

NUMERICAL AND EXPERIMENTAL ANALYSIS OF ISOTHERMAL FORGING PROCESS OF RIBBED PLATES MADE OF 2099 ALUMINIUM ALLOY FOR AIRCRAFT STRUCTURES

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Summary

The analysis of isothermal forging process of ribbed plates made of multicomponent (Al-Cu-Li-Zn-Mg system) third generation 2099 aluminium alloy is presented in the paper. Numerical simulation of forging was performed by finite elements method (FEM) using the QForm v.7 commercial software. Obtained results were the base for selection of conditions of isothermal forging for examined aluminium alloy. It was assumed in the work that ribbed plates could be produced by one-step forging. The isothermal forging at the temperature of 450°C was conducted on designed test bed. Satisfactory shape accuracy and high quality surface of the forging were found. Evaluation of alloy's microstructure before (T-83 condition) and after forging was performed by microscopic examination. It was found that obtained results of numerical simulation and experimental research can be a base for elaboration of industrial process of plastic forming of complex geometry flat structural parts made of 2099 aluminium alloy.

Keywords: FEM numerical simulation, isothermal forging, Al-Cu-Li-Zn-Mg alloys, microstructure, aircraft structures

Analiza numeryczna i doświadczalna procesu kucia izotermicznego płyt żebrowanych ze stopu aluminium 2099 do konstrukcji lotniczych

Streszczenie

W pracy przedstawiono analizę wyników badań procesu kucia izotermicznego płyt żebrowanych z wieloskładnikowego (układ Al-Cu-Li-Zn-Mg) stopu aluminium trzeciej generacji 2099. Symulacje numeryczne kucia wykonano metodą elementów skończonych (MES) z zastosowaniem komercyjnego programu QForm v.7. Uzyskane wyniki były podstawą doboru warunków próby kucia izotermicznego badanego stopu aluminium. W badaniach przyjęto założenie, że jest możliwe kucie matrycowe płyt żebrowanych wykonanych w jednej operacji. Próbę kucia izotermicznego w temperaturze 450°C prowadzono na zaprojektowanym stanowisku badawczym. Stwierdzono zadowalającą dokładność kształtu i wysoką jakość powierzchni wykonanej odkuwki. W badaniach mikroskopowych dokonano oceny mikrostruktury stopu przed (w stanie T-83) i po procesie kucia. Stwierdzono, że wyniki symulacji numerycznej i badań eksperymentalnych mogą stanowić podstawę opracowania warunków

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przemysłowego kształtowania plastycznego panelowych elementów konstrukcyjnych o złożonej geometrii ze stopu aluminium 2099.

Słowa kluczowe: symulacja numeryczna MES, kucie izotermiczne, stopy Al-Cu-Li-Zn-Mg, mikrostruktura, konstrukcje lotnicze

1. Introduction

Aluminum alloys are extensively used as a structural materials due to their properties – low density and high specific strength (R_m/ρ), good electrical and thermal conductivity and good technological properties – good castability and plastic deformability. Wrought aluminium alloys has significant contribution to aerospace industry development, including light and ultra-light aircraft. Despite the modern airframes are more and more built from composite materials new generation aluminum alloys are still used in the load-bearing structures of aircraft [1, 2].

The use of aluminum alloys containing lithium in aerospace applications began in the late 1950's with alloy 2020. Initially these alloys did not achieve widespread use due to properties anisotropy, low toughness, poor corrosion resistance and/or manufacturing issues. New generation of Al-Li alloys provides not only density weight savings, but also many property benefits such as excellent corrosion resistance, good fatigue crack growth performance, a good strength and toughness combination and compatibility with standard manufacturing techniques [3].

The 2099 alloy (also designated C460) is a third-generation aluminium alloy. Its chemical composition has been developed on the basis of the experimental knowledge of the first and the second generation alloys. It belongs to 2xxx series alloys which contain Cu as the main alloying element. The 2099 aluminium alloy found applications in the aerospace industry, due to its unique mechanical and functional properties. Higher strength and stiffness with lower density, better weldability, excellent tolerance for damage and higher corrosion resistance in comparison to conventional aluminium alloys, these are some of the characteristics of the 2099 alloy. The precursor of the 2099 is the 2090 alloy. Comparison of these two alloys indicate that the 2099 has fewer planar anisotropy, higher ductility and toughness and the same cryogenic properties as the 2090. Increased specific strength, defined as the ratio of tensile strength and density, is the main property of the alloy. It is achieved by addition of lithium. Every 1% of lithium added to the alloy lowers its density by 3% and enhances Young modulus by 5 to 6% [4-12].

