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**FORMING OF HOLLOW SHAFT FORGING FROM TITANIUM ALLOY Ti6Al4V BY MEANS OF ROTARY COMPRESSION****KSZTAŁTOWANIE ODKUWKI DRAŻONEGO WAŁKA ZE STOPU TYTANU Ti6Al4V METODĄ OBCISKANIA OBROTOWEGO**

This paper presents chosen results of theoretical-experimental works concerning forming of hollow shafts forgings from titanium alloys, which are applied in aviation industry. At the first stage of conducted analysis, the forging forming process was modeled by means of finite element method. Calculations were made using software Simufact Forming. On the basis of performed simulations optimal parameters of rotary compression process were determined. Next, experimental tests of forging forming in laboratory conditions were made. For the research needs, a forging aggregate, designed by the Authors, was used. Conducted research works confirmed the possibility of metal forming (by means of rotary compression) of hollow shafts from hard workable titanium alloys. Numerous advantages of rotary compression process, make it attractive both for low series production (aircraft industry) and for mass production (automotive industry).

*Keywords:* rotary compression, hollow forgings, titanium alloys, FEM, experiment

W opracowaniu przedstawiono wybrane wyniki prac teoretyczno - doświadczalnych dotyczące kształtowania odkuwek drażonych wałków ze stopów tytanu, które znajdują zastosowanie w przemyśle lotniczym. W pierwszym etapie prowadzonych rozważań, zamodelowano proces kształtowania odkuwki, wykorzystując w tym celu metodę elementów skończonych. Obliczenia wykonano w programie Simufact Forming. Na podstawie wykonanych symulacji określono optymalne parametry procesu obciskania obrotowego. Następnie przeprowadzono próby doświadczalne kształtowania odkuwek w warunkach laboratoryjnych. Do badań wykorzystano kuźniczy agregat, który został zaprojektowany przez autorów. Przeprowadzone badania potwierdziły możliwość kształtowania plastycznego (metodą obciskania obrotowego) drażonych wałków z trudnoobrabialnych stopów tytanu. Szereg zalet, którymi cechuje się proces obciskania obrotowego czynią ten proces atrakcyjnym zarówno dla produkcji małoseryjnej (przemysł lotniczy), jak również produkcji wielkoseryjnej (przemysł motoryzacyjny).

**1. Introduction**

Observed recently increase of interest in designing solutions reducing machines and devices weight results from numerous economical-operational factors [1]. Such an interest is well seen mainly in automotive, aircraft and aerospace industries. Reduction of vehicles and aircrafts weight is connected with smaller fuel consumption, increase of power transmission system efficiency and their dynamics improvement and load capacity increase. Smaller construction weight is very often coupled with lower material and energy consumption needed for their manufacturing. The construction weight can be reduced in many ways, they include, e.g: application of lighter material instead of steel, application of materials of high resistance properties at simultaneous sections minimizing, hollow parts in the place of full parts. However, the best results can be achieved by connecting the mentioned earlier methods, that is forming of hollow elements from light metals alloys of high resistance properties (aluminum, titanium, magnesium). At present, more often strongly loaded elements used in aircraft industry are made from titanium alloys, which in compar-

ison with other materials are characterized by favourable resistance and operational properties [2, 3]. The most important advantages of titanium alloys are: high resistance-density ratio, resistance to corrosion, high resistance in higher temperatures and creep resistance. These features cause that titanium alloys participation in aircraft construction is still growing [4]. At the same time, the usage of these material in other industrial branches also increases. Various elements used in automotive industry such as: connecting rods, valves, axles, bushings, exhaust manifolds and other high loaded parts [5] are more often manufactured from titanium alloys.

Titanium alloys belong to hard workable materials [6]. It results from their physicochemical properties such as: large chemical activity, low thermal conductivity, tendency for accretion presence and chips sticking to tools. Moreover, manufacturing of hollow elements in machining processes is connected with large material loses, which is not very profitable at titanium alloys high prices. Hence, metal forming technics for hollow semi-finished parts production with leaving small allowance for finishing [7, 8] are more often used. In the result it is possible to reduce considerably material, tools and

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work consumption. It should be, however, noticed that metal forming of titanium alloys is more difficult for realization in comparison with forming of constructional steel. This happens due to specific physical and mechanical properties and narrow scope of forming temperatures in hot conditions [9]. Because of that, it is justified to search for new technological solutions which will allow for more effective plastic forming of titanium alloys.

