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ANALYSIS OF KINEMATIC AND FORCE PARAMETERS OF THE DIE-FORGING PROCESS PERFORMED ON A CrNiN ALLOY

This article presents the results of studies of simulations of die forging of a drive shaft for small and medium watercraft. The formed material is a chromium and nickel alloy endogenically modified with nitrogen. Numerical simulations were carried out using the DEFORM-3D program, by means of which a map of mean stresses, temperature, deformation intensity, and cracking according to the Cockroft-Latham model were obtained. The results of the conducted studies will enable selection of the appropriate technological parameters in the process of forging CrNiN alloys.

1. INTRODUCTION

The development of materials engineering – the development of new construction materials capable of carrying fast-changing high-amplitude load cycles, working at high operating temperature, and resistant to the corrosive action of the environment – is a basic condition for improving the designs of machines and equipment. This is particularly apparent in such innovative branches of the economy as the energy, aviation, bioengineering, chemical processing, and environmental protection engineering industries.

Among known construction materials, the above conditions are fulfilled by high melting alloys based on titanium, nickel, or chromium [1],[2],[3],[4], which exhibit a particular suitability for operation in highly corrosive operating environments.

Protecting construction from the effects of an aggressive operating environment is one of the main tasks facing the designer and user. This interaction is generally perceived as chemical or electrochemical corrosion on the metal-environment phase boundary and is also manifested in the form of other complex physical phenomena.

Chromium-nickel alloys are used both as cast and, more and more often, after plastic working which enables homogenisation of their original structure and gives them high, targeted properties of strength. However, such plastic working, particularly when its result

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is the acquisition of load-bearing machine elements of a complex shape, is prone to essential difficulties related to high deformation resistance and very low formability specific to these alloys.

2. GOAL OF THE STUDIES

The goal of these studies was to select parameters and analyse the process of drop forging of a drive shaft for small and medium watercraft made from the new CrNiN alloy.

The most responsible (load-bearing) parts of machines and equipment operating with large and variable loads are currently produced primarily by means of forging processes. The demand for these parts has been subject to rapid growth in recent years in terms of both the variety and volume of production.

Thus, it was decided to conduct studies on the influence of plastic deformation on the change in the properties of the CrNiN alloy based on the process mentioned above.

3. NUMERICAL ANALYSIS

Numerical calculations were carried out using the DEFORM-3D commercial program dedicated to the simulation of plastic working processes, among other things.

A geometrical model of the charge (a shaft made of CrNiN alloy), that is, a tool (upper and lower die) (Fig. 1), was created in the UGS NX 6 program and then exported with the *.step extension to the DEFORM-3D program. Studies were conducted on half of the model, since it is symmetrical relative to the vertical plane oriented along the length of the shaft.

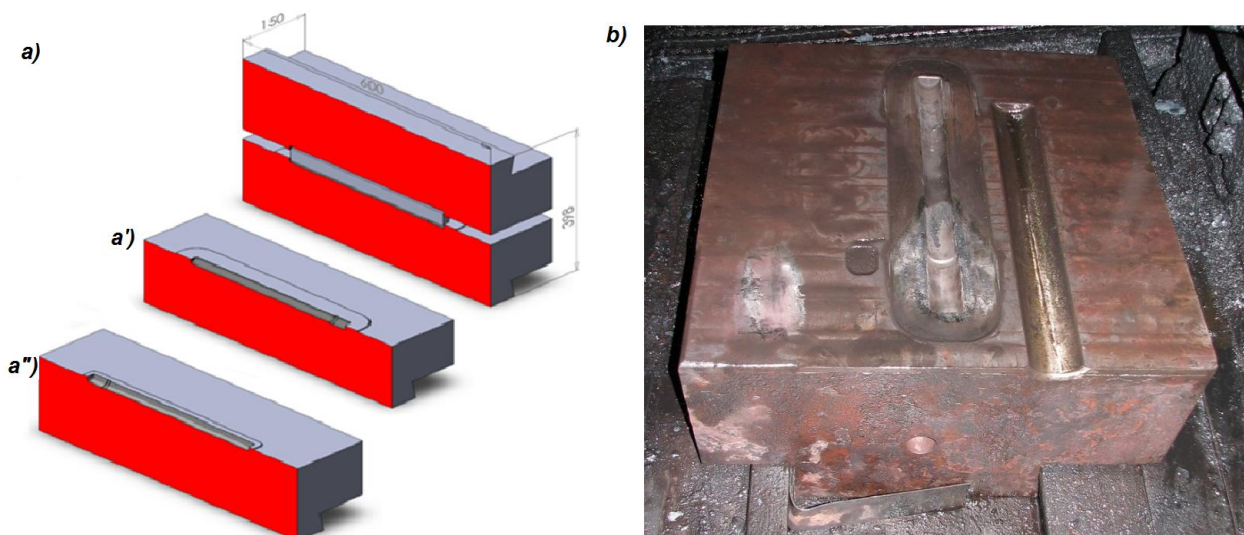


Fig. 1. a) Geometrical model of the set of die charges assumed for analysis of the process; a') lower die; a'') upper die; b) lower die used in experimental research

