Publishing House
AKAPIT

COMPUTER METHODS IN MATERIALS SCIENCE
Informatyka w Technologii Materiałów

Vol. 15, 2015, No. 2

PREDICTION AND INVESTIGATION OF FRACTURE INITIATION IN WARM FORGING OF MARTENSITIC STAINLESS STEEL WITH AID OF FEM SIMULATION

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Abstract

Warm forging brings together advantages of hot (e.g. forging load reduction) and cold (e.g. no scale) metal forming operations. However, due to decreasing the process temperature, the risk of fracture occurrence increases. In this paper the risk of cracking initiation during warm forging of surgical forceps made of martensitic stainless steel is estimated. The investigations assume the analysis of the fracture initiation point in the component during forging and attempt to define the critical value of process parameters by means of laboratory tests and FEM numerical simulation.

Key words: martensitic stainless steel, warm forging, fracture criteria, workability

1. INTRODUCTION

Martensitic stainless steels are structural materials combining unique operational properties with good mechanical properties. Combining excellent mechanical properties and moderate corrosion resistance they can work under high and low temperatures (Samolczyk et al., 2007). The need for superior properties in specific applications led to wide researches on the performance improvement of these steels (Nasery Isfahany et al., 2011). Despite relatively low content of costly alloying elements, in the composition of grades such as X20Cr13 or X20Cr46, contrary to comparable corrosion resistance materials, the material costs of martensitic stainless steel still arises the tendency for precision forging of complex-geometry parts. Another reason promoting the net forging is excellent hardenability of these steels, allowing small-sections to be through-hardened into martensitic structure, which practically excludes machining in as-forged condition. Thus, precision forging tend to be competitive method of manufacturing complex-shape parts of martensitic stainless steels.

Warm forging brings together advantages of hot (e.g. forging load reduction) and cold (e.g. no scale) metal forming operations. However, due to decreasing the process temperature, the risk of fracture occurrence arises. Due to complex state of stress and strain in closed-die forging, (particular hammer forging with high strain rates) the forming technology is conditioned by the use of proper technique, with of plasticity of the forged material taken into account. Selection of the working conditions can be aided with processing maps. However, they do not refer to the effect of state-of-stress, which apart from the intrinsic workability contribute to plasticity in the given thermo-mechanical conditions of deformation. That aspect can be taken into consideration by formulation of failure criteria and determination of its threshold value.

 ISSN 1641-8581

The fracture criteria have been extensively studied for the last decades and there can be dozens of different formulas found in the literature, accounting to different thermo-mechanical parameters. They cover a wide range of technological instances. It gives a wide spectrum of parameters to be included in the design of technology, but on the other hand, it makes it hard to select appropriate criterion for an individual case. In the presented study, results of criterion selection for identification of fracture initiation in warm forging of martensitic stainless steel X20Cr13 are presented. The research is oriented at coupling the proper criterion to high-strain rate forging process in the lower work range and calculation its limiting integral, with a view to its application to hammer forging process of surgical forceps. This process is utilized as a case study, which allows validation of applicability of the presented models and results.

2. MATERIAL AND METHODS

The methodology used in the study combined laboratory experiments and numerical modelling with finite element method in the stages of analysis of a fracture model. In experimental procedure, two geometries of cylindrical sample were involved, plain and flanged one, which indicates higher sensitivity to concentration of state of stress in preceding numerical analysis (figure 1). The compression tests were carried out on a laboratory rig based on a hydraulic press of capacity 5 MN. The press enabled precise registration of process parameters such as force, velocity and temporary position of the upper tool or temperature. Flat surface tools were used, made of cold-work tool steel. Dry frictional conditions were maintained. The process involved upsetting of samples with a large deformation, up to 1.6 logarithmic strain with recording of the process parameters in order to capture the moment of fracture initiation.

