РАЗДЕЛ I
МОДЕЛИРОВАНИЕ ПРОЦЕССОВ ОБРАБОТКИ ДАВЛЕНИЕМ

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NUMERICAL AND PHYSICAL MODELING OF OPEN-DIE FORGING OF HEAVY POWER-PLANT COMPONENTS MADE OF CR-NI-MO-V STEEL

Introduction

Heavy components for energy and powerplant applications, including large shafts wieighing up to hundreds of tons, are manufactured by open-die forging of large ingots. The forging sequence has a critical meaning for final operational properties [1]. Of particular significance is the total amount of deformation and deformation zones distribution produced during breakdown of the cast structure [2]. In cogging, the main operation in open-die forigng cycle, several essential parameters are to be selected. In this respect, the tendency is to impose as large bites as possible, which influence both economical efficiency and the quality of the final product. Increased feed length, however, requires considerable loads, which for high-alloy steels such as Cr-Ni-Mo-V grades may be a problem. Limited reductions could adversely affect final mechanical properties and distribution of them. Another important stage in the production cycle is heat treatment. Forging must produce uniform and refined microstructure to prevent from nonuniformity [3].

Implementation of new technology in industrial conditions requires determination of the most favourable process conditions on the all of the technological chain. Preliminary studies, which form the basis for determination of the process parameters, are usually carried out on a small-scale models. Combination of numerical and physical modeling can provide complementary information as for bahaviour of the material in conditions, which can be precisely described with state-of-stress and strain indices, obtained with finite element method [4].

In the work concerned, level and distribution of strain after forging, achieved in the experiment with application of the highest possible deformation degree, are calculated in numerical simulation with finite element method. Physical modeling of forging carried out on the small-dimensions ingot of the analysed steel is used for correlation of the amount of strain with the resultant microstructure of Cr-Ni-Mo-V steel used for the manufacture of powerplant high-duty forgings.

Objectives and procedures

The main objective of the studies and experiments included in the work was determination of the effectiveness of grain refinement and mechanical properties enhancement in the aftermath of cogging process with typical values of unit reductions and feed lengths in order to define technological guidelines of open-die forging process of steel Cr-Ni-Mo-V.

As for correlation between final microstructure, mechanical properties and total amount of deformation resultant from imposed reductions and bites in conditions predicted for the industrial process (work temperature, strain rate etc.), physical modeling on actual analysed steel grade were carried out. On account of cost savings, large ingot of a dozen of tons was replaced with small-size one-hundred kilograms' ingot as a sample, attaining geometrical and themomechanical similarity criteria in physical modeling process. The magnitude of strain in the bulk of the deformed ingot was defined by means of numerically calculated effective strain.

Final result of the evaluation of the correctness of the forging process was condition of microstructure and final mechanicla properties. As the real manufacturing process involves heat treatment, it also had to be taken into consideration in the evaluation of the final mechanical properties and microstructure. To investigate uniformity of the material grain structure and repetitivenenss of mechanicla properties, several samles from locations on the length were examined.

Physical modeling of the cogging process

Execution of the forging modeling in accordance with the guidelines for established technology for the predicted conditions of industrial process was realized with application of research material Cr-Ni-Mo-V steel, commonly used for manufacture of power industry elements. Physical modeling on ingot weighing 100 kg of chemical composition shown in Table 1 was performed. Table 2 lists the required mechanical properties of the elements demanded by the power industry made in the steel grades CrNiMoV.

Table 1

Chemical composition of ingot used to tests

Chemical composition, % weight											
Chemical element	C	Mn	Si	P	S	Cu	Cr	Ni	Mo	V	Al.
Content, %	0,26	0,99	0,17	0,008	0,004	0,01	1,25	0,96	0,34	0,128	0,0040

Table 2

Requirements imposed on the analysed steel Cr-Ni-Mo-V

$Rp_{0,2}$, MPa	Rm, MPa	A5, %	Z, %	Impact resistance KV, J (-40ºC)	FATT
≥ 750	900–1000	≥ 15,0	≥ 55	≥ 27	≤ 0 ºC

Technology of forging involved the following steps: heating the ingot to a temperature of 1250 °C, cogging of the ingot to Ø90 mm (Fig. 1) and controlled cooling. Forging on a hydraulic press with pressure of 300 Mg was done. Relative deformation value was 35 to 40 %, relative bite, referred to as the ratio of feed length to initial diameter, ranged 0.7 to 1.0. As a result, the total cumulated cross-sectional reduction obtained in the experiment ranged from 3.0 in the bottom to 4.3 in the head of the ingot.