This made it possible to concentrate on the finite element mesh in the next phase of creation of a discrete model, which also enabled improvement of the accuracy of calculations without prolonging them.

The final generated mesh of tetragonal four-nodal elements numbered 173,920 elements (39,328 nodes), for a prismatic charge with a diameter of $\varnothing = 40\text{mm}$ and length of 374mm.

The CrNiN material was defined using yield stress as a function of strain value, strain rate, and temperature, and results were obtained using the Gleeble 3800 system [5]. The graphs below presents the above function for a temperature of 850°C, 1150°C and strain rates of 1, 10, 40, and 100 s⁻¹. (Fig. 2)

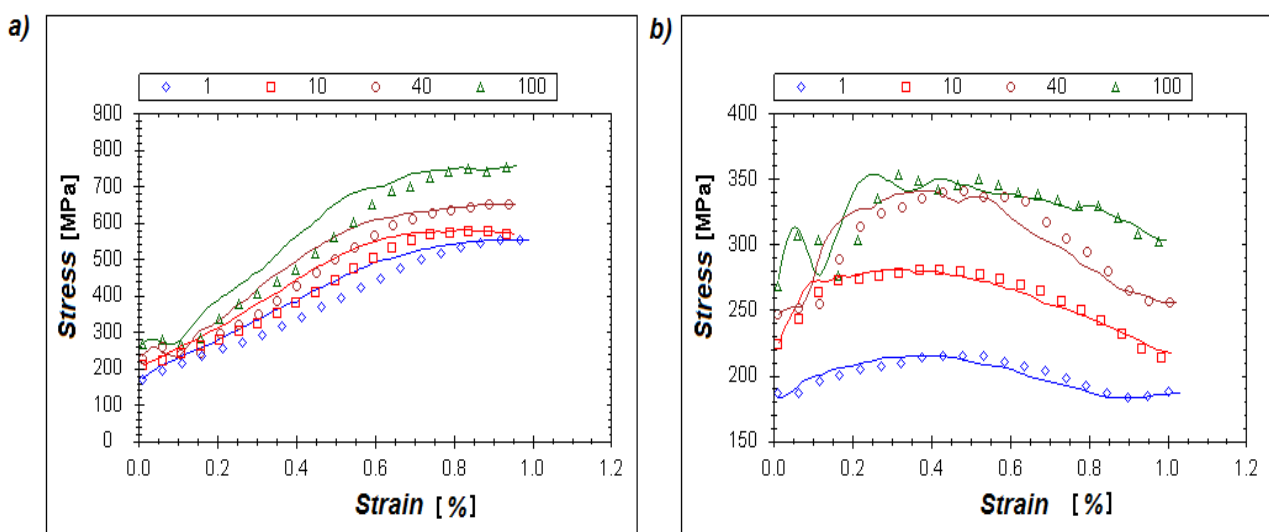


Fig. 2. Influence of strain rate in the uniaxial compression test performed on the CrNiN alloy heated to a temperature of a) 850°C and b) 1150°C

Based on observations of the course of transport of the charge between the furnace and hammer at the Mechanical and Forging Plant in Wolbrom (the site of the experimental studies), the following thermal parameters of the process were determined:

- charge temperature after its removal from the furnace – 1150°C,
- average time of transport of the charge from the furnace to the hammer – 15 s,
- average ambient temperature – 20°C,
- average flow rate of air around the charge – 2.0 m/s,
- convection coefficient – 0.02 N/s/mm/°C,
- die temperature – 300°C.

Contact pairs were modelled indicating the space encompassing the charge (plastic) and die (rigid) and defining the value of internodal tolerances as 0.0002mm.

After identification of the charge object as the ‘Slave’ and the die (upper and lower) as the ‘Master’, the program automatically generated contact pairs.

