FORGING OF GAS TURBINE SHAFT - NUMERICAL MODELLING OF TECHNOLOGICAL PROCESS

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Abstract

In the paper the analysis of the gas turbine forging process made from highly alloyed steel NiCrMoV to power engineering application was done. Numerical analysis of material flow in following stages of forging process also effective strain distribution in forging was introduced. Industrial technology of forging process with numerical calculations results was compared.

Keywords: Gas turbine shaft, degree of forging, numerical modeling

1. INTRODUCTION

Primary stock to the process of open die forging and semi-open die forging are ingots cast in the traditional way. Forging of large masses - the order of tens of Mg, such as: rolls for rolling mills, marine shaft lines, rotors of turbogenerators, components for nuclear power - stock is almost exclusively forging ingots [1]. Forging ingot structure (**Fig. 1**) forces the use of high-grade forging respectively, so as to achieve the required level of the product properties. Typical structure of the ingot consists of a thin layer of fine-grained at the surface, zone of columnar oriented dendrites, an intermediate zone containing columnar oriented dendrites and randomly oriented dendrities and area of equiaxed crystals at the center of the ingot [2]. Central zone is formed in the final stage of crystallization and has a high segregation of elements. It also contains non-metallic inclusions which quantity and distribution is subject of the steel purity. The size of this zone can be greatly improved by electromagnetic stirring during casting [3].

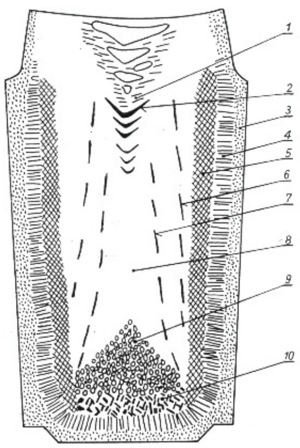


Fig. 1 Structure of ingot: 1 - positive segregation; 2 - V segregation; 3 - small equiaxed grains; 4 - columnar grains; 5 - dendritic grains; 6 - inverse V segregation (external lines); 7 - A segregation (internal lines); 8 - negative segregation; 9 - sedimentational cone; 10 - oxide deposit [4]

The problem of hydrogen cracks in forgings of high weight is an integral part of the forgings production. It occurs to a greater or lesser extent despite the vacuum degassing of the steel. It is observed with the high intensification particularly in the production of forgings such as shafts of wind turbines, hypereutectoid steel rolls with about 1% C with chromium as well as in the classic forgings - rings - produced from steel with increasing metallurgy purity. These defects result in the forging waste practically at the end of manufacturing process thereby affecting a significant increase in production costs [5]. Devices in the energy industry are subjected to the influence of high temperature and pressure. Occurring in these conditions processes of materials degradation are a potential cause of failure or destruction of machines and installations [6].

Labor issues in changing conditions occupy an important position in the design and operation of gas turbines and mathematical and numerical modeling has now become the primary research technique [7]. The gas turbine is a heat engine that retrieves the driving energy of flowing exhaust gas or other carrier gas called the thermodynamic factor or working. The term gas turbine relates to a machine consisting of a compressor and turbine (usually connected with a common shaft) and the combustion chamber positioned between them [8]. **Fig. 2** shows the ingot, forging of finished shaft and its location in a gas turbine type MS9001E.

a) b) c)

Fig. 2 Ingot (a), the forging (b) and shaft location in gas turbine (c) [9]

Materials used in the energy industry operate under the influence of complex and variable thermal and mechanical loads and environmental impact because of that strict requirements are placed to them [10]:

- stability of microstructure and mechanical properties (especially creep) at elevated and high temperatures,
- high ductility and fracture toughness,
- high resistance to thermal and thermo-mechanical fatigue,
- high resistance to oxidation in an exhaust gas enviroment,
- good weldability.

Material of shafts and rotors during operation moves the stresses of its own weight, torque and centrifugal force and is subject to the combined action of high temperature changing along the refrigerant flow and the temperature difference along the radius. The most loaded part of the shaft should be made from the bottom of the ingot. Steel for shafts and rotors should be killed and well-degassed, melted in electric furnaces. Thus obtained ingot is subjected to multiple forging in order to obtain uniformity of metal. Heat treatment of the rotor consists mostly of normalization or quenching and tempering and mechanical processing (turning, milling, drilling, grinding) [11].

2. TECHNOLOGICAL FORGING PROCESS OF GAS TURBINE - NUMERICAL MODELING [12]

The paper presents an analysis of issues related to the technology of carrying out the gas turbine shaft of elongated shape and variable cross section, which is produced in the CELSA group. Numerical calculations were performed for the process of multi-stage shaft forging produced from ingot Q16 with commercial program QForm3D based on the finite elements method. Numerical calculations were performed for two cogging variants: 1) the beginning of the forging process from the top of the ingot - in line with the technology (**Fig. 3a**) and **b**) the beginning of the forging process from the bottom of the ingot - proposed change of forging scheme (**Fig. 3b**). The casted ingot of 15 Mg mass in the grade of steel NiCrMoV and delivered to the press shop is heated in a car bottom furnace to forging temperature 1200 ± 20 °C.

