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COMPUTER AIDED DESIGN OF MANUFACTURING TECHNOLOGY FOR COPPER-CHROMIUM ALLOYS

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Abstract

Forged products made of copper-chromium alloys are considered in the paper. Analysis of possibilities of manufacturing of these products is the main objective of the work. Two technological variants are considered. The first is composed of casting, hot extrusion, cooling, heating to the temperature between 800-900°C, hot forging, cooling, saturation annealing and ageing. It is proved in earlier publications that this technology allows to obtain required properties of products, but it is expensive. Therefore, in the present paper the proposition of substituting the final heat treatment by additional cold forging is considered. Simulations of the manufacturing process for four different products were performed using finite element software FORGE 3. Results of numerical simulations, including the distribution of hardness in the volume of the forgings, are presented in the paper. Implementation of additional cold forging allowed to obtain the required hardness, comparable to that obtained after heat treatment, for some of the forgings.

Key words: Cu-Cr alloys, hot forming, cold forming, numerical simulation, design of manufacturing technology

1. INTRODUCTION

Simultaneous development of metal forming and materials technology leads to continuous search for new materials, which when subjected to thermomechanical processing, gain special in-use properties. Non-ferrous metals, in which relevant control of precipitation yields particularly high mechanical properties, are an example of such an approach (Deschamp & Brecht, 1999). Engineers designing new technologies have to focus not only on obtaining the dimensional accuracy, but also on the proper control of microstructure evolution. Due to a wide range of possible technological variants for processing of these materials, computer simulation plays a crucial role in the design of new products and processes. Efficient application of computer simulations in the technology design requires realistic and accurate models.

The objective of the present work is the investigation of possibilities of computer aided design of manufacturing of copper-chromium alloys. This goal is reached in several steps, which include material testing and development of the rheological model, development of the FE model for forging Cu-Cr alloys and, finally, performing numerical tests for industrial forging processes. Two technological variants are considered and the capability of achievement of required mechanical properties of products is evaluated.

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2. HEAT TREATMENT PRIOR TO DEFORMATION AND RHEOLOGICAL MODEL

Accuracy of numerical simulations of forming processes depends on the correctness of description of boundary conditions and material properties. The latter problem is considered in this work. Although the rheological models are well explored for various steels, there is still lack of models for copper alloys. Thus, the prime objective of this part of the project was performing uniaxial compression tests for the Cu-Cr alloy at temperatures 500-1000°C and strain rates 0.1-100 s^{-1}, application of the inverse analysis (Szeliga et al., 2006; Szeliga & Pietrzyk, 2007) to the interpretation of results of those tests and development of the rheological model, which is applicable for the investigated range of parameters. The tested material was Cu-Cr alloy containing < 0.001As, < 5 ppm Bi, 0.81%Cr, 0.026%Fe, < 0.001%Ni and balance Cu. Detailed description of these experiments can be found in (Pietrzyk & Kuziak, 2008). Three states of the alloy, giving different mechanical response during deformation, were considered: A) samples after super saturation annealing at 1000°C; B,C) samples after hot extrusion, followed by different preheating processes: B) heating to the test temperature, maintaining for 120 s and deformation; C) heating to 950°C, maintaining for 300 s, cooling to the test temperature, maintaining for 60 s and deformation. Inverse analysis gave the flow stress independent of the influence of such disturbances as friction or deformation heating for all the investigated cases. Analysis of results showed (Pietrzyk & Kuziak, 2008) that oscillations in the material response occur for low Zener-Hollomon parameters for samples B and C.

Microstructure of the samples was investigated prior to deformation and after each test. Correlation between flow stress and preheating conditions (microstructure) was determined, see selected results in figure 1. Investigation of the deformed samples has shown that their flow stress depends strongly on the initial state of the material.

Under the same deformation conditions, as extruded samples heated to the test temperature showed dynamic recrystallization (DRX) during the deformation. Their structure was fully recrystallized and finer grains were observed for lower deformation temperature and larger strain rate. In other specimens, the DRX was not easily initiated during deformation below 900°C and their microstructure was partly recrystallized. The microstructure prior to deformation is expected to be the reason of this behaviour. Thus, grain size of the samples was measured and results for variants A and B are presented in figure 2. Selected microstructures for variant A are shown in figure 3. It is seen that within the temperature range 700-900°C the grain size for variant A is much lower. This may be connected either with the fact that the samples contain some undissolved Cr precipitates hindering the grain growth or with the effect of Cr in solid solution.