The friction conditions on the surface of contact of the charge with the die impression were described, with acceptance of the ‘Shear’ model with a friction coefficient designated by the program as equal to 0.7 (for hot plastic working). A strain rate $\dot{\rho}$ corresponding to the characteristics of the steam-air MPM 3150B hammer was assumed, with an initial speed of falling parts estimated at 6m/s.

4. RESULTS OF NUMERICAL ANALYSIS

The results of numerical analysis were presented in the form of a map of temperature, strain intensity, average stresses, and the distribution of the value of the Cockcroft-Latham integral in the final step of calculations. During simulations of forging of the drive shaft, two opposing (in terms of their effect) phenomena can be observed in Fig. 3:

- increase of temperature as a result of the conversion of part of the kinetic energy of the hammer’s impact to heat,
- decrease of temperature as a result of contact of the charge with the surfaces of the die impression at a significantly lower (approx. 300°C) temperature.

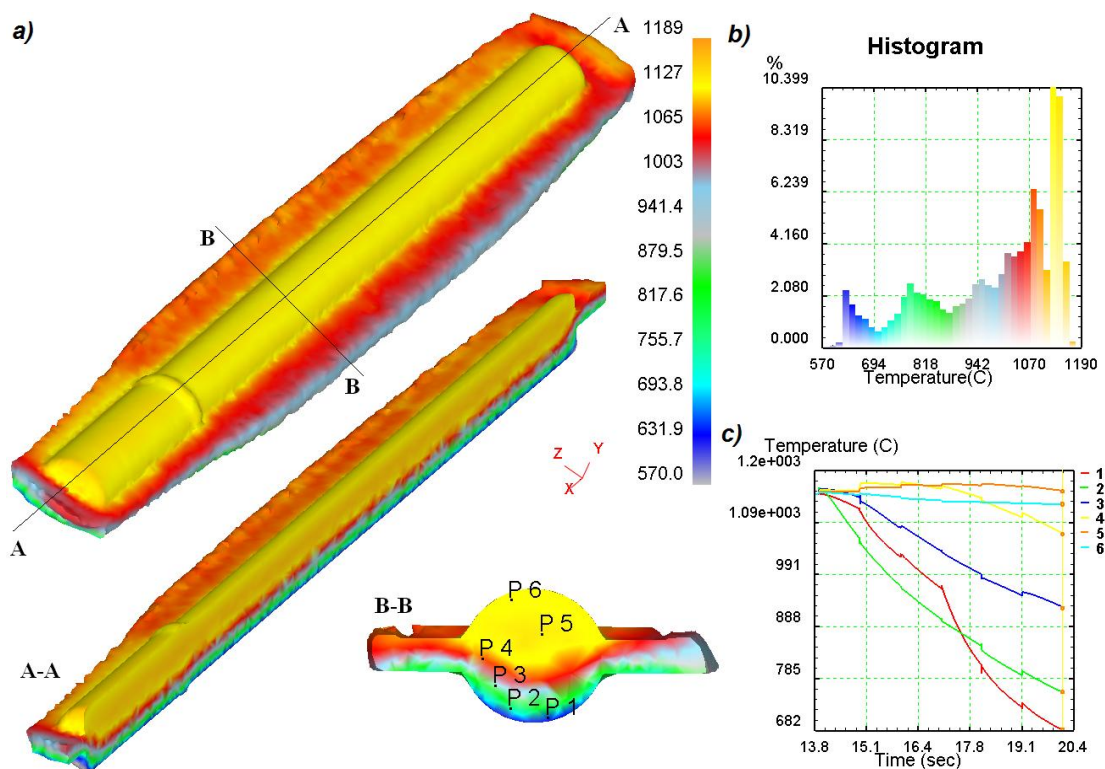


Fig. 3. a) Temperature distribution in the finished forging after the conclusion of the process; b) histogram of the percentage of FEM mesh nodes at a given temperature; c) temperature changes at selected points (P1–P6) of the forging over the duration of the process

The influence of the former phenomena is dominant in the central part of the forging, particularly in zones adjacent to the flash of high-intensity deformation, the increase in temperature reaches 39°C.

Significantly greater temperature changes, up to 580°C, occur on the contact surface of the material and tool.

Besides temperature distribution maps, the DEFORM-3D program also enables preparation of a histogram expressing the percentage share of the number of FEM mesh nodes of a given temperature value in the global result of calculations. This, in turn, enables a more precise interpretation of the obtained results, as shown in the sample histogram in Fig. 3.

