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STRAIN DISTRIBUTION ANALYSIS IN UPSET-FORGED FLANGED TURBINE SHAFT

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Abstract

In the paper numerical analysis of the upsetting is presented with focus on the possibilities of the quality improvement by equalization of strain distribution with simultaneous reduction of the forging load. This goal is achieved by the use of multi-stroke progressive upsetting, which depends on sequential deformation of small portions of the total volume at reduced load. As the results show, this approach also allows reduction of nonuniformity of strain in the forged flange. Calculated fields of effective strain distribution and plots of its profile on cross-sections confirm the reasonability of technological modifications.

Key words: open-die forging, upsetting, windmill shaft, heavy ingot, high-duty forgings, FEM analysis

1. INTRODUCTION

Among heavy open-die forgings a large group includes high-duty applications for oil, marine, powerplant industry etc. Because of large size and weight, as well as high requirements for mechanical properties, non-competitive technology of manufacturing such parts is open-die forging or semi-open die forging (Schäfer et al., 2011). The analysed powerplant shaft is an example of such a part.

Turbine shafts are regarded one of the largest and the most responsible of the large forgings. As such, turbine shafts must attain structural integrity and metallurgical soundness, which altogether determine superior performance. For that reason, despite unfavourable geometry, these products are forged. Typical forging sequence of cogging relies on proper selection of geometrical variables of the forging process to provide the required minimum of strain level on the length. However, of the most importance is the last to be shaped, flange of the shaft. Because of large cross section in relation to drawn out section of the shaft, the flange can only be obtained by upsetting. If the press capacity allows accommodation of the forging pressure, upsetting is usually completed at one blow. However, strain nonuniformity and reheating, which is often a must to enable this, deteriorate the quality of the forged part.

The feedstock for manufacture of large size forgings is forging ingots weighing several to dozens of tons. During solidification process shrinkage takes place heading from the wall of the ingot mould inwards. In the aftermath, in the core central shrinkage cavity or porosities are found, often covered by bridge. As the crystallization front moves on from the outer parts of the ingot micro- and macrosegregation occurs resultant from pushing alloying elements up and into the core. Also zones of segregation are found, produced by gravitational sedimentation of heavy crystallites and gathering of impurities

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during crystallization. In result, both the chemical composition and metallurgical soundness are differentiated within the bulk (Lesolut, 2005).

The metallurgical structure can be healed during plastic working. With deformation a breakdown of the ingot structure is achieved as well as closing and welding of internal discontinuities (Skubisz et al., 2008). The heavier the ingot, the bigger the segregation, which may cause a sort of stripes of concentration which affects workability and machinability of the work material. Excessive gases are the cause of bubbles-alike porosities in which impurities are concentrated, which makes it hard to close and weld them under compression. Therefore, selection of forging process parameters becomes no longer a matter of shaping the metal, but firstly, ensuring the conditions for improvement of metallurgical structure of the material.

2. CHARACTERISTICS OF THE FINISHED PART

The forged part concerned is a main shaft in transmission system of a windmill powerplant – the most significant part in a 3,6 MW power station (figure 1). As it transfers mechanical energy from rotor hub to generator, where it is transformed into electric energy, it is referred to as a high-duty part and as such, must provide reliable performance.

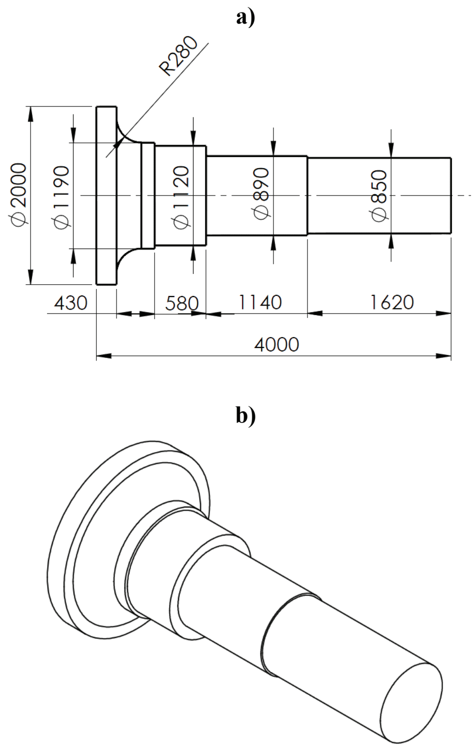

Fig. 1. Windmill main shaft: a) dimensions, b) isometric view.