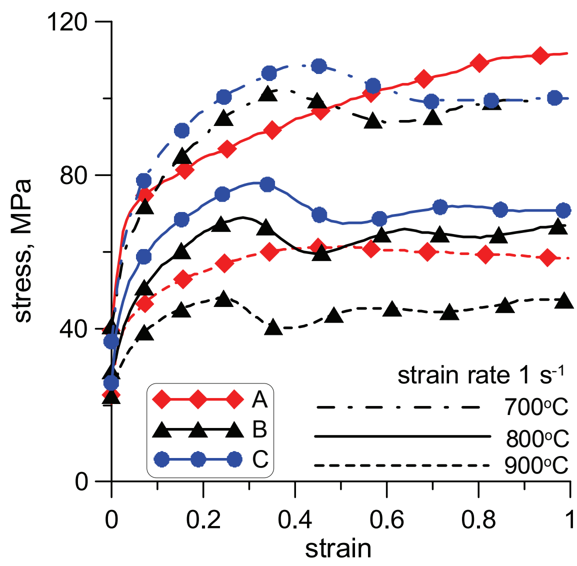


Fig. 1. *Flow stress for different initial state of the samples.*

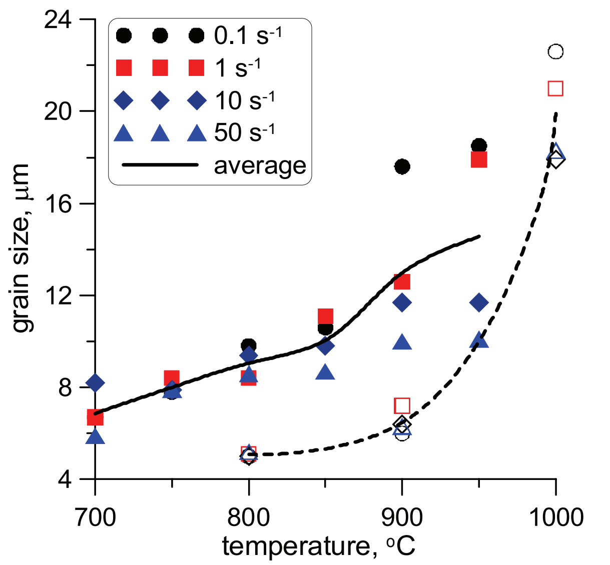


Fig. 2. *Grain size for various strain rates and temperatures of deformation for variant B (filled points and solid line) and variant A (open points and dotted line).*

The solute drag effect of Cr atoms exerted on the recrystallization nuclei boundaries is a next possible reason of different behaviour of the samples. Chromium effect on the stacking fault energy is the alternative reason. In the extruded samples all chromium precipitated out of the solution. The precipitates were relatively large and they did not affect the recrystallization process substantially. Thus, the supersaturated samples exhibit the greatest effect of Cr on the recrystallization. Samples reheated to 950°C prior to the deformation show the intermediate effect, and the effect of Cr is almost negligible in the extruded samples.

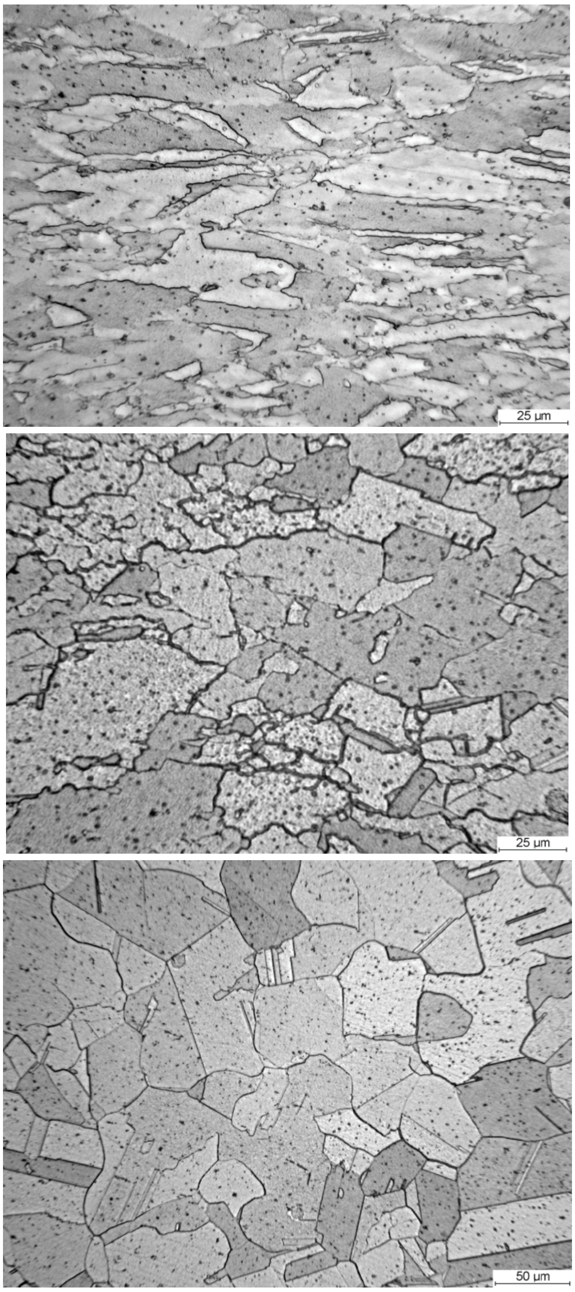
a)
b)
c)


Fig. 3. *Microstructure of samples deformed at 1 s⁻¹ and at temperatures 800°C (a), 900°C (b) and 1000°C (c), variant A.*

After analysis of results of all experiments the preheating schedule C was chosen as the best, due to the lower flow stress than in the schedule A and more stable response to deformation comparing to schedule B. All further simulations presented in this paper will be performed for the schedule C. The following equation is used as the rheological law (Gavrus et al., 1996):

$$\sigma = \sqrt{3}\left[kqW\varepsilon^n + \left(1-W\right)k_{sat}q_{sat}\right]\left(\sqrt{3}\dot{\varepsilon}\right)^m \qquad (1)$$

where:

$$W = \exp\left(-w\varepsilon\right)$$

$$q = \exp\left(\frac{Q}{RT}\right) \quad q_{sat} = \exp\left(\frac{Q_{sat}}{RT}\right)$$

Due to problems with evaluation of the strain rate sensitivity m for the whole range of temperatures, linear relation of this coefficient on temperature is introduced:

$$m = a + b\left(0.002T - 1\right) \qquad (2)$$

There are nine coefficients in the flow stress model: k, k_{sat}, Q, Q_{sat}, m, n, w, a, b. These coefficients were determined using the inverse analysis and their values are given in Table 1. The temperature in equation (1) is in °C.

Table 1. *Coefficients in the flow stress model obtained from the inverse analysis*

k	n	Q	k_{sat}
20.76	0.356	12030	1.26
Q_{sat}	w	a	b
29950	2.49	0.256	0.077

Further plastometric tests were performed at the room temperature, accounting for the deformation heating. The following flow stress model was obtained for the temperatures 20-150°C:

$$\sigma = A\exp\left(m_1T\right)\varepsilon^{m_2}\dot{\varepsilon}^{m_3}\exp\left(\frac{m_4}{\varepsilon}\right) \qquad (3)$$

The following values of the coefficients in this model were determined using the inverse analysis: m_1 = -2.504×10^{-3} K^{-1}, m_2 = 0.362, m_3 = 0.098, m_4 = 1.3338×10^{-4} and A = 468 MPa·s^{m_3} .