The shape of specimens used in the compression test and the flow curves of the investigated material covering boundary temperatures, are shown in figure 2a and 2b, respectively. A cylindrical specimen upset into a flat pancake, is usually considered to be a standard bulk workability test. The average stress state during testing is similar to that in many bulk deformation processes, without introducing the problems of necking (in tension) or material reorientation (in torsion). Therefore, a large amount of deformation can be achieved before fracture occurs. The stress state can be varied over wide limits by controlling the barreling of the specimen through variations in geometry and by reducing friction between the specimen ends and the anvil with lubricants.

The experiment involved uniaxial compression at different temperatures within the warm forging range, 720-860 °C. During deformation, welded-on thermocouple was used for temperature measurement, accompanied by plotting of the load digital camera recording for detection of fracture initiation location and time. FEM allowed estimation of mechanical parameters, introduced into several fracture criteria, which were further used for the analyzed case study – the industrial process of warm hammer forging.

The material used in the study was AISI 420 martensitic stainless steel (DIN/EN: X20Cr13, steel code: 1.4021), commonly used for the manufacture of forged parts such as surgical and dental instruments, steam generators, mixer or turbine blades,

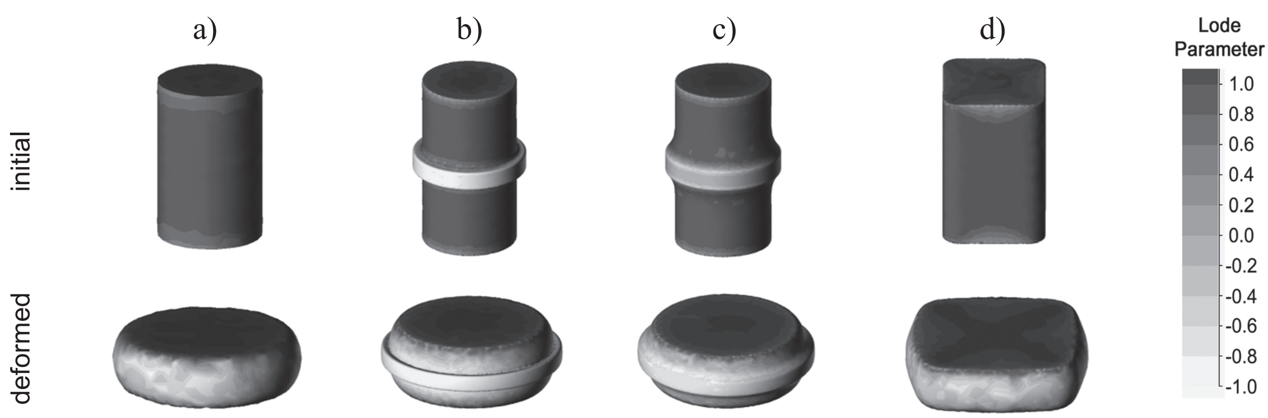

Fig. 1. Effect of geometry on stress concentration sensitivity in compression tests: a) plain cylindrical, b) cylindrical-flanged, c) cylindrical-flanged with generous fillet, d) cuboidal sample

