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
Volume 59 2014 Issue 3
DOI: 10.2478/amm-2014-0167

A. ŁUKASZEK-SOŁEK*

EFFECT OF TECHNICAL QUALITY OF THERMOMECHANICAL DIE FORGING OF AA2099 ALLOY

EFEKT JAKOŚCI TECHNICZNEJ TERMOPLASTYCZNEGO KUCIA MATRYCOWEGO STOPU AA2099

The paper presents the results of investigations of a multicomponent third-generation aluminium alloy, classified as AA2099. The actual forging conditions were determined basing on the assessment of the quality of side surface of specimens subjected to compression in Gleeble 3800 simulator and on flow curves of the alloy, as well as numerical modelling of forging process performed with application of QForm 3D v.7 software. Compression tests were realized at temperatures 400-500°C, with a strain rate of 0.001-100 s^{-1}, up to a specified constant true strain value of 0.9. Microstructure examination in as-delivered state was performed with application of Leica DM 4000M optical microscope. The obtained results of isothermal deformation of specimens were correlated with the analysis of a characteristic layered pancake-type microstructure. The simulation of die forging of a complex-shape forging (high-current contact tip used in power engineering) at the temperature 500°C, was performed. The shape of a forging makes it possible to fully analyse the influence of thermomechanical process conditions on technical quality of a product. The simulation of forging process showed full correctness of material flow, with no signs of instability. At the same time, the analysis of investigations allowed to prepare and realize the industrial forging trials for a forging of a very complex shape, in a single step, at the temperature 500°C, with application of thermomechanical treatment. The forging attained high quality of shape and surface. Directional specimens were taken, in order to be subjected to microstructure examination and hardness testing. The data obtained from industrial tests, combined with the results of testing using Gleeble simulator as well as from numerical modelling, make up the guidelines for mechanical processing of AA2099 alloy at the temperatures 470-500°C.

Keywords: hot forging, thermomechanical treatment, microstructure, simulation

W pracy analizowano wyniki badań wykonanych na wieloskładnikowym, trzeciej generacji stopie aluminium, klasyfikowanym jako AA2099. na podstawie oceny stanu powierzchni pobocznicy próbek ściskanych w symulatorze odkształceń rzeczywistych Gleeble 3800 i krzywych płynięcia stopu, modelowania numerycznego procesu kucia w programie QForm 3D v. 7 ustalono warunki przemysłowej próby kucia stopu. Badania ściskania przeprowadzono w temperaturze 400-500°C z szybkością odkształcania 0.001-100 s^{-1} do stałej wartości odkształcenia rzeczywistego 0.9. Wykonano badania mikrostruktury w stanie dostawy na mikroskopie świetlnym Leica DM 4000M. Uzyskane wyniki odkształcenia izotermicznego próbek skorelowano z badaniami charakterystycznej warstwowej mikrostruktury typu "naleśnik". Dokonano symulacji procesu kucia matrycowego odkuwki o bardzo złożonym kształcie (nakładka wysokoprądowa dla energetyki) w temperaturze 500°C. Kształt odkuwki umożliwia pełną ocenę wpływu warunków termomechanicznych procesu na jakość techniczną wyrobu. Symulacja procesu kucia wykazała pełną poprawność płynięcia stopu bez żadnych efektów niestabilności. Jednocześnie analiza badań pozwoliła na opracowanie i przeprowadzenie prób kucia przemysłowego odkuwki o bardzo złożonym kształcie w jednym wykroju w temperaturze 500°C z zastosowaniem obróbki cieplnoplastycznej. Odkuwka uzyskała wysoką jakość kształtu i powierzchni. Pobrano próbki kierunkowe do badań mikrostruktury i twardości. Uzyskane dane z prób przemysłowych w połączeniu z wynikami uzyskanymi z symulatora Gleeble i modelowania numerycznego stanowią wytyczne do kształtowania plastycznego stopu AA 2099 w zakresie 470-500°C.

1. Introduction

The investigated Al-Cu-Li-Zn-Mg alloy is the latest third-generation alloy containing the addition of lithium. Alcoa concern classifies it as AA2099-T83. The alloy shows unique mechanical, technological and functional properties. The most important distinctive feature is the increased specific strength, described by the tensile strength to density ratio, which is the evaluation factor for high-tech level of light materials [1, 2]. These alloys gain widening industrial applications in many strategic key branches of aircraft, spacecraft, military and war industries, as they can replace conventional alloys. They are perceived as high-tech construction materials including rolled shapes, forged, extruded and pressed products, which are suitable to be applied as demanding elements showing favourable combination of properties and features [1, 2, 3, 4]. Apart from the above mentioned advantages, there are only few documented examples of application of these alloys in the forging

