A R C H I V E S O F M E T A L L U R G Y A N D M A T E R I A L S
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COMPUTER SIMULATION AIDED STUDIES ON THE IMPACT TRANSITION TEMPERATURE OF MICROALLOYED STEEL FORGINGS

WSPOMAGANA SYMULACJĄ KOMPUTEROWĄ ANALIZA TEMPERATURY PRZEJŚCIA W STAN KRUCHY W ODKUWKACH ZE STALI MIKROSTOPOWEJ

The ability to design metal forming processes requires knowledge of continuum mechanics and materials engineering. The papers presents the results of research on the complete analysis of the forging process of microalloyed steel. The forging process assessment was performed based on thermomechanical calculations and using microstructural modeling. Hardness tests were employed for the verification of computed results. A method of predicting the relation between quality of final product and history of metal forming as well as microstructural development using an FEM simulation is also presented here. The results of the FEM-simulation for the forging process and material are compared with experimental data to show the feasibility of the proposed method. Finally, it is stated that by using properly built software it is possible to eliminate brittle cracking in the forged products, especially at low temperatures.
Keywords: metal forming, microalloyed steel, microstructure, mechanical properties, computer simulation

Właściwa analiza procesów przeróbki plastycznej metali wymaga zarówno wiedzy z zakresu mechaniki ośrodków ciągłych, jak i inżynierii materiałowej. Przedstawione wyniki badań stanowią przykład kompleksowego podejścia do oceny zjawisk mikrostrukturalnych towarzyszących procesowi kucia matrycowego stali z mikrododatkami stopowymi. W oparciu o wyniki obliczeń w części termomechanicznej przeprowadzonej analizy oraz wykorzystując podstawowe modele opisujące zmiany zachodzące w mikrostrukturze odkształcanego materiału przeprowadzono ocenę poprawności przeprowadzonej symulacji komputerowej procesu wytwarzania odkuwki o złożonym kształcie. Weryfikacja uzyskanych obliczeń została wykonana za pomocą pomiarów twardości. W efekcie sformułowane zostały wnioski wskazujące na ścisły związek pomiędzy jakością wyrobu gotowego a całą historią procesu przeróbki plastycznej i związanym z tym rozwojem mikrostruktury. Stwierdzono, że wykorzystując poprawnie zbudowany program symulacji procesu kucia możliwe jest zlokalizowanie obszarów najbardziej narażonych na kruche pęknięcia w czasie eksploatacji w niskich temperaturach.

1. Introduction

Correlation between deformation history and inhomogeneity of mechanical properties is usually shown as an effect of simultaneous thermomechanical treatment and microstructural analysis. The result is usually distribution of particular properties, most commonly represented by hardness, as an effect of individual hardening mechanisms (strain, precipitation, solid solution and grain boundary hardening). In the present work, Impact Transition Temperature (ITT) was taken into discussion as a very important property of forged products. Every from above-mentioned hardening mechanisms is a function of process and material parameters. In case of the Impact Transition Temperature, which is usually determined in Charpy impact test at various temperatures, microstructural influence is especially important. Local decrease of formability in forged materials, which are used as structural material working at low temperatures, could cause cracks nucleation, what finally could lead to the component destruction. In many cases there are discrepancies between valuation of usability based upon most commonly used mechanical properties, and valuation based on ITT analysis. The usage of computer simulation to determine the local values of ITT is a good example that in some cases, when conducting experiments is impossible, simulation is the only means of determining ITT value in the final product. ITT is an effect of microstructure development, which in turn is a function of deformation history. The problem pre-

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sented in this paper seems to be especially important for the evaluation of computer simulation effectiveness in tracing particular phenomena taking place in the deformed material. Still, there is a lack of possibility to observe processes occurring within the microstructure during the deformation, especially at high temperature. The current level of theoretical analysis allows one to use various models based on physical phenomena during the simulation process. However, the issue of experimental verification of obtained data remains open, especially in the case of a complex microstructure development that depends on the whole deformation history.

2. Research description

The process of drop forging was chosen for the discussion of the relationship between strain history, more exactly strain path and microstructure inhomogeni-ty as well as mechanical properties. In the current work, high-strength low-alloy (HSLA) steel was used with the chemical composition summarised in Table 1. This material was processed by a two-stage drop forging according to scheme presented on Fig. 1. The first step was to prepare the prior shape (Fig. 2). Because of Nb alloy, the final microstructure of examined steel is the effect of interaction between solid solution hardening, precipitation process – especially strain-induced precipitation of Nb(C,N) as well as dynamic, metadynamic and static recrystallization. The cooling conditions during the experiments ensured the domination of ferrite structure at room temperature. A competition between precipitation process and recrystallization (Fig. 3) enables controlled microstructure development and controlled properties of final products made from microalloyed steel. A relatively small change in the process conditions can cause acceleration or deceleration of the processes of precipitation and recrystallization, which at the end can cause changes in the microstructure and mechanical properties of the final product and increase its inhomogeneity.