3. Cu-Cr FORGINGS – ADVANTAGES AND REQUIREMENTS

Automotive and airplane industries stimulate continuous endeavors towards substitution of commonly used conventional materials by new materials with exceptional properties. Substituting steel forgings by non-ferrous alloys forgings is a part of this tendency. In general, materials used for products designated to exploitation in low temperatures have to be characterized by hardness above 100 HB and high wear resistance. On the other hand, these materials have to be ductile (high hardening coefficient) in the metal forming range of temperatures and they have to possess high thermal properties. Beyond this, the chemical composition of these materials has to guarantee stable microstructure in the temperature range, in which considered part is exploited.

Copper is characterized by very high thermal properties (heat conductivity), electrical properties, corrosion resistance and workability. On the other hand the mechanical properties of copper are too low and density is too high to allow wide applications of this material. It is a substitution for steel only at certain particular applications, when high strength to weight ratio is not required. Using copper in applications, which require high strength, in particular at elevated temperatures, is not possible. Stabilization of the microstructure and significant improvement of mechanical properties, without the loss of excellent thermal and electrical properties, can be obtained when additional elements are added to copper. One percent addition of chromium is considered in the present paper.

Cu-Cr forgings have much larger than copper mechanical properties within the temperature range 20 – 600 $^{\circ}$C (microhardness 1450 MPa for Cu-Cr and 1270 MPa for Cu at $T = 20^{o}$C for cold worked material and 850 MPa for Cu-Cr and 430MPa for Cu for material preheated at $T = 500^{o}$C for 3 hours). Due to precipitates, parts made of Cu-Cr achieve properties comparable to some steels, while high thermal and electrical properties, as well as high cold formability, are maintained.

Apart from the applications in the automotive and airplane industries, copper alloys are of interest for the electrical industry (high voltage applications). Lower hardness, minimum 65 HB, is allowed on certain part of the surface of these forgings. Higher hardness is required only on the contact area of the forging.

Table 2. *Comparison of mechanical properties of commercially pure copper and Cu-Cr alloy.*

technological variant		Re	Rm	A5	HB
		MPa	MPa	%	Kg/mm^2
Cu	cold rolling, recrystallization annealing 500^{o}C/1h	25-40	210-240	40-60	≈40
Cu - 0.95%Cr-0.035%Si	after casting	65-85	200-230	34-48	≈60
	hot forging	130-150	260-270	39-43	63-73
	saturation annealing	65-100	200-250	37-48	57-76
	aiging	290-340	400-450	24-26	… - 160

Achieving high properties for such materials as Cu-Cr alloys is possible by combination of various processes such as preheating, relevant hot and cold deformation, super saturation (at high temperatures), cooling with control of precipitation within the temperature range 400-600^{o}C (aging – depending on the temperature hardness of the Cu-Cr increases from 40-60 HB to 140 HB). Table 2 contains comparison of mechanical properties of commercially pure copper and Cu-Cr alloy (Szablewski, 1989). Various heat treatment methods are considered in this table. On the basis of the performed plastometric tests and data in table 2 various variants of manufacturing of Cu-Cr products are proposed in the next chapter.

4. PROPOSITION OF THE MANUFACTURING TECHNOLOGY

Achievement of required properties, in particular hardness, is the main problem in design of the manufacturing technology for Cu-Cr alloys. The standard hot forming results in hardness around 70 HB, which is too low. Beyond this, the microstructure of the material contains too large chromium precipitates, which are not effective in increase of strength. Improvement of the mechanical properties can be obtained by additional heat treatment composed of saturation followed by aging. Figure 4 shows schematic illustration of the manufacturing design for Cu-Cr forgings, which allows to obtain satisfactory for the users hardness above 100 HB. This hardness is obtained due to combined processes of plastic deformation and structure homogenization during solution treatment followed by fine precipitation processes during aging.

This process gives good results as far as mechanical properties are considered. On the other hand, the technology is expensive and requires high energy consumption. Alternative solution, which is proposed, assumes that increase of properties can be obtained by additional cold forming (strain hardening). This alternative is marked by dotted line in figure 4. Right after hot deformation fast cooling follows and chromium in the solution is maintained when cold forging begins. During deformation the dislocation density in the material increases, what leads to the increase of nucleation sites for precipitation and, finally, to very fine precipitates and to the increase of hardness. In consequence, expensive processes of solution treatment and aging can be eliminated and costs and energy consumption can be lowered, while the high mechanical properties are maintained.

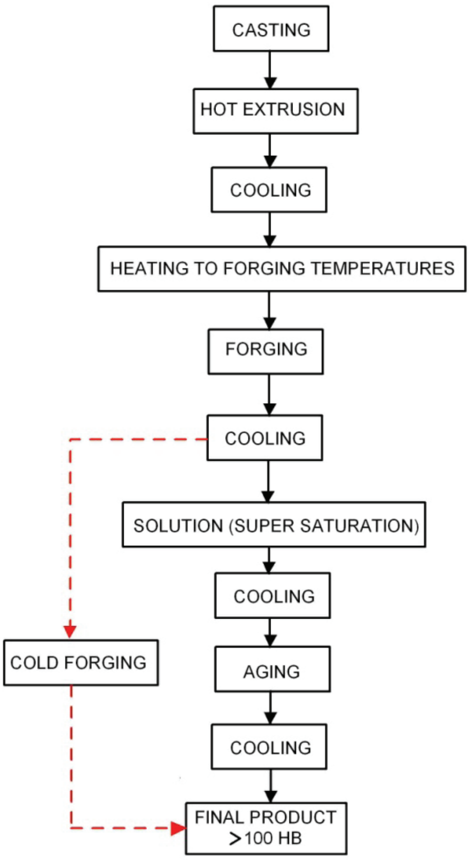


***Fig. 4.** Schematic illustration of the investigated manufacturing cycles for Cu-Cr forgings with hardness above 100 HB.*

5. SIMULATIONS OF FORMING OF SELECTED PRODUCTS

All simulations in this work were performed using Forge3 finite element software, which is based on the Huber-Mises yield criterion and viscoplastic Norton-Hoff flow rule. Details of this constitutive model can be found in (Chenot & Bellet, 1992). Preliminary results of simulations of forming of Cu-Cr alloys are presented in (Pietrzyk et al., 2008; Pidvysotskyy et al., 2008). The effect of precipitation during solution treatment and aging is analyzed mainly in those papers. Continuation of these research with focus on cold forging and analysis of various variants of manufacturing technology is presented below.