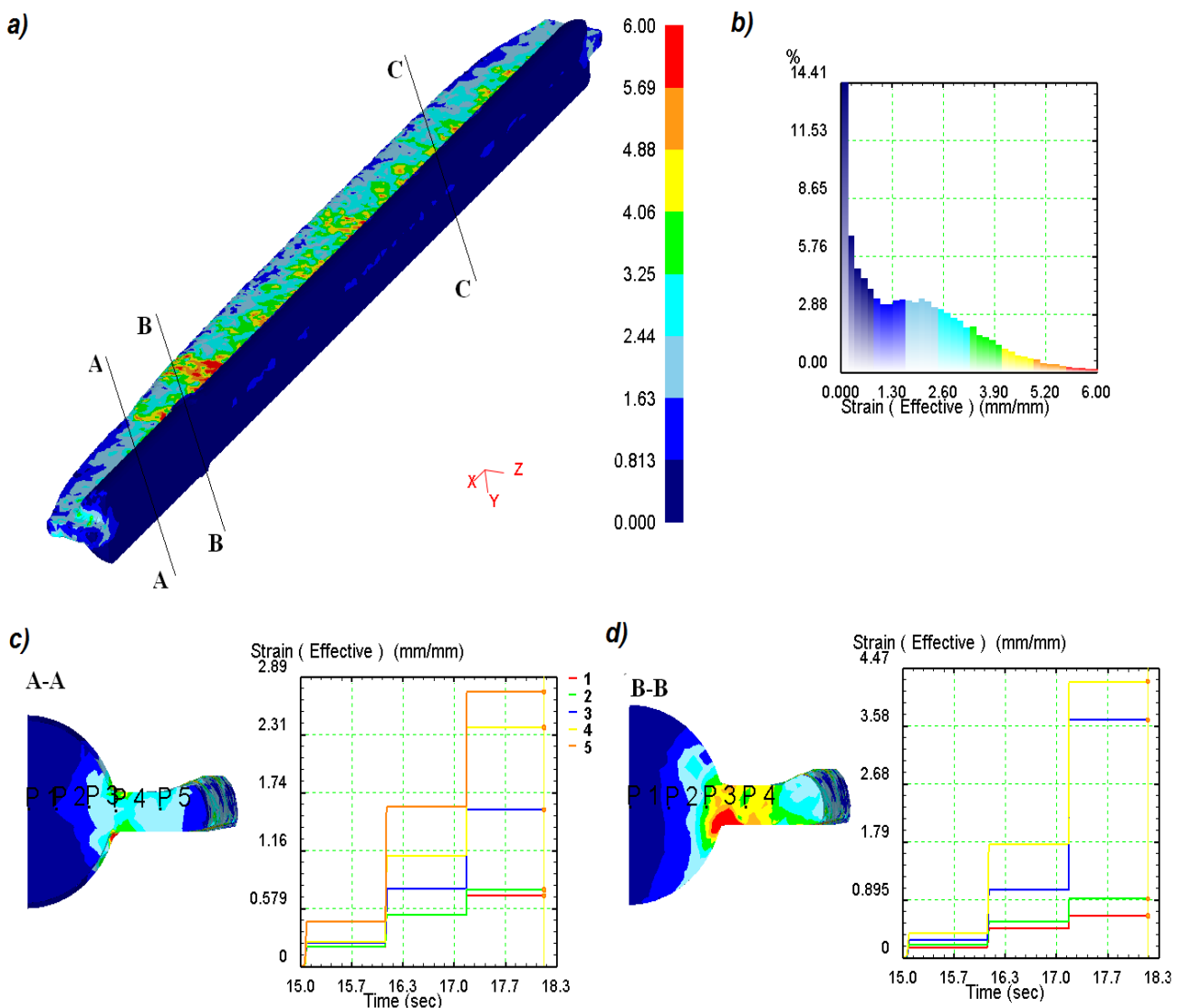


Fig. 4. a) Distribution of deformation intensity ϵ_i in a forging made from a charge $\varnothing=40$ mm; b) histogram of the percentage of FEM mesh nodes with a given value of deformation intensity; c, d) courses of deformation intensity over the time of the process determined for forging cross-sections A-A, B-B

According to legend (Fig. 3a) shows that the maximum temperature forging of 1189°C while a drop in temperature reaches 570°C , after taking into account the percentage of the temperature distribution histogram (Fig. 3b), we can correct the result of the maximum temperature of 1170°C forgings for about 3% of the quantitative occurrence of nodes and accordingly the largest temperature drop of the histogram reaches 510°C at 2% incidence of nodes.