TABLE 1

Chemical composition of examined steel

C	Mn	Si	P	N	Nb
0.07	1.36	0.27	0.015	0.009	0.07

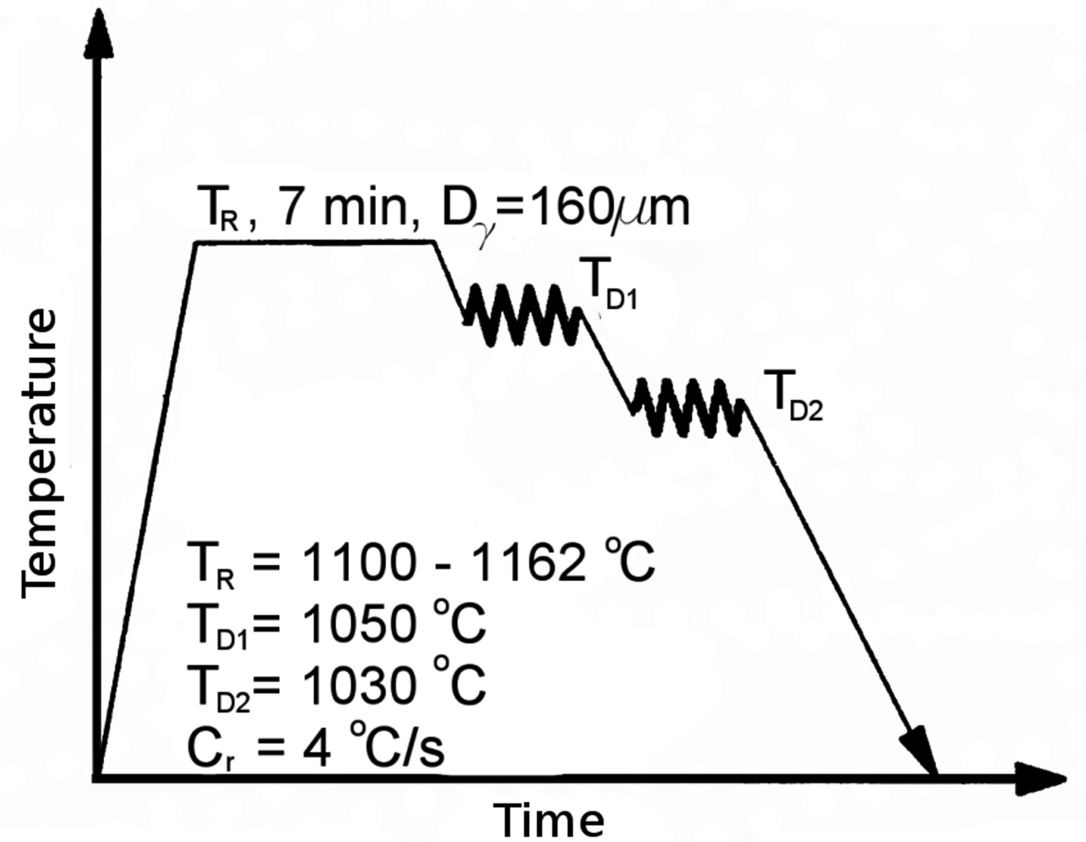

Fig. 1. Scheme of deformation history in examined forging process

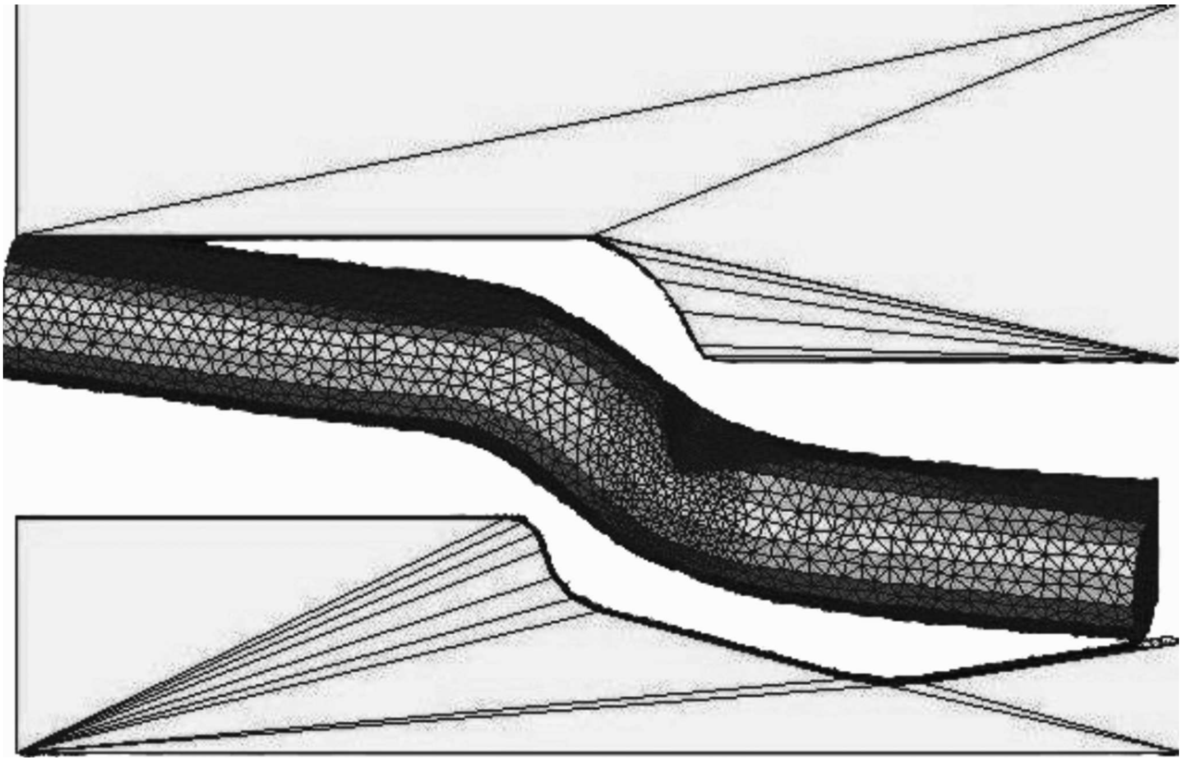

Fig. 2. Result of simulation of the first stage of forming

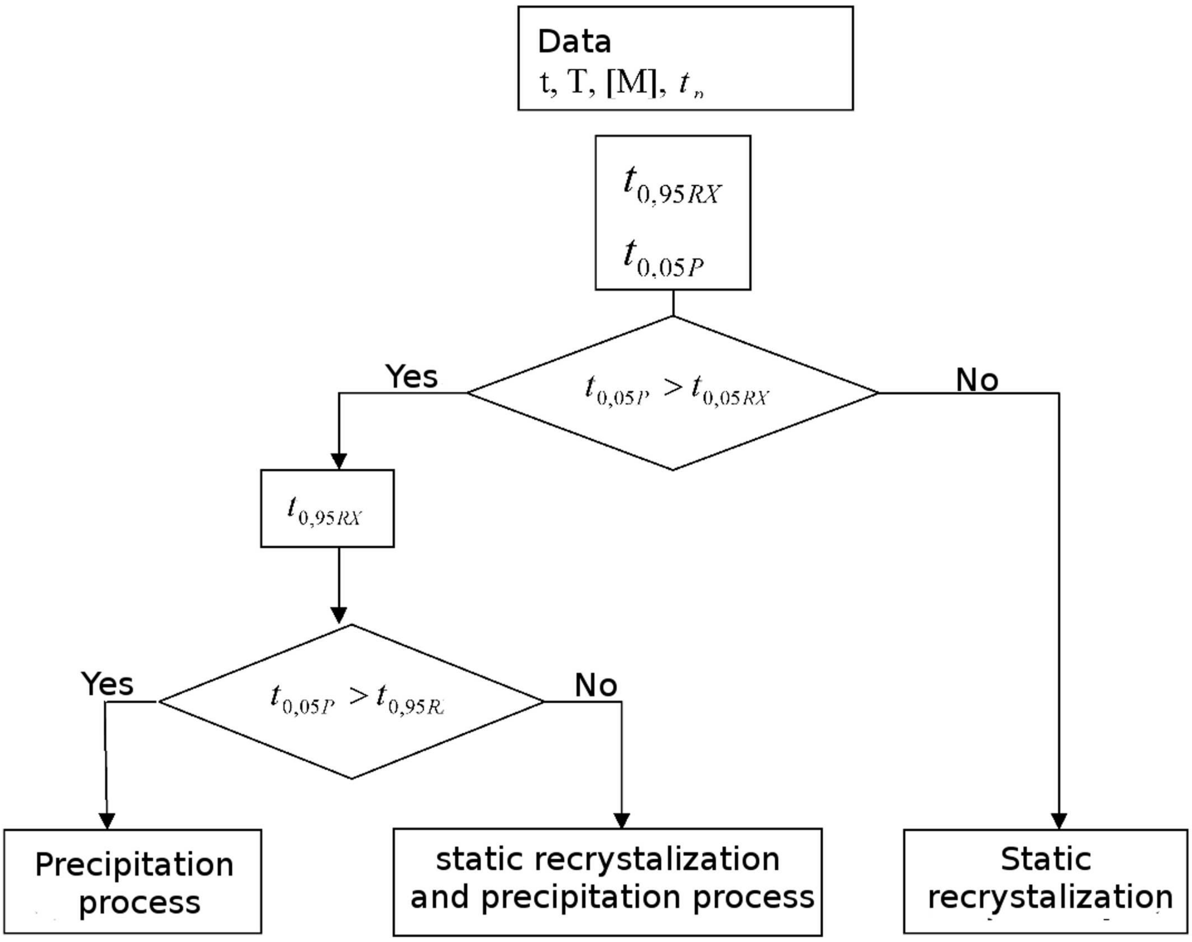

Fig. 3. Algorithm of chosing the main termomechanical process taking place in the material

2.1. Computer simulation

A general diagram of the relationship between fundamental microstructural phenomena used in the discussed computer simulation of drop forging is presented on Fig. 3. The thermo-mechanical computations were made with the use of FORGE3® software [1]. In order to properly represent the relationship between the deformation process, microstructure