* AGH UNIVERSITY OF SCIENCE AND TECHNOLOGY, FACULTY OF METALS ENGINEERING AND INDUSTRIAL COMPUTER SCIENCE, AL. A. MICKIEWICZA 30, 30-059 KRAKÓW, POLAND

branch. The alloy AA2099 is subject to precipitation hardening and its final structure and resulting properties depend on the technological conditions in each stage of manufacturing process [5-10]. In that case, the analysis of the alloy's behaviour during die forging at specified temperature, strain rate and amount of deformation becomes the important research problem, in aspect of presenting the possibility of production of die forgings. The measurable effect of investigations should be the preparation of technological fundamentals for thermomechanical processing of Al-Cu-Li-Zn-Mg alloy, which is competitive with conventional alloys and not widely used in forging branch. A compact forging of a complex shape was selected to the investigations of hot die forging process in conventional conditions. Within the volume of a forging there are regions undergoing different amounts of deformation. The parameters determining final properties of a product, including the distributions of temperature, effective strain and mean stress, were analysed basing on numerical calculations. Additionally, the microstructures of selected sections of a forging after forging in industrial conditions were presented, basing on the parameters determined during modelling.

2. Material under investigation

The material under investigation was AA2099-T83 alloy with a chemical composition (Table 1) obtained as a result of melting from pure elements in an electric furnace. The alloy after DC cast showed coarse-grained dendritic structure and underwent the full process of thermomechanical treatment (double homogenizing), with subsequent extrusion, water cooling and cutting into blanks [1, 5-8]. The T83 temper means, that the obtained blanks (extrusion) has been solution heat treated and stress-relieved by stretching to produce a nominal permanent set of 2.5%, but within the range of 1-4%, and then artificially aged. This temper has the maximum mechanical properties [1, 5].

TABLE 1
Chemical composition (weight percent) of the investigated AA2099 alloy

Cu	Li	Zn	Mg	Mn	Zr	Ti	Fe	Al
2.6	1.8	0.7	0.29	0.3	0.1	0.03	0.02	Bal.

The alloy AA2099-T83 was delivered in the form of a bar of 100 mm diameter. The microstructure of the alloy in as-delivered condition is shown in Fig. 1.

3. Experimental procedure

The investigations of plastic deformation were preceded by the detailed analysis of a mathematical model of a forming process, basing on the latest version of FEM commercial software QForm 3D v.7, with application of the alloy's characteristic determined using Gleeble 3800 simulator. For that purpose, specimens of 10 mm diameter and 12 mm height were prepared from the initial material and then subjected to uniaxial compression at temperatures ranging from 400°C to 550°C, with strain rates from 0.001 s^{-1} to 100 s^{-1}, up to a specified constant true strain value of 0.9. For the interpretation of the results obtained from axisymmetrical compression tests, the inverse method was applied. This method was described in detail by Szeliga et al. [11]. The example flow curves of the alloy under investigation, determined basing on the inverse method, are shown in Fig. 2. The flow curves were then converted into tabular form and loaded into QForm software as one of the boundary conditions for the simulation of hot forging of Al-Cu-Li-Zn-Mg alloy [4, 16].

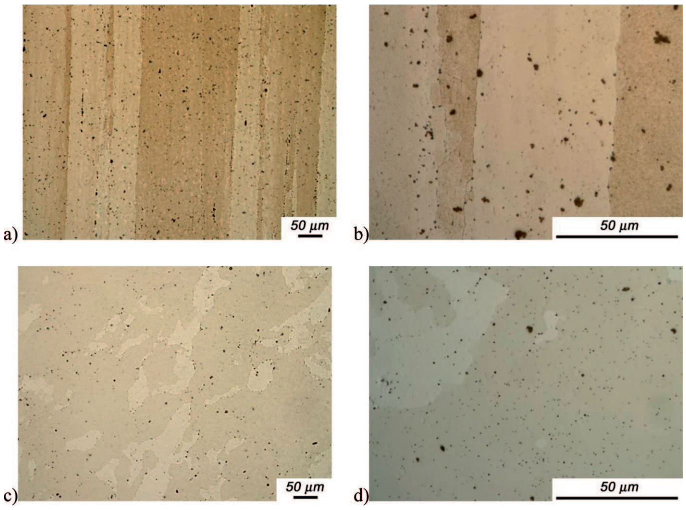

Fig. 1. Microstructure of the investigated alloy (as-delivered conditions): (a), (b) longitudinal section of a bar, (c), (d) cross section of a bar