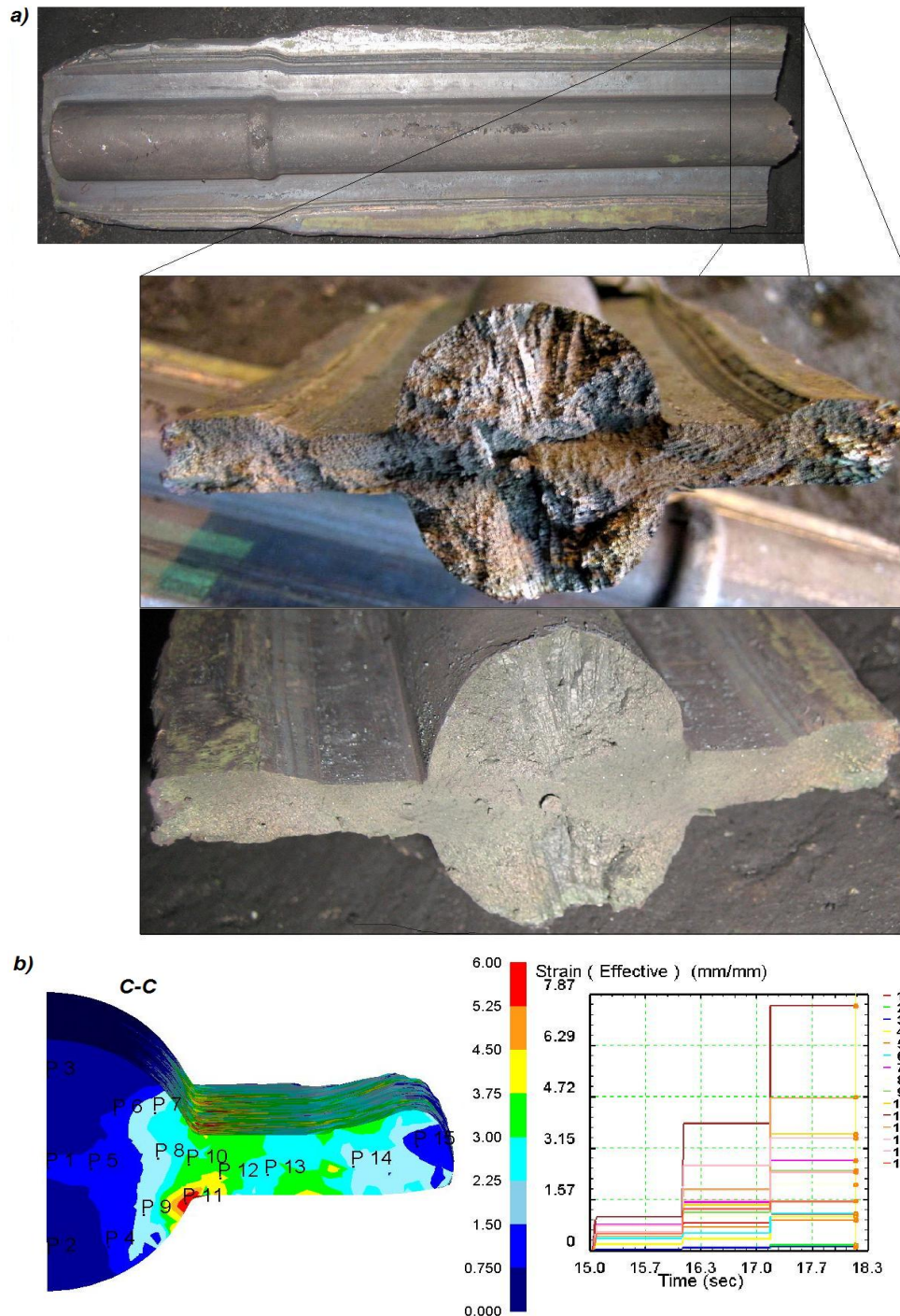


Fig. 5. a) Breakthrough forgings of macrostructure shown; b) distribution of deformation intensity ε_i over the time of the process determined for forging cross-sections C-C (Fig. 4a)

Considering that the charge in the forging process is an ingot with a primary casting structure, numerical calculations were focused on determining the distribution of deformation intensity ε_i . Awareness of this distribution provides basic information concerning the forging reduction ratio of the forging material depending on the shape of the die impression and other technological process parameters [6].