One of innovative processes for forming of axi-symmetrical hollow semi-finished parts is rotary compression. This technology of hollow parts making was worked out and is still being developed at Lublin University of Technology [10, 11]. This process is characterized by numerous advantages, resulting from material flow kinematics and a simple forming schema, especially from the possibility of application of pipe billets. The schema showing the rule of rotary compression is presented in Fig. 1. The essence of rotary compression is based on a semi-finished part – 4 forming, mainly pipe-type one by means of three wedges – 1, 2, 3 rotating in the same direction with constant velocity  $n$ , which move in the radial direction with velocity  $v$  at the same time. The billet in the result of rolls acting is put into rotary motion around its axis, during which reduction of external diameter of subsequent steps of the product takes place accompanying by increase of the billet wall thickness.

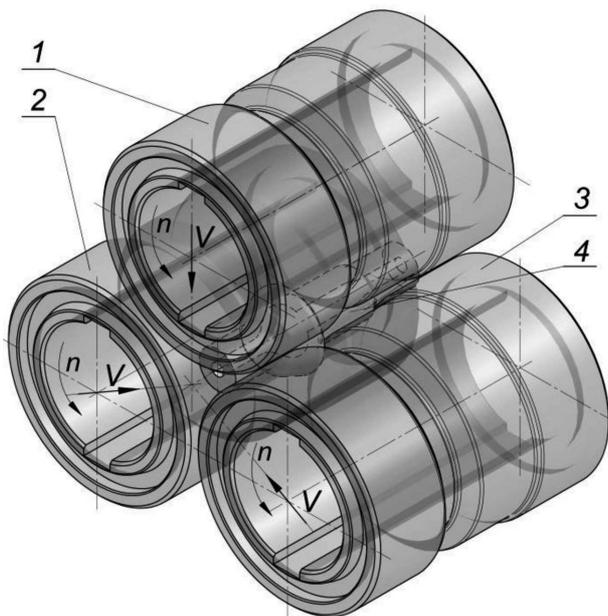


Fig. 1. Schema of rotary compression process of stepped shaft hollow forging : 1, 2, 3 – tools, 4 – the formed semi-finished product

## 2. Subject of research

Satisfactory results of conducted research works on rotary compression processes of hollow forgings from steel caused that attempts were made to determine forming possibilities by means of this technology of semi-finished parts from non-ferrous metals, including titanium. In order to do this, the process of rotary compression of multi-stepped hollow shaft from titanium alloy Ti6Al4V was analyzed. The chosen shaft is used in the helicopter drive transmission unit. The conducted research works covered two stages: multi-option numerical modeling of

the process with the application of finite element method and experiments of hollow forgings from titanium forming in the forging aggregate of own construction. Shape and dimensions of the finished shaft, hollow shaft forging and applied in the process semi-finished product are presented in Fig. 2. Due to limited space dimension of the aggregate the research works were conducted for the shaft in 1:2 scale.

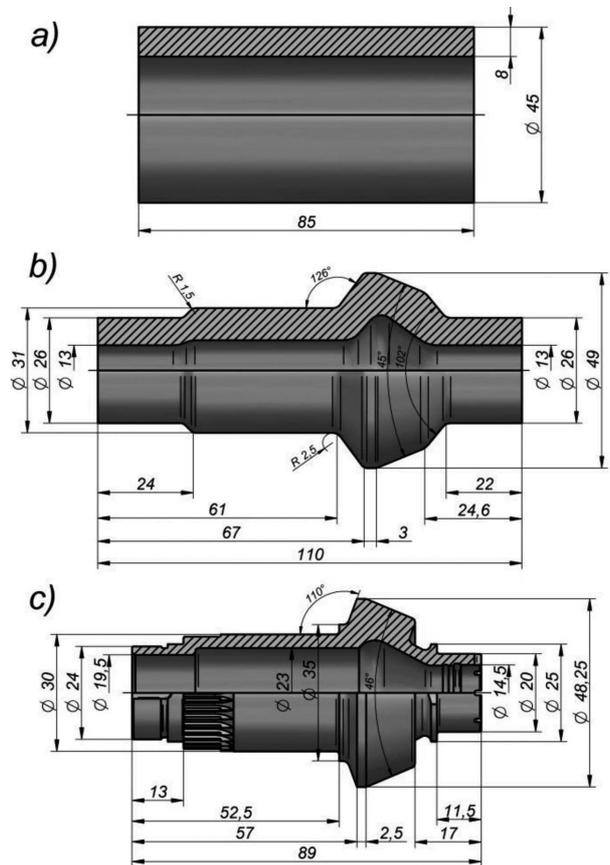


Fig. 2. Geometry a) pipe billet, b) hollow forging of drive shaft, c) hollow drive shaft