Those extraordinary properties make 2099 aluminium alloy suitable for manufacturing structural elements of an aircraft. Forging allows to obtain the required mechanical, macro- and microstructural, and geometrical parameters together with high quality of the surface. Manufacturing elements of very complex cross-sections are usually too expensive or even impossible with application of various techniques.

The analysed material can replace aluminium alloys 2xxx, 6xxx, 7xxx series in applications with statically and dynamically loaded structures of the hull, the lower wing stringers and other elements which require high stiffness [5-11].

The 2099 alloy is subjected to precipitation hardening. Its final structure and properties depend on the conditions at each stage of the production process. The research should be oriented for optimisation of the thermomechanical conditions of technological processing of the alloy Al-Cu-Li-Zn-Mg [5].

The forging of light alloys is commonly used in the aviation industry. In case of complex shape elements, having ribs and recesses, special thermal and mechanical conditions of forging process should be used. The main aim of this work was to analyse the possibility of isothermal forging of ribbed plates made from the new generation 2099 aluminium alloy.

2. Experimental procedure

Commercial 2099-T83 aluminium alloy was used in investigation. The material was prepared by melting accurately weighed components (Tab. 1) in an electric arc furnace, cast and extruded into shapes of rods. The prepared rods were afterwards cut and subjected to the processes of solution annealing (stretching in the range of 1-4%) and aging (T-83 condition). This procedure ensures optimal combination of mechanical and plastic properties (Tab. 2) [12].

Table 1. Chemical composition of the investigated 2099-T83 alloy [12]

Alloying element, wt. %							
Cu	Li	Zn	Mg	Mn	Zr	Ti	Al
2.4-3.0	1.6-2.0	0.4-1.0	0.1-0.5	0.1-0.5	0.05-0.12	0.1 max	bal.

Table 2. Physical and mechanical properties of the investigated 2099-T83 alloy [12]

Density ρ , g/cm ³	2.63
Young modulus E , GPa	78
Yield Strength σ_s , MPa	595 (L), 520 (T)
Ultimate tensile strength σ_s , MPa	505 (L), 470 (T)
Elongation ϵ , %	9 (L)
Toughness K_{IC} , MPa·m ^{0.5}	30 (L-T), 27 (T-L)

L and T – longitudinal and transverse direction respectively

The microstructure of 2099-T83 aluminium alloy rod was composed of grains of α (Al) phase elongated in the extrusion direction and precipitates homogeneously distributed in the matrix (Fig. 1).

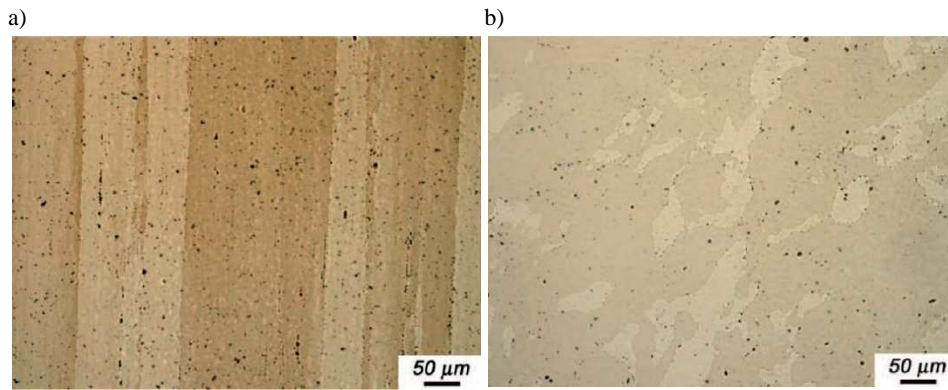


Fig. 1. Microstructure of investigated 2099 alloy in as-received condition (T-83) – longitudinal (a) and transverse (b) cross-section [5]

The conditions of forging were established based on the numerical modelling of the process in the Q Form 3D v.7 software supported by the literature review. Commercial program QForm is convenient for the development of open die forging process, checking plastic deformation distribution inside the ingots, evaluation the heating and cooling during the whole technological chain and technology optimization. QForm is a program that is based on a complex approach for the simulation. Finite-Element Method (FEM) and Voronoi Cells (VC) are implemented for discretization and solving the thermo-mechanical problems. The discretization of the thermal problem is carried out by dividing the simulation domain into small finite volumes (Voronoi Cells) while for discretization of the mechanical problem implemented FEM is used. The grid of Voronoi Cells is based on the finite element mesh. QForm provides simulation of the coupled thermo-mechanical problem during the contact of workpiece-dies. The dies may be considered as an assembled body. It is possible to consider the plastic deformation of the several workpieces in the mutual contact. The isothermal forging was proposed in the investigation [13].