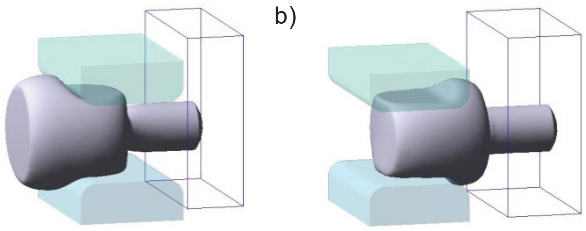


Fig. 3 Forging process schedule: a) forging from the top of the ingot, b) forging from the bottom of the ingot

Then on the 32 MN press from the top of the ingot a porter is forged and rounded it to the diameter of 950 mm. Another technological operation is ingot heating up to the temperature of 1200 ± 20 °C in the hearth furnace and his upset at the 80 MN press to the height of 1100 mm. The ingot is forged to circle ∅ 1000 mm by the square of 1000 x 1000 mm in flat anvils with a width of 800 mm. Again reheating of turbine shaft in hearth furnace and selects the length of the individual shaft shoulders. All shaft shoulders are carried out according to the same pattern reforging consecutively on the square, hexagon, octagon and circle. Forging is cogged in flat anvils to obtain the respective shaft shoulders. The first shoulder is forged at the diameter of 1000 mm, second to ∅ 820 mm and the following at ∅ 680 and ∅ 520 mm. After forging all shoulders allowances are cut off from the top and the bottom of the ingot which uses a press with a pressure of 32 MN. Forging is reheated and then on 80 MN press performs the last operation which is die forging of the turbine shaft flange. The study shows the effective strain distribution maps in formed material for specific steps in the process of gas turbine shaft forging. In order to determine the degree of forging on the basis of the effective strain results the following equation is used (1) [13]

$$k = 1 + 1.3 \cdot \varepsilon_i \tag{1}$$

where: k - degree of forging and ε_i - effective strain.

The obtained information are the basis of the selection of the correct forging technology to the minimum required degree of forging. For the numerical calculations boundary conditions were adopted in accordance with the used in the industry of CELSA "Huta Ostrowiec" Sp. z o. o. Forging is forged in the grade of high alloy steel NiCrMoV at 1200 °C. The steel composition is shown in **Table 1**. The forging processes were performed on a hydraulic press. In the program a hydraulic press with parameters corresponding to industrial conditions was bulit. Adopted tool temperature of 300 °C and a press cross-bar speed of 10 mm/s.

Table 1 Chemical composition [9]

%C	%Mn	%Si	%P	%S	%Cr	%Ni	%Mo	%Cu
0.25÷0.33	0.20÷0.80	max 0.35	max 0.012	max 0.010	1.30÷2.00	2.50÷3.50	0.20÷0.70	max 0.35
%V	**%Al**	**%Sn**	**%Sb**	**%As**	**%Ca**	**O, ppm**	**N, ppm**	**H, ppm**
0.07÷0.15	max 0.025	max .015	max .003	max .020	max 0.010	max 75	max 100	max 2.0

3. ANALYSIS OF RESEARCH RESULTS

In **Figs. 4÷5** the effective strain distributions for the following operation of the gas turbine shaft forging process are shown. **Fig. 4** shows the effective strain distribution for the upsetting operation. On it three zones of deformation can be distinguished. Zones adjacent to the anvils front surfaces deform at least which is caused by friction forces on these surfaces. Values of these deformations are in the range 0.25 ÷ 0.65. The maximum strain in both directions (axial and radial) occurs inside of the ingot and are equal 1. Medium deformation zone occurs in the side area, unrestricted by the tool.

