9. *Hollowed products obtained in rolling extrusion process at feed rate p given in the photo together with distribution of walls thickness in longitudinal section*

Conducted at this stage of research measurements of obtained hollowed products show small departures in comparison with data obtained in numerical research, which confirms the rightness of process model assumed for calculations.

Tests of further limiting of feed value on rotation *p* led to intensive flow of metal in reverse direction to pusher movement in upper layers of formed product. In the result of this phenomenon, characteristic burring of metal at external flange diameter. This led to limiting of width of local thickening which resulted in more difficult obtaining of stepped products (especially of full section). An example of full product formed at feed rate on rotation p = 2.5 mm/rot. is shown in Fig. 5.10.

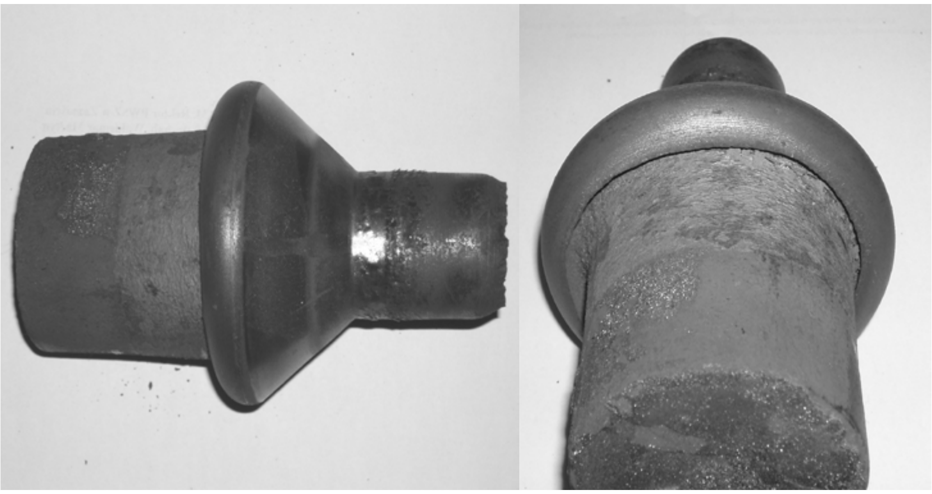


Fig. 5.10. *Full products with characteristic ,backward flanging caused by too small value of feed rate (p= 2,5 mm/rot.)*

Verifying tests show additional limitation of the process in the form of billet cooling before forming zone. This phenomenon was especially intensive for rolling extrusion case from hollowed billets, however, also for full billets it was a limitation forcing forming process interruption because of the risk of seizure of excessively upset billet in the pusher rotary head – Fig. 5.12. Conducted at the further stage research show that it is necessary to foresee, in designing of rolling extrusion processes, appropriate length of billet mounting zone for guaranteeing its proper guiding during the process. Adding to the planned length of the product before deformed zone a part not undergoing metal forming favors, of course, easier removing of product from pusher working head after conducted forming process. Because of that, it is very important to determine influence of process parameters on the length of upset zone before work space between tools rolls. In extreme cases, such as presented in Fig. 5.9, it was necessary to stop rolling extrusion process. Removal of upset billet from pusher rotary head was not problematic in that case, because on this product a guiding ring mounted inside head seat was seized. Due to installed in the described head bearings, leaving in the mounting seat hot billets is not advisable for the further proper exploitation of sensitive to temperature bearing.

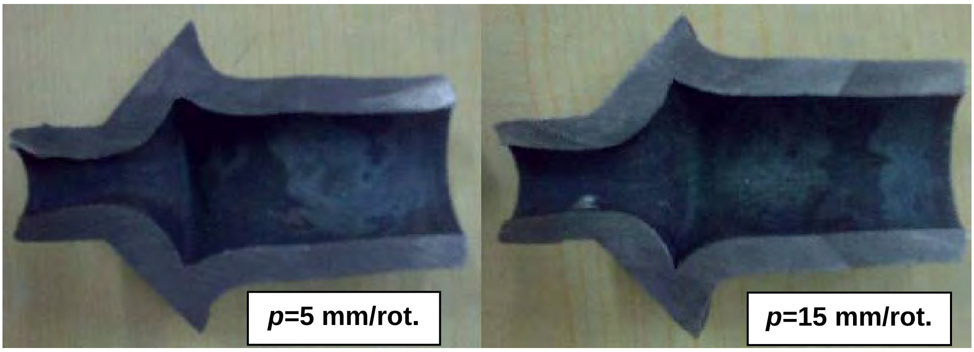


Fig. 5.11. The distributions of wall thickness of rolled – extruded billets at given p values

Fig. 5.12. *Phenomenon of excessive billet upsetting before tools rolls forming zone (p=1 mm/rot.)*

Visible in Fig. 5.11 considerable amount of crumbling scale on the surface of deformed billet was caused by box-type furnace usage in heating process. At applied in research billets overall dimensions, in order to achieve equal heating of forgings to temperature 1150°C, it was necessary to keep them in the furnace for about 30 minutes. At simultaneous heating of few billets (especially of full section), heating time increased even to 60 minutes.