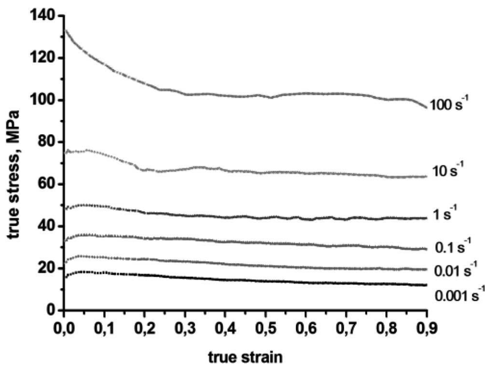

Fig. 2. Stress-strain curves obtained for temperature 500°C and strain rates ranging from 0.001 s^{-1} to 100 s^{-1}

The forging process parameters determining the properties of a final product, such as the distribution of temperature, effective strain and mean stress as well as Zener-Hollomon parameter, were analysed basing on numerical calculations. The forging tests in industrial conditions were realized taking into account the most favourable thermomechanical parameters determined in the simulation of forging of the investigated alloy. The microhardness measurements were performed using Innovatest apparatus, on longitudinal sections of specimens prepared from initial material and from final forging. The microstructure of the alloy under investigation was analysed with application of Leica DM 4000M optical microscope.

4. Numerical modelling and industrial testing

The numerical calculations of hot forging of high-current contact tip from AA2099 alloy were performed with application of QForm 3D v.7 software. The model of a forging is presented in Fig. 3a. The following boundary conditions were assumed: stock temperature (500°C), tool temperature (180°C), time of stock transportation to the press (2 s), time of stock cooling in a die cavity before forging (1 s), height of a flash land (1 mm). Single-operation forging process was realized using screw press of 20 kJ maximum striking energy and 450 mm/s maximum velocity. In the calculations, a graphite-water emulsion was assumed as a lubricant, with a friction factor m = 0.5. The effective heat transfer coefficient between stock and tools was assumed equal to 4000 $W \cdot m^{-2} \cdot K^{-1}$. The stock dimensions were 35 mm in diameter and 49 mm in height.

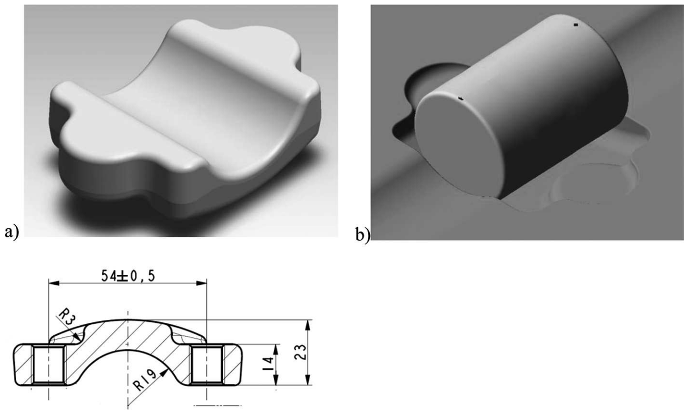

Fig. 3. Shape of the final forging of a contact tip (a) and position of a blank placed in the finishing impression (b)

Different positions of a stock placed in the finishing impression were considered. Taking into account the directional grain pattern existent in the structure of a stock, lengthwise positioning was chosen (Fig. 3b). The distributions of temperature, effective strain and mean stress were determined. Moreover, Zener-Hollomon parameter (Eq. 1) was calculated numerically using the formula [14]:

$$Z = (\dot{\varepsilon}) \exp\left(\frac{Q_{EW}}{R \cdot T}\right) \tag{1}$$

where:$\dot{\varepsilon}$ – strain rate, s^{-1}, Q_{EW} – activation energy (Eq. 2), J/mol, R – gas constant (8.3145 J/mol/K), T – temperature, °C. Every material is characterized by its specific activation energy. However, the general relationship can be given as follows:

$$Q = C_1 + C_2 \cdot T + C_3 \cdot \bar{\varepsilon} \tag{2}$$

where: T – temperature, °C, $\bar{\varepsilon}$ – effective strain, C_1, C_2, C_3 – coefficients. For Al-based alloys, the following values of coefficients were assumed: C_1 = 156000 J/K, C_2 = 0, C_3 = 0.

The conditions established during numerical modelling were also applied to the industrial forging tests [15]. The stock was heated in an induction furnace to the temperature 500 C. The temperature was measured using a thermocouple, with 5°C measuring accuracy. The stock was placed lengthwise in the finishing impression, according to the grain pattern, in order to improve strain uniformity and increase the resistance to longitudinal cracking. The tests were carried out with a graphite-water emulsion as a lubricant. The application of this type of lubrication effectively eliminates the possibility of material sticking on die surface, decreases frictional resistance and improves filling of corners and surface quality. After forging, the forgings were intensively water-cooled. The thermomechanical treatment allows to obtain the microstructure which can guarantee the best combination of strength and crack resistance. As a result of numerical modelling, a distribution of flow lines was obtained, reflecting the kinematics of material flow. It was then compared with the macrostructure of a forging (Fig. 4).