## 3. Numerical modelling of rotary compression of forging from titanium alloy Ti6Al4V

Theoretical analysis of the rotary compression process of drive shaft hollow forging was made basing on numerical modelling. Calculations were made by means of finite element method (FEM) in software Simufact Forming in 12.0 version, applied many times by the Authors for the analysis of rotational metal forming processes of metals and their alloys [12, 13]. Geometrical model of the process, worked out for the conducted analysis needs, was consistent with the compression schema shown in Fig.1. The model consists of three identical tools-formed wedges and billet (pipe part from titanium alloy Ti6Al4V of external diameter  $D = 45$  mm, wall thickness  $g = 8$  mm and length  $L = 85$  mm), modeled by means of hexahedral elements of the first type. Material model of alloy Ti6Al4V used in calculations was taken from the library of the applied software [15].

Moreover, it was assumed that billet material at the beginning of the process was heated in its whole volume to the temperature  $960^{\circ}\text{C}$ , yet tools had constant temperature  $150^{\circ}\text{C}$ .

During the process wedges rotated in the same direction and with the same velocity  $n = 36$  rot/min and they moved towards the billet axis with constant velocity  $v = 4$  mm/s at the same time. Material-tools contact surface was described by constant friction model, which factor was equal  $m = 0.8$ . Coefficient of heat exchange between material and tools was assumed equal  $25 \text{ kW/m}^2\text{K}$ , yet between material and environment equal  $0.5 \text{ kW/m}^2\text{K}$ . Due to a very narrow scope of titanium alloys metal forming temperatures, the forging compression process was divided into three stages, during which reduction of the semi-finished product external diameter was gradually increased. Before each stage of compression partially formed material was reheated to the temperature  $960^\circ\text{C}$ . Such a schema of the process realization was connected with the danger of excessive temperature decrease of the forging during its forming, which, in the case of titanium alloys, affected adversely plastic properties of the formed material and resistance properties of forgings.

Determined during numerical analysis the shaft forging shape at subsequent stages of compression together with marked strain intensity distribution is shown in Fig. 3. It is well visible that during forming rotating tools reduce the external diameter of successive forging steps. This causes material displacement in the radial direction, which leads to the increase of the wall thickness in comparison with the initial thickness. It can be also observed that during compression material flows in the axial direction as well, which results in elongation of the forging extreme steps. Material axial displacement happens mainly in the superficial areas of extreme pins, causing the appearance of concave head surfaces and the decrease of the wall thickness in comparison with the initial thickness. It should be, however, noticed that extreme steps of the shaft forging are formed mainly in the result of the material axial flow. Material flow in the axial direction allows also for increase of the external diameter of the forging conical step. Billet upsetting somehow takes place here, which causes material flow both in the axial and radial directions (in the direction of external surface of the forging), increasing wall thickness and the forging external diameter in comparison with the initial dimension.

Analyzing distributions of strain intensity, it can be noticed that maximal values are localized in the area of central step. The strains assume considerably smaller values in comparison with processes realized at one stage. This is caused by material reheating before each stage of the process up to  $960^\circ\text{C}$ , during which strain history was removed in the result of recrystallization of the deformed material. Heterogeneity of strains in the formed forging is also visible. Superficial layers undergo relatively larger deformation in comparison with other areas of the forging, which is the result of unnecessary strains generation in the circumferential direction by friction forces. Extreme strains values are localized in the transitional area, between external and central step of the forging. Large increase of strains in this area is due to material torsion resulting from circumferential velocities differences of particular steps of the compressed semi-finished product. It can be also noticed that strain intensity in the forging extreme steps, where the largest reduction of external diameter takes place, is considerably lower than in the area of central step. This may result from the fact that extreme steps are formed mainly

in the action of postaxial material flow. However, the central step, in which the largest increase of the wall thickness takes place, appears in the result of material radial flow.