6. Forming of a stepped shaft – process analysis

6.1. Choice of parts of stepped shaft type – FEM calculations

On the basis of analysis of rolling extrusion process parameters of hollowed and full products, it was decided to conduct forming tests of a chosen hollowed forging – Fig. 6.1. This product is characterized by a flange and dimensional proportions, corresponding with the assumptions of forming process conducting by means of rolling extrusion. An attempt to obtain a hollowed product according to technological documentations was to check in practice possibilities of designing manufacturing technology of this type of products.

Billet used in the process ,in the form of thick walled tubes, had external diameter D_Z = 68 mm and internal diameter D_W = 40 mm. External diameter of the billet was reduced to the value D_R = 42 mm (behind rolls) and enlarged to D_S = 98.5 mm (in front of rolls), according to profiled rolls working outline showing dimensions of a formed product – Fig 6.2, during the rolling extrusion process simulations.

As earlier numerical calculations showed, strict dependency between applied in rolling extrusion process feed values on rotation p, in numerical calculations it was decided to use changeable values of this parameter. The following dependencies were considered:

- larger value of feed on rotation – stronger upsetting of billet in front of tools rolls;
- smaller value of feed on rotation – higher dimensional precision and lack of characteristic flanging.

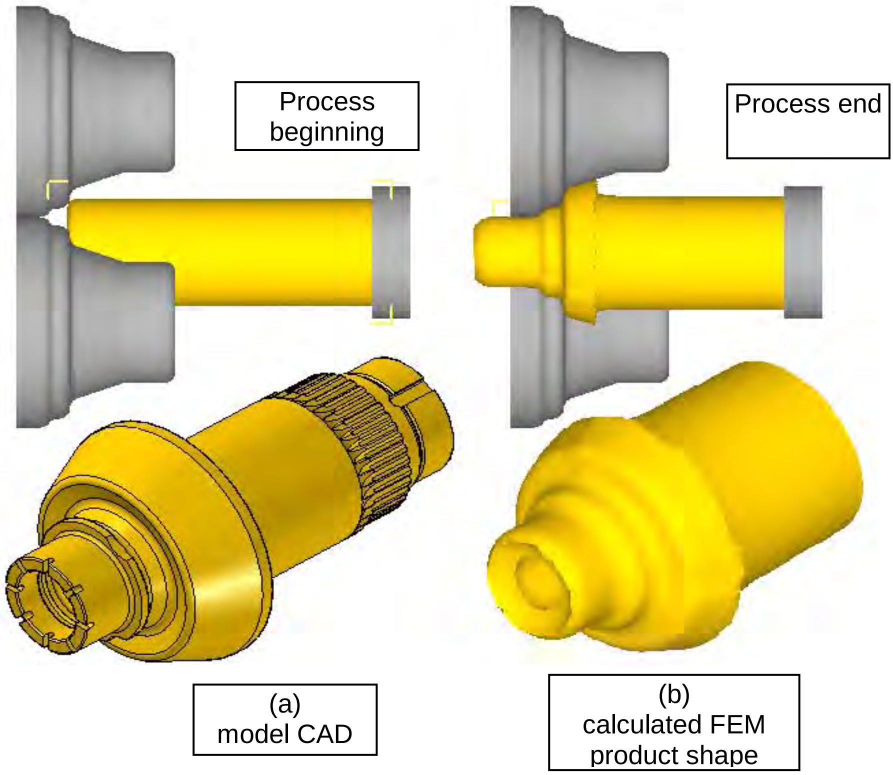


Fig. 6.1. *Model CAD of finished product (a) and obtained in the result of FEM calculations shape of a part (b) after rolling extrusion process*

Considering the mentioned above dependencies and basing on results of earlier analyses, in calculating of forming process of a chosen product it was decided to apply various values of feed on rotation p within the range $p = 2 \div 10$ mm/rot. In the first numerical tests conducted at the highest values of feed on rotation ($p = 5 \div 10$ mm/rot.) it was noticed that billet upsetting intensity increased while the formed part length increase was limited. In the result of this, it was difficult to remain product cylindrical shape before the formed flange, and circularity disturbances in cross sections appeared due to disturbance of metal axial flow by too quick implementation of the metal into workspace between rolls.