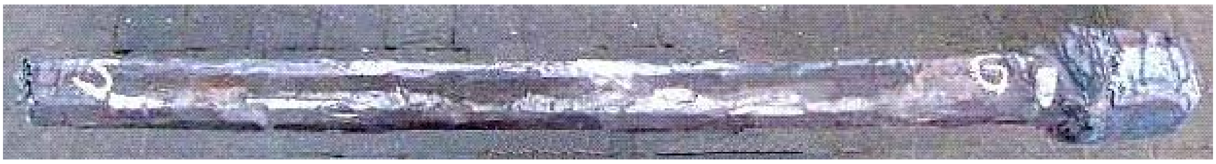


Fig. 1. Experimental shaft forged from the 100 kg ingot

Numerical modeling of the cogging process

Numerical modeling of the cogging process realized on the ingot weighing 100 kg (Fig. 2, a) was performed in accordance with the experiment. Ingot of a square cross-section had a length of 500 mm. The ingot sidewalls were tapering in the length, starting from 165 mm in the head of the ingot to140 mm in the bottom end. Like in the experiment, the initial temperature of the ingot was assumed 1250 °C, the temperature of anvils 300 °C. In simulation Levanov's friction model was used, with assumption of friction coefficient of 0.15 and friction factor 0.3. Ram speed 10 mm/s was defined for nominal load of hydraulic press 80 MN.

The final product of the cogging process is a rod of diameter 90 mm (Fig. 2, c). For the cogging flat anvils were used, hence the near-octagonal cross-section in the final stage of forging was considered equivalent to round cross-section, since reductions in final stage are small and are believed not to effect the total amount of work. To obtain high efficiency of cogging process the relative reduction applied in the first phase equals up to 35 % with a relative bite of 0.8 (Fig. 2, b) [5]. This allowed for deformation of the ingot axial zones with high values of effective strain in each single deformation (Fig. 2, d). The final value of the effective strain distribution measured along the rod radius for the three areas is shown in Figure 3.

