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STUDYING THE EFFECTIVENESS OF THE NiCrN ALLOY FORGING PROCESS

Jerzy Schmidt[1], Alexander Kazakov[2], Andrzej Zagórski[3], Andrzej Świątoniowski[4]

[1] *Cracow University of Technology, Poland*
[2] *St. Petersburg State University of Technology, Russia*
[3] *Warsaw University of Technology, Poland*
[4] *AGH Unversity of Science and Technology, Poland*

Corresponding author:
Jerzy Schmidt
Cracow University of Technology
Institute of Processes and Products Innovation
Al. Jana Pawła II 37, 31-864 Kraków, Poland
phone: (+48) 12 374-32-74
e-mail: schmidt@mech.pk.edu.pl

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Abstract
Chromium- and nickel based alloys offer good mechanical properties, while keeping them also in highly corrosive environment. In addition, the introduction of the nitrogen at the level of 0.3 to 0.5% to the alloy structure, increases the plastic deformation ability of the cast alloy. This observation is fully confirmed by the results of the plastic deformation tests (performed on Gleeble), which are presented in this paper. The laboratory samples made of NiCrN wrought alloy and processed by die forging, demonstrated the significant increase of the yield stress and plastic deformation ability for the applied deformation degrees. The experiments showed about twofold increase of the resistance to cyclic loading for the forged products, when comparing it to the initial alloy state after casting. The developed technology (validated by numerical simulations) has been used to manufacture the workpiece for the propeller shaft. The results of the deformation performance for the element subjected to plastic processing have been compared with the material in its cast state.

Keywords
alloy NiCrN, forging process, mechanical propertis.

Introduction

Superalloys based on nickel and chromium are structural materials offering excellent mechanical properties and performance characteristics, usually applied in as-cast state. Yet, the material in as-cast state is both structurally and chemically heterogeneous having, moreover, some defects important under long-term loads or stress transfer under the near-boundary conditions. Therefore an important task is to improve the structural homogeneity of alloy, widening also its plastic deformability range under the operating conditions close to ambient temperature. A significant improvement of plastic properties in alloys with composition close to the equilibrium amounts of nickel and chromium was obtained by alloy modification with nitrogen. Forecasting the alloy behaviour was done by A. Kazakov from the St. Petersburg State University of Technology [1]. The selection of alloying elements and heat treatments proposed for this alloy has provided the as-cast mechanical properties at a level of 450 MPa to 1000 MPa with plastic deformability in a range from 50% to 10% [2]. Working under the project completed in 2007, an alloy dedicated for the heavily-loaded marine propellers for small and medium-sized marine vessels was developed. The composition of the alloy and its production technology were developed by the authors under the project carried out in SPECODLEW Foundry Innovative Enterprise in Krakow in collaboration with Foundry Research Institute. The developed cast alloy is characterised by high mechanical strength of 800 MPa to 900 MPa combined with the plastic deformability of 20% to

15%. The marine propellers made by this technology have successfully been tested since 2006 on ships in the Baltic Sea. The demonstrated insensitivity of alloy properties to the seawater environment enabled extending the range of alloy applicability to include other high-loaded parts of marine equipment requiring a homogeneous structure and high resistance to fatigue loads. This possibility gives the application of plastic working technology. The phenomena associated with plastic deformation of alloys based on nickel and chromium are still little understood, while the newly developed NiCrN alloy is additionally technologically difficult to produce even at the level of casting technology. Therefore it has been suggested to check the possibility of changing the alloy properties by forging using the developed model of the occurring phenomena and experimental studies. Modelling and experimental studies of the forging process were carried out on a model of the screw drive shaft geometry (the shaft with a graduated 27.5 mm and 23.5 mm diameter, 367 mm long) designed for the speedboat engine.

Test material and method

The use of forecasting method enables designing structures such as NiCrN in a wide range of basic mechanical properties. Depending on the required characteristics, the prevailing alloy constituent may be nickel or chromium in the presence of a sufficiently high nitrogen content. The mechanism of the nitrogen impact on alloy structure consists in extending the range of the austenite occurrence and in increasing the occurrence of nitrogen-containing dispersion compounds, making precipitation hardening of the structure with a reduced volume fraction of the α phase possible [3]. For practical implementation of the plastic working process, the alloy composition characterised by a possibly broad range of elasto-plastic deformation, allowing for strain hardening of the processed material, was adopted. Under these assumptions, an alloy with the basic composition containing 54% nickel, 45% chromium and an addition of 0.47% nitrogen has been made. The structure of this alloy is composed of γ nickel austenite with a small amount of $\gamma - \alpha$ eutectic and α phase. The matrix has carbonitride precipitates and small amounts of TCP secondary phases present in the interdendritic regions (Fig. 1).