The following parameters have been adopted in the simulation:

- batch temperature: 450°C,
- tools temperature: 450°C,
- pressure: 5 MN,
- forming speed: 0.5 mm/s.

The calculated volume of the forging batch of a single plate was about 11451,69 mm³ with the large flash of approximately 45%. This is related to the complex shape of the forging (Fig. 2), where the correct filling of the die cavity requires a wider groove for the flash. The forging process was carried out in the open dies, and the shape of the finished ribbed plates is shown in Fig. 1.

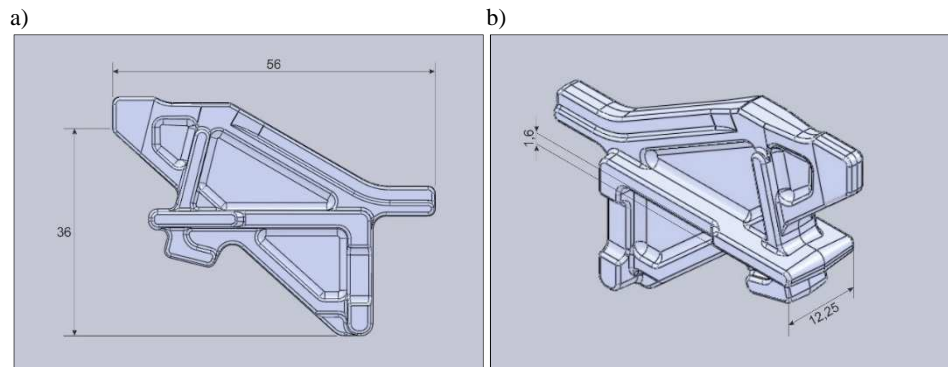


Fig. 2. The ribbed plate taken into consideration: a) top view, b) isometric view

The isothermal forging process was performed on laboratory test bed based on hydraulic press Zamet 500 Mg (Fig. 3) in Department of Metal Forming of AGH University of Technology. Graphite-water emulsion was used as a lubricant in the die surface while the surface of feed is covered with glass in order to reduce a friction during forging. The temperature was constantly monitored with three thermocouples placed in the chamber of the furnace. The process carried out in the isothermal conditions at temperature of 450°C and the forming speed of 0.5 mm/s.

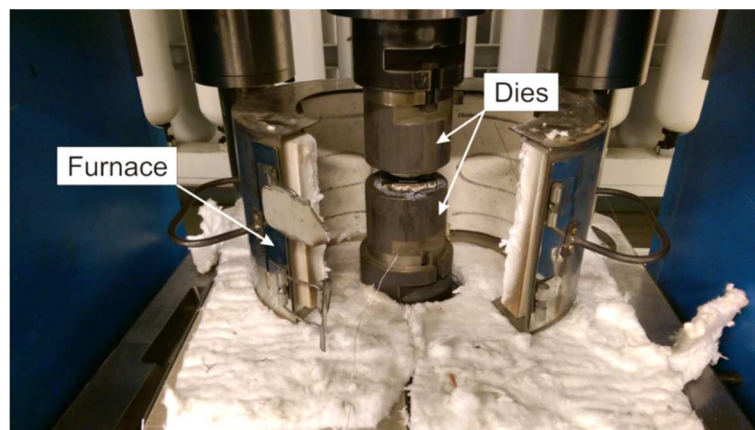


Fig. 3. The test bed for isothermal forging process

The forging was cooled in the water after plastic deformation process and cut for metallographic specimens preparation. Microstructural investigations were carried out using Carl Zeiss Axio Vert 200 MAT light microscope (LM) and JEOL JEM – 2100 transmission electron microscope (TEM).

3. Results and discussion

3.1. FEM analysis

The complicated shape of the forging results in high rigidity, toughness and fatigue resistance. In spite of such features of the forging a single operation was planned, which is an important attribute of the technological process. During the open-die forging filling of the dies is carried out by complex operations, such as upsetting, extrusion and piercing. The difficulties of the modelling process are mainly related to the selection of the optimal parameters. This make filling of the die cavity possible in one operation without any defects. Furthermore, the forging should be characterized by fine-grained fibrous microstructure and high quality surfaces [4, 5].

Based on numerical analysis results it was found that deformation temperature of forging during the isothermal process is very homogenous (Fig. 4) – the temperature spread is less than 2°C.