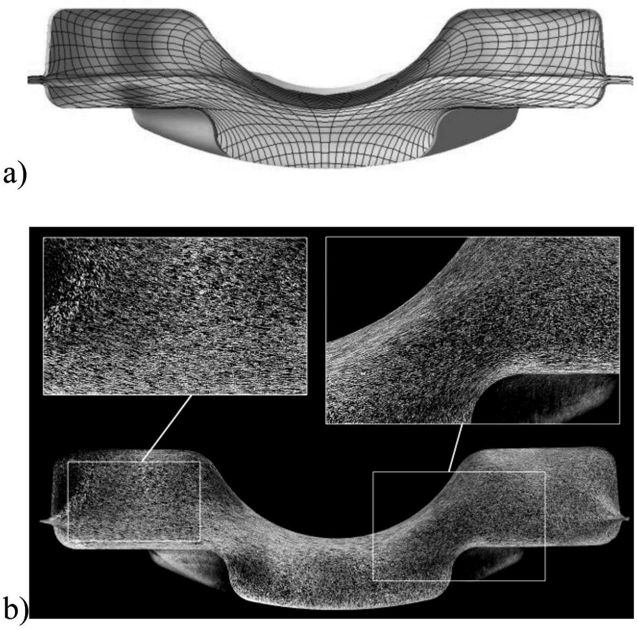

Fig. 4. Flow lines (grain pattern): (a) determined numerically, (b) actual flow lines

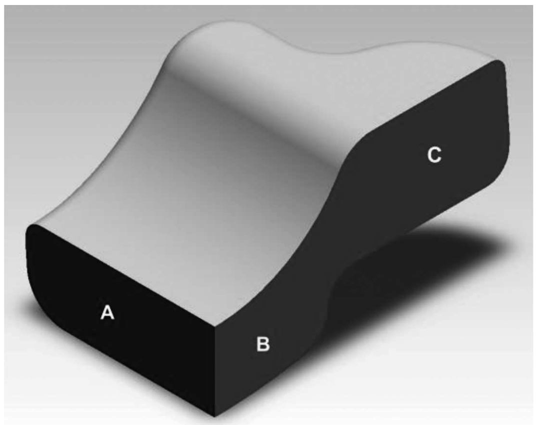

Fig. 5. Locations of metallographic examination performed on longitudinal and cross sections of a forging

The specimens for metallographic examination were prepared from the characteristic sections of a forging. Fig. 5 shows the regions on the analysed sections in which photographs were taken for the observation of microstructure (Fig. 10). Moreover, the microstructure of a forging was also analysed in a region where the impression passes into the flash gap, on both longitudinal and cross sections of a forging (Fig. 11).

Chosen results in characteristic cutting planes of a forging, obtained from numerical calculations are shown in Figs. 6-9. The distributions of: Zener-Hollomon parameter (Fig. 6), temperature (Fig. 7), effective strain (Fig. 8), mean stress (Fig. 9) were analyzed.

5. Results and discussion

The alloy in as-delivered condition was characterized by a layered fibrous microstructure with grains of similar size (Fig. 1) elongated in extruding direction, observed on longitudinal section, and microhardness of 180 HV. Equiaxed grains were observed on the cross section. This material is characterized by a small quantity of large iron-based intermetallic phases. No signs of recrystallized zone were observed near the edges. The chemical composition of the alloy is optimum for the formation of intermetallic precipitates, crystal nuclei, fine-grained dispersoids and boundary precipitates. Fine spherical precipitates were observed sporadically in the alloy's microstructure. Basing on literature [3, 13], they were identified as T_2 phases (Al_6CuLi_3), obtained as a result of dynamic deformation of the alloy in a single forging operation at the process temperature. T_1 and T_2 phase precipitates contain mainly Cu, which leads to hardening of the alloy. T_1 and δ' phases are a significant component of the alloy's microstructure. The addition of Zr – 0.1% results in the formation of fine-grained dispersoid $\beta'(Al_3Zr)$, induced by plastic deformation at the temperature 550°C, from heat activation within the die, which influences the recrystallization and grain size in the structure of fibres and facilitates the nucleation of δ' precipitates [3, 13]. Mn and Fe lead to the formation of crystal nuclei and boundary phase precipitates (AlCuMn) as well as residual AlCuFeMn [2, 5, 7, 9]. Generally, Zr increases tensile strength and shock resistance [3].