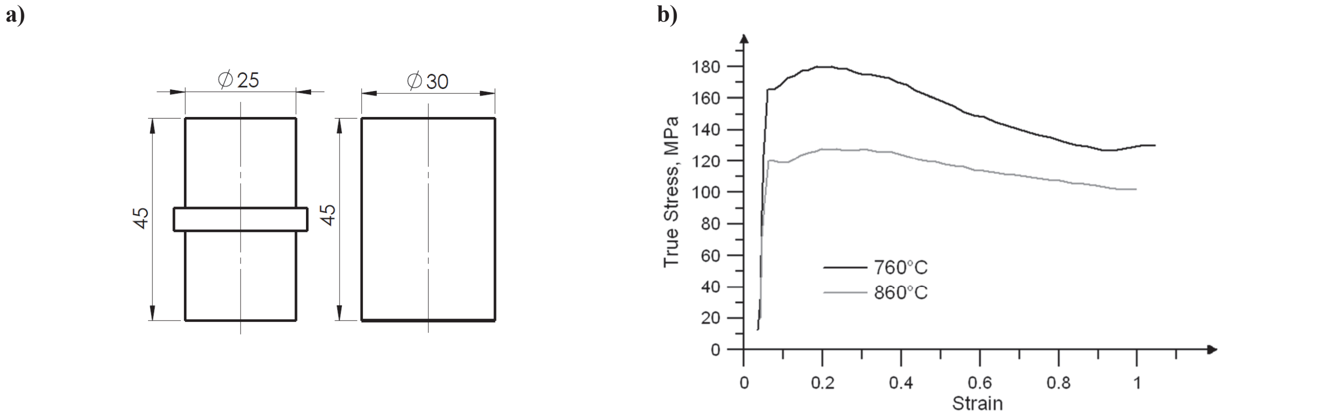

Fig. 2. Samples used in the compression test: a) geometry, b) stress-strain curves of the investigated material (effective strain rate 0.2 s^{-1})

pump components, piston rods, shafting fittings, steel balls, bolts, nuts, valves, glass and plastics processing tools, cutlery and various hand tools (Brnic et al., 2011). Chemical composition of the steel presented in table 1. The material features good plasticity in hot working conditions. However, taking advantage of benefits offered by warm forging, can influence its mechanical behaviour, as denoted by (Skubisz et al., 2012). Increasing the risk of fracture occurrence in the material usually leads to the defects formation (Byrer et al., 1985). Figure 4a shows the analyzed component with a visible fracture. The aim of the work enables determination of the conditions yielding to crack, in addition to the validation of the crack prediction method and its parameters.

***Table 1.** Chemical composition (wg. %) of the investigated steel*

C	Si	Mn	P	S	Cu	Cr	Ni	Mo	V
0,19	0,22	0,4	0,027	0,003	0,05	13,33	0,33	0,1	0,05

3. MODELING ASSUMPTION AND CRITERIA MODELS

Laboratory tests of upsetting were carried out so as to induce cracking. The numerical simulation determines the thermo-mechanical parameters at fracture initiation. This approach allow identifying the parameters in fracture criterion. For this purpose, numerical simulations of the compression tests and of the actual technology of closed-die warm forging process with use of a commercial software QForm3D were conducted. FEM analysis involved three-dimensional state of strain both in compression test and in the drop forging process, with assumption

of visco-elastic-plastic model of the deformed body and elastic-plastic model of tools. To reflect the real industrial process conditions, boundary restrictions on the nods in surfaces were defined and coupled thermal-mechanical analysis was used. Levanov friction law was used

$$\tau = m\frac{\sigma_p}{\sqrt{3}}\left(1 - e^{-1,25(\sigma_n/\sigma_p)}\right) \qquad (1)$$

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

In the light of the importance of the largest tensile stress σ_θ Cockcroft and Latham (2) (Gouveia et al., 1996) have suggested fracture criterion based on a critical value of the tensile strain energy per unit of volume. The criterion is not based on a micro mechanical model of fracture, but simply recognizes the dependence of the critical value at fracture upon the level of the largest principal of stress. The dependence of the level of both the largest principal stress and the hydrostatical stress σ_m was suggested by Brozzo (3), with empirical modification of the criterion. Recent experimental results conclusively show that ductile fracture in bulk metal forming process fits a void growth model (Hütter et al., 2013).

According to this model, voids initiating at inclusions or hard second phase particles in region that are highly deformed, grow under plastic deformation caused by normal or shear stress and finally link up with one another to form macroscopic coalescent event. Based on this hypothesis several criteria were suggested e.i. by Rice and Tracey (4) (Andrade Pires et al., 2003).

Table 2. Fracture criteria analyzed in the study

Cockcroft and Latham		Brozzo		Rice and Tracey	
$\int_0^{\bar{\varepsilon}_f} \sigma_\theta d\bar{\varepsilon} = C_1$	(2)	$\int_0^{\bar{\varepsilon}_f} \frac{2\sigma_\theta}{3(\sigma_\theta - \sigma_m)} d\bar{\varepsilon} = C_2$	(3)	$\int_0^{\bar{\varepsilon}_f} \exp(\frac{3\sigma_m}{2\bar{\sigma}}) d\bar{\varepsilon} = C_3$	(4)
where $\bar{\sigma}$ is the effective stress and $\bar{\varepsilon}$ is the effective failure strain.					