To withstand severe dynamic loads in complex state of stress, to which the shaft is subject in service, the forged material must combine high strength, ductility, impact strength and crack resistance. These requirements are met with use of medium-alloy steels, which after heat treatment attain microstructure of tempered lath martensite. Chemical composition of analysed steel, used for manufacture of windmill shaft is shown in Table 1.

Table 1. *Chemical composition of steel used for windmill shaft (Lisiecki, 2012).*

Element	C	Mn	Cr	Mo	Ni	Si	P	S
Weight, %	0,34	0,65	1,5	0,23	1,5	0,4	0,02	0,01

3. FORGING TECHNOLOGY OF TURBINE FLANGED SHAFT

The technology of forging of windmill shaft with flange is regarded a complex and demanding multistage process, on account of both geometry of the part and the manner in which it is realised. Differentiated cross-section on the length makes it hard to produce even or comparable degree of deformation after the cogging sequences, which results in nonuniformity of strain, both in longitudinal and transverse direction. Production chain includes operations of open-die forging (cogging and upsetting), semi-open die forging (shaped-die cogging or open-impression upsetting), heat treatment and machining.

The work material in a form of large ingot weighing 50 Mg in heated up in a gas furnace to obtain uniform temperature 1250°C. After hold time required for equalisation of temperature it is transferred to the press table. The press of capacity 80 MN is used to conduct cogging and upsetting operations aimed at initial work of the ingot (figure 2). As the first bulk forming operation, upsetting of the draft free ingot is carried out (figure 2 c). The increased cross-section is then reduced in flat-die cogging for breakdown of the cast structure, followed by smoothing with combined-die cogging for smaller allowances. Thus the main diameter is obtained (figure 2 d), from which smaller sections are offset (figure 2 e). Such sequence ensures minimum of the required amount of deformation and sound microstructure with refined austenite grain in a bulk at every section, in result. Then the flange is formed in upsetting operation.

It is worth mentioning that the largest concentration of internal discontinuities and metallurgical imperfections are found in the upper portion of the ingot, which constitutes the main section of the shaft, which has the largest diameter. As a consequence, severe working is required to heal off the imperfections. The main diameter is also the portion from which flange is formed. In the aftermath of upsetting, change in the metal flow direction by 90 degrees occurs. Hence, the elongated grains or bands as well as shrunk imperfections, turn from longitudinal from lateral orientation producing state of stress promoting center-burst alike phenomena. If the amount of deformation is insufficient, these defects may occur. As numerous studies show, proper sequence and reduction degrees must be provided.

metal flow, forging load can be limited by the press capacity. Therefore, the tendency is to carry out upsetting piece by piece as a progressive sequence (Sińczak & Żurek, 2011).

The progressive upsetting is realized with 300 mm wide flat upper die at reduction limited by the press capacity. Hence, there are a number of various sequences to achieve equivalent deformation, with use of different length of pass (bite) and unit deformation. In this work assumption was made to use maximum bite, reaching 1 (deformed section equal to the width of the flat die). Upsetting is realized in three stages: first – three passes on the cross-section