The resulting as-cast mechanical properties can satisfy the requirements of the alloy plastic working. In a uniaxial tensile test, the strain hardening occurs in 30% to 40% of the total deformation range. The evaluation of the wrought structure highlighted the need for further heat treatment to improve the practical alloy properties. Based on experience, the heat treatment parameters were established to change the alloy structure after deformation and obtain optimum mechanical properties (Fig. 2).

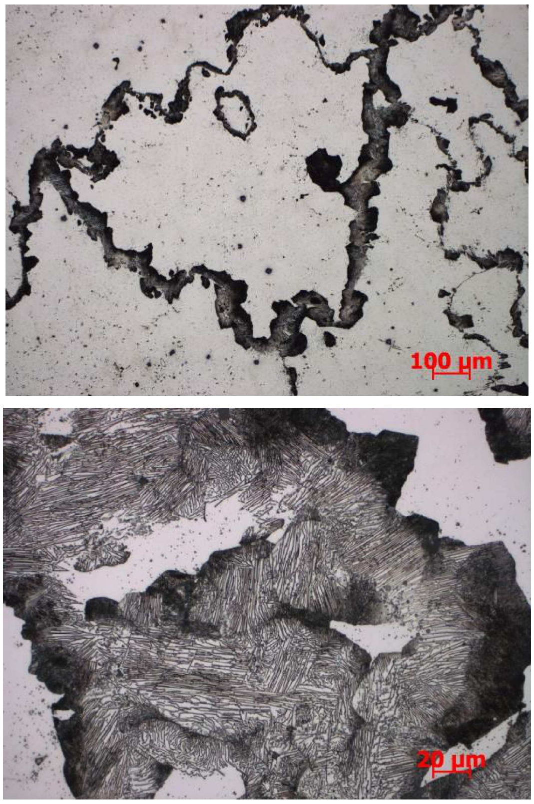

Fig. 1. Microstructure of the NiCrN alloy, are visable precipitate secondary phase.

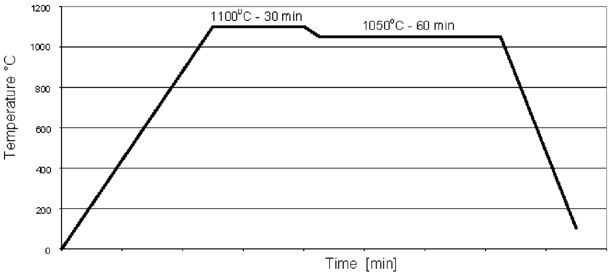

Fig. 2. Flowchart of heat treatment after die forging with times of holding calculated for 200 mm^2 cross-section.

Plastometry

The technological trials of plastic deformation of an NiCrN alloy required carrying out the preliminary model testing. To obtain the planned alloy properties and hardening degree, the forging process must take place within a predetermined range of temperatures and at a deformation rate resulting from the characteristics of the device used [4]. To determine these parameters, the hardening curves were plotted on a Gleeble 3800 simulator. Studies were conducted on 12 mm thick samples of 10 mm diameter placed in a Hydrawedge system in a protective gas atmosphere (Fig. 3).

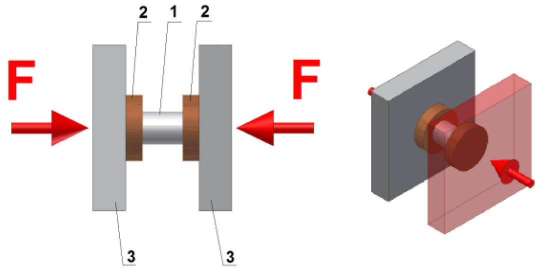

Fig. 3. Schematic representation of alloy deformation in a Gleeble 3800 simulator: 1 – alloy sample, 2 – copper substrate, 3 – anvil.

The study was conducted in a temperature range from 450°C to 1150°C. The stress-strain characteristics determined in an axisymmetric compression test were described as a function of yield stress. The test results expressed as a temperature effect on the yield stress of the investigated NiCrN alloy have logically indicated a decrease in the required yield stress with the increasing temperature (Fig. 4). Indeed, the values of yield stress are reduced at temperatures above 1050°C.