Four various forgings were selected in the present work to investigate possibilities of computer aided design of manufacturing of Cu-Cr products. Forgings 1, 2 and 3 are axisymmetrical and 2D simulations are possible. Forging 1 is presented in (Pietrzyk et al., 2008) and is not repeated here. Forgings 2, 3 and 4 are shown in figure 5.

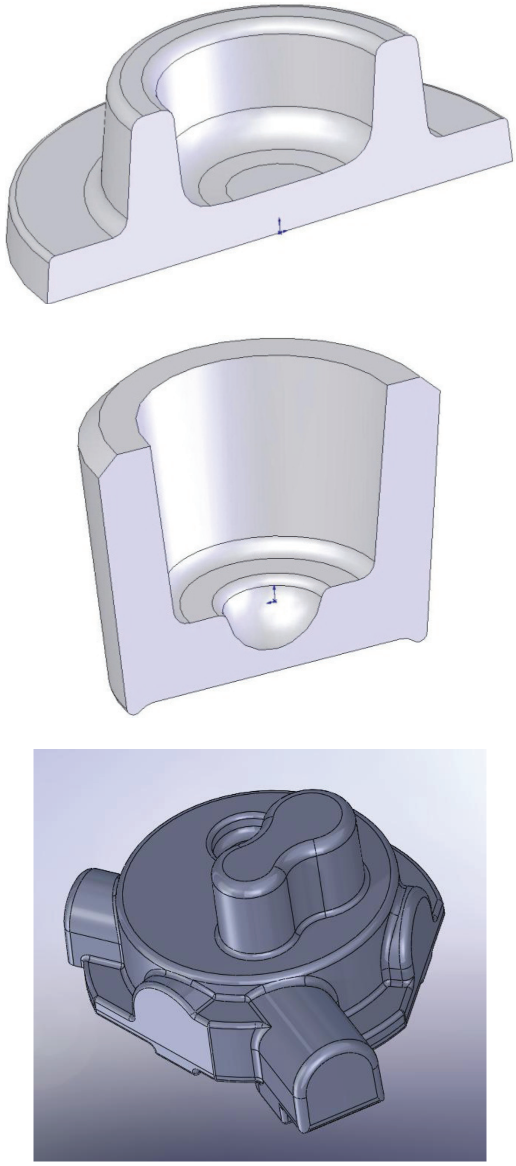


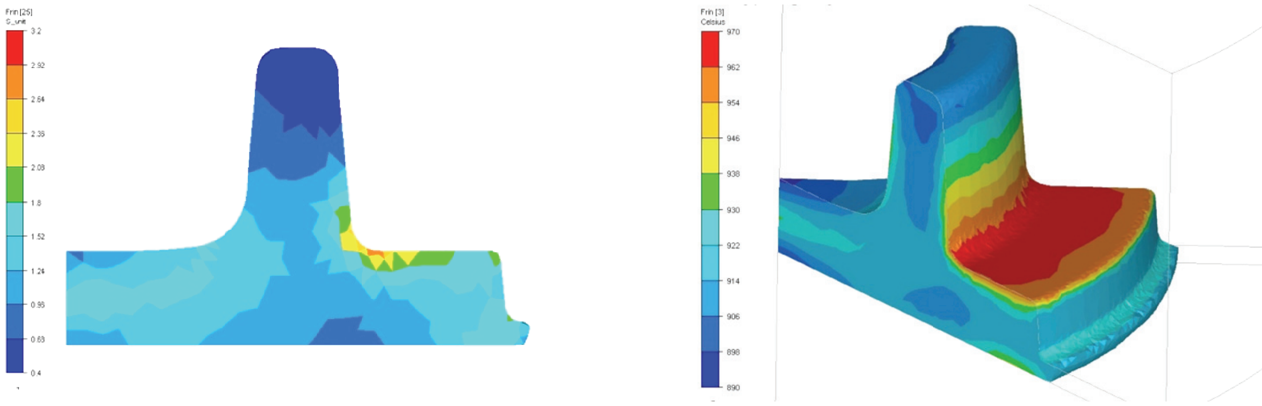
***Fig. 5.** Shape of the investigated forgings 2, 3 and 4.*

The stock material for all considered cases were cylinders with dimensions ϕ60×55 mm (forging 1), ϕ90×75 mm (forging 2), ϕ90×145 mm (forging 3) and ϕ55×50 (forging 4). The initial forming temperature was 900°C in all cases.

According to the proposed manufacturing variants (figure 4), the required properties of products are achieved in two stages. In the first variant hot forged product (1st stage) is cooled to the room temperature and then subjected to saturation annealing and aging (2nd stage), as described in (Pietrzyk et al., 2008; Pidvysotskyy et al., 2008). The second variant, which is the subject of the present work, assumes that hot forming is stopped few millimeters before the final dimension is achieved (1st stage) and cold forging is applied to achieve the required dimension.

possibility of achieving required properties by combined hot/cold forging. Two cold reductions were considered, 2 mm and 5 mm. Results of calculations of cold deformation strain, which controls hardness of products, are presented in figures 7–9.