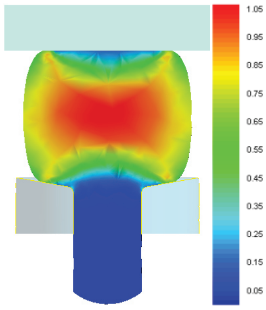
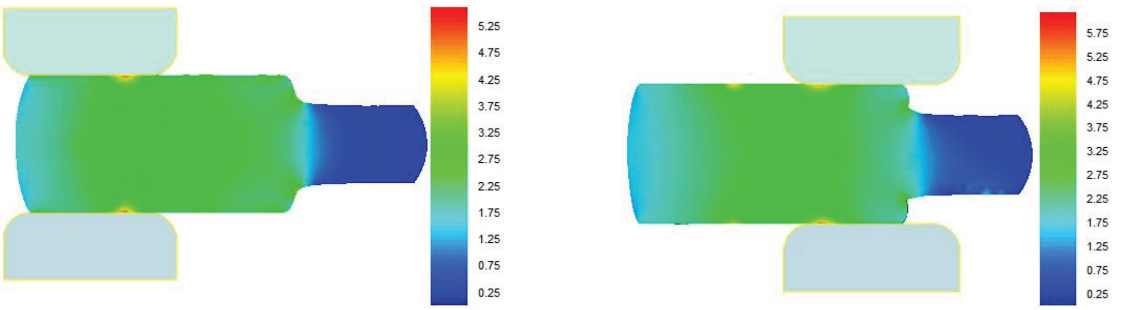


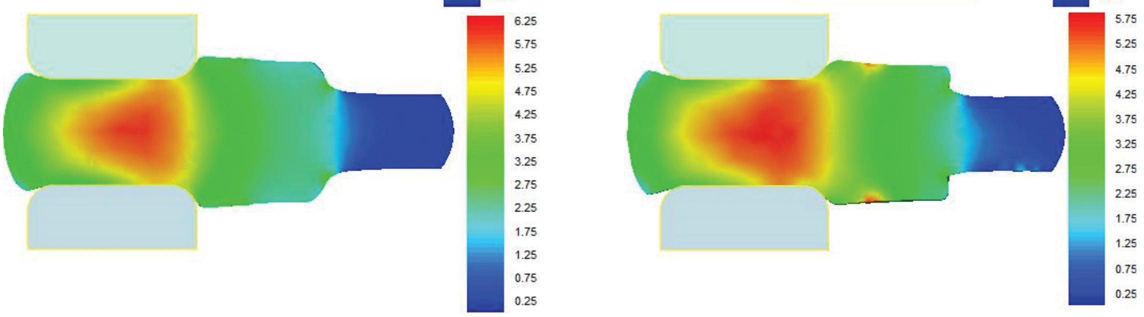
Fig. 4 Effective strain distribution in upsetting process

Fig. 5a shows the effective strain distribution in subsequent operations of cogging to square, hexagon and octagon regular realized in flat anvils. Introduced distribution retains overall deformation upward trend. The use of different variants of the cogging process (forging from the top and the bottom of the ingot) gives different effective strain distributions. Comparing the first cogging operation it can be observed that in a variant of forging from the bottom of the ingot occurs greater strain values than in the forging from the top of the ingot. Until the forging to a circle with a diameter of 1000 mm effective strain values for the forging from the bottom of the ingot are higher then in the technology used in industrial conditions. In **Fig. 5b** effective strain distribution for the following cogging operations to obtain a second shoulder to the diameter of 820 mm are shown. After forging to circle the individual variants differs in size and values of strain. When forging from the top of the ingot zone of deformation is smaller but has a higher value than the forging from the bottom of the ingot. Effective strain distributions after the third shoulder forging the diameter of 680 mm are shown in **Fig. 5c**. Both distributions and values of deformation are similar. Slightly higher values are obtained by forging from the top of the ingot which is in accordance with the technology. Comparing the deformations in **Fig. 5d** it can be seen that the slightly higher values are obtain during forging from the bottom of the ingot. **Fig. 5e** shows the view of the forging after cut-off process from the top and the bottom of the ingot and the last operation which is flange die forging. After the aforesaid operations deformation have increased. Obtain favorable strain distribution for the forging from the bottom of the ingot.

a)



b)