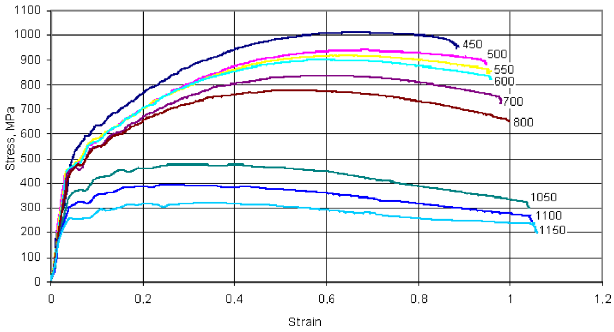

Fig. 4. Temperature effect on the yield stress of NiCrN alloy at the strain rate of 40 s^{-1}.

Within the whole studied range of temperatures no significant influence of the strain rate on the yield stress value has been reported. The metallographic analysis conducted on the specimens after upsetting revealed distinct deformation of the alloyed austenite γ phase showing traces of slip or deformation twins (Fig. 5).

The process of upsetting did not cause the occurrence of cracks in the examined specimens in a volume of the deformed material. The results of the conducted tests evidence the correctness and effectiveness of the process of alloy deformation under the test conditions of a Gleeble device.

Fig. 5. Microstructure of the specimen (differential contrast – DIC), visible is strongly deformed alloyed austenite, 500×.

Simulation of the forging process

Tests on rods of the 40 mm starting diameter (dictated by the dimensions and geometry of a model shaft) carried out on an industrial press did not confirm the, suggested by the results of plastometric tests and model calculations, good deformability of alloy under the conditions of free forging process. These tests have also showed that under the present conditions and state of strain, the material suffers cracks and is not suitable for deformation by the free forging process technology. The additional laboratory experiments have shown that under the conditions of free forging, the alloy deformation is critical to a level of 10% to 13%; any further deformation requires in each case a recrystallisation process. Analysing the test results, the necessity of applying a die forging process, enabling alloy deformation under the conditions of a triaxial state of strain, has been acknowledged. Based on the results of plastometric studies and analysis of temperatures of the dissolution of brittle phases during a thermodynamic process, the temperature of plastic forming was established at a level of 1050°C to 1150°C. To prepare the experiment, a simulation of the process was performed using the Q Form 3D and Deform 3D programmes [7]. To analyse the kinematics of the alloy flow under the conditions of the technological process, the temperature of 1150°C was adopted as a temperature of the stock, and 300°C as a temperature of the die. The calculations of the deformation process showed a decrease of forging temperature by 200°C near the die impression, combined with slight temperature increase in the flash area. The result is the lack of any more significant plastic deformation degree. The area of intensive deformation is only in the zone adjacent to the die parting plane. A solution improving the throughput of feedstock can be the application of a two-stage process. In the first operation, the rod is flattened along its entire length in an oval impression, while in the second operation, after rotation by 90°, it is forged to the final dimension [5]. The results of modelling the two-stage forging process for the deformation intensity distribution in forged material predict technological effectiveness of the planned experiment (Fig. 6).