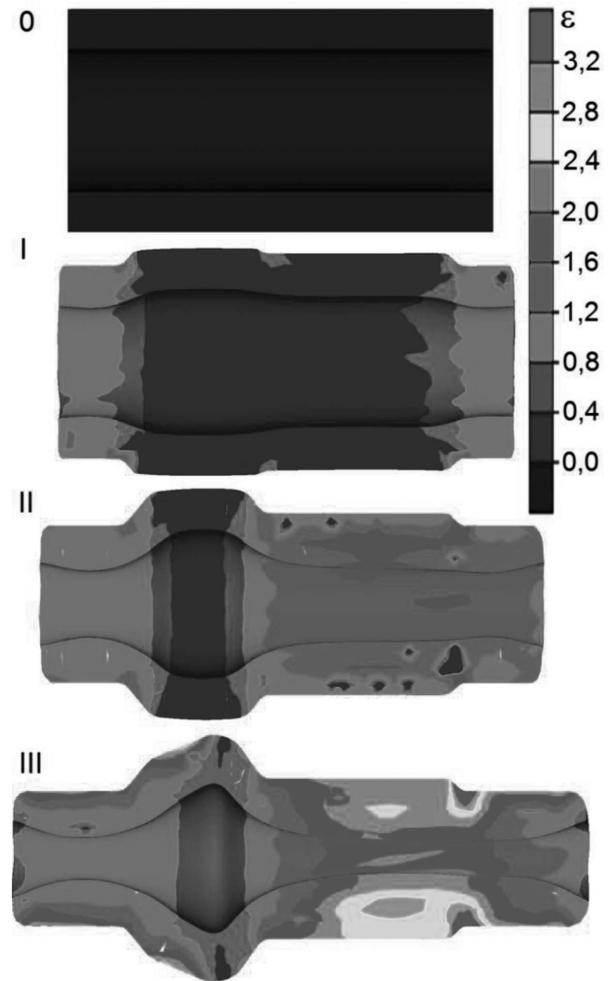


Fig. 3. Determined by FEM shape progression of hollow drive shaft forging together with marked strain intensity distribution at subsequent stages (I, II, III) of the rotary compression

As it was mentioned earlier, difficulties connected with titanium steps forming arise from a very narrow scope of metal forming temperatures. According to data, titanium alloy Ti6Al4V should be formed within the scope of temperatures  $980\text{--}900^\circ\text{C}$ , yet the final temperature should not be lower than  $800^\circ\text{C}$  [15, 16]. Hence, during conducted research thermal parameters of the formed forgings underwent detailed analysis. Distribution of temperature after each stage of compression of the shaft forging is provided in Fig. 4.

A characteristic feature of the obtained distributions is intensive decrease of temperature in layers near the surface of the forging, at relatively large values of temperature in the central areas at the same time. Strong cooling of the material on the forging surface is connected with the semi-finished product contact with colder tools. Although the forging is reheated before next forming stages, layers near the surface cool themselves even up to  $700^\circ\text{C}$ . Such a feature of temperature distribution is the result of low coefficient of thermal conductivity of titanium alloys. This leads to small heat flow between the areas with large temperature gradient and hinders compensation of superficial heat loss. Strong cooling of the

forging surface during forming will unfavorably influence the compression process course and mechanical properties of the formed semi-finished products. Hence, in order to limit excessive temperature decrease, it is indicated to apply initial tools heating to relatively large values of temperatures (300-400°C).

these will be the areas of the largest danger of material coherence loss during forming.

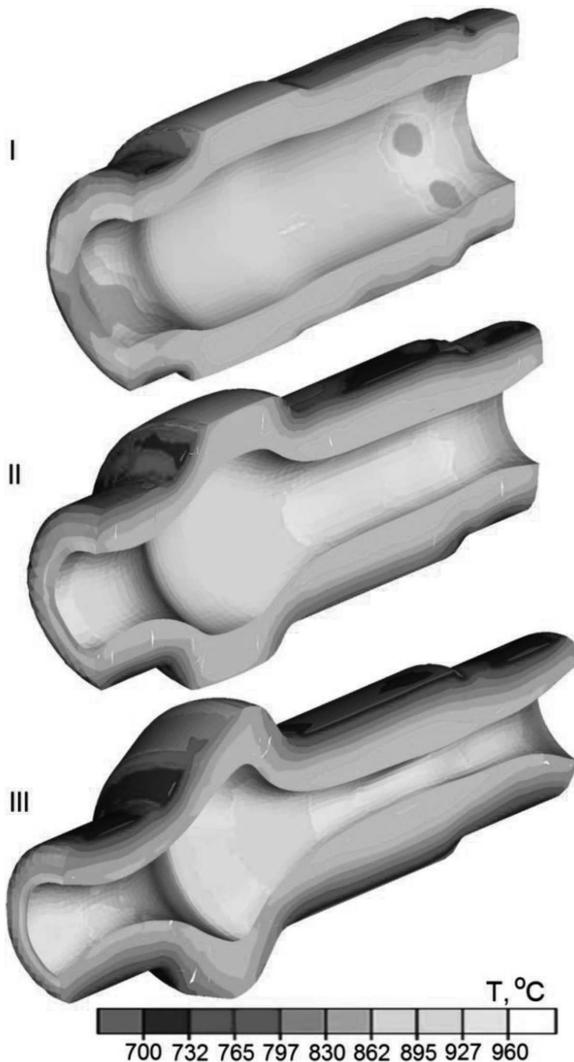


Fig. 4. Determined FEM strain intensity distributions at subsequent stages (I, II, III) of rotary compression of shaft hollow forging

During research works, analyses were also conducted, aiming at determining dangers of presence of phenomena limiting the rotary compression process. One of such limits is splitting of the formed material. In order to foresee cracks in the deformed material, one of the empirical criteria was used according to Cockroft-Latham, which is accessible in the software applied for calculations. Determined by FEM distribution of Cockroft-Latham integral at the subsequent stages of the process is shown in Fig. 5. It can be seen that achieved distributions of cracking criterion are connected with strain intensity distributions. Extreme values of the integral are localized in the steps area of the largest values of plastic strains.