Forging 2



Forging 3

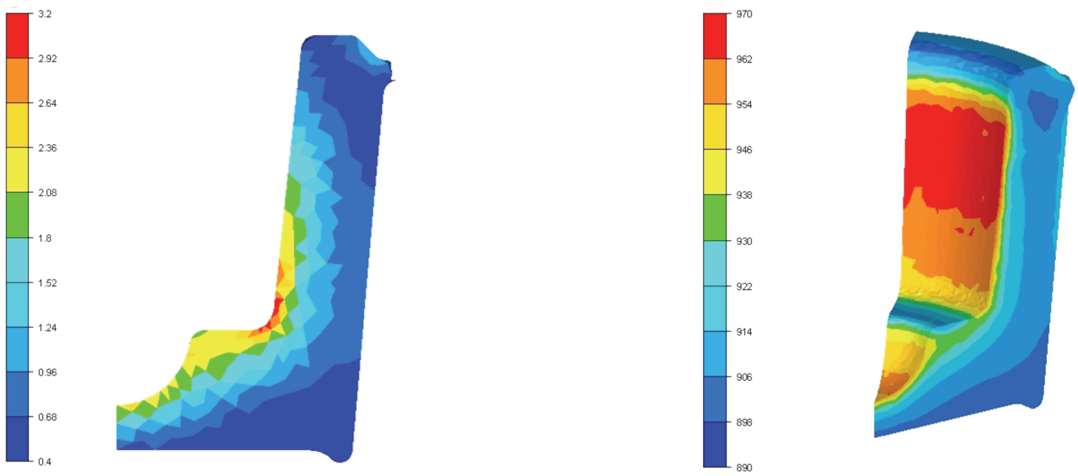


Fig. 6. *Selected example of calculated distribution of strain (left) and temperature (right) at the end of the hot forging, for forging 2 and forging 3, from the top.*

Simulation of hot forming process is performed first for all axisymmetrical forgings. Due to symmetry, only half of the cross section is presented in all figures. Distributions of strains, strain rates, temperatures and stresses were calculated and selected results obtained for forgings 2 and 3 are shown in figure 6. Areas of strain concentration, as well as areas of maximum temperature drop due to contact with the tool, are clearly seen in this figure.

The analysis of these results shows that hardness of products is below the required. Therefore, the second technological alternative was considered. Hot forging was stopped few millimeters before the end and cold forging followed. The objective of simulations was to supply information regarding

Additional tests on the Gleeble 3800 simulator in the Institute for Ferrous Metallurgy in Gliwice were performed to determine relation between the cold deformation strain and the hardness. Cylindrical samples were cold deformed to various reductions and the hardness of these samples was measured. In consequence, the following relation was determined:

$$HB = 88 + 32\left[1 - \exp\left(-3\varepsilon\right)\right] \qquad (4)$$

Calculated hardness distributions for the investigated variants of forming are presented in figure 9. The zones, in which hardness exceeds 100 HB, are marked in red. It can be concluded from this figure that efficiency of the additional cold forging depends on the shape of the forging. In the case of forging 1, additional cold reduction of 5 mm results in the required hardness at the major part of the cross section of the product. In forging 2 the required hardness was obtained in the whole lower part and in the small area on the top of the wall. Central part of the wall was not deformed in cold forging and the hardness in this area is low. Similar situation is observed for forging 3, where the area of low hardness is even larger.

between 0.5 and over 2. Applying additional cold forging would lead in this case to strong inhomogeneity of properties (hardness). Therefore, only the first technological variant composed of hot forging followed by saturation annealing and aging is considered below.