4. RESULTS AND DISCUSSION

4.1. Calculated stress fields in the forged part

Analysis of the forging process was focused on state of stress components and strain distribution in the fracture area and on detailed study of these parameters development at the point of crack initiation was done. State of stress, depicted by behaviour of mean stress and/or maximum principal stress, shows prevailing tensile component of ever-increasing but moderate level. In the aftermath, the integrals are high enough for the rupture to occur, which means that the defined critical values of individual fracture criteria are reached.

principal stress are very similar to each other, except that the sudden increase occurs between 0.07 and 0.08 second and the maximum value is reached at 0.086 second, that is, the moment that intense flow of the material outward the impression to the flash gutter took place.

It was found, that the area in which the discontinuity of material occurred, was characterized by the metal flow induced by tensile stress concentration. At the moment of forging completion both σ_θ and σ_m reached their peak values (figures 3a, 4b, 4c). The diagram allows to conclude, that despite seemingly most comparable state of stress in compression test and good agreement in prediction of the spot of the fracture, estimation of limiting integral requires

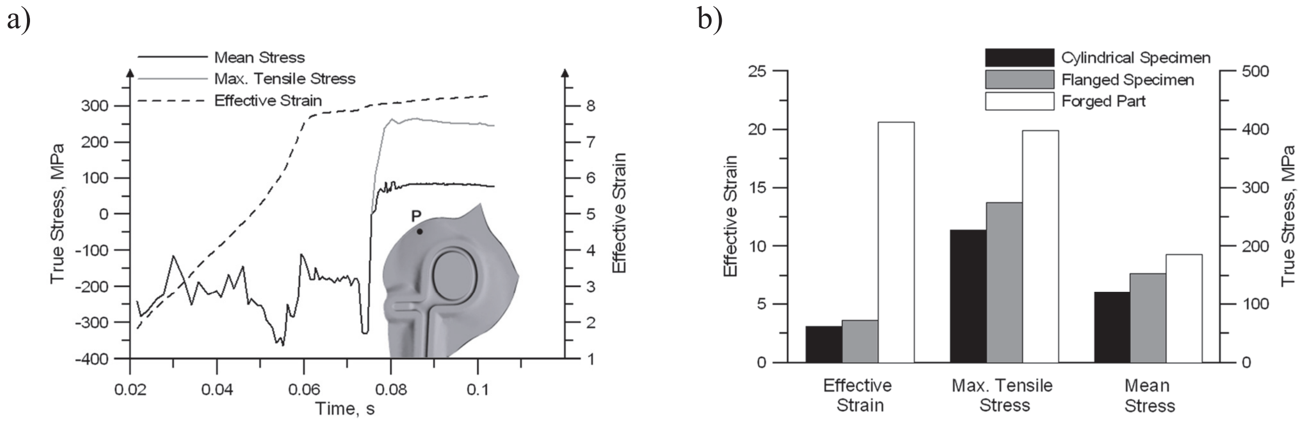

Fig. 3. Results of the FEM modeling: a) plots of the analyzed parameters in the point P, b) comparison of the maximum values of Effective Strain, Maximum Tensile Stress and Mean Stress for cylindrical, flanged specimens and the forged part in point P

All of the used models are based on the effect of the tensile stress, directly or as mean stress, and all of them indicate the crack formation spot with good consistency to one another and to the factual workpiece. Analysis of the parameters in the crack initiation point (point P) showed an increase in both effective strain, mean stress and maximum principal stress. Figure 3a shows, the high slope of effective strain evolution from the beginning of the process to 0.06 sec. From this moment on, the increase is relatively small. The plots of mean stress and maximum

utilization of other type of tests. Comparison of the calculated values of strain and stress indicators in the free surface of compressed specimens in the location P of the warm drop-forged workpiece suggested significantly higher values (figure 3b).