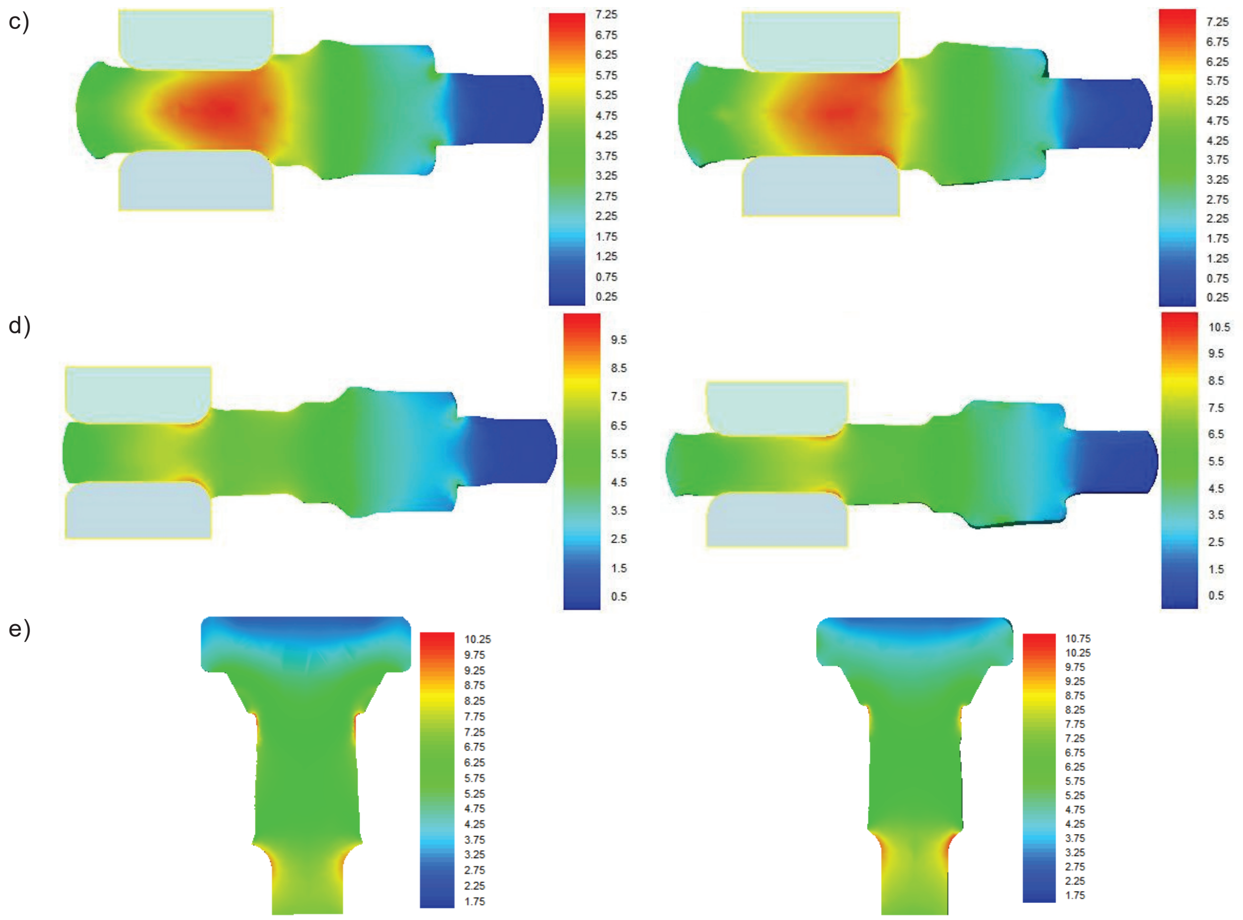


Fig. 5 Effective strain distribution in following shaft forging operations: a) first shoulder cogging, b) second shoulder cogging, c) third shoulder cogging, d) fourth shoulder cogging, e) flange die-forging
Left: forging from the top of the ingot, right: forging from the bottom of the ingot

4. SUMMARY AND CONCLUSIONS

Studies on the forging process of the gas turbine shaft forging was directed toward the analysis of the technology used in industrial and efficient method for finding a new forging in comparison with the previous solution. Forging qualified for this study as a product which improve the technology can bring the greatest benefit to Celsa "Huta Ostrowiec". This selection was based on the criterion of the volume of production is expected to increase as the demand for the product and the criterion of significance for the activities of the forge - a new assortment. Forging process of a gas turbine shaft forging technology include very complex due to the shape and the way the execution. The shape of the forging determine different degrees of deformation while the method of execution (flange die forging) allows to obtain a suitable effective strain distribution and the degree of deformation of the forging.

Numerical modeling of a gas turbine shaft forging process allowed to verify the technology used in industrial conditions (forging from the top of the ingot) and propose alternative technology (forging from the bottom of the ingot). In both variants of the technology the same absolute feeds and similar relative deformation were used. That allows to interpret the results of calculations under comparable conditions of plastic forming. The characteristic stages of deformation having a decisive influence on the effective strain distribution and forging ratio were analyzed.

In the upsetting process of the stock there is a traditional strain distribution in the axial section of the forging. The maximum value of the effective strain occurs in the central portion (ε_i = 1.05). Minimum deformation zone is located in the forging axis, wherein penetrates deeper into the porter side. Cogging process of the ingot to the circle, carried out in the flat anvils taking into account forging to square, hexagon and octagon, increases effective strain to an average of approx. 4.25. Locally at the surface effective strain is on average even 4.75. However in the forging axis does not exceed 3.75. After taking into account equation (1) the minimum degree of forging (calculated numerically) in the axis of forging exceeds 5.9. Analysis of the effective strain distribution after forging of the last shoulder and flange die forging allowed to indicate more favorable effective strain distribution for the proposed technology (forging from the bottom of the ingot). Based on the results of effective strain can be concluded that both technologies provide comparable quality forgings for the shape, dimensions, structure and mechanical properties, as well as going forward - productivity.

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