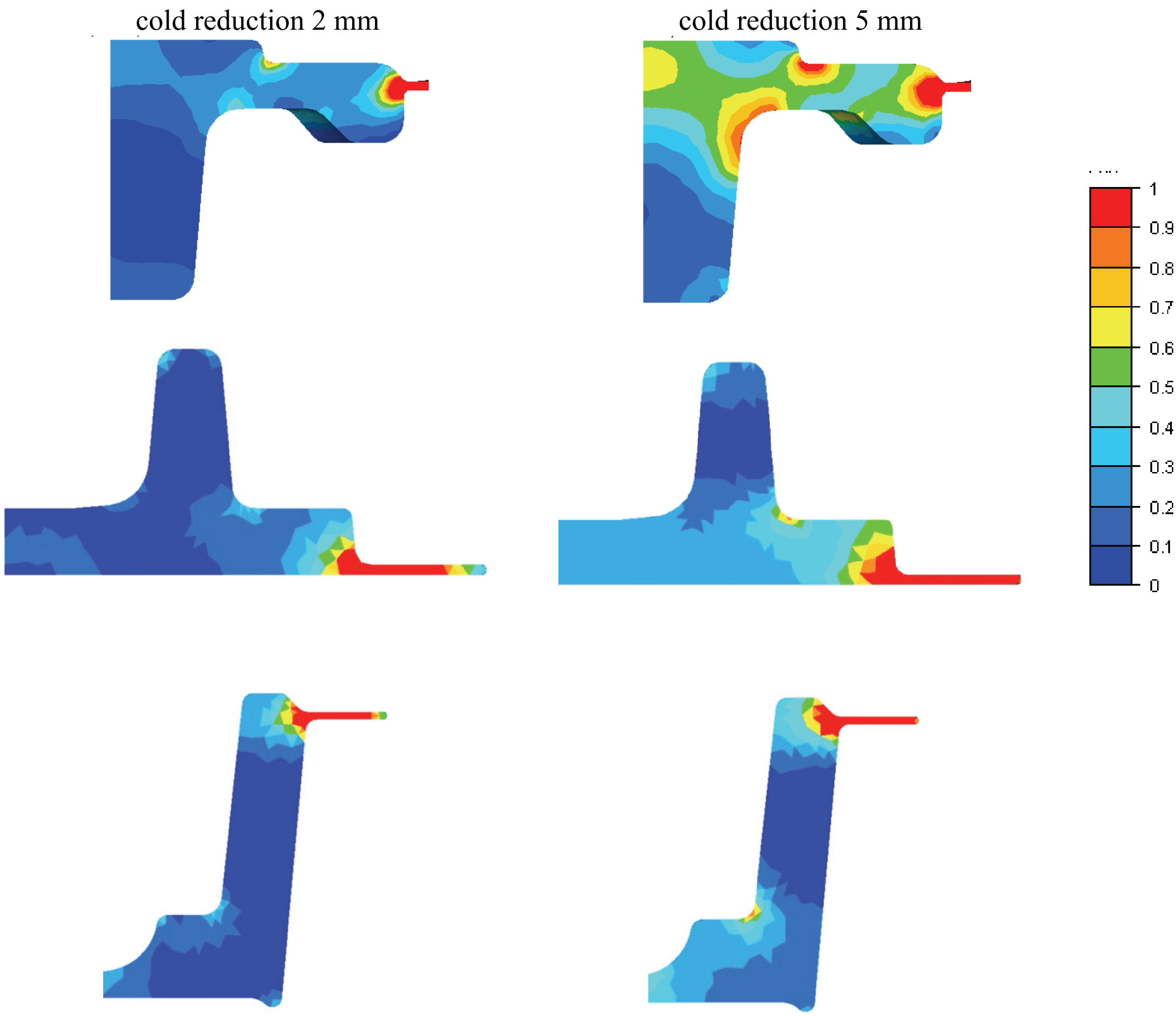


Fig. 7. Effective strain distribution due to additional cold forging with the reduction of 2 mm (left) and 5 mm (right), for forgings 1, 2 and 3, from the top.

6. 3D FORGING

Simulation of hot forging process of the 3D part is the next objective of the paper. The view of the selected forging is shown in figure 5. Primary simulations have shown that in the considered case a significant inhomogeneity of deformation is observed, see figure 10. Hot deformation strains vary

Calculated temperature distributions at the end of the hot forging process are presented in figure 11. The difference between maximum and minimum temperature reaches 100°C. This difference has also influence on the properties of product and has to be accounted for in the design of manufacturing technology.

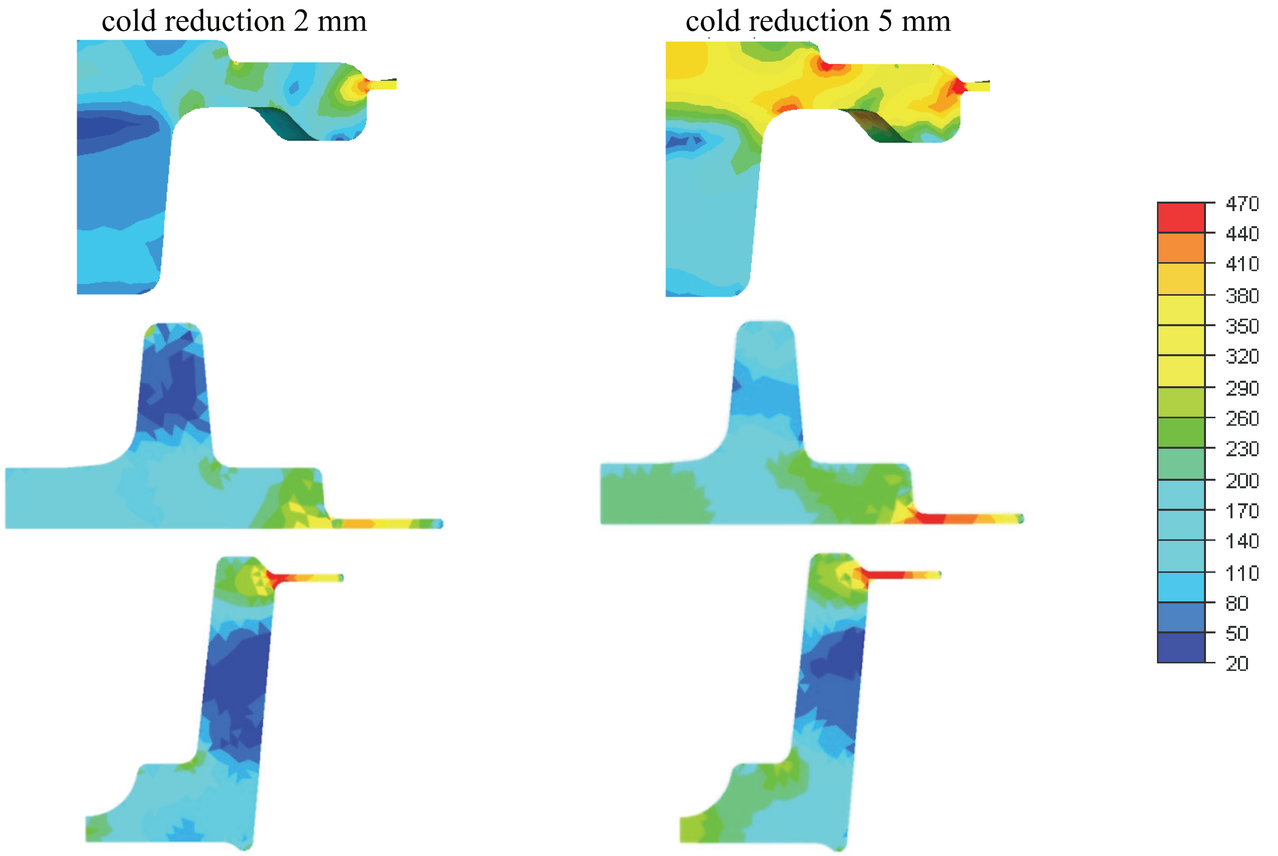


Fig. 8. Effective stress (MPa) distribution after additional cold forging with the reduction of 2 mm and 5 mm, for forgings 1, 2 and 3, from the top.