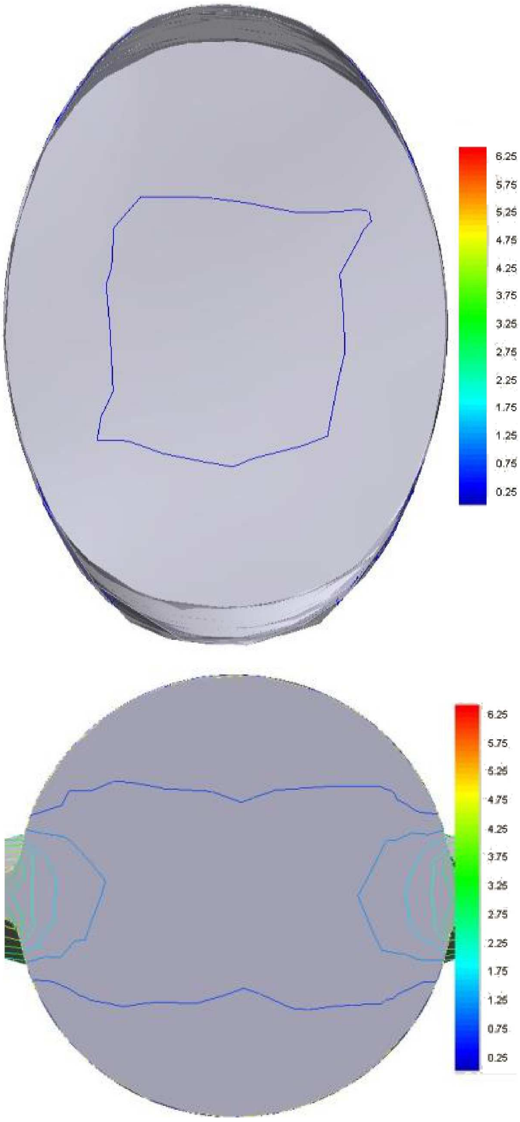

Fig. 6. Deformation intensity distribution in forged material after the process of preshaping in die impression and proper shaping-ready to the final dimension; two-stage forging process.

Results of die forging experiments

The starting material for the forging process were also rods of 40 mm diameter and 370 mm length. According to the suggestions arising from modelling, the shaping process was performed in a double-impression die. Rods were pre-heated before forging to a temperature of 1150°C. As a result of the plastic forming process, the geometry of a two-stage forged rod with flashes has been obtained. For after-forging state, metallographic examinations of the modified structure were performed (Fig. 7), in matrix are visable twins formed after partial recrystalization.

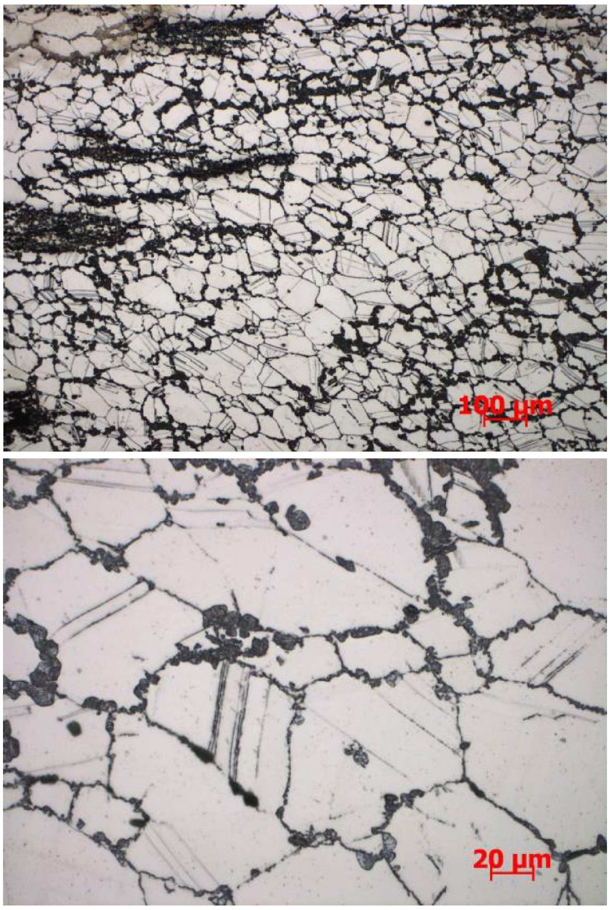

Fig. 7. The structure of NiCrN alloy after forging.

Analysis of the structure and the results of mechanical tests carried out on alloy after the process of forging pointed out to the necessity of a heat treatment process, because strongly deformed structure reduces the material plastic deformability, necessary in alloy application for operation as a structural material. Additionally, due to temperature drop under the conditions of a forging process, the brittle intermetallic phases related with the decrease of chromium solubility in nickel in the solid state start precipitating. By analysis it has been demonstrated that the range of recrystallising annealing should lie above the temperature of thermodynamic decomposition of the brittle precipitates. According to the assumptions previously developed, to improve the structural properties of alloy, forgings were subjected to a heat treatment according to the scheme shown in Fig. 2. The structure after the process of forging shows a substantial refining of the alloy grains. The images of microstructures show the changed geometry of the alloyed austenite γ grains of different orientations with twins formed also under the conditions of heat treatment and after finish process of recrystalization (Fig. 8).