Analysis of the distribution of fracture criteria values (figures 4d, 4e, 4f) indicates, that the area, where fracture appeared, is particularly vulnerable to the occurrence of damage. The modeling results suggest significant role of positive stress in the failure onset, which is also indicated in the applied fraction criteria. Figures 4g and 4h shows Lode parameter (5) and Triaxiality factor (6) distribution which exhibit stress state in the part of analyzed component so as to enhance the effect of state of stress in the model.

As mentioned, the cylindrical specimens were subject to uniaxial compression to be upset-forged to logarithmic strain 1.6, applying variable work temperature. State of stress components are derived from numerical simulations, which results are shown in figure 1.

Table 3. *Calculated values of state of stress factors considered in estimation of plasticity*

Parameter	Description		Uniaxial Tension	Compression
Triaxiality Factor	$TF = \frac{(\sigma_1 + \sigma_2 + \sigma_3)}{\sqrt{0,5[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]}}$	(5)	1	-∞
Lode Parameter	$\mu = \frac{2\sigma_2 - (\sigma_1 + \sigma_3)}{\sigma_1 - \sigma_3}$	(6)	-1	1

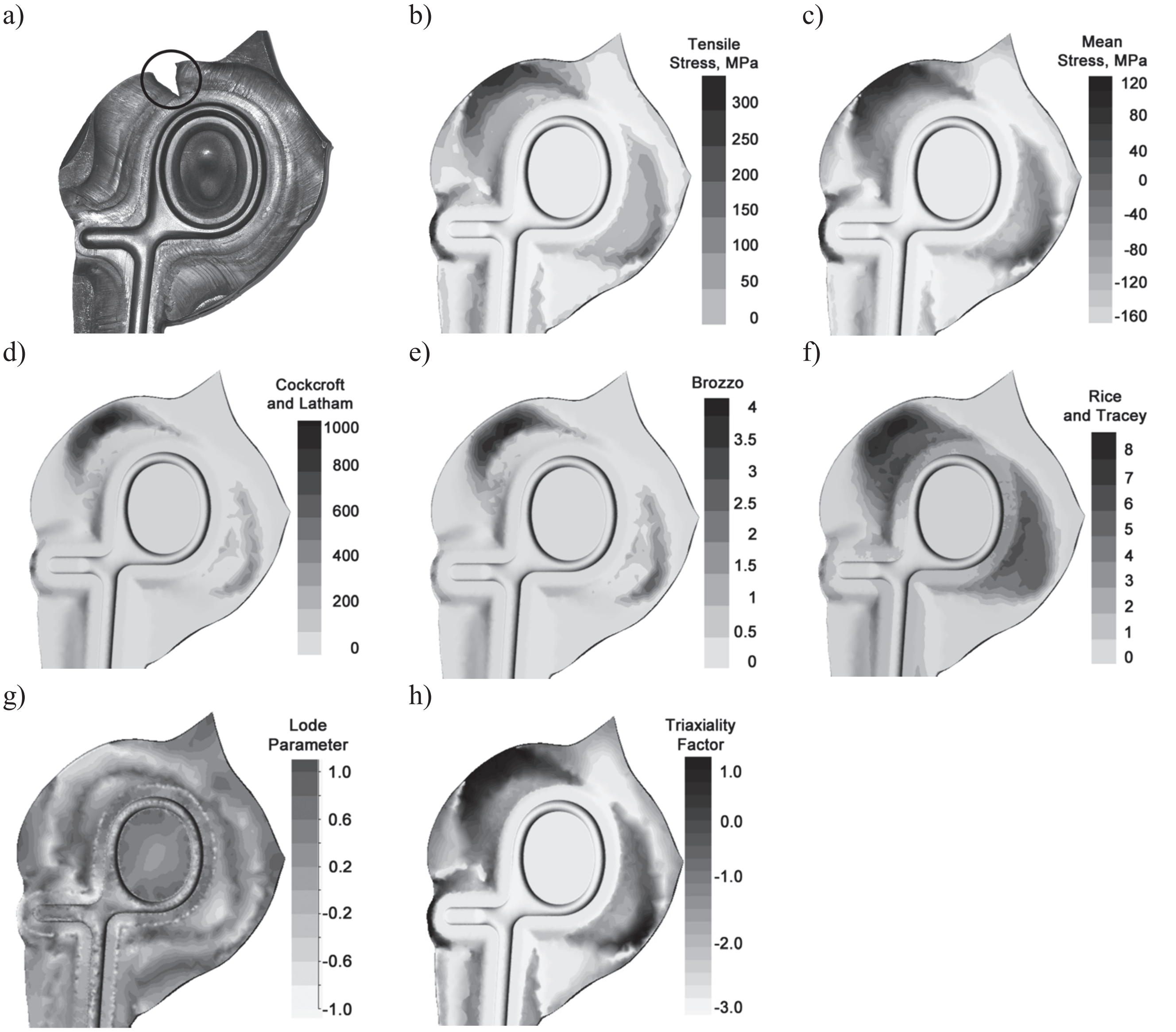

Fig. 4. *Forged part with damage (a), and b)-h) distribution of the calculated parameters: b) tensile stress, c) mean stress, g) Lode parameter, h) Triaxiality Factor, and fracture criteria indices distribution: d) Cockcroft and Latham, e) Brozzo, f) Rice and Tracey*

4.2. Stress analysis in compression tests

The intended result of the test was to estimate the critical value of deformation (the failure strain).

For credibility of the established simulation parameters the simulation was validated by comparison of load and temperature recorded during the tests. As shown in figure 5, perfect fit was obtained, which confirms good consistency of flow stress and material-thermal data. During compression at lower ram velocity, 5 mm/s the fractures on the sample surface were not observed. Similar