Distributions of deformation intensity in the longitudinal section and in cross-sections A–A, B–B, and C–C (Fig. 5), respectively, of the forging are shown in Fig. 4. They confirm non-uniform (along with intensiveness of deformation) working of the material in the volume of the forging. This non-uniformity is present even with respect to its central part, in which the value of deformation intensity increased from about 0.9–1.0 to 2.31–3.58 in the flash area (Fig. 4).

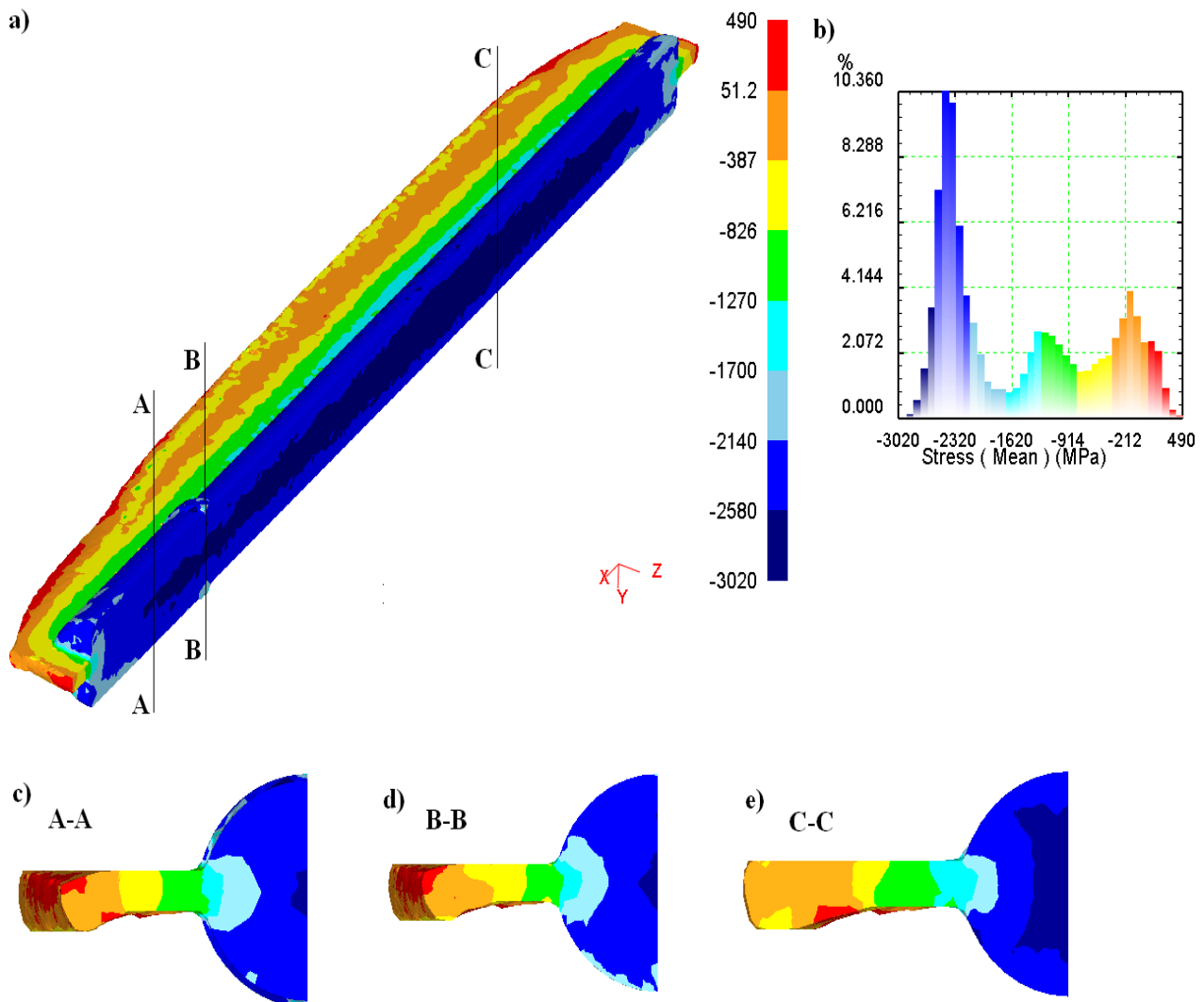


Fig. 6. a) Distribution of mean stress in the volume of the forging made from a charge $\varnothing=40\text{mm}$; b) histogram of the percentage of FEM mesh nodes with a given stress value; c, d, e) distribution of average stress in forging cross-sections A–A, B–B, C–C

After the process of plastic deformation in the core zone of the forging can be observed change in the structure of the casting on microcrystalline structure oriented (Fig. 5). At 30% of charge diameter reduction, however, it was not possible in the simulated process to obtain a degree of plastic working of the material over its entire volume that was meaningful enough to guarantee the assumed increase in its strength properties resulting from hardening.