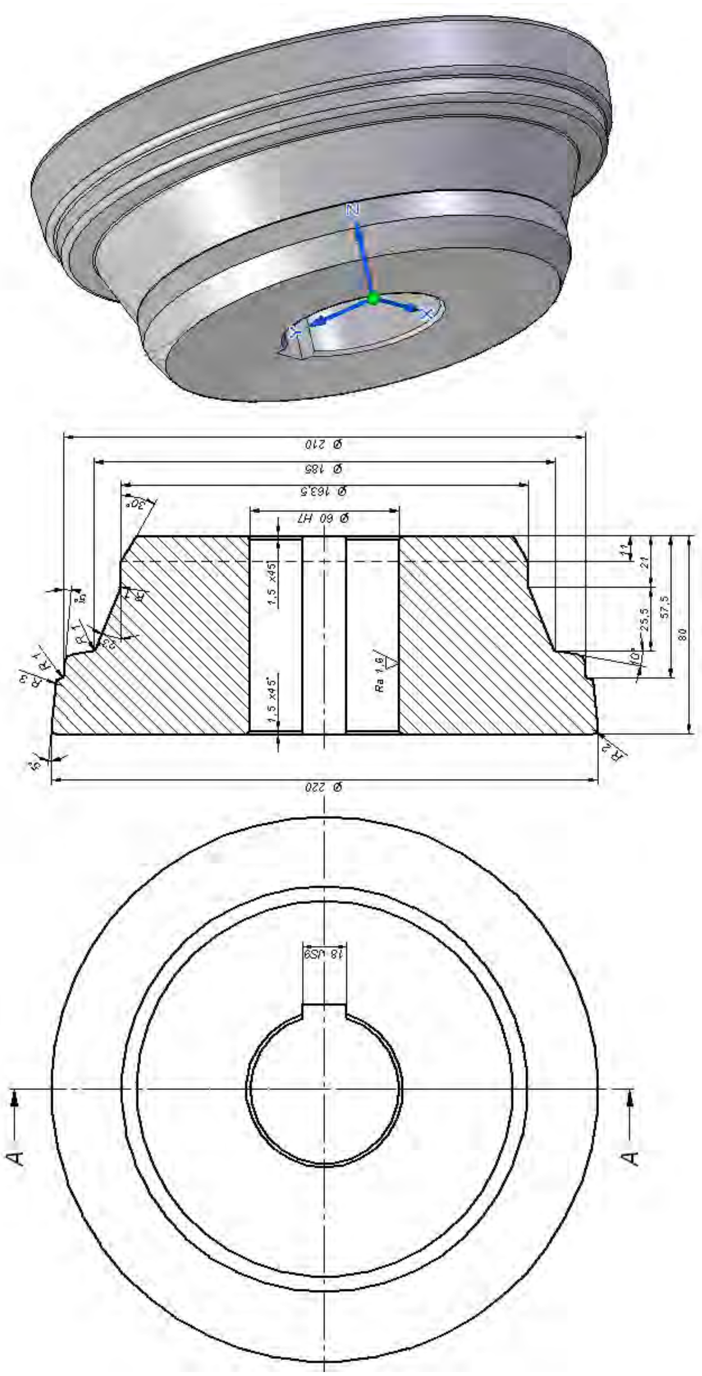
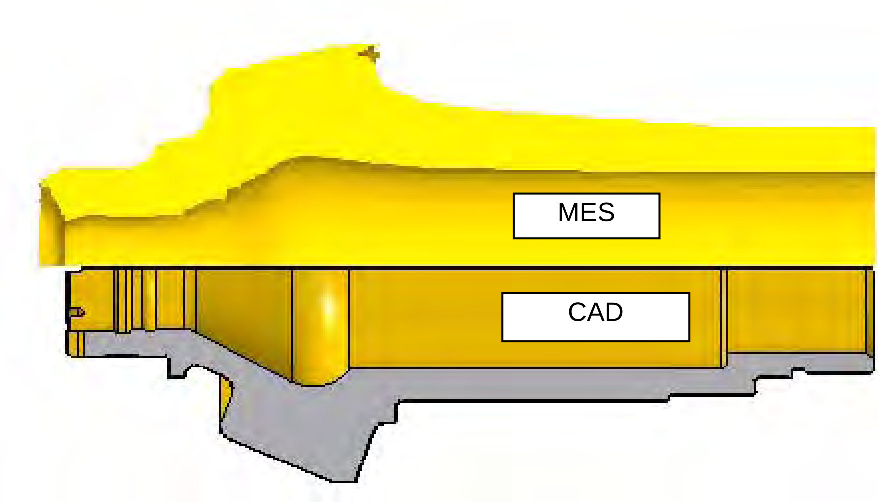


Fig. 6.2. *Model and sketch of working rolls designed for forming of stepped shaft*

In the analyzed case, only putting together changing(decreasing) during the process feed values allowed for obtaining the proper shape of hollowed product. In Fig. 6.3 are presented longitudinal cross sections of finished part model and a product obtained in simulations with changing feed values.