Yet, the area of their presence covers mainly layers near the surface of the hole, where large compression stresses appear (radial and circumferential) and transition area between the formed steps of various reduction ratio, where the shaft forging torsion happens. Therefore it should be concluded that

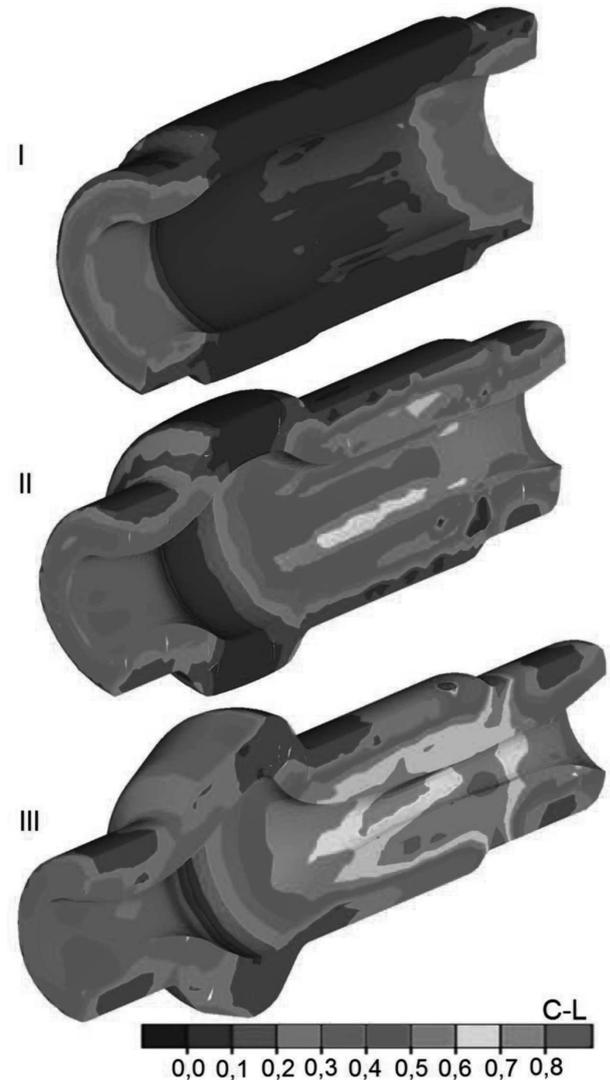


Fig. 5. Determined by FEM Cockroft-Latham damage criterion distribution after each stage of the forging rotary compression

#### 4. Experimental verification of the forming process

Experimental verification of the forming process of drive shaft hollow forging from titanium alloy was conducted on a prototype aggregate, designed and constructed at the Department of Metal Forming and Computer Modelling at Lublin University of Technology. General view of this aggregate is shown in Fig. 6a.

This machine of modular construction consists of support frame – 1, drive unit – 2, toothed rolls box – 3, forming rolls box – 4, hydraulic power transmission system of forming rolls – 5, electric feed system – 6 and monitoring-measurement unit – 7. The rotary compression process is realized in the forming rolls box, in which three slides with working shafts bearing in them move radially. On working shafts are mounted three pairs of forming segments (Fig. 6b), which external outline corresponded with geometry of the compressed forgings. For registering of force and kinematics parameters during the process, a measuring unit was used, equipped with

rotary moment converter, displacement converter and pressure convertors. Signals from all sensors are registered digitally by means of measuring chart and portable computer.

ly, each of the stages ended with sizing, during which tools performed only rotational motion removing deformation of the semi-finished products cross section.