Besides the deformation intensity ε_i described above, the distribution of mean stress in the forging volume was also subjected to analysis. The obtained results are shown in Fig. 6.

The maximum values of compressive stresses occur in the core area of forgings which take 2980MPa. This can be explained by the observed (Fig. 3) significant decrease in temperature during transport of the hot charge material as well as direct contact with the forging dies.

In the end region of the bead tensile stresses are a maximum value of 430MPa. These stresses created because the deformable material is not limited by the die, this condition is unfavorable for materials difficult to deform.

Unfavorable drop in temperature as well as the presence of such large stresses reaching 2980MPa will result lot of pressure on the dies shaped material causing rapid die and frequent repairs.

For the calculation of cracking in the analysis of forging alloy CrNiN fracture model was used by the normalized Cockroft-Latham criterion described by the formula:

$$\int_0^{\varepsilon^*} \frac{\sigma_1}{\sigma_i} d\varepsilon = C_{gr}$$

where:

σ_1 - maximal principal stress,

σ_i - equivalent stress,

ε^* - cracking limiting strain,

C_{gr} - material constant determined in experiments

C_{gr} integral value determined from comparison trials uniaxial tension with the results of numerical simulations corresponding to the above-described test. The moment when a rupture of the test sample during the uniaxial tension values corresponded to a deformation which was compared with the values of the numerical calculations. The value of the integral Cockroft-Latham alloy CrNiN assumed at 0.35.

The figure below (Fig. 7) presents a map of the distributions of cracks, generated with the use of normalised Cockroft-Latham criterion [7],[8].

Thus, in the central part of the forging, the value of this integral remains with in the range 0.22 to 0.30 and therefore below $C_{gr} = 0.35$. A different situation applies in the flash zone, where the integral accepts values from the range 0.42–0.6.

In regard to simulation and the experimental results (Fig. 7), was mainly due to the stress state (Fig. 6a), which is in the middle of the forging takes the form of triaxial

compressive stress, thereby preventing the formation of cracks all the more difficult for the alloy which is newly machinable composed CrNiN.

In the case of the flash as shown in (Fig. 6a) are a tensile stress was observed mainly in the flash ends of the fixed area. This state of stress increases the possibility of cracking, as confirmed by physical examination.