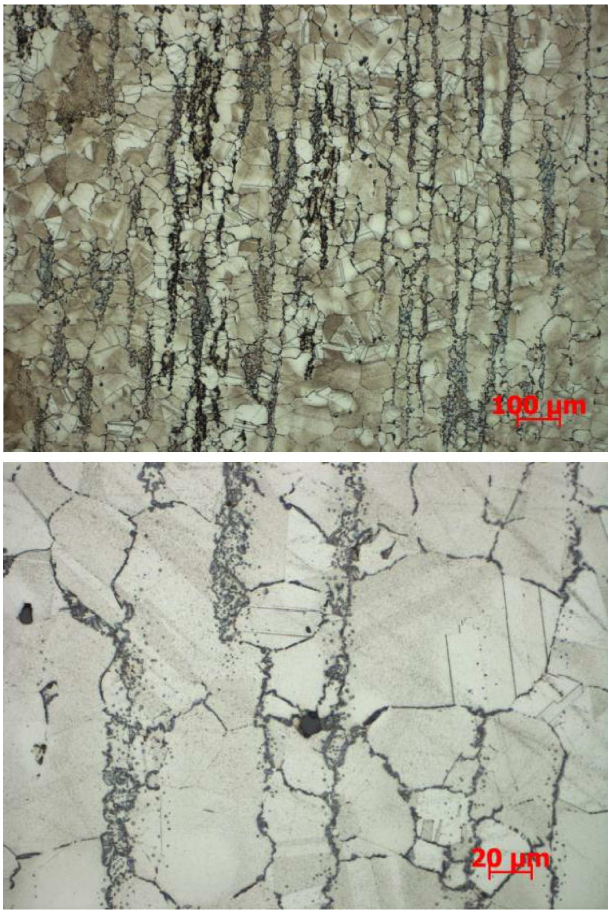

Fig. 8. The structure of NiCrN alloy after forging and heat treatment.

The analysis of alloy phase composition confirms the presence of two major structural constituents, i.e. the alloyed austenite γ solid solution (FCC lattice) and α solid solution (BCC lattice). The alloy structure also includes an Ni_2Cr phase and nitrogen-containing phases type Cr_2N, ε, π [3, 6]. As a result of the conducted plastic deformation process, material characterised by strength higher in respect of the base state and high plastic deformability was obtained (Table 1).

Table 1
Materials parameters.

	R_m [MPa]	$R_{0.2}$ [MPa]	A_5 [%]
As-cast	597	440	39
After forging	806	654	33
After forging and heat treatment	967	639	56

The graph (Fig. 9) show the resalts of the thermodynamic modeling of the tested alloy composition using the Fact Sage program. Austenite γ degradation starts at about 950°C, and the first particles are relased at the 875°C. The resalt of modeling confirms the austenitic structure and the incidence decay of nitride particles in the adopted forming temperature.

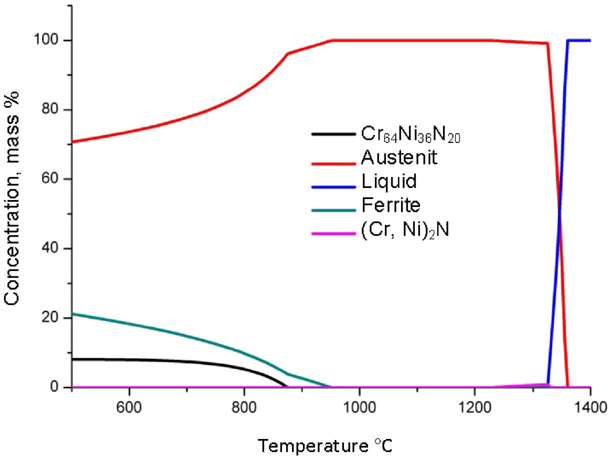

Fig. 9. Distribution of phase precipitate for tested NiCrN composition.

The alloy parameter relevant for the proposed use of this alloy for the heavily loaded carrying elements in the shipbuilding industry is the value of the fatigue limit determined under the environmental conditions of seawater and under ambient conditions. The level and ratio of these values are of considerable practical importance because changing stresses in the seawater environment give rise to sharp pits filled with corrosion products usually resulting in a reduction of fatigue limit. The fatigue limit was determined in a tensile test under the sinusoidal unilaterally positive load and studies were performed in Laboratory of Polish Naval Academy. In accordance with the standard requirements for material of this type, the limit number of load cycles was 20 million. The tested alloy showed no response to the seawater environment, having under both conditions a very high fatigue limit Zrj at a level of 550 MPa (Fig. 10).