changes and mechanical properties it is necessary to take into consideration the interactions between individual components of the complex model (Fig. 4). Because of microstructure development taking place during forging, processing variables and microstructural variables, have a strong influence on each other during the computation process. A precise representation of these relationships in the simulations is vital. Presented research was focused on influence of deformation history on microstructure development and inhomogenity of mechanical properties. Additionally influence of heat generated during deformation on inhomogeneity of temperature field and its consequences on microstructure development was analysed. Most important models used in the present computer simulation are shown in Table 2. The performed computer simulation of the drop forging process allows one to establish the local values of Impact Transition Temperature. So far, it has been proven [2] that the lack of information on both the average value and local fluctuations of ITT can result in a fatal crash. One of the causes of material destruction in this case is the premature initiation of brittle fractures in low temperatures. Hence, the influence of deformation history and the resulting microstructure development are key factors determining the value of Impact Transition Temperature.

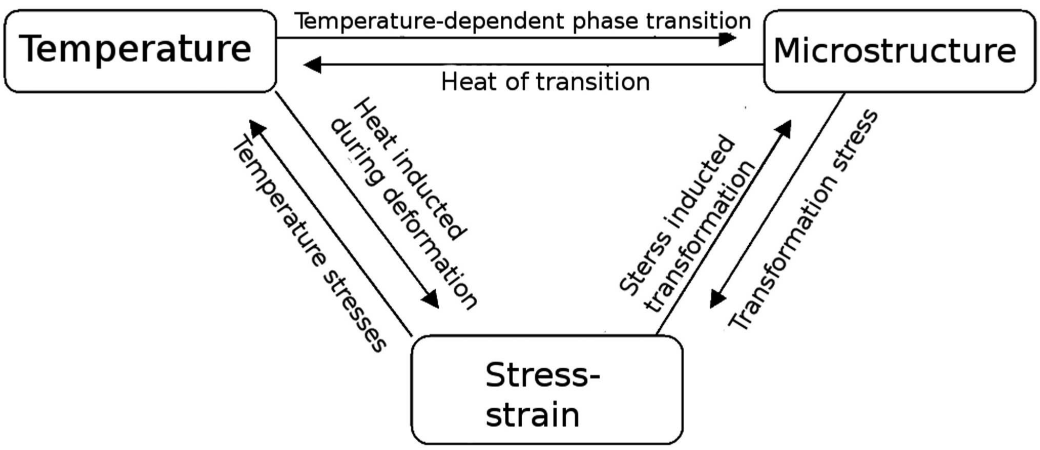

Fig. 4. Scheme of relations between elementary components of microstructure development model

Fig. 5. Forging made in drop forging process and the cut sample used in hardening measurements