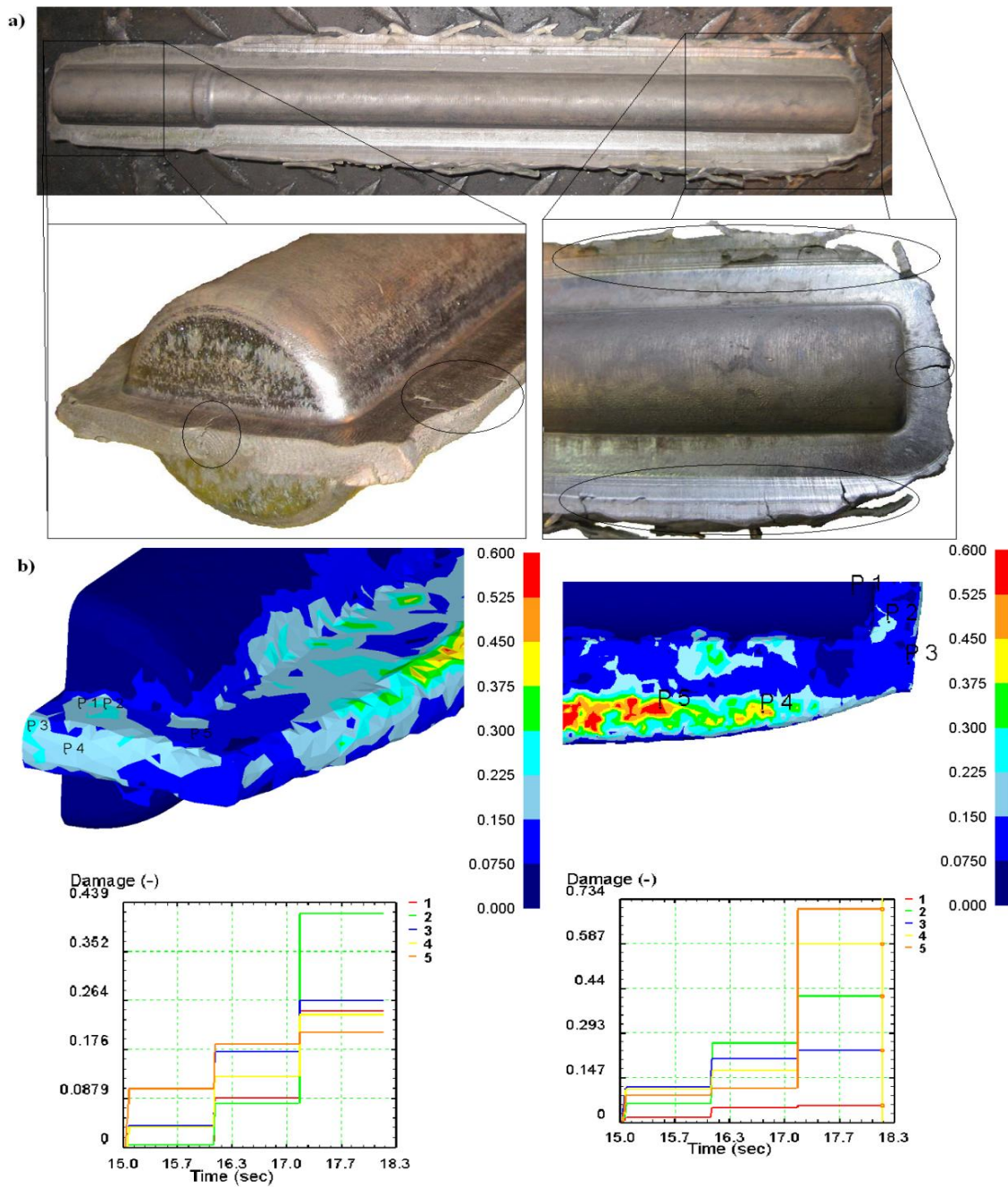


Fig. 7. Comparison of actual and resulting simulation zones of a breach coherence of the material in the flash forging; a) forging view at the end of the process; b) distribution of Cockroft-Latham in selected areas forging

It should also be noted too close to the occurrence of cracks near the flash butt forged part (Fig. 7), which is associated with a high risk of fracture passage forging. The solution to this problem is to change the shape of the geometry of the die is an increase in the area of this part of – the bridge in order to limit to a greater extent the flow area restricted tools.

5. CONCLUSIONS

The CrNiN alloy based on nickel and chromium is a newly developed construction material with a number of favourable qualities, which is why it was subjected to plastic working for the purpose of enhancing its properties. Forging, due to its broad and constantly increasing application in production processes of parts of machines, equipment, and various types of installations, was chosen as the method of working.

The results of the studies fully confirmed that chromium-nickel alloys, including the studied CrNiN alloy, are characterised by a low degree of formability and high deformation resistance [9]. This quality fundamentally limits the ability to obtain the high degree of material working that would be required to restructure its internal crystalline structure and to obtain improved and isotropic properties over its entire volume.

Due to the lack of technical ability to measure stress during the forging process, the verification of simulation follows from a comparison of the geometric shape of the forging and the nature of the material flow.

The test results as tensile strength R_m , yield strength $R_{0.2}$, A_5 elongation, and Brinell hardness HB are compared in (Table 1) with the parameters of the cast before being forged.

Samples for the implementation of the static tensile tests were taken from forgings after heat treatment - homogenization and solution heat treatment - carried out in the framework of the research work No. R15 039 02 [10].

Table 1. Comparison of mechanical properties the alloy CrNiN the structure of the cast and the forged

Description	R_m [MPa]	$R_{0.2}$ [MPa]	A_5 [%]	HB
Structure of the material after casting	597	440	39	-
Structure of the material after casting and heat treatment [10]	768	612	33	229
Structure of the material after forming and heat treatment [10]	976	650	58	-

The CrNiN alloy also exhibits high susceptibility to changes in thermal process conditions, and its plastic resistance continues to be determined by a deformation

mechanism dependent on (in addition to the working temperature mentioned above) the degree of deformation, and particularly its rate, which oscillates over a range of 10 to 250 s^{-1} in the case of drop hammer forging.

Analysis of these phenomena requires the conduct of further studies; however, it can already be stated that as the strain rate increases, the plastic hardening and resistance of the CrNiN alloy also increase.

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