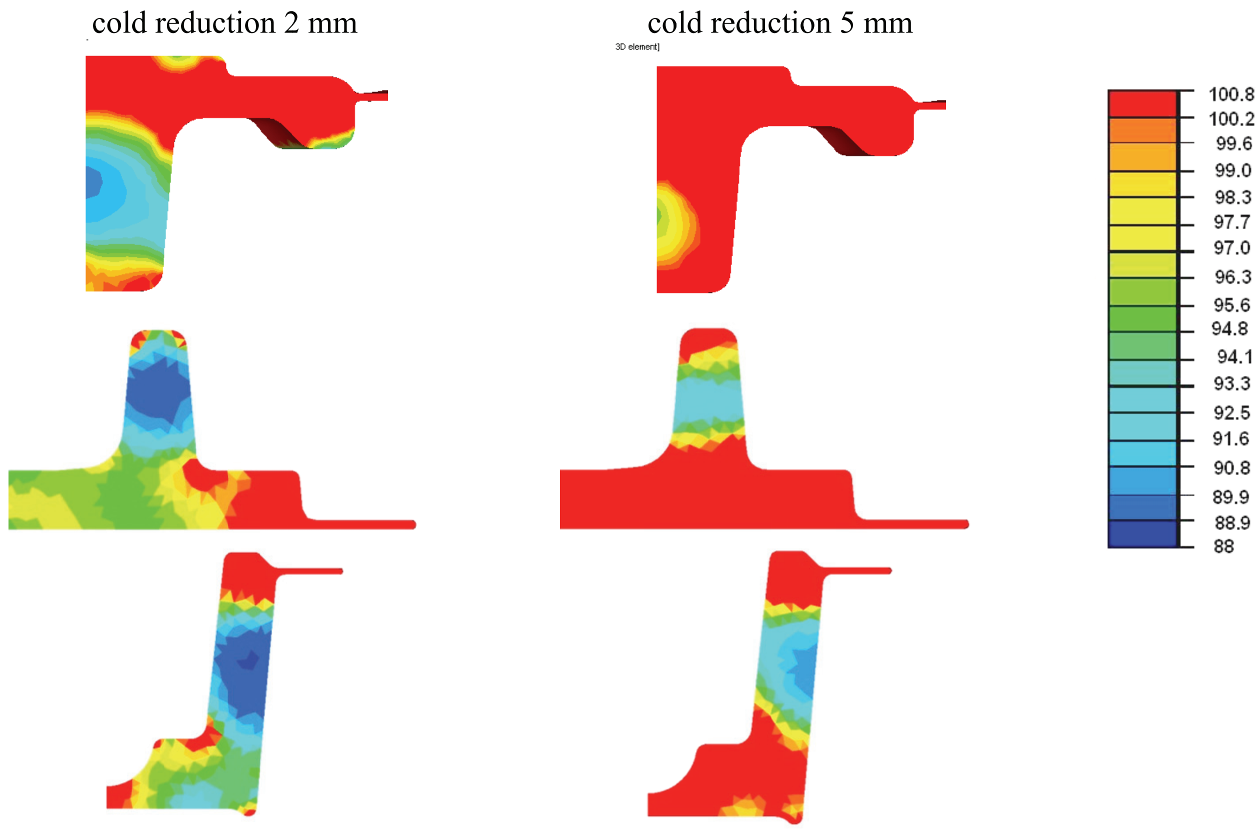


Fig. 9. Hardness distribution after additional cold forging with the reduction of 2 mm and 5 mm for forgings 1, 2 and 3, from the top.

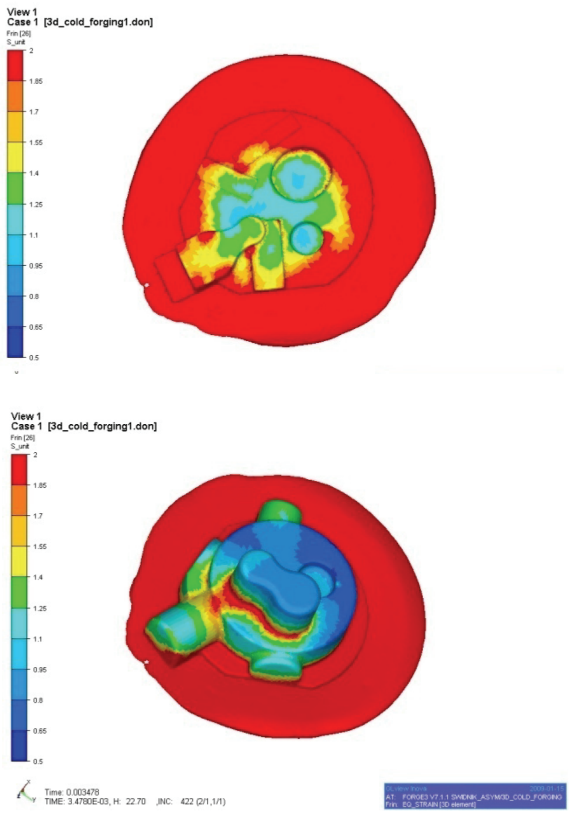


Fig. 10. Strain distribution after hot forging, view from the top (up) and bottom (down).

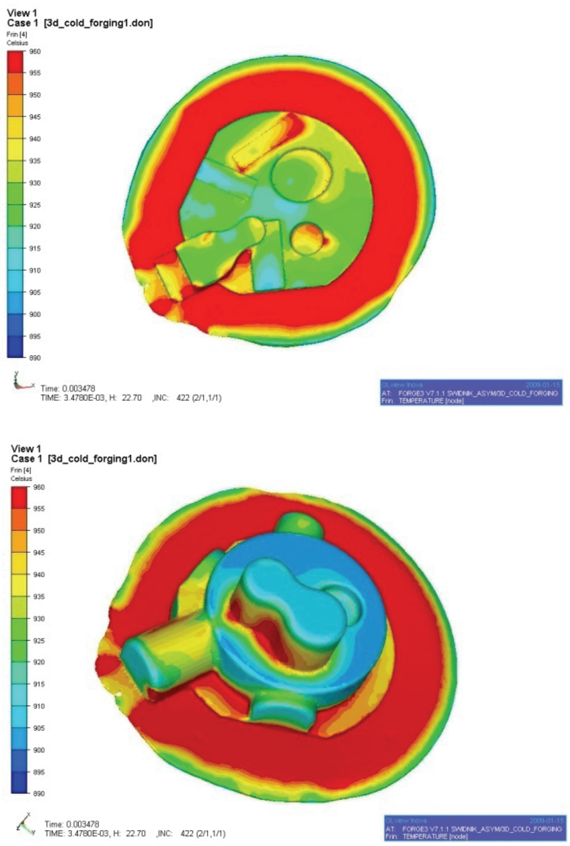


Fig. 11. Temperature distribution after hot forging, view from the top (up) and bottom (down).