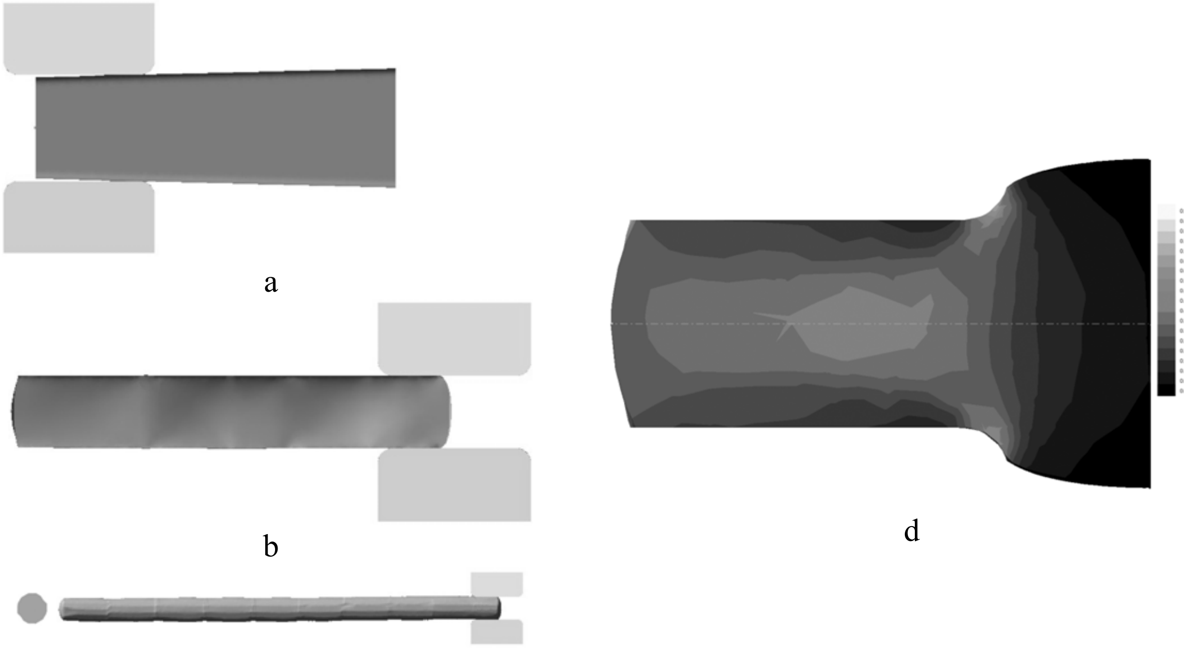

a
b
c
d

Fig. 2. Scheme of cogging process sequence in numerical modeling of ingot 100 kg:

a – start of cogging process; b – preforming with 35 % unit reductions; c – final product in the form of a round rod; d – effective strain distribution in longitudinal section of the ingot after relative deformation one displacement of upper anvil

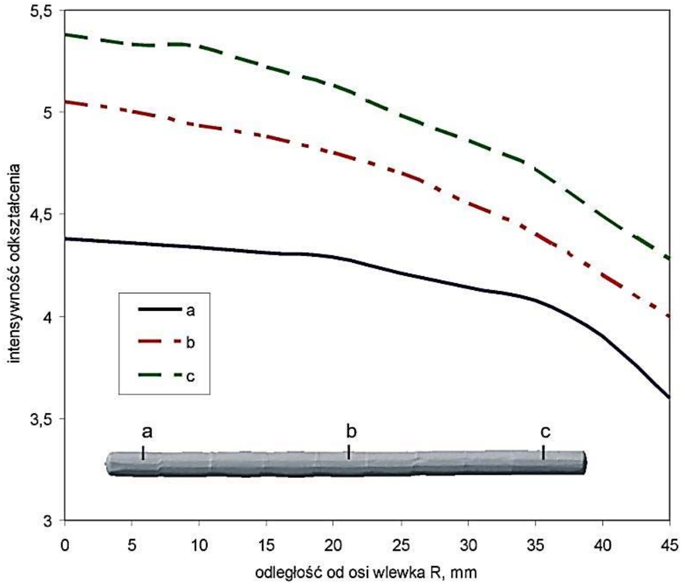


Fig. 3. Value of effective strain along the radius in three locations:

a – bottom; b – centre; c – head

The highest value of the effectives strain was observed in the head of the ingot (Fig. 3, curve c). Effective strain gradient for three analyzed sections is similar. The difference between the highest and lowest value of effective strain in the cross-section is approximately 0.8. It should be expected, that uniform mechanical and plastic properties on cross-section related to distribution of local amounts of the plastic work. The quality examination carried out on samples taken from different areas of the obtained model forging confirms that conclusion.

Modeling of heat treatment in the laboratory conditions

The analysed steel is not designed to be used in high-duty applications in as-forged condition. To obtain final mechanical properties it must undergo heat treatment. Most often it involves normalizing for finer and uniform grain followed by quenching with required cooling rate when machined. Therefore, estimation of the forigng process was done in a context of quench-tempered final condition. To attain full processing history, the heat treatment was modelled on the specimens taken out from as-forged material.

In Fig. 4 locations of specimen selection are indicated. The specimens were both used for initial microstructure analysis and the final microstructure after heat treatmen laboratory tests. These tests included:

- Normalizing (900 ^{o}C/4h, sample a in Fig. 4);
- Normalizing followed by oil quenching (900 ^{o}C/4h, OH: 620 ^{o}C/6h, sample b in Fig. 4);
- Normalizing followed by water quenching (900 ^{o}C/4h, OH: 620 ^{o}C/6h, sample c in Fig. 4).