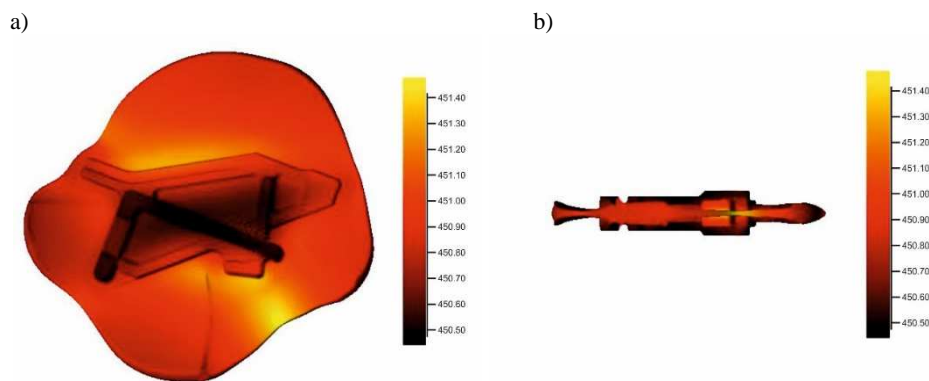


Fig. 4. Distribution of deformation temperature in the forging: a) top view, b) end view

Numerical analysis confirmed the complex state of stresses in the forging during plastic deformation (Fig. 5). The compressive stresses in the forging were predicted, while tensile stresses were possible only in the flash. It is generally advisable during the forging – compressive stresses enhance plastic formability of material and allow to avoid microcracking.

FEM analysis of plastic strain in the forging revealed that the most intensive plastic flow of the material is in the flash volume (Fig. 6). The lowest values of strain were found in the region between ribs (Fig. 6a) – dead zone. Formation of the dead zone is either caused by the rapid occurrence of the flash or a large height difference and a high radius in the ribbed plate.

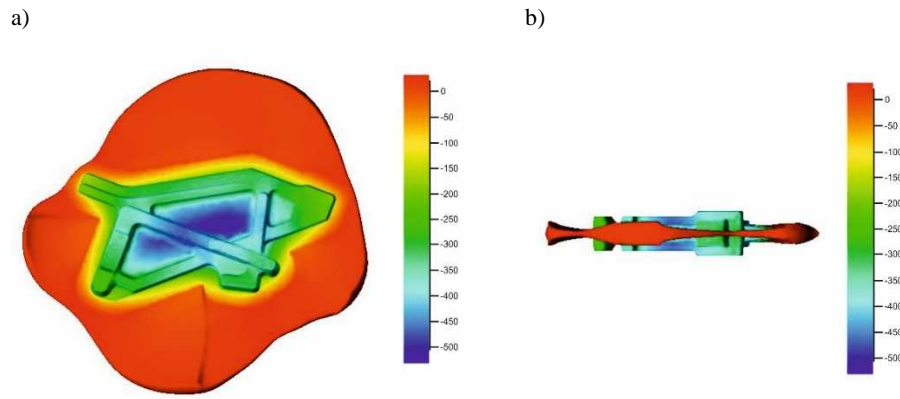


Fig. 5. Distribution of mean stress in the forging: a) top view, b) end view

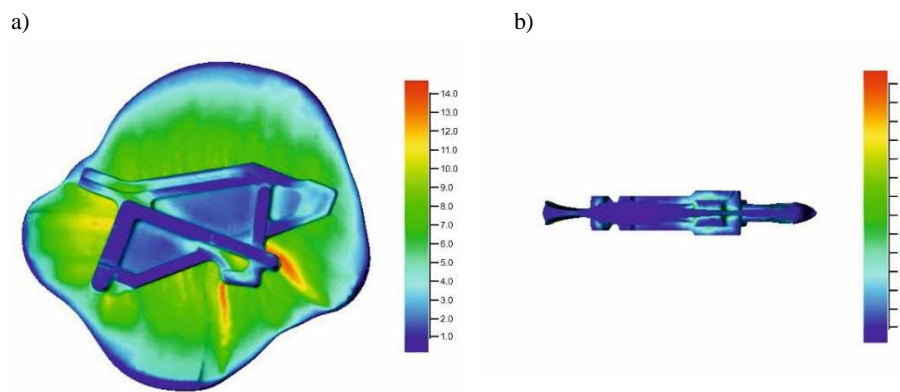


Fig. 6. Distribution of effective strain in the forging: a) top view, b) end view

Performed numerical simulation enabled calculation of parameters (Tab. 3) of one-step isothermal forging of ribbed panel. The physical process of forging on laboratory test bed was planned and carried out for the verification of obtained results.