2.2. Experimental verification of results

Experimental verification of computer simulation results was conducted with the use of hardness measurements (Fig. 5). The measurements enabled the local evaluation of mechanical properties and the indirect representation of basic microalloyed steel hardening mechanisms: precipitation hardening, solid solution strengthening, grain boundary hardening. During the planning stage several methods of determining the Impact Transition Temperature were considered. The most common method is the Charpy impact test, performed at low temperatures where the energy necessary to fracture the sample is measured. Under the influence of low temperature, the energy needed to brake a sample decreases when brittle cracking takes place. Temperature connected to these conditions is called Impact Transition Temperature (ITT). Because of the small size of the forged part and the need to evaluate inhomogeneity, this method could not be used in the current work.

Another method of determining ITT is a use of ultrasonic waves [8]. It is an indirect method using the correlation between dissipation of sonic waves on grain boundary and Impact Transition Temperature. The main advantage of this method is its non-destructive character and a relatively short time needed to perform experiments. In the case of the examined forging the main disadvantage of this method is little area available for testing and its roughness. Additionally, the values obtained by this method are averaged according to the thickness of the given area, possibly causing a significant error in estimations when the gradient of properties is high. Nevertheless, this method can be highly effective in the quality control of huge batches of products with the proper shape and dimensions. In the case of examining single forgings a direct optic method of grain size estimation can be successfully employed to evaluate local ITT values. This method enables us to obtain very accurate ITT values due to the use of a realistic microstructural image of the examined material. The accuracy of data obtained through this method, especially in the case of the microalloyed steel forging examined here, is increased thanks to the termination of deformation process in the austenite temperature area. This has eliminated the influence of the ferrite texture. The main disadvantage of this method is the time needed to obtain image of the examined material microstructure. Additionally, only a limited number of grains may be taken into account for a single measurement, which can negatively affect the evaluation of properties. In this paper, the choice of hardness measurements for the experimental verification of computer simulations was caused by the possibility to perform tests for a large number of measuring points. This allowed the evaluation of the properties inhomogeneity, especially when large gradients were present. In conjunction with microstructure imaging, it was possible to determine the influence of a larger volume of material, for instance the grains present under the surface of cut. This increased the probability of a correct representation of the mechanical properties of the examined forged parts. In order to improve the accuracy of hardness testing and its inhomogeneity estimation it is necessary to exclude other factors, other than those used to estimate the grain size. In practice, it means evaluating the particular influence of other hardening mechanisms on the final mechanical properties. The solid solution hardening is assumed to be the same in the entire forging volume because of a homogenous chemical composition. The influence of precipitation hardening was taken into account according to the formulas from Table 2, part G. In this case, because of inhomogeneous microstructure development, some discrepancy between individual areas of forging may occur but its impact on the final result is negligible. Participation of other hardening mechanisms, i.e. work hardening and texture hardening can be disregarded, because the deformation process terminated high above the austenite-ferrite transformation temperature, and its effects are eliminated during this transformation and are not present at room temperature.