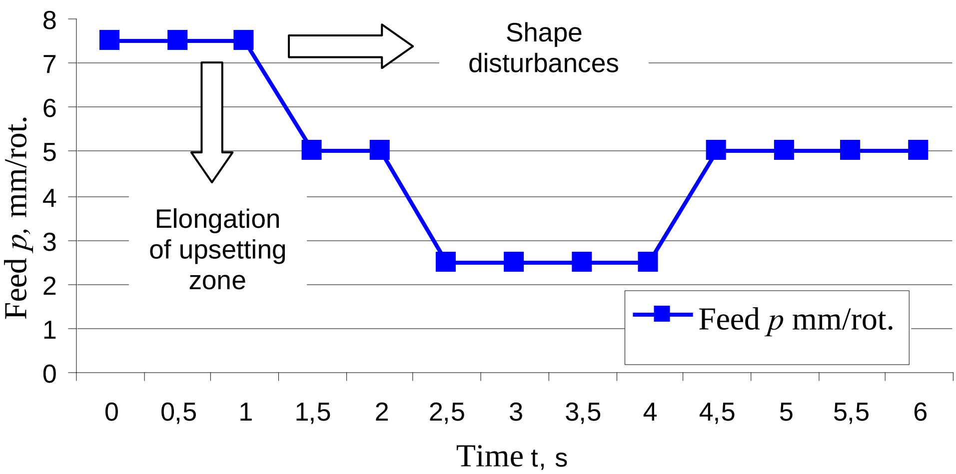


Fig. 6.3. *Obtained in the result of simulation FEM longitudinal section of product compared with analogous section of the model CAD and changes of feed on rotation p values during forming process*

Analyzing the obtained results of numerical calculations it should be noticed that the applied simplifications in tools rolls design were reflected in the obtained product dimensional allowance. It can be well seen in the head part after the product diameter reduction between rolls and in the area of upsetting before formed flange. Obtained in this case dimensional allowance should be estimated at about 4 – 5 mm.

Considering shown in Fig 6.3 range of changes of feed on rotation p values, it should be noticed that the process was started with the highest value p = 7.5 mm/rot. and this value was reduced in two stages to p = 2.5 mm/rot, in order to increase slightly this parameter up to p = 5.0 mm/rot. The beginning of the realized process, at larger forming velocities, guaranteed proper billet upsetting, which led to obtaining proper diameter and wall thickness in the area of product flange forming. Limiting this velocity at the further stage of the process led to shape mistakes reduction, which was shown in the description of Fig 6.3. Explanation of feed value increase at the last stage of the process was limiting of tendency for product flanging and shortening of process working time.

6.2. **Experimental research of stepped shaft forming process**

Favorable results of numerical research of rolling extrusion process of stepped shaft (Fig 6.1) were used in experimental research on this process in aggregate PO – 1. On the basis of working tools numerical models, necessary tooling (Fig 6.4) was made and steel billets of C45 type with diameters assumed in numerical research were used. Similarly, as in the previous experimental research with the previous tools set, rolls were heated up to about 200°C, which was extremely important in the case of applied hollowed billets.

Fig.6.4 *Working rolls for rolling extrusion process made according to Fig. 6.2*

Billets used in research were heated in electric box-type furnace, up to 1150ºC and later formed at chosen parameters of feed on rotation, within the feed range on rotation p = 2.5 ÷ 7.5mm/rot.

In the basic conception of PO – 1 aggregate, there was no possibility of change of feed on rotation value during the process realization. Such possibilities would guarantee the application of electro-valve steering in time of hydraulic oil expenditure, transmitted to a pusher servo-motor, or implementation of vector inverter with faster reduction time for rotary velocity changes needs. Hence, described in the later part of the chapter, forming tests were conducted at chosen constant values of this parameter. Obtained hollowed products-in the rolling extrusion process-have external shape consistent with the shape assumed at the stage of tools designing and process parameters determining.

In Fig.6.5 rolling extrusion process of stepped hollowed shaft with application of designed rolls tools and example of a full product are shown. The presented process was made with the application of constant value of feed p = 5 mm/rot, what in the presented case of forming from full billet, did not guarantee obtaining full assumed width of shaft flange. In this case, however, apart from the mentioned flange dimension, the shape closest to assumed shape of remaining parts of product was obtained. Both edge part, destined for further cutting of splines, and head part, destined for bearing mounting, were characterized by good quality of surface and material allowance not exceeding 0.2 mm. Narrowing this scope of dimensional tolerances of obtained products below the mentioned above limit allows for reducing the further machining to grinding operation, which is one of the main aims in searching for manufacturing savings.