test was conducted at higher straining rate, resulting from increasing ram velocity to 50 mm/s. However, no failure was observed. The compression tests were repeated with the use of cylindrical specimens with a flange (figure 2a), meant for tensile stress concentration. Despite almost 50% higher tensile stress level, no defects were induced.

For unequivocal interpretation of the fracture origin, metallographic examination was done in order to determine the occurrence of internal defects that could be the cause of fracture initiation of the material (figure 6). No material defects were reported. In vicinity of single precipitates reaching 20 microns at maximum, there were no microcracks, which could join in chains. The fracture was attributed to the specific state of stress in this area of the element.

ing hot forging of the surgical component made of stainless steel, have proved good forgeability of the material in warm forging range both at moderate and high strain rate, close to the conditions expected in hammer forging, withstanding relatively high tensile stress level.

In initial stages of the process tensile stresses prevail. With completion of the die impression fill-up, near hydrostatic state of stress is observed, which allow low level of fraction criteria parameters in the region of the part alone. Seemingly it makes no hazard of failure, however, the tensile stress inducing in the flash periphery are much bigger than those observed in compression tests. Rupture originating in the flash may propagate inward the part, and if it goes undetected, may cause serious hazard in service. Also effective strain values are higher than in the axis of the upset-forged specimens.

Comparative analysis of the both cases leads to conclusion, that the fracture criteria, based on compression tests provide insufficient strain and stress levels so as to represent conditions inside the die impression. However, they are too low in reference to those observed in the flash, where fracture can be observed.