TABLE 2

Basic models used in computer simulation

Equation	Comment	Lit.
A. Rheology model		
$\sigma_a = \sigma_G + c_2 \varepsilon^{0.5}$ $\exp(-c_3 T + c_4 T \ln \dot{\varepsilon}) + k d^{-0.5}$	Zerilli-Armstrong model c_1, c_2, c_3, c_4, c_5– coefficients determined by the inverse method.	[3]
B. Dynamic recrystallization		
$X_{dyn} = 1 - \exp\left(-0.693 \left(\frac{\varepsilon - \varepsilon_c}{\varepsilon_{0.5RX}}\right)^2\right)$ $\varepsilon_{0.5RX} = 1,144 \cdot 10^{-3} D_0^{0,25} \dot{\varepsilon}^{0,05} \exp\left(\frac{6420}{T}\right)$ $d_{rek} = AZ^p$ $Z = \dot{\varepsilon} \exp\left(\frac{Q}{RT}\right)$	Volume fraction of dynamically recrystallized austenite. $\varepsilon_{0.5RX}$ strain for 50% of dynamic recrystallization. Z – Zener-Hollomon parameter	[4]
C. Metadynamic recrystallization		
$X_{md} = 1 - \exp\left(-0.693 \left(\frac{t_p}{t_{0.5md}}\right)^{1.5}\right)$ $\mathrm{t}_{0.5md} = 4.42 \cdot 10^{-7} \cdot \dot{\varepsilon}^{-0.59} \exp\left(\frac{153000}{RT}\right)$ $\mathrm{D}_{MD} = BZ^q$	$t_{0.5md}$ the time for a 50% softening by metadynamic recrystalization Grain size after dynamic recrystallization $B = 1.4 \cdot 10^2 \quad q = -0.13$	[1][4]
D. Static recrystallization		
$X = 1 - \exp\left[-0.693 \left(\frac{t_p}{t_{0,5p}}\right)^k\right]$ $\varepsilon_\gamma = (1 - X)\varepsilon \quad \bar{d} = X d_{rex} + (1 - X) d_0$	Volume fraction of the statically recrystallized material.	[1][5]
E. Precipitation process inducted by deformation		
$t_{p0,05} = f \varepsilon^{-1} A [Nb]^{-1} Z^{-0,5} \exp \frac{270000}{RT} \exp \frac{B}{T^3 [\ln (k_s)]^2}$ $f = \left(10^{-2.26-0.9[Mn]+2.85[Si]}\right)^{-1} \quad k_s = \frac{[Mb] \cdot \left[C + \frac{12}{14} N\right]}{10^{2.26 \frac{6770}{T}}}$	$t_{p0,05}$ the time for 5% strain-induced precipitation. $A = 3 \cdot 10^{-6}$ $B = 2,5 \cdot 10^{10}$	[5]
F. Austenite-to-ferrite phase transformation		
$T_s = A_1 - A_2 C_r^a - 0.5 \exp\left[\frac{A_3 D_\gamma + A_4}{(A_5 + \varepsilon_a)^b}\right]$ $a = \left(-\frac{6770}{T_s + 273} + 0.28 \cdot [Mn] + 2.15\right) \cdot \ln 10$ $b = \frac{[C] + \frac{12}{14}[N]}{[Nb]} \quad [Nb^*] = \sqrt{\frac{7.7 e^a}{b}}$ $d_\alpha = \left\{29 - 5 \cdot C_r^{0.5} + 20\left[1 - \exp\left(-1.5 \cdot 10^{-1} D_\gamma\right)\right]\right\}\left(1 - 0.8 \varepsilon_a^{0.15}\right)$	Austenite-to-ferrite transformation start temperature. $[Nb^*]$– Nb in solid solution at the start of austenite-to-ferrite transformation. $d_{\alpha-}$ Ferrite grain size.	[6]
G. Mechanical properties		
$R_m = 164.9 + 637.7 \cdot [C] + 56.3 \cdot [Mn] + 99.7 \cdot [Si] +$ $+651.9 \cdot [P] + 3339.4 \cdot [N] + 2500 \cdot [Nb^*] + 11 \cdot (d')^{-\frac{1}{2}}$ $HV = \frac{R_m}{a}$ $ITT = 37 - 0.8\sigma_g + 0.5\left(\sigma_p + \sigma_d\right)$	Tensile strength Hardness $a = 2.75$ Impact transition temperature	[7]
$K_p(\max) = 3000$ $K_p(r) = 1500$ $\sigma_p = K_p[M]$:where $[Nb] = 0 \div 0.08$	Precipitation hardening	[6]

3. Experiments results and their discussion

Fig. 6 shows the comparison of hardness measurements with the results obtained from computer simulation. The series of measurements for the plane parallel to the die parting line are presented here. The obtained results confirm the accuracy of computer simulations. Fig. 7 shows the results of computer simulations of impact transition temperature (ITT). Dark areas represent places where expected ITT values are high due to a large ferrite grain size. This means that these places are vulnerable to brittle cracking at low temperatures. In the case of the examined forging process, it is possible to distinguish two types of areas, for which the values of Impact Transition Temperature are high:

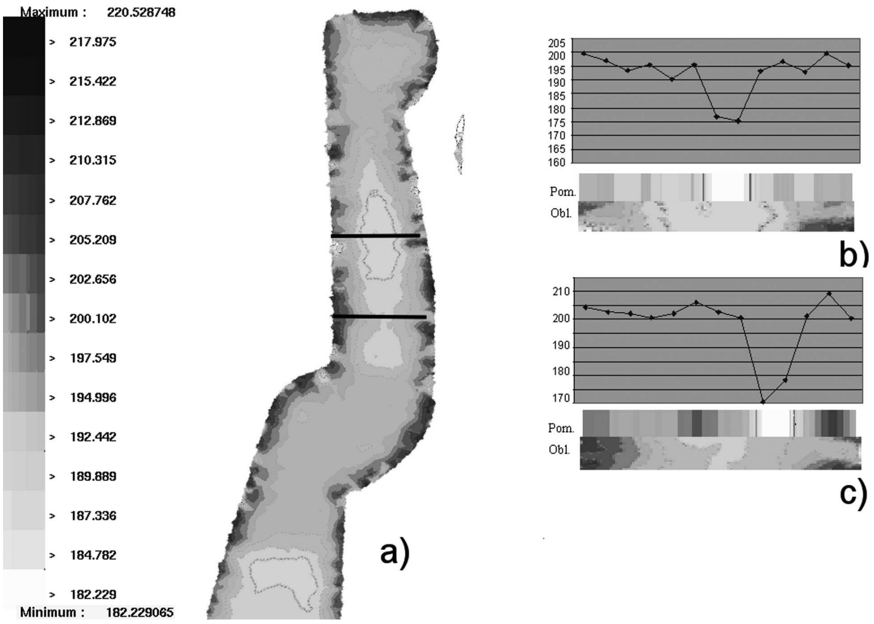

Fig. 6. The comparison of hardness measurements with the results obtained from computer simulation

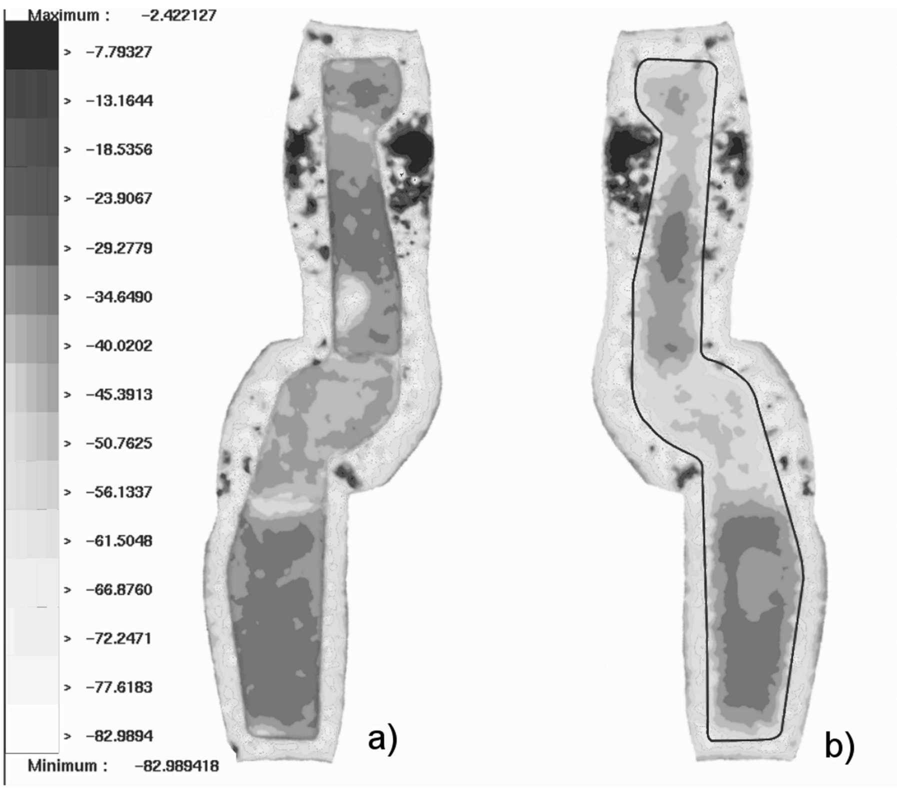

Fig. 7. Distribution of Impact Transition Temperature, on the surface of forging – a) and on the cross-section parallel to the plane of matrixes division line with line of flash cut – b) marked