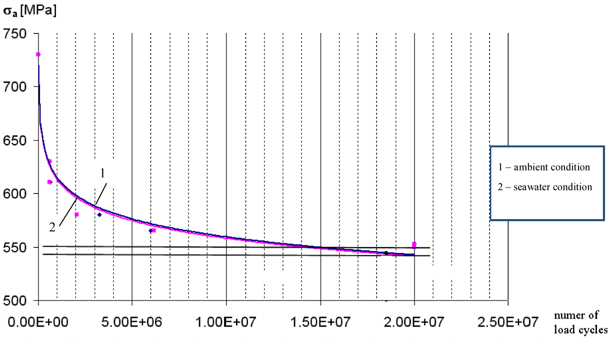

Fig. 10. Wöhler curves for alloy tested in seawater and in air at a temperature of 20°C.

To test in practice the evaluation of the benefits resulting from an increase in the mechanical properties of the structure as a result of plastic forming, using the designed loading system, mechanical tests of shape resistance were carried out on a model of a drive shaft of the geometry as described in introduction to this article. Loading with static forces in a scheme corresponding to the operating conditions was applied to models of the shaft made from the material in as-cast state and from the material after die forging. By the method of strain gauge tensometry, the deformation was measured in the direction of the main model zones loaded by the torque and bending moment. Comparing the characteristics of deformation, a clear increase in the shaft shape resistance was obtained as a result of the forging technology. Figure 11 shows examples of the deformation values obtained along the shaft axis on the cross-section of 23.5 mm (Fig. 11).

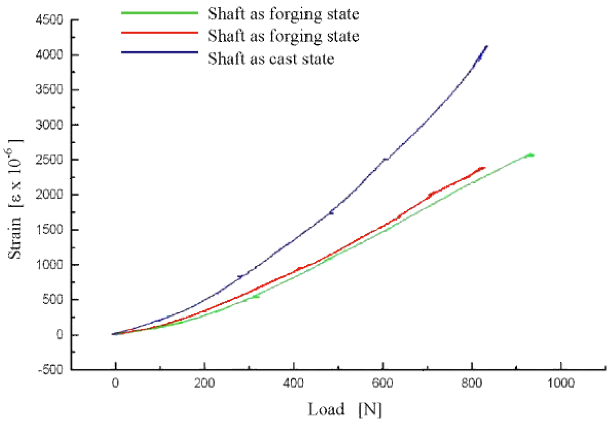

Fig. 11. The value of deformation measured along the shaft axis under the conditions of the simulated operating loading of the drive shaft model.

The apparent significant change in deformation of the material structure in both states confirms the usefulness and effectiveness of the application of the process of plastic working for enhancing the mechanical properties of an NiCrN alloy.

Final remarks

The conducted technological experiments and material tests enable drawing the following conclusions:

- By the method of forecasting the alloy properties it is possible to propose the chemical composition ensuring the structure in an NiCrN alloy making it capable of strain hardening in as-cast state without the need for heat treatment.
- The conducted studies showed that the mechanical properties of an NiCrN alloy can be significantly modified by plastic working in the form of forging under the conditions of a triaxial state of strain, while hardening of the material increases with the degree of plastic deformation.
- The elimination of as-cast structure on the entire cross-section is possible by application of a multistage plastic forming process allowing in the technology developed for alloy crack-formation sensitivity.
- The structure rebuilt by two-stage die forging confirmed the, proved for as cast state, insensitivity of alloy to the seawater environment; high values of the fatigue limit Zrj amounting to 550 MPa at 20 million load changes and amounting to 600 MPa at 2 milion load changes, as compared to the fatigue limit of 300 MPa at 2 million load changes for alloy of the same strength limit as cast and forged state were obtained.
- The resulting mechanical properties do not represent the limit values for the structure obtained by forging, and the actual strength is dependent on the deformation degree as a result of the multistage forging process with interoperational recrystallisation.
- The plastic working of NiCrN alloys should be carried out at temperatures from 1100°C to 1150°C, conferring the necessary technological ductility to the alloy and reducing the precipitation of brittle intermetallic phases that cause alloy hardening in the process of deformation.
- The simulation results indicate that the main factor responsible for the resistance to deformation during plastic forming of an NiCrN alloy is the deformation mechanism dependent on the temperature of plastic forming, the deformation degree and speed of the process.
- The characteristics of the hardening process obtained in upsetting tests performed on the Gleeble simulator indicate a stable deformation of alloy under the experimental conditions (homogeneous state of deformation, speed of deformation and homogeneous temperature field), which, nev-

ertheless – as found experimentally for alloy of a given composition, does not provide relevant and useful information to design the NiCrN alloy forging process for application under the production conditions.

- The individual character of the deformation process suggests the need of its closer examination for each NiCrN alloy composition before the development of a plastic forming technology.

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