Fig. 6.5. *Rolling e xtrusion pr ocess of s tepped hol lowed s haft w ith t he application of designed rolls tools and obtained full product (p=5mm/rot.)*

Excessive upsetting of the area directly behind the formed flange is caused, of course, by too large values of feed on rotation, which led to the presence of considerable dimensional allowance in this area. However, the lack of considerable shape mistakes (circularity deviations are within the scope up to 0.4 mm in analyzed cases) points to proper, without disturbances, flow of metal. Similar results of research, for a wider scope of applied values of feed on rotation p, mean that it is possible to change this parameter, according to results of conducted numerical simulations.

Direct influence of various values of feed on rotation is shown in Fig. 6.6, in which this parameter influence on the finished product shape is presented. Too small forming velocity, resulting in longer time of the process, means that undesired flanging appears before its assumed width is formed (Fig. 6.6.a). On the other hand, the application of excessive feed velocity leads to the appearance of uncontrolled upsetting of products before the area of desired flange forming (Fig. 6.6.b). The presented cases show that it is necessary to determine proper equilibrium between axial and radial metal flow in rolling extrusion process at its particular stages.

Fig. 6.6. *Influence of various values of feed on rotation p on finished product obtained shape: (a) p = 2,5 mm/rot.; (b) p = 7,5 mm/rot.*

The lack of appropriate choice of correlation of working rolls rotary velocity with pusher linear velocity during rolling extrusion process leads, in this case, to narrowing of this method application to simple axi – symmetrical products with steps with appropriate side walls inclination. In the case of forming of products with more complex outline, obtained results confirm the necessity of application in the process changing values of feed on rotation.

Especially in the case of parts of complex shape, after process finishing, problems with removing of finished product from workspace were noticed. As in the presented results of experimental research (with rolls of inclination angles $\alpha = 30^{\circ}$ and $\alpha = 35^{\circ}$) removing of formed full product or hollowed product was not problematic, in the presented here process this operation required working rolls spreading by manual change of their spacing. Because of such a strong compressing of formed product by tools rolls, rolls outline was pressed on material (Fig. 6.7), which should be eliminated in the future by implementation of steering of these tools spacing. Final application of this solution, apart from easier removal of products after forming process, will be the possibility of modelling of shape of obtained products by changing rolls spacing during rolling extrusion process.

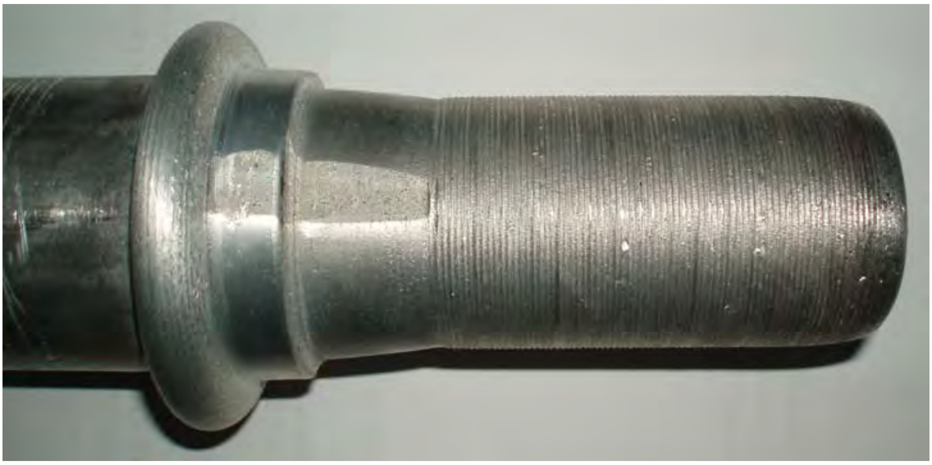


Fig. 6.7. *Marking of tools rolls outline on rotary extruded full product (p = 7.5 mm/rot.)*

7. Summary

This paper presents all stages of research work on rolling extrusion technology development. The scope of initially conducted numerical calculations provided further possibilities of this forming technology development. Three years have passed from getting appropriate finances for the process analysis to obtaining presented here results. In the meantime, theoretical research dealing with numerical simulations of rolling extrusion process by means of software MSC.SuperForm 2005 and Deform 3D were done. At this stage ,experience gained during numerical simulations of different processes, where advantages and disadvantages of this software were noticed, was extremely important. Favorable results of theoretical analyses on rolling extrusion technology of a single step of hollowed and full shafts showed that this method allows for forming of stepped axi – symmetrical hollowed and full products of an assumed shape.