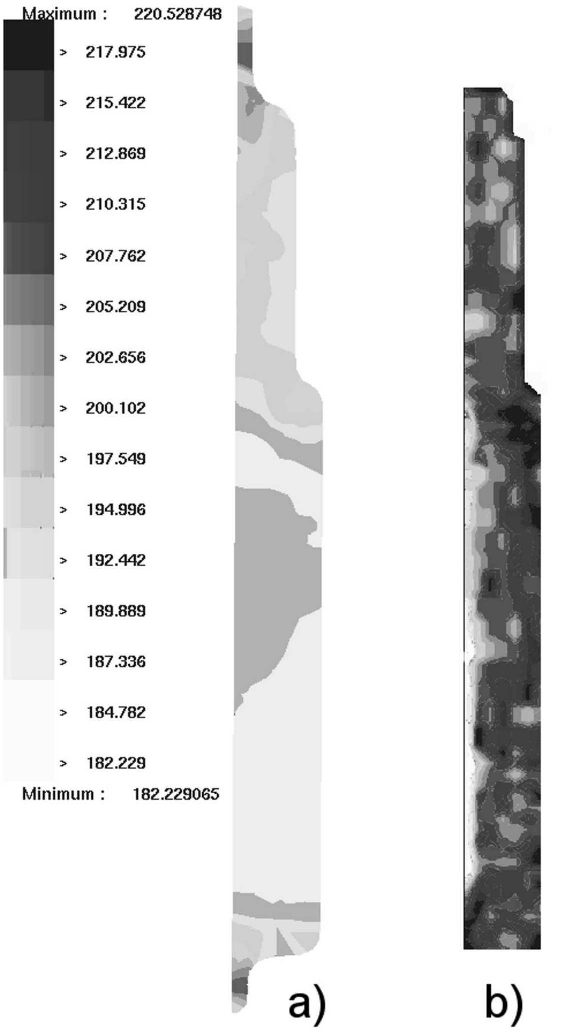

Fig. 8. Map of hardness distribution on a sample from second half of forging, obtained from computer simulation a) and experimental measurements b)

i) places where, due to small deformations, the transition temperature is between 20°C and -30°C, and distribution is almost uniform, (no high gradients),
ii) places with high Impact Transition Temperature where the deformation is the highest. Conducted simulations show that deformation accumulation and the increase of temperature enabled static and dynamic recrystallization in these areas. The elimination of strain effects caused by recrystallization affected the austenite-ferrite transformation, resulting in the increase of ferrite grain size (by decreasing the number of nuclei). This is shown by formulas in Table 2, part F. In the cases presented here, most of these areas are located in the flash, which will be cut in next stage, as shown on Fig. 7. For this reason they do not constitute a defect of the final product. Nevertheless, as seen in Fig. 7.b, the recrystallized fragments of material touch the flash cutting line, which in some cases could promote fracture, because after the cutting of flash, these places are located at the surface and are exposed to extended stress. It is also possible to locate areas vulnerable to potential brittle cracking at low temperatures. The reason for this is that these areas are located near the surface exposed to the highest values of extended stress during the folding of the material. In the samples from second half of the forged part, there are significant differences between experimental results and simulations. In order to interpret them, an accurate map of micro hardness has been made (Fig. 8). The analysis of simulation results allows one to speculate that this side was located in the lower tool. The higher cooling rate than expected caused by a prolonged contact of the material with the tool after deformation, induces the appearance of a microstructure with much higher durability properties. Some confirmation of this thesis can be the fact that in areas close to the center of the forging the simulation results are closer to the experimental values.

4. Summary and conclusions

The research presented here shows that computer simulation with the use of microstructure development and mechanical properties models is a highly effective tool facilitating the processes of planning and control of plastic deformation. Obtained data allow the foreseeing of areas of safe applications of the final products even under the most difficult operating conditions. Two main advantages of using computer simulation with use of relations between deformation history and microstructure development in forged products can be highlighted:

– the possibility to design products with known microstructure distribution in order to control the inhomogeneity of mechanical properties.

– computer modelling can be an indispensable help in search for weak points in forged products, because it allows one to calculate the values of mechanical properties which are hard to obtain experimentally.

The increase of accuracy of obtained results allows one to make a qualitative and quantitative evaluation of microstructure evolution what requires precise information about process factors like: the time required in particular stages of forging, time in with the forging has contact with tool after deformation, the resulting heat transfer, the position of material in tool. This enforces a far better communication between persons conducting the computation and the persons responsible for manufacturing the final product. Also, the use of symmetry plane based only on the shape of the manufactured forging could be a mistake because of discrepancy between thermodynamic conditions. It should be pointed out that during the optimization of the Impact Transition Temperature distribution, taking into account the minimal cooling rate possible in the process, and locally in the product, seems to be the most beneficial for the final product, because it will determine critical ITT value. This stems from the fact that a higher cooling rate leads to smaller grain size, which is shown in the table 6, part G, and at the end to a lower ITT value. It is necessary to remember about the possibility of bainitic or martensitic transformation when the cooling rate is high. The prospect of the appearance of new microstructure components requires a much more sophisticated model with more precise knowledge about the thermodynamic conditions, because the maximal ITT value does not have to coincide with the minimal cooling rate. This greatly complicates the determination of safety work conditions for the final product.

Acknowledgements

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