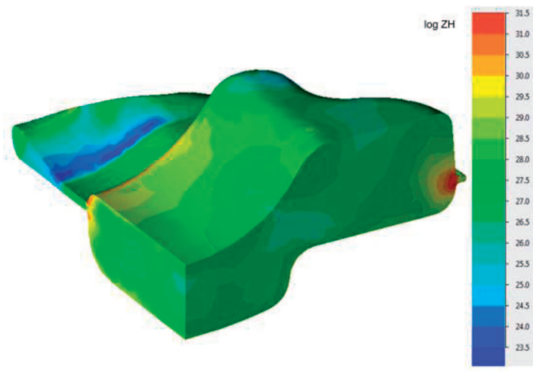

Fig. 6. Distribution of Zener-Hollomon parameter in AA2099 alloy forging

The flow curves (Fig. 2) present the flow stress σ_{pl} as a function of strain, at constant temperature 500°C and at different strain rates ranging from 0.001 s^{-1} to 100 s^{-1}, up to a specified true strain value of 0.9. The characteristic initial increase of flow stress is observed (with the exception of strain rate $\dot{\varepsilon} = 100 s^{-1}$) up to a very small true strain of about 0.05, with subsequent uniform drop observed over the whole remaining range of strain. At the true strain of about 0.8-0.9 the flow stress value stabilizes, which may testify for the completion of the minimum process of rebuilding (recovery) of microstructure of the alloy after deformation. The flow curves of the material obtained at the temperature 500°C and strain rate 100 s^{-1} show the optimum selection of temperature-strain rate parameters for Al-Cu-Li-Zn-Mg alloy, with a distinct lowering of stresses and thus stabilizing the process of deformation of specimens up to strain value of 0.9.

The maximum value of flow stress $\sigma_{pl\,\max}$ (Eq. 3) is related proportionally to Zener-Hollomon parameter, according to the formula [12]:

$$\sigma_{pl\,\max} = C \cdot Z^m \tag{3}$$

where: C – constant, m – index of sensitivity of stress to strain rate, Z – Zener-Hollomon parameter. This relationship is confirmed by numerically determined values of Z parameter in a region where the impression passes into the flash gap. The maximum values concentrated in this region are connected with intensive flow of large volumes of a material moving into the flash. For this region, the value of Z parameter for the forging under investigation obtained during simulation was $\ln Z_{\max} = 31.4$ with $\sigma_{pl\,\max} = 179$ MPa, while for unessential regions of a flash it was $\ln Z_{\min} = 23.3$ with $\sigma_{pl\,\min} = 34$ MPa (Fig. 6). The calculated value of Z parameter indicates the correlation between its increase and the process temperature and the dynamic stroke of a top die towards the flash plane.

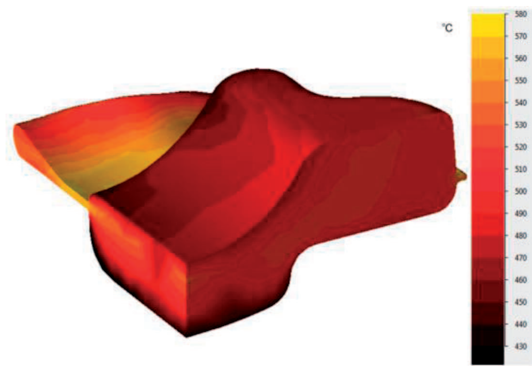

Fig. 7. Distribution of temperature in AA2099 alloy forging

The complex shape of a forging forces the finishing impression to be filled with a material by means of upsetting and lateral extrusion. The changes of cross section with narrowing from spherical (convex) part of a forging into a flat part require moving of large volumes of a material. During the final forging stage the temperature of a forging rose significantly as a result of conversion of work of plastic deformation into heat energy, effectively accumulated and then rapidly transferred to the material. For the analysed forging conditions, the temperature in the analysed section of a forging ranges from approximately 425°C to 570°C (Fig. 7). The minimum temperature is determined by tool temperature. As a result of conversion of energy of plastic deformation into heat energy in a region where the impression passes into the flash gap and moving large volumes of material into the flash, the temperature in the flash land rose up to 580°C, i.e. close to the phase equilibrium of the alloy. This phenomenon is intensified by a heat flux orientation density in relation to die contact surface. Microhardness testing performed in the central region of longitudinal section of specimen (region A) gave the result of approximately 150 HV, which differs by about 17 % from the initial condition of a stock with T83 temper. Moreover, the conviction is confirmed about the properly determined temperature of hot forming process (470-500°C), since the temperature 470°C was assumed for the extrusion of bars of 16 mm diameter, with the cross-sectional area being about 4.5 times smaller than that of the forging under investigation. The forging attained the assumed dimensions, as shown in Fig. 3, with 1 mm flash land height, identically as in the simulation of forging process.