Table 3. Deformation parameters calculated in numerical simulation of isothermal forging process

Deformation temperature, °C	Stress, MPa		Effective strain	
	min	max	min	max
450	21.6	-507.0	0.1	14.9

3.2. Isothermal forging

Parameters of isothermal forging on hydraulic press Zamet 500 Mg used in investigation were collected by monitoring system. The maximum recorded force was about 598 kN for time of 30 s (Fig. 7).

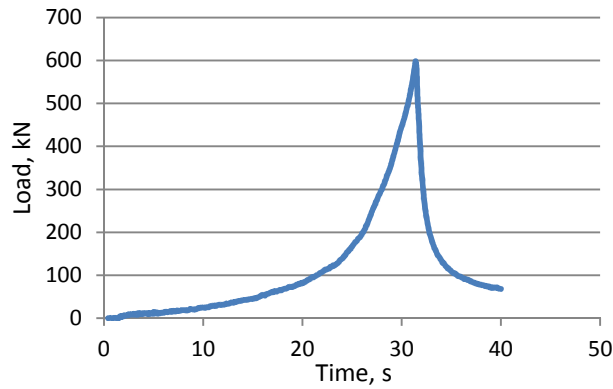


Fig. 7. Tool force during the forging process

Based on temperature measurements (Fig. 7) it was found that at the beginning of forging process the heating up to the temperature of 350°C was quite fast. There were not determined significant differences between forging and dies temperature (Fig. 8).

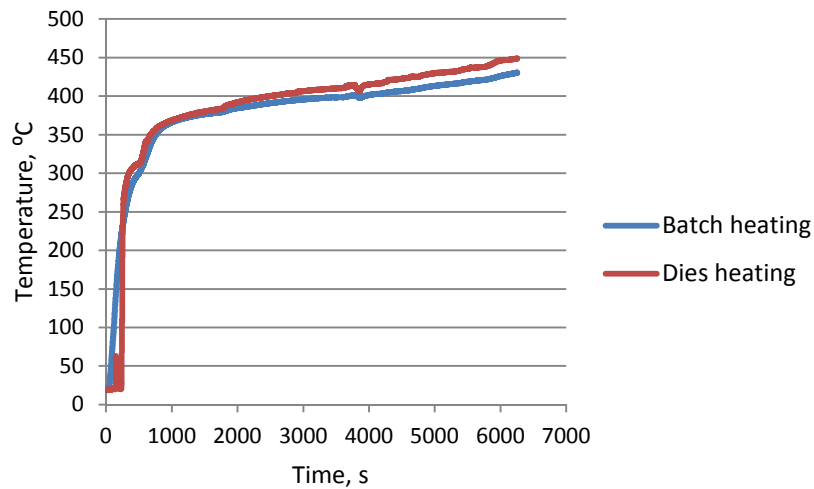


Fig. 8. Forging and dies temperature during heating stage of the process

Proposed one-step isothermal forging enabled to produce good quality semi-product having required shape and dimensions (Fig. 9).



Fig. 9. The view of isothermally forged ribbed plate

3.3. Microstructure analysis

The microstructure of 2099 alloy isothermally forged is fibrous (Fig. 10a). Grains morphology is strongly related to the state of stress. They are elongated in the extruding direction and their size decreases in the compression direction (Fig. 10b). Developed microstructure is multiphase – contains dispersed and fine precipitations (Fig. 10c,d). There is no occurrence of cracking or other defects in the microstructure of the ribbed plate no signs of overheating either.

Detailed phase analysis of examined 2099 alloy was not planned in the frame of presented work. Based on literature data [5-7, 10] the formation of intermetallic phases and fine particles precipitates in the $\alpha(\text{Al})$ matrix and grain boundaries is possible. After forging process at the temperature between 400 and 500°C the formation of T_1 ($\text{Al}_2\text{CuLi-Mg}$) and T_2 (Al_6CuLi_3) phases is expected [4,5]. Phases T_1 and T_2 in the 2099 alloy are fine and dispersed and have form of regular spheres. They contain mainly Cu, which improves the plasticity and mechanical properties of the alloy.

T_1 and δ' (Al_3Li) phases are essential components of the alloy which have an impact on the strengthening. The addition of 0.1 wt. % of zirconium results in a fine dispersoid of the form of β' (Al_3Zr) which increases the tensile and impact strength. The T_1 and δ' started growing above the temperature of 550 °C, thereby contributing to the inhibition of the dynamic recrystallization and affecting the