Determining conditions of even distributions of product walls thickness in longitudinal and cross sections is an extremely important issue in the case of forming from hollowed billets. Simultaneously conducted theoretical analyses of full and hollowed products rolling extrusion allow to state that application in the process of these two types of billets requires double-track of conducted research. It is directly connected with different kinematics of metal flow and presence, in the given text, process limitations.

Presented in the next part of the work stages of a prototype stand mounting (assembling) for realization of rolling extrusion processes show in what way, gained earlier, theoretical knowledge was used for designing of research stand for forming of full and hollowed products. Designing of a prototype aggregate for rolling extrusion PO – 1 is based, to a large extent, on experience gained at Department of Computer Modelling and Metal Forming at Lublin University of Technology, during working out and manufacturing of machines made earlier, that is cross – wedge rolling press and 3 – slide forging press.

A different issue is described in the text certification procedure of aggregate PO – 1, which, in the result of conducted research works, was given “CE” mark confirming fulfilling safety requirements according to legal acts valid in European Union. Transition stage in adjusting European legal regulations concerning machines is best visible in presented example. Analyzed here Directive 98/37/WE connecting different existing acts 89/392/EWG, 91/368/EWG and 93/44/EWG will be changed soon. The new Directive 2006/42/WE from 17.05.2006 will replace presented above old one at 29.12.2009. It is an extremely important change because basing on actual directives detailed norms and other EU regulations are worked out.

Presented later chosen results of experimental tests on new forming process show rightness of assumptions for conducted numerical calculations and for designing of aggregate construction.

Revealing at this stage possibilities of working subassembly modification, in order to improve the machine, were considered by adding a massive rotating in the pusher unit.

This solution in a considerable way minimize vibrations of this unit, improving quality of surfaces of obtained products and prolonging durability of seals of hydraulic servo – motor.

Practical realization of tests with application of steel billets formed in hot conditions allowed for laboratory verification of numerical calculations results. Within the scope of full and hollowed products, good convergence of results was obtained, measured by shape of obtained products, shape deviations and process force parameters, that is, spreading force acting on working rolls and axial force caused by a pusher acting on billet placed into workspace between rotating rolls.

In new method’s assumptions, it was decided that designing of technology of manufacturing of products with external diameters within the scope 30 ÷ 100mm, at billet whole length 250 mm, would be considered. The longest, applied in experimental research billets had the length

200 mm at diameter 60 mm. Maximal, measured diameters of upset products flanges (for rolls at angle $\alpha = 35°$) were at about 120 mm (at diameter reduction of products behind rolls to 40 mm). Unfortunately,

at such a strong upsetting, buckling of product part before workspace between rolls took place.

Connection between pusher linear velocity and rotary velocity of working rolls in the form of feed on rotation p[mm/rot] allowed for fast operating, from the forming stability point of view, this basic process parameter. Direct influence of applied tools velocities is shown in Figures 5 and 6, where results of experimental research are presented. Conclusions concerning rolling extrusion tests of full and hollowed products, described in chapter 5, were directly used in working out forming technology of axi – symmetrical stepped shaft from hollowed billet. Described in chapter 6 case of forming of hollowed shaft shows practical possibilities of rolling extrusion technology usage. Unfortunately, applying in this case verified in former research (theoretically and practically) values of feed results in forming of a product of assumed shape but with considerable dimensional allowance. Such process of metal forming seems to be economically unjustified and deprives the product of one of the basic advantages of forging: material fibres continuity, guaranteeing perfect mechanical characteristics of finished product. Hence, in further numerical analyses it was decided to apply changeable values of feed on rotation, which proved to be correct solution resulting in product shape similar to planned to obtain CAD model outline.

The present PO – 1 aggregate configuration does not, unfortunately, guarantee quick possibility of feed on rotation value change during the process. Because of that, conducting verifying research works for changing forming velocities is not possible. Basing here on results of numerical simulations, it should be stated that implementation of design modification within the scope of change of pusher velocity will allow for forming of products within wider range of diameters and length of shafts steps changes.

Certain problems mentioned in chapters describing experimental tests show that also this stage of the process should be improved. In place of manual tools rolls spacing on electric bolt (after the previous mounting of fixing screw), it is proposed to use toothed ring interconnecting rolls eccentric motion and hydraulic drive to this mechanism. The possibility of rolls spacing regulation (searched for in this solution) during rolling extrusion process allows for further, potential widening of scope of this method application. Increase, in that way, of tooling universal usage allows for further decreasing of costs of production starting. Obtaining satisfactory results of experiments as a verifying stage of earlier numerical analyses, allows for working out implementation offer for this innovative technology.