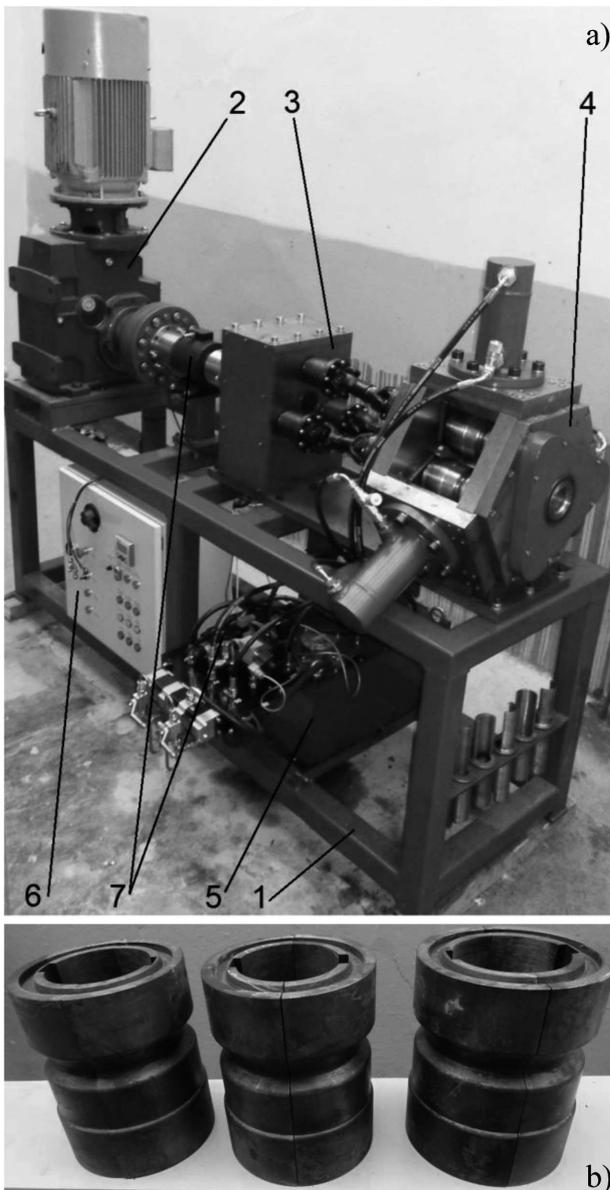


Fig. 6. Research post: a) aggregate for rotary compression, b) tools segments for drive shaft forging forming (description in the text)

During the experiment similar technological parameters as during numerical calculations were assumed. As semi-finished products bushes from titanium alloy Ti6Al4V were used. They had the following dimensions: external diameter  $\varnothing 45$  mm, wall thickness  $g = 8$  mm and length  $L = 85$  mm. Billet for the process was heated in electric box-type furnace to the forming temperature equal  $960^{\circ}\text{C}$ . Yet, the compression process was conducted at three stages, applying the semi-finished part reheating before the second and the third forming stage. The further stages of stepped shaft hollow forging compression were shown in Fig. 7. The heated pipe billet was placed in the machine working space by a special feeder, which positioned its position between rotating rolls. In each of the three stages of compression, tools moved of  $1/3$  of the whole way needed for obtaining finished forging.