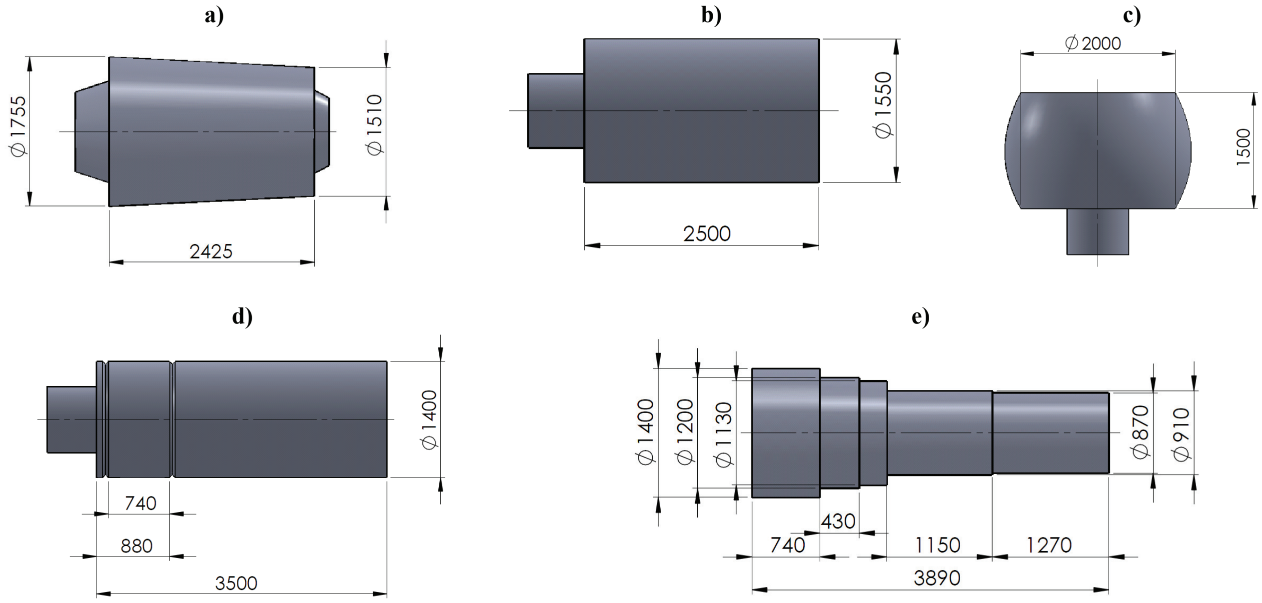

Fig. 2. *Forging operations sequence in open-die forging of the windmill main shaft: a) ingot, b) preliminary smoothing of ingot draft, c) upsetting, d) cogging, e) drawing out of the offset sections (Lisiecki, 2012).*

with parallel placement of the flat die, second – next three passes after 90° rotation, and third – last blows to equalize surplus of the metal and complete fill out of the corners (figure 3).

It might seem that forging with one blow is easier (figure4); however, in addition to excessive load there are also other setbacks to cope with. Firstly, the flat die must be wider than the final diameter. In this case it would be over 2 meters. Besides, as proven other studies, in some cases of aspect ratio unfavourable flow pattern is observed, resulting in laps formation. Last but not least, single blow upsetting will not always provide complete fill-up of the corners. In case of sequential forging any corrections in this aspect can be easily introduced by repetition of blow with slight change of the position of the upper die.

In addition to the listed questions, there is one more to be answered: what effect progressive se-

4. SEMI-OPEN-DIE UPSETTING OF THE FLANGE

As mentioned, when the main section of the shaft is completed the flange is still to be shaped. Relatively low thickness and diameter almost twice as big as that of the main section make it feasible to be obtained in conventional open-die forging stages only at generous allowances and large amount of machining. Therefore, other means are used. Preformed shaft with one-side offset sections is subject to upsetting in a die-set composed of an "impression" and two distance rings. The preform is placed into the die set with the thin end down, positioned with one of the rings. In order to get the final shape is achieved in upsetting operation is necessary. For smaller shafts it causes no particular problem, however, for the two-meter diameter with restraint of the quence of upsetting can have on the final strain distribution as compared to single blow? The presented study is to investigate and answer this question.

deformation was neglected. Frictional conditions on the interface metal-tool was described with Levanov friction model, in which tangential stress are defined as

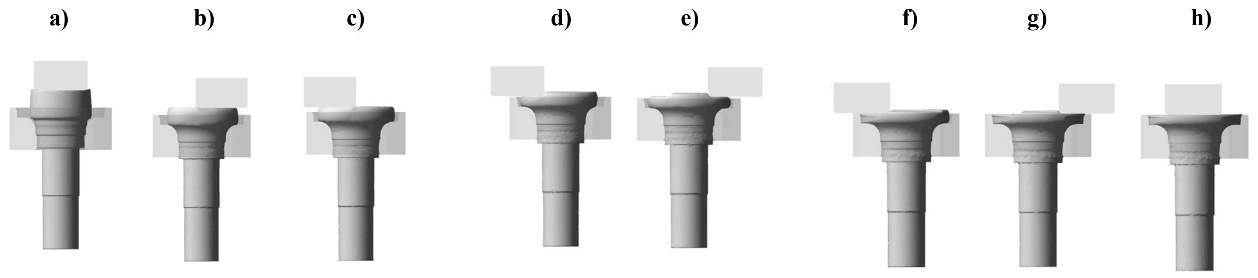

Fig. 3. *Sequence of blows in progressive upsetting of the flange: a)÷c) first sequence of blows with initial position of the flat die, d),e) second sequence of blows after rotation of the flat die by 90°, f)÷h) final sequence of blows to get required height.*