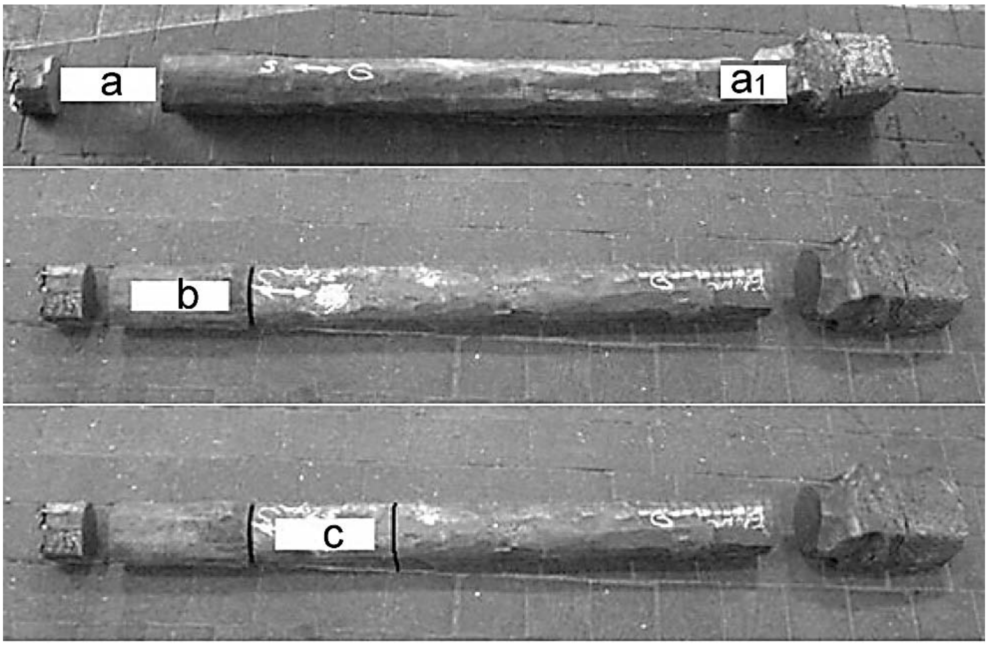


Fig. 4. Specimens taken out for heat treatment modeling

Microstructures of nital-etched specimens of forged and heat treated material are shown in Table. 3. Specimens A and B represent microstructure after normalizing and controlled air cooling, derived from samples a and a1 in fig. 4. Specimen C stands for sample a after additional normalizing. Micrographs D and E are obtained by quenching and tempering in oil and water, respectively (samples b and c in fig. 4). Microstrucural components was investigated and grain size accoriding to ASTM-E was estimated. The results are shown in Table 3, column 3.

To measure the effect of designer processing regimes mechanical testing was carried out. Mechanical tests included estimation of ultimate tensile stress and tensile yield stress, hardness, as well as impact strength and its dependence on temperature, summarized by FATT diagrams. The results of mechanical tests carried out for selected treatment cycles are summarized in Tables 4 and 5. Final dependence of ductility versus temperature is shown in Fig. 10 in form of diagrams of the character of fracture versus temperature, with indication of FATT.

Table 3

Microstructure and grain size estimation of forged and heat treated Cr-Ni-Mo-V according to ASTM E–112-10