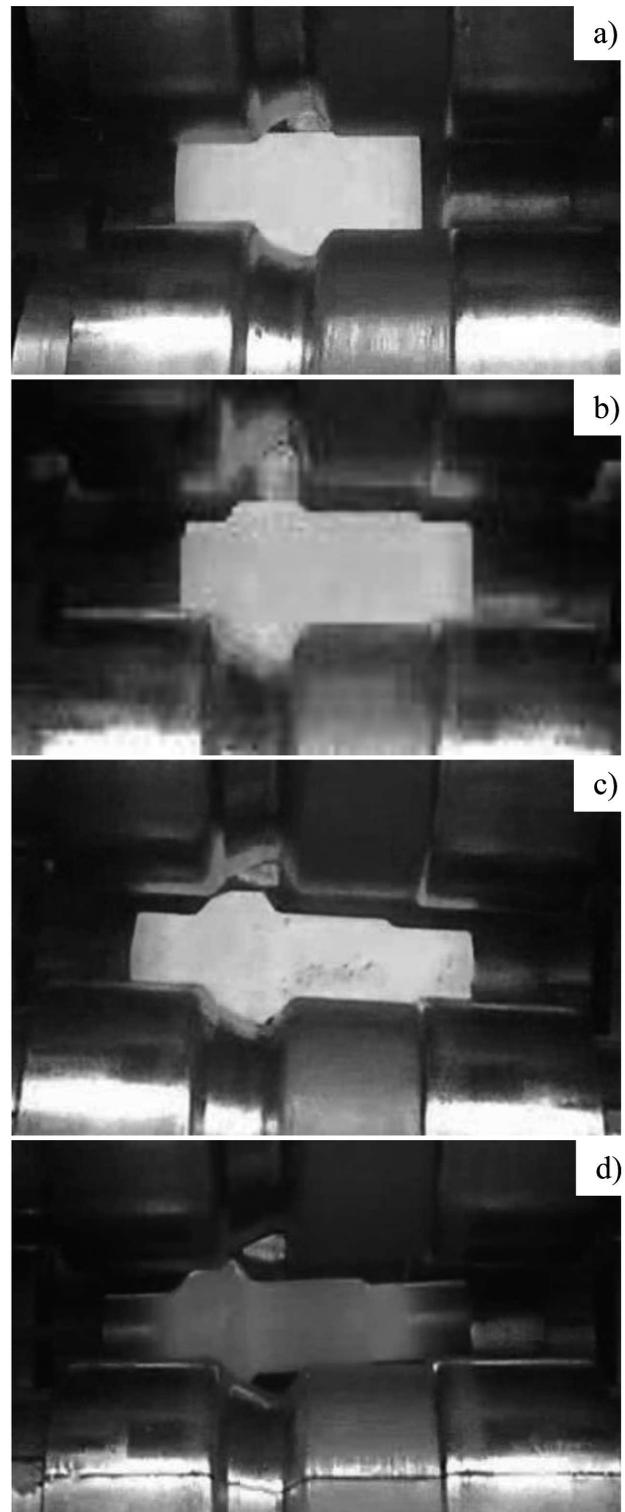


Fig. 7. Experimental tests of hollow forging from titanium alloy Ti6Al4V forming: a) the beginning of I stage, b) the beginning of II stage, c) the beginning of III stage, d) the end of III stage-finished forging

The next Figure 8 presents geometry of the drive shaft hollow forging, which was obtained during experimental tests with the semi-finished part shape, determined numerically and

by CAD model, worked out during the technology designing. A good convergence of geometry can be seen, which unequivocally confirms the possibility of titanium alloys forming by the discussed method. After inspection and measurement of forgings obtained in experiment, superficial faults, cracks and cross section deformation were not observed. Also dimensions of the semi-finished products were within the scope of tolerance, proper for forging parts (formed in hot conditions). The only disadvantage was incomplete filling of the outline in the area of conical step. It should not, however, be regarded as a fault excluding the further usefulness of the formed forging, as reduction of diameter resulting from infilling of the outline stays within the scope of allowance for machining. What is more, during the experiment, larger elongation of the forging extreme steps, in comparison with this forecast during designing of technology and numerical calculations, was obtained. This phenomena can be explained by more intensive material flow in the axial direction, caused by smaller values of the friction force at the tools-material surface of contact in relation to values resulting from friction factor, assumed in calculations.

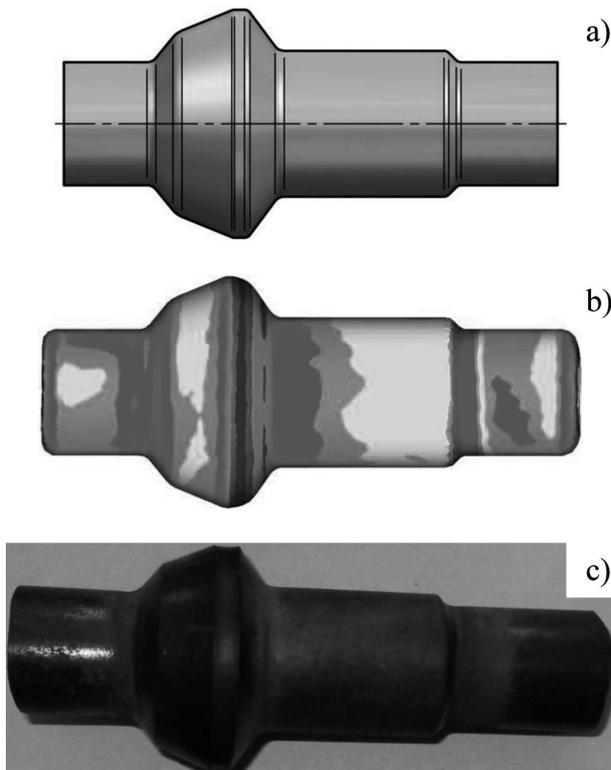


Fig. 8. Geometry of drive shaft hollow forgings: a) CAD model, b) determined by FEM, c) obtained in experiment

During theoretical-experimental research works also rotary compression force parameters were registered (tools load force and rotary moments), which results in the form of diagrams are shown in Figure 9. Results obtained for the next stages of compression are characterized by large convergence both qualitative and quantitative. Analyzing achieved data it can be noticed that the first stage of forming runs at relatively lower force and rotary moments values in comparison with next stages. This is connected with the forging material forming only on its length fragment. Also important is the value of the semi-finished product wall relative thickness ( $g/D$ ), which

at this stage of the process is the smallest, hence resistance of material plastic flow is the smallest (at attaining other parameters of the process at similar level). At further stages, where almost whole length of billet undergoes squeezing and where intensive increase of the wall relative thickness takes place, considerably larger force values (of about 65%) and moments (of about 100%) are observed. Kinematics of material flow also influences larger values of forces and rotary moments in the second and third transition. At these stages a conical step of the forging is formed, which outline, apart from material squeezing, is additionally filled in the result of upsetting.