7. CONCLUSIONS

Two methods of manufacturing of Cu-Cr parts were considered. One is composed of casting, hot extrusion, cooling, heating to the temperature within the range 800-900°C, hot forging, cooling, saturation annealing, ageing. In the second manufacturing cycle final heat treatment is replaced by additional cold forging. Performed analysis and simulations allow to draw the following conclusions:

- Cu-Cr forgings are suitable for parts in applications, where very good thermal and electrical properties are needed. Required properties (hardness) depend on the kind of application. In electrical applications only some parts of surface, which are in the contact with another part, should have higher hardness around 100 HB. Lower hardness, minimum 65 HB, is allowed on the remaining part of the surface. In automotive and airplane applications higher hardness is usually needed on the whole surface.
- Additional heat treatment composed of saturation annealing followed by ageing allows to obtain required properties of Cu-Cr products (Pietrzyk et al., 2008; Pidvysotskyy et al., 2008), but this technology involves high costs.
- Application of additional cold deformation for hot forged parts allows, in some cases, to obtain the required hardness and to avoid additional expensive heat treatment. However, the efficiency of cold deformation depends on the shape and size of the forging. Good results characterized by reasonably uniform hardness above 100 HB were obtained only for forging 1 (figure 9). In the remaining two axisymmetrical forgings areas with low hardness of about 90 HB remained in the central part of the wall of the product. Thus, the decision regarding selection of the manufacturing technology has to be made on the basis of numerical simulation and perspective application of the part. As it has already been mentioned, in several applications the high hardness is required only on certain parts of the surface of products.
- 3D forgings are usually characterized by strong inhomogeneity of deformation, therefore, applying of hardening by cold deformation may lead to significant inhomogeneity of properties in products, and is not advised.

Recapitulating, application of the described technological variants allows to obtain required properties for small forgings. It is much more difficult for large forgings. Neither heat treatment nor additional cold forming give homogeneous distribution of properties in large products. This problem will be a topic of the further research.

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REFERENCES

Deschamp, A., Brecht, Y., 1999, Influence of predeformation and aging of an Al-Zn-Mg alloy – II. Modelling of precipitation kinetics and yield stress, *Acta Mater*., 47, 293-305.

Chenot, J.-L., Bellet, M., 1992, The Viscoplastic Approach for the Finite-Element Modelling of Metal Forming Processes, Numerical Modelling of Material Deformation Processes, eds, Hartley, P., Pillinger, I., Sturges, C.E.N., Springer-Verlag, London, Berlin, 179-224.

Gavrus, A., Massoni, E., Chenot, J.L., 1996, An inverse analysis using a finite element model for identification of rheological parameters, *J. Mat. Proc. Techn*., 60, 447-454.

Pidvysotskyy, V., Kuziak, R., Pietrzyk, M., 2008, Modelling of production chain based on forming of copper-chromium alloy, *Steel Research International*, 79, spec. edition Metal Forming Conf., 2, 826-833.

Pietrzyk, M., Kuziak, R., 2008, Model reologiczny miedzi chromowej w procesach obróbki plastycznej na gorąco, *Obróbka Plastyczna Metali*, 19, 3-13 (in Polish).

Pietrzyk, M., Pidvysotskyy, V., Kuziak, R., 2008, Cu-Cr alloys as alternative for steel forgings for the automotive industry, *Proc. 17th Int. Conf. Design and Technology of Drawpieces and Die Stampings*, Poznań–Wąsowo, 153–162.

Ryś, J., Rdzawski, Z., Sajdak, R., 1979, Wpływ starzenia na twardość i przewodność miedzi chromowej, *Rudy Metale*, 24, 204-209 (in Polish).

Szablewski, J., 1989, *Wpływ obróbki cieplno-plastycznej na wydzielenie i rekrystalizację w miedzi chromowej*, PhD thesis, Politechnika Wrcławska, Wrocław (in Polish).

Szeliga, D., Gawąd, J., Pietrzyk, M., 2006, Inverse Analysis for Identification of Rheological and Friction Models in Metal Forming, *Comp. Meth. Appl. Mech. Engrg*., 195, 6778-6798.

Szeliga D., Pietrzyk M., 2007, Testing of the inverse software for identification of rheological models of materials subjected to plastic deformation, *Arch. Civil and Mech. Eng*., 7, 35-52.

WSPOMAGANE KOMPUTEROWO PROJEKTOWANIE TECHNOLOGII WYTWARZANIA WYROBÓW ZE STOPÓW Cu-Cr

Streszczenie

Celem pracy była analiza możliwości kucia produkcji odkuwek o różnych kształtach z miedzi chromowej z zastosowaniem nowej technologii kucia. Rozważono dwa warianty technologiczne. Pierwszy składa się z odlewania, chłodzenia, nagrzewania do temperatury z przedziału 800-900°C, kucia na gorąco, chłodzenia, przesycania i starzenia. We wcześniejszych pracach wykazano, że ten wariant pozwala uzyskać wymagane własności wyrobu, ale jest kosztowny. W niniejszej pracy zaproponowano alternatywny proces polegający na zastąpieniu obróbki cieplnej dodatkowym dokuwaniem na zimno. Obliczenia numeryczne dla czterech odkuwek zostały przeprowadzone programem Forge3 opartym na metodzie elementów skończonych. W artykule przedstawiono wyniki symulacji obejmujące także rozkłady twardości w objętości odkuwek. Wprowadzenie dodatkowego odkształcenia na zimno pozwoliło dla niektórych odkuwek uzyskać wymaganą twardość porównywalną z otrzymaną po kuciu na gorąco z dodatkową obróbką cieplną.

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