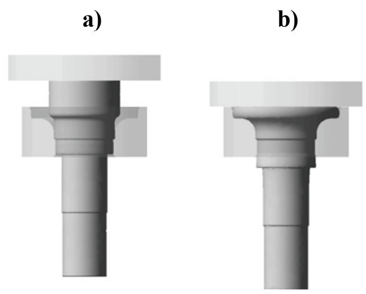

Fig. 4. *Single blow upsetting of the flange, where: a) initial, b) final position and shape of the forged shaft.*

5. OBJECTIVES AND ASSUMPTIONS

Large number of combinations of bites and passes during progressive deformation of the end of the shaft admits a number of various possible sequences to achieve equivalent deformation, with different path of deformation. As it turns out, sequence applied may result in entirely different strain distribution. The goal of the study is a verification of feasibility of technological realization of progressive upsetting and analysis of the final strain distribution on the cross-section of the upset-forged flange of the windmill main shaft in order to determine an influence of application of progressive upsetting versus single blow upsetting.

For quantitative analysis, as a measure of accumulated reduction in a point, effective strain was used. Because, from the standpoint of efficiency of microstructure and soundness of the material after forging the core zone is of most interest, distribution of effective strain was plotted throughout the cross-section in the axis of the flange.

Numerical simulation was conducted with use of commercial code QForm3D based on Finite Element Method (FEM). In calculations viscoplastic model of deformed body and rigid-elastic model of tools was assumed. On account of large deformation, elastic

$$\tau = m\frac{\sigma_p}{\sqrt{3}}\left(1 - e^{-1.25\,(\sigma_n/\sigma_p)}\right) \qquad (1)$$

where: σ_p – flow stress of deformed material; σ_n – normal stress in the contact point; m – friction factor.

The boundary conditions for simulation were assumed in accordance with industrial process conditions. The most important parameters are summarized in Table. 2.

Table 2. *The boundary conditions used in simulation.*

Parameter	Value, unit
Work temperature	1200ºC
Average tool temperature	200ºC
Ambient temperature	20ºC
Maximum load	80 MN
Ram velocity	250 mm/s
Emissivity coefficient	0,6
Heat transfer coefficient	30 W/m^2K
Friction factor	0,4
Friction coefficient	0,15
Effective heat transfer coefficient	2500 $W/m^2{\cdot}K$

6. RESULTS AND DISCUSSION

On the basis of numerical simulation, first and foremost, the forging load was analysed for both single-blow and multiple-blow progressive upsetting. This allowed evaluation of the load necessary for completion of total deformation in a single compression stage. The result of this effort is shown in figure 5 a. The calculated pressure amounts to 250 MN, which is way to much for existing forging equipment. The readout of final height resulting from maximum capacity of the available press 80 MN goes along the industrial measurements 250 mm.

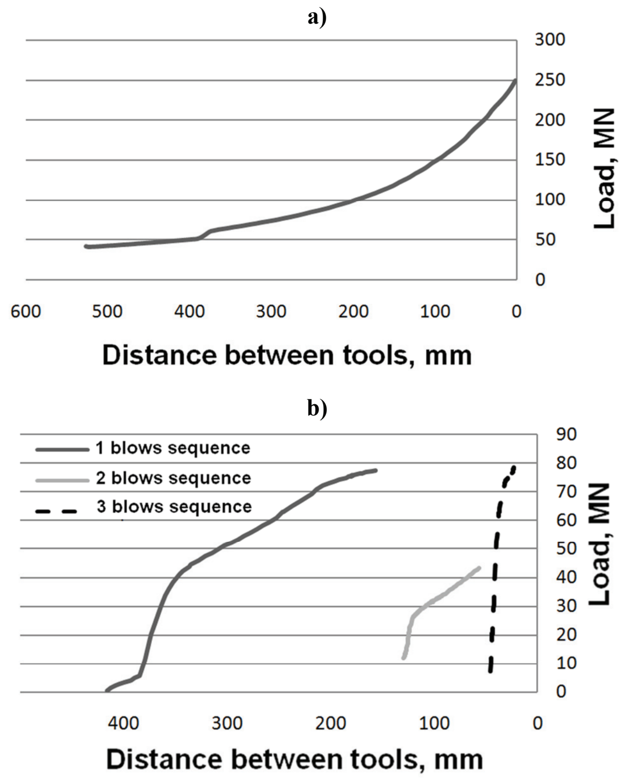

Fig. 5. *Numerical estimate of the forging load for: a) single-blow, b) progressive upsetting of the flange.*