The material, especially in case of conventional forging, undergoes smaller deformation in zones near to the contact surface with a tool, in comparison with central regions. However, considering the changes of cross sections of the forging, as well as good formability at temperatures 470-500°C, the material flows intensively from the central region of cross section towards the flash gap [4]. This is confirmed by numerically determined distribution of flow lines, which can reflect the actual grain pattern in the forging. High concentration and distortion of flow lines occurs in the central region (spherical/convex part) at the upper edge of finishing impression and at the inner fillet radii (where the convex part of a clamp passes into the flat part) of bottom die edges (Fig. 4a). The flow lines bend when passing from the analysed section B to section C (Fig. 5). These bends form convex surfaces restraining the zone of intensive plastic deformation. The photograph of the macrostructure of the forging was taken to reveal the actual grain pattern (Fig. 4b). The grain flow pattern determined numerically is similar to that observed during forging tests.

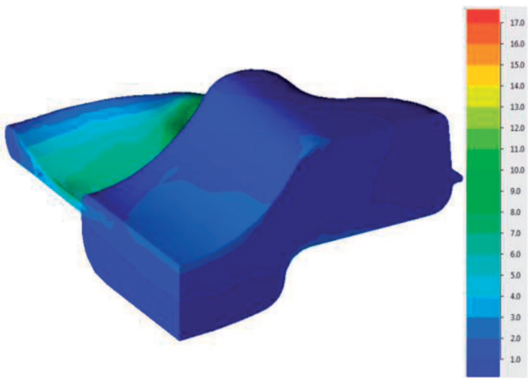

Fig. 8. Distribution of effective strain in AA2099 alloy forging

The distribution of effective strain (Fig. 8) is non-uniform and reflects the amount of deformation in individual regions of a forging. In the central region of a forging, near the contact surface with the bottom die, the smallest strains can be observed, amounting to approximately 0.2. The effective strain occurring in the same part of a forging, but close to the contact surface with the top die, amounts to about 2.3. As expected, the highest values of effective strain were observed close to the flash gap and amounted to approximately 3.3. This region is also characterized by the maximum value of Zener-Hollomon parameter: ln Z_{max} = 31.4 (Fig. 6), so it appears to be a specific zone of maximum process parameters.

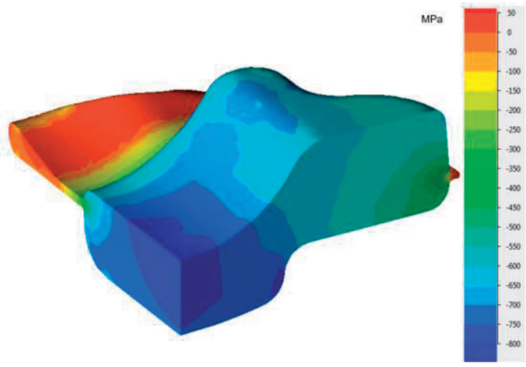

Fig. 9. Distribution of mean stress in AA2099 alloy forging

The mean stresses occurring during forging (Fig. 9) are compressive, with a uniform distribution on the surface, attaining the value of approximately (-788.4) MPa in the central part. Tensile stresses occur only at the circumference of a flash.

The forging has the regions of diversified effective strain values. The maximum value occurs at the narrowed part of the impression (cross section of a forging) and is connected with the flow of excess material towards the flash. A slight deformation of subgrains, characteristic for this type of material flow, can be observed (Fig. 10).