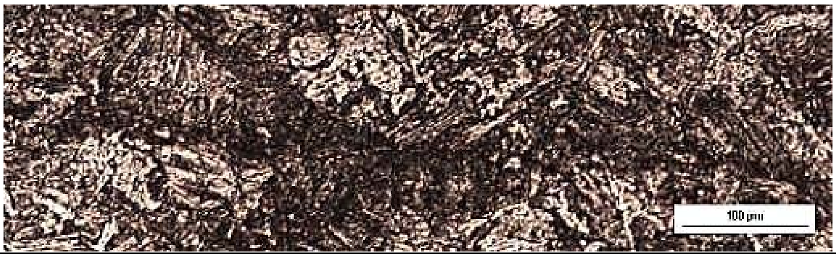
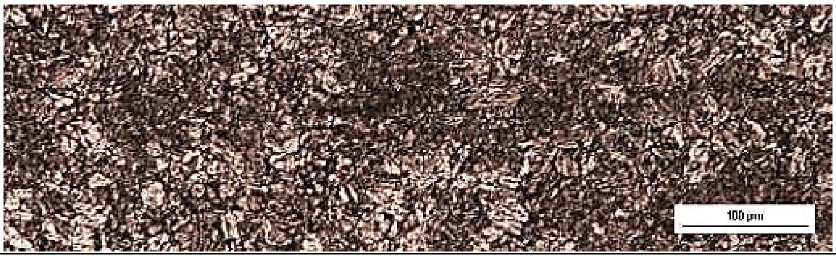
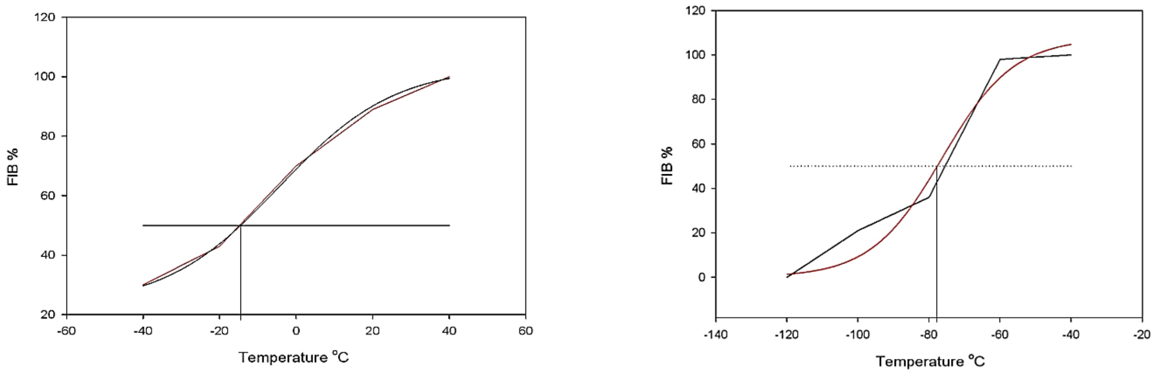
No.	Specimen location	ASTM grain size	Microstructure
A	a	7	
B	a1	9	
C	a	9	
D	b	9	
E	c	9	

Table 4

Results of mechanical testing

Heat treatment	Specimen location	Mechanical properties			
		$TYS_{0,2}$, MPa	UTS, MPa	Hardness, HBW	Impact strength KV, J (-40 ºC)
Normalized and oil Q&T	b	830	916	263	23; 21;38 (average: 27)
Normalized and water Q&T	c	838	912	285	116;108;118 (average: 114)



a

b

Fig. 5. FATT 50/50 estimated for specimens b and c, respectively

SUMMARY AND CONCLUSIONS

The presented results include confirmation of the possibility of open-die forging of steel grades Cr-Ni-Mo-V. The physical modeling shows the cogging process parameters, especially high values of relative bites and employed reductions in height amount of work is sufficient to break down and refine cast structure of ingot, with no adverse effect on workability.

The applied forging conditions produced uniform strain distribution on the length of the model shaft, which is confirmed by effective strain distribution calculated with finite element method, as well as, by the mechanical testing results, especially FATT, which was -14 ºC fro specime a and -78 ºC for specimen c. The resultant microstructure was uniform and the grain size ASTM-E 9 is observed with local occurrence of coarser grain 7 ASTM-E in as-forged condition. After quality heat treatment, 9 ASTM prevail in the whole volume.

Final mechanical properties meet the typical requirements towards power-plant components, which confirms the correctness of the designed technology to be used for steel grades Cr-Ni-Mo-V. As such, the results of the experimental work can be regarded as guidelines for open-die forging in the context of subsequent heat treatment.

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