8. **Appendix – table 4.1.**

Risk evaluation for rolling extrusion aggregate PO–1

PN–N–18002:2000

Risk	No	Necessary actions
Very small	1	It is not necessary to take steps
Small	2	It is advisable to consider possibility of risk level lowering or guaranteeing that risk remains at the same level
Medium	3	Taking steps which aim at risk lowering
Large	4	Application of protectives. Work cannot be started until risk is lowered to permitted level.
Very large	5	Work cannot be started and continued until risk is lowered to permitted level

Risk evaluation for rolling extrusion aggregate PO–1

No	**Risks**	**Nr table A1 Norms PN-EN 10-50:1999** pts	Source	Risk degree	Degree of risk appearance "before"	Circumstances of risk appearance	Means lowering risk	Degree of risk appeara nce "after"	Residual risk
1	2	3	4	5	6	7	8	9	10
1	**Mechanical risk** caused by	**1.0.**							

	- machine parts or machined elements ,resulting from e.g: a) shape b) mutual position d) mass and velocity (part kinetics energy connected with controlled or uncontrolled movement e) not adequate mechanical strength			1 1 1 1	1 1 1 1			1 1 1 1	
No	**Risks**	**Nr table A1 Norms PN-EN 10-50:1999** pts	Source	Risk degree	Degree of risk appearan-ce “before”	Circumstances of risk appearance	Means lowering risk	Degree of risk appear ance “after”	Residual risk
1	2	3	4	5	6	7	8	9	10

	- energy stored in machine e.g: g) in liquids or in gases under pressure		oil pressure in hydraulic unit	3	2	- exceeding permitted pressure - damage of wires and connections	- overflow valve with manometer - inductors regulating pressure hydraulic set elements with certificates		
	Risk of crushing	1.1.	- clamp of servo-motor end to forging - servo-motor piston rod jointed shafts drive gear	5	3	- forgings placing - sudden movement of piston rod rotating toothed wheel	- use pliers for forgings placing - hydraulic inductors with regulation - fixed shields		
No	**Risks**	**Nr table A1 Norms PN-EN 10-50:1999** pts	Source	Risk degree	Degree of risk appearan-ce “before”	Circumstances of risk appearance	Means lowering risk	Degree of risk appear ance “after”	Residual risk

1	2	3	4	5	6	7	8	9	10
	Risk of drawing in or catching	1..5.	- rotating jointed shafts -rotating shafts which drive rolls	4 3	3 2	- direct contact with shafts - not proper clothes	- shafts shielded by fixed covers. In order to eliminate shields with shafts rotating they were connected with chains working clothes	1 1	pictogram “Attention Rotating shafts” “Attention Rotating rolls”
	Risk of injury	1.8.		1	1			1	
No	**Risks**	**Nr table A1 Norms PN-EN 10-50:1999** pts	Source	Risk degree	Degree of risk appearan-ce “before”	Circumstances of risk appearance	Means lowering risk	Degree of risk appear ance “after”	Residual risk

1	2	3	4	5	6	7	8	9	10
	Risk of liquid ejection under high pressure	1..9.	- pump - wires - connections - servo-motor	3	2	- exceeding permitted pressure - damaging of wires and connections	- overflow valve with manometer - inductors - hydraulic set elements with certificates	1	
2	**Electrical risks** caused:	**2.0.**							
	Touching by an operator of parts under voltage (direct contact)	2.1.	- steering unit - wires	5 5	3 3	- during steering operating accessories not isolated wires	- steering unit with CE sign closed with the key - isolated wires with certificates - wire ducts with insulation	1 1	pictogram warning against danger of electric shock
No	**Risks**	**Nr table A1 Norms PN-EN 10-50:1999**	Source	Risk degree	Degree of risk appearan-ce "before"	Circumstances of risk appearance	Means lowering risk	Degree of risk appear ance "after"	Residual risk

		pts							
1	2	3	4	5	6	7	8	9	10
	Touching by an operator of parts under voltage due to damage (indirect contact)	2.2.	areas between electric ducts and machine body	5	3	damage of wires insulation and electric elements	- grounding - sealed holes of housing	1	
3	**Thermal risks** which can cause:	**3.0.**							
	Burns and other injuries caused by contact with devices or materials of high or low temperatures, flame or explosion, and with thermal radiation	3.1.	- hot forgings	4	3	carrying forgings from furnace to aggregate	- use pliers for placing and removing of forgings - use protective gloves	1	Pictogram „Attention hot forgings”