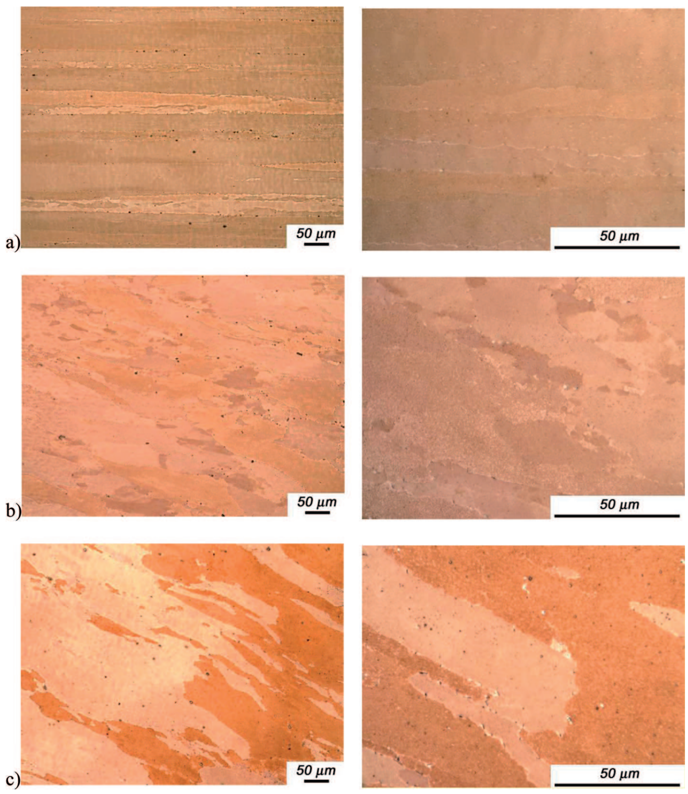

Fig. 10. Microstructure in central part of a forging: (a) longitudinal section (region A), (b) cross section (region B), (c) cross section (region C)

However, the grain size is similar for both the stock and the forging. In lengthwise direction the fibrous structure was maintained, characterized by the decreasing grain size in the direction of compression. The most intensive elongation and refinement of grains occurred in the direction of the most intensive material flow (flash) (Fig. 11). Considering the character of conventional forging process as well as rapid water cooling, the material did not undergo recrystallization. Moreover, it can be presumed that the application of additional heat treatment will result in obtaining similar or better properties than those characterizing the initial material. The intensive temperature rise (the limit of upper solidus below the tie line) in the flash land did not cause melting on grain boundaries.

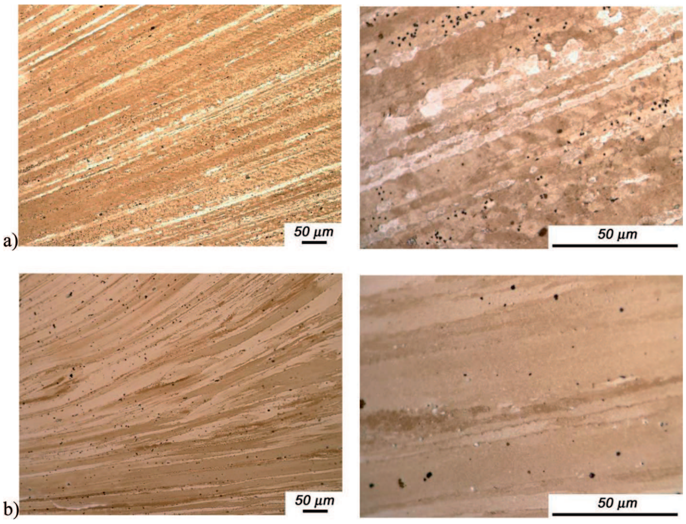

Fig. 11. Microstructure in a region where the impression passes into the flash gap: (a) cross section, (b) longitudinal section

6. Conclusions

The results obtained within this research work, combined with the data collected from the literature, are supplementary to the knowledge about the plastic deformation realized by means of extrusion [5, 7]. They confirm the character of precise relationships between microstructure, microhardness and actual process parameters. The range of deformation parameters (temperature and strain rate) improves the kinematics of material flow, with no signs of instability. The investigations presented in this paper make up a complex approach to the problem of determination of actual process parameters of die forging of Al-Cu-Li-Zn-Mg alloy, basing on the determination of rheological characteristic of a material, with application of Gleeble 3800 simulator, computer simulation of forging process realized using the FEM-based software – QForm 3D v.7, as well as the analysis of up-to-date literature. The analysed production technology involves the application of single-operation die forging, which results in the minimization of loss of energy and the improvement of structure of a blank after forging. The proposed technology makes it possible to obtain high dimensional accuracy of forgings, through the precise representation of the shape of dies. The additional trump of the realization of the process in one operation is time and energy saving as well as lower tool costs. Basing on the results of simulation, the forging conditions were determined, in which the overheating of a material does not take place, lapping, underfill and cracks do not occur, and there are no defects in the structure. The correctness of data obtained during modelling was verified experimentally in industrial conditions. The obtained forgings were characterized by good quality and correct geometry testifying for the proper filling of dies. The metallographic examination of a forging indicates the absence of intensive processes of rebuilding material's structure (recovery, recrystallization), which positively influences the final mechanical properties of a forging.

Considering the specific orientation of microstructure obtained in the extrusion process, the favourable position of a blank in a die cavity was selected, which guaranteed high quality of thermomechanical forging process resulting from the lengthwise arrangement of a fibrous structure. No risk occurred concerning the stabilization of forging process as well as the evolution of the alloy's structure, mainly the refinement of grain fibres and homogenization of the distribution of phases and precipitates. The realization of forging process allowed to obtain the forging of a good quality of shape and microstructure. The microhardness measured on the surface of specimen prepared from the forging without complete heat treatment amounted to approximately 150 HV on longitudinal section. For comparison, in case of a forging of PA6 alloy (AlCu4MgSi according to ISO) forged in the same conditions, the measured microhardness is about 63 HV. As a result of the realized research and analyses of AA2099-T83 alloy, the assumed high technical quality was achieved for the forging of a contact tip for power engineering, during the industrial tests of thermomechanical forging.