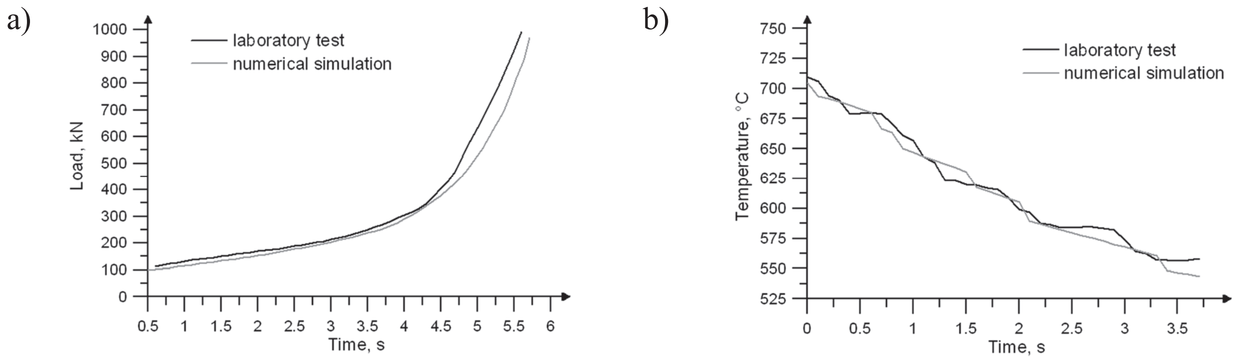

Fig. 5. *Comparison of simulated and experimental values of: a) forging load, b) specimen temperature*

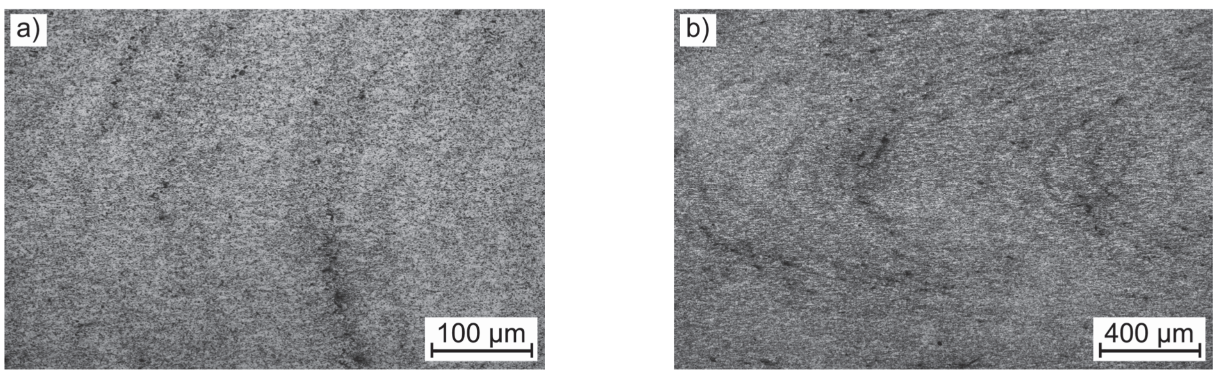

Fig. 6. *Micrographs of the specimen after compression test at 780°C. Etched in 5 ml H_2O; 7 ml HNO_3; 8 ml HCl*

5. SUMMARY AND CONCLUSIONS

The conducted uniaxial compression tests, aimed at determining the risk of occurrence of cracks dur-

As displayed by fraction criteria parameters distribution maps calculated with FEM based simulation, the applied models allowed accurate prediction of fracture location.

ACKNOWLEDGEMENTS

Special thanks are addressed to Tadeusz Skowronek for support in metallographic work.

Financial assistance of NCBiR within the project PBSII, agreement 19.19.110.86730.

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PRZEWIDYWANIE I ANALIZA POWSTAWANIA PĘKNIĘĆ PODCZAS KUCIA NA CIEPŁO NIERDZEWNEJ STALI MARTENZYTYCZNEJ PRZY POMOCY SYMULACJI NUMERYCZNEJ MES

Streszczenie

Kucie na ciepło łączy ze sobą zalety procesów przeróbki plastycznej na gorąco (np. zmniejszenie siły nacisku narzędzi) oraz na zimno (np. brak zgorzeliny). Jednakże obniżeniu temperatury procesu towarzyszy zwiększone ryzyko powstawania pęknięć. W artykule oszacowano ryzyko występowania pęknięć podczas kucia na ciepło kleszczy chirurgicznych z martenzytycznej stali nierdzewnej. Badania zakładają analizę miejsca inicjacji pęknięcia podczas kucia oraz próbę określenia krytycznych wartości parametrów procesu przy pomocy metody łączącej testy laboratoryjne oraz symulację numeryczną MES.

Received: October 31, 2014
Received in a revised form: November 20, 2014
Accepted: November 23, 2014