Analyzing force parameters distributions it can be noticed that the results obtained from FEM and experiment for the initial phases of the subsequent stages have similar character. Yet, a considerable difference can be observed for the last stage of the process-sizing. At this stage values of forces and moments determined in experiment decrease more slowly in comparison with distributions determined by means of FEM. This probably caused by more intensive cooling of superficial layers of the formed forging in relation with the assumed numerical model. As a consequence, removing of the shape imprecision (more often ovalization of cross section of compressed steps) takes place at larger resistance of material plastic flow, which impinges on the character of tools load forces and rotary moments distributions.

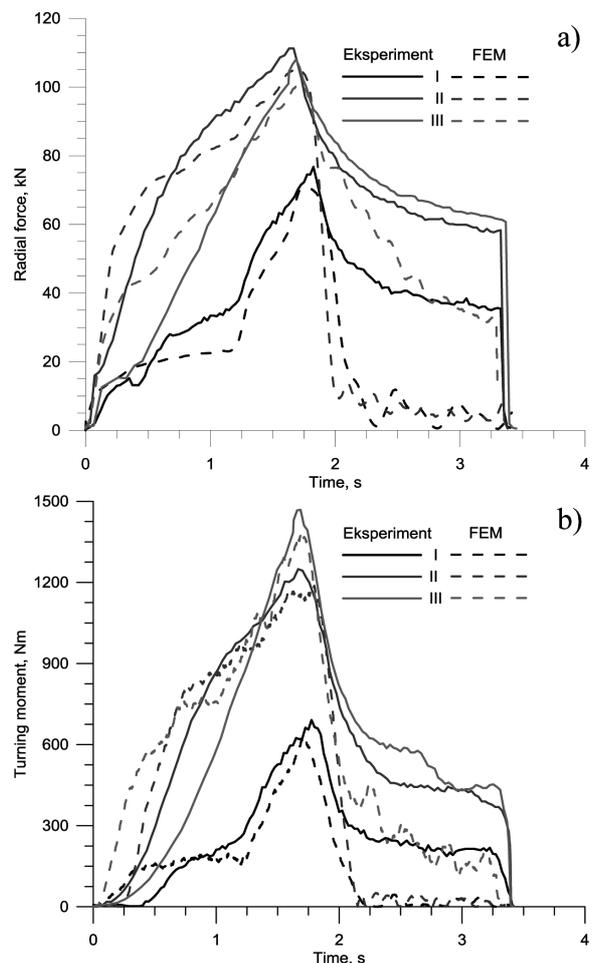


Fig. 9. Distributions of force parameters in the subsequent stages of the rotary compression process of hollow forgings from alloy Ti6Al4V: a) load forces course, b) rotary moments course

## 5. Summary and conclusions

Forming by means of metal forming methods of hollow axles and shafts, especially from titanium alloys with application of pipe billet, causes a lot of difficulties. These problems result e.g. from a very narrow scope of temperatures of metal forming in hot of these materials and smaller rigidity of pipe semi-finished products in comparison with full billets. Hence, new technological solutions are still being searched for, allowing for stable process course with the application of hollow billets. One of innovative methods of hollow products manufacturing is rotary compression, which makes possible forming of axi-symmetrical forgings from pipe semi-finished products at relatively small implementation costs. Numerous advantages which may result from industrial implementation of rotary compression processes led to undertaking research works widening technological possibilities of this promising method, for example of titanium alloy forming. Obtained research results show that it is likely to form stepped shafts hollow forgings from titanium alloy by means of rotary compression technology.

Basing on the acquired results it was possible to form the following conclusions:

- Rotary compression of hollow forgings from titanium alloys should be conducted at multistage, with semi-finished product heating between particular stages.
- During rotary compression process an intensive decrease of temperature is observed, mainly in superficial layers of the formed forging.
- Before titanium alloys forming process it is advisable to initially heat tools to relatively high temperatures.
- During rotary compression of hollow forgings from titanium alloys the danger of semi-finished product internal wall cracking appears.
- During rotary compression mutual torsion of steps of forgings formed with various reduction ratio takes place.
- It is advisable to conduct further research works aiming at determining connections between the process parameters and quality and properties of formed forgings.

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