Acknowledgements

The research project was financed by the Polish Ministry of Science and Higher Education (AGH-UST statutory research project no. 11.11.110.292) and Structural Funds in the Operational Programme – Innovative Economy (IE OP) financed from the European Regional Development Fund – Project WND-POIG.01.03.01-12-004/09.

The author of this research would like to thank: Tomasz Tokarski, Krystyna Płońska-Niżnik, Marek Wojtaszek and Jan Sińczak for their help in the realized investigations.

REFERENCES

[1] Technical information from Alcoa Inc. June 2007, Alcoa Salles Office.
[2] S. Dymek, Nowoczesne stopy aluminium do przeróbki plastycznej, Kraków 2012.
[3] C. Giummarra, B. Thomas, R.J. Rioja, New aluminium lithium alloy for aerospace applications, Proceedings of the Light Metals Technology Conference, 2007.
[4] A. Łukaszek-Sołek, T. Tokarski, M. Wojtaszek, K. Płońska-Niżnik, The technology of industrial forging of the advanced aluminium alloy, poster (silver medal), Brussels Innova, the International Exhibition of Innovation, Entrepreneurship and New Technologies, Bruksela, 14-16 listopada 2013.
[5] Y. Lin, Z. Zheng, S. Li, X. Kg, Y. Han, Microstructures and proporties of 2099 Al-Li alloy, Materials Characterization **84**, 88-99 (2013).
[6] Y. Ma, X. Zhou, G.E. Thompson, T. Hashimito, Distribution of intermetallics in an AA2099-T8 aluminium alloy extrusion, Materials Chemistry Physics **126**, 46-53 (2011).
[7] Y. Lin, Z. Zheng, S. Li, Effect of solution treatment on microstructures and mechanical proporties of 2099 Al-Li alloy, Archives of Civil and Mechanical Engineering **14**, 61-71 (2014).

[8] T.L. G i l e s, K. O h - I s h i, A.P. Z h i l y a e v, S. S w a m i n a t h a n, M.W. M a h o n e y, T.R. M c N e l l e y, The Effect of Friction Stir Processing on the Microstructure and Mechanical Properties of an Aluminum Lithium Alloy, Metallurgical and Materials Transactions, Part A **40**, 1, 104 (2009).

[9] W. L i a n g, Q. P a n, Y. H e, Y. L i, X. Z h a n g, Flow stress behavior of Al-Cu-Li-Zr alloy containing Sc during hot compression deformation, Journal of Central South University of Technology **15**, 3, 289-294, June 2008.

[10] H. Z h a n g, N. J i n, J. C h e n, Hot deformation behavior of Al-Zn-Mg-Cu-Zr aluminum alloys during compression at elevated temperature, Transactions of Nonferrous Metals Society of China **21**, 437-442 (2011).

[11] D. S z e l i g a, J. G a w ą d, M. P i e t r z y k, Inverse analysis for identification of rheological and friction models in metal forming, J. Comp. Meth. Appl. Mech. Engrg. **195**, 6778-6798 (2006).

[12] W. S z k l i n i a r z, Stopy na osnowie faz międzymetalicznych z układu Ti-Al, Wyd. Politechniki Śląskiej, Gliwice 2007.

[13] G. A v r a m o v i c - C i n g a r a, D.D. P e r o v i c, H.J. M c - Q u e e n, Hot deformation mechanisms of a solution-treated Al-Li-Cu-Mg-Zr alloy, Metallurgical and Materials Transactions A **27**, 11, 3478-3490, November 1996.

[14] D. K u c, E. H a d a s i k, I. S c h i n d l e r, P. K a w u l o k, R. Ś l i w a, Characteristics of plasticity and microstructure of hot forming magnesium alloys Mg-Al-Zn type, Archives of Metallurgy and Materials **58**, 1, 151-156 (2013).

[15] A. G o n t a r z, Z. P a t e r, K. D r o z d o w s k i, Forging on hammer of rim forging from titanium alloy Ti6Al4V, Archives of Metallurgy and Materials **57**, 4, 1239-1246 (2012).

[16] A. Ś w i ą t o n i o w s k i, J. S i ń c z a k, A. Ł u k a s z e k - S o ł e k, J. S c h m i d t, Analysis of forging process of the NiCrN superalloy for motor boat driving shaft, Archives of Metallurgy and Materials **57**, 3, 719-725 (2012).

Received: 10 January 2014.