No	**Risks**	**Nr table A1 Norms PN-EN 10-50:1999**	Source	Risk degree	Degree of risk appearan-ce “before”	Circumstances of risk appearance	Means lowering risk	Degree of risk appear ance “after”	Residual risk

		pts							
1	2	3	4	5	6	7	8	9	10
4	**Noise risks** causing:	**4.0.**							
	Lack of hearing (deafness), other physiological results (equilibrium disturbances, lowering of concentration)	4.1.	- hydraulic servo-motor - rolls drive	3	2	- engine and pump work - engine and rolls drive gear work - rotations of jointed shafts and rolls drive shafts	Declared level of noise max. 80 dB (A) In case of overlapping of intensity with other machines and exceeding noise level above 85 dB(A) use hearing protectives	1	Use pictogram order of hearing protection
	Limiting of speach possibility, receiving acoustic signals etc.	4.2.		1	1		-	1	
No	**Risks**	**Nr table A1 Norms PN-EN**	Source	Risk degree	Degree of risk appearan-ce "before"	Circumstances of risk appearance	Means lowering risk	Degree of risk appear ance "after"	Residual risk

		10-50:1999 pts							
1	2	3	4	5	6	7	8	9	10
5	**Risk caused by not obeying rules of ergonomy in designing of machines** e.g:	**8.0.**							
	Not proper position or excessive effort	8.1.		1	1			1	
	Not adequate considering of man's anatomy in relation to sets of hand-arm,foot-leg	8.2.		1	1			1	
	Not using individual protectives	8.3.	- rotating shafts of rolls drive and rolls	4	2	drawing in of clothes	working clothes	1	
	Not proper lightening	8.4.		1	1			1	
	Excessive or too small physical load, stresses	8.5.		1	1			1	
No	**Risks**	**Nr table A1 Norms PN-EN**	Source	Risk degree	Degree of risk appearan-ce "before"	Circumstances of risk appearance	Means lowering risk	Degree of risk appear ance "after"	Residual risk

		10-50:1999 pts							
1	2	3	4	5	6	7	8	9	10
	Mistakes and behavior of man	8.6.		1	1			1	
	Not proper design, placing or recognition of steering elements	8.7.	Steering of aggregate	4	3	mistakes in sequence of starting and stopping	-durable, well visible signs, understood in Polish language training of operators	1	
6.	**Unexpected st arting, unexpected r otation, excessive velocity** (or comparable disturbances)caused:	**10.0.**							
No	**Risks**	**Nr table A1**	Source	Risk degree	Degree of risk appearan-	Circumstances of risk appearance	Means lowering risk	Degree of risk appear	Residual risk

		Norms PN-EN 10-50:1999 pts			ce “before”			ance “after”	
1	2	3	4	5	6	7	8	9	10
	Restoring of power supply after break in its supply	10.2	- hydraulic servo-motor - rolls drive	4	3	Not stopping machine after lack of power	Two contactor switches	1	
	Risk of external factors influence on electric appliances	10.3.	- short- circuit - breakdown	3	3	- dusting - moisturing	Advised in DTR environmental conditions	1	
	Software mistakes	10.5.	- electronic equipment of inverter	3	3	Not proper positioning or damage in steering	Positioning or repairing by service or qualified specialist	1	
7.	**Lack of possibility of machine stopping in optimal way**	**11.0.**	Aggregate drives: rolls drive - hydraulic servo-motor	5	3	- electric failure	- two switches socket-plug - two main switches - two contactor switches - failure switch	1	
No	**Risks**	**Nr table A1**	Source	Risk degree	Degree of risk appearan-	Circumstances of risk appearance	Means lowering risk	Degree of risk appear	Residual risk

		Norms PN-EN 10-50:1999 pts			ce “before”			ance “after”	
1	2	3	4	5	6	7	8	9	10
8	**Break in power supply**	**13.0.**	Aggregate drives: - rolls drive hydraulic servo-motor	5	3	- repair - maintenance - survey - cleaning	- two switches socket-plug - two main switches closed with padlock - failure switch closed with key	1	Safety tag ”Attention repair”
9	**Damages in steering unit**	**14.0.**		1	1			1	
10	**Eclating during working**	**16.0.**		1	1			1	
11	**Falling or throwing away things or liquid ejection**	**17.0.**	forgings	3	4	Forging falling after rotary extrusion	- container for falling forgings	1	
No	**Risks**	**Nr table**	Source	Risk degree	Degree of risk	Circumstances of risk	Means lowering risk	Degree of risk	Residual risk

		A1 Norms PN-EN 10-50:1999 pts			appearan-ce "before"	appearance		appear ance "after"	
1	2	3	4	5	6	7	8	9	10
12	**Loss of stability, machine falling down**	**18.0.**	Aggregate placing	4	3	Unintentional catching by means of transport	- leveling mounting to the surface by means of screws	1	
13	**Slipping and operator falling down (connected with machine)**	**19.0.**	Falling in the aggregate direction	3	2	Slipping, stumbling	- non slipping surface - clean floor		1	

Legend:

Degree of risk appearance probability	Degree of risk
1- very rarely	1– very small
2- rarely	2– small
3- moderate	3– medium
4- often	4– large
5- very often	5– very large

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