Alternative forging cycle to complete required deformation is multistroke process of progressive upsetting with flat dies in sequence. Numerical simulation confirmed correctness of industrial trial and error procedure, resulting in selection optimal magnitude of reduction on height, which allow complete fill out of the die in as least as possible number of blows. Illustration of the pressure estimated with FEM for consecutive series of blows is shown in figure 5 b.

To investigate the actual strain distribution after both single blow and multiple-blow progressive upsetting of the shaft end, observation of the real process in industrial conditions was made. On this basis unit reductions in height were selected to reflect real deformation process, depicted in figure 3. Maps of effective strain distribution on axial cross-section of the shaft are shown in figure 6.

Similar simulation was carried out to investigate strain uniformity in flange shaped in a single blow upsetting. Maps of effective strain distribution in conventionally upset-forged flange are shown in figure 7, as compared to those after progressive upsetting. In figure 7 a and b, axial crosscuts are com-

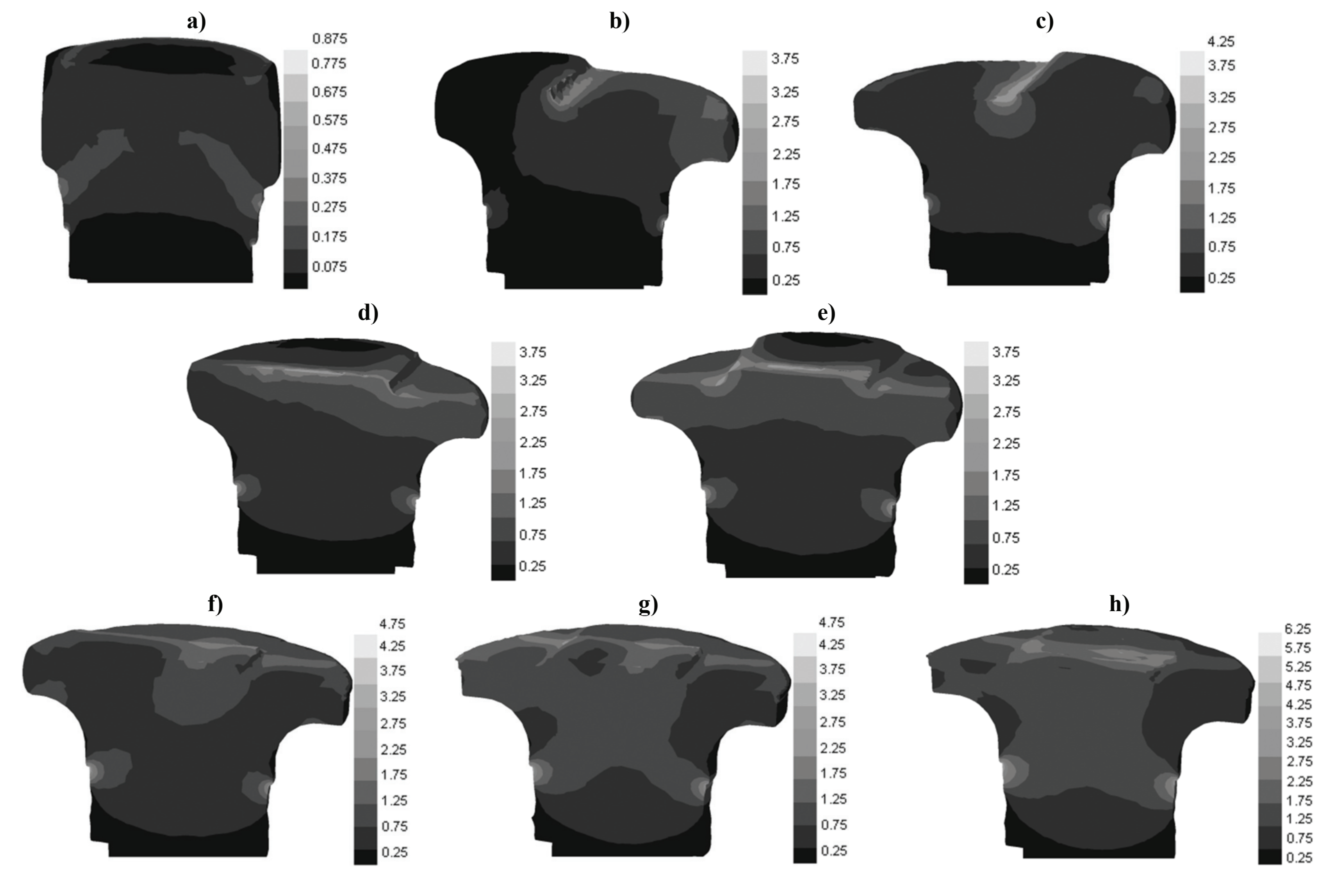

Fig. 6. *Fields of effective strain after consecutive blows in progressive upsetting of the end of the shaft: a)÷c) first sequence of blows with initial position of the flat die, d),e) second sequence of blows after rotation of the flat die by 90°, f)÷h) final sequence of blows to get required height.*

pared; in turn, in figure 7 c and d transverse crosscuts.

As the maps indicate, in both cases nonuniformity of strain can be observed. However, in upsetting with single blow it is much more distinct. Values of effective strain in this case retain minimum in the core and smoothly increase radially towards the edge of the flange. On the contrary, strain distribution produced by progressive upsetting indicates clear maxima near the center, whereas in the outer zones it decreases below 2.

In investigation of the effect of the manner of upsetting, analysis of transverse plots of effective strain on the cross-section (figure 8) provides more quantitative information. In the diagram, plot of effective strain produced in upsetting operation only is analysed. The results are a kind of surprising. Plot of effective strain on diameter of the flange show, that single blow upsetting brings no contribution to working of metal in the core. In fact, considerable deformation take place in the outer flange zone in an axi-symmetrical pattern. In superposition with

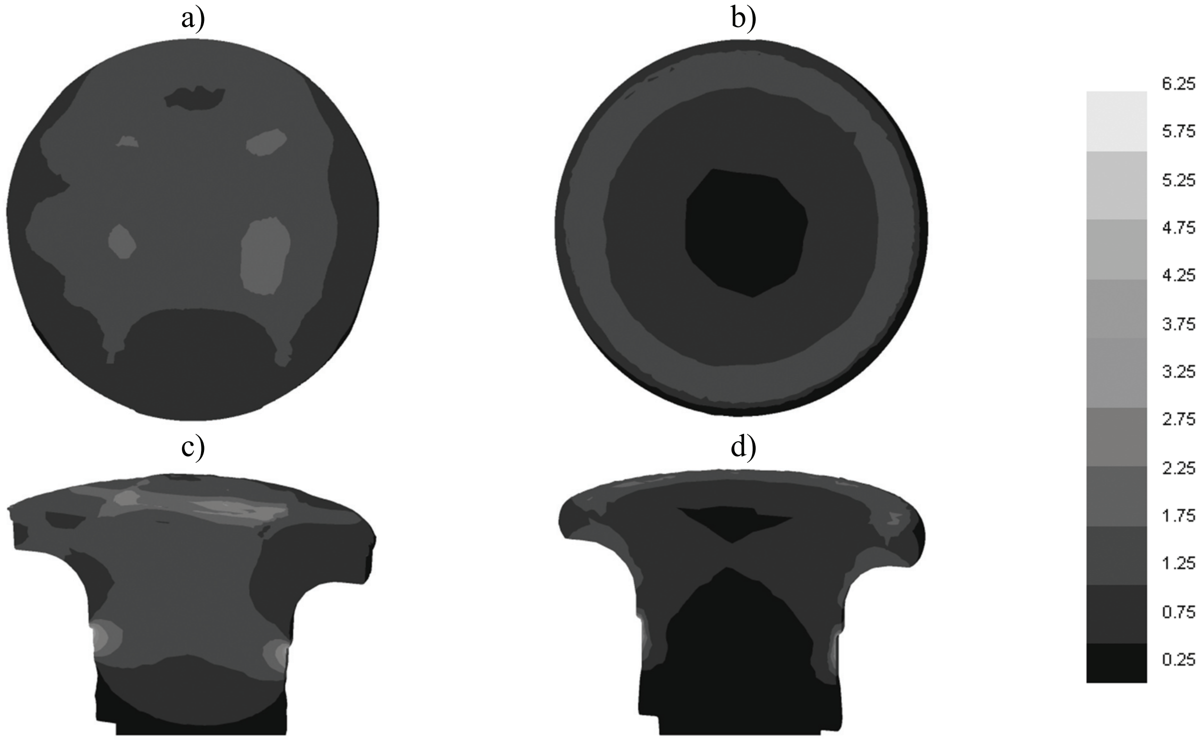

Fig. 7. Fields of effective strain in flange upset-forged: a), c) progressively, b), d) conventionally on longitudinal (a, b) and transverse (c, d) crosscuts.

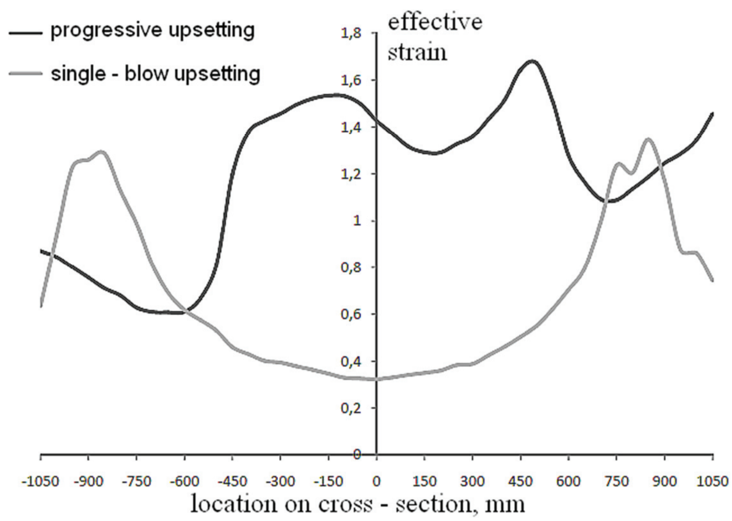

***Fig. 8.** Plot of effective strain on the cross-section of the flange obtained with both methods of upsetting.*

similar distribution of strain after cogging, it turns out only to enhance the existing nonuniformity.Contrary to the abovedescribed, the plot of effective strain after progressive upsetting has lower values on the outer region of the flange, to reach significant 1.6 in the central zone. Taking into consideration the whole processing history, it is the central zone where strain enhancement is needed. Firstly, the core is the location of increased concentration of porosity and discontinuities. Secondly, in cogging sequence strain tends to cumulate in the surface and undersurface portion of the shaft, therefore, the only concern is to avoid abnormal grain growth in the aftermath of excessively low amount of deformation.

7. CONCLUSIONS

The presented study of the process of upsetting the flange of the windmill main shaft provides a lot of information verifying industrial process and justifying reasonability of progressive upsetting method. First and foremost, the forging load analysis confirm no possibility of completion of required deformation in a single-blow upsetting, as well as, feasibility of the sequence of progressive upsetting, regarded as optimal. Calculated load did not happen to exceed 80 MN – the capacity of available forging press.

Analysis of strain in a bulk of the flange, based on effective strain distribution on a cross-section of the flange indicates definitely more favourable strain distribution in a flange forged with multiple progressive blows with use of a narrow flat die. The observed effective strain level in the core exceeds 1.6, which suggests expecting healing of internal defects originating in ingot, whereas in conventional single-blow upsetting, typical of upsetting nonuniformity of strain magnifies distribution inherited from cogging operation.

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ANALIZA ROZKŁADU ODKSZTAŁCENIA PODCZAS SPĘCZANIA KOŁNIERZA WAŁU TURBINY WIATROWEJ

Streszczenie

W artykule przedstawiono numeryczną analizę kształtowania kołnierza wału elektrowni wiatrowej z uwzględnieniem możliwości poprawy jakości wyrobu przy jednoczesnym obniżeniu siły kucia. Cel ten zostaje osiągnięty dzięki operacji segmentowego kształtowania kołnierza. Wynikiem badań jest zmniejszenie maksymalnej siły kucia i poprawa rozkładu intensywności odkształcenia w porównaniu z kształtowaniem kołnierza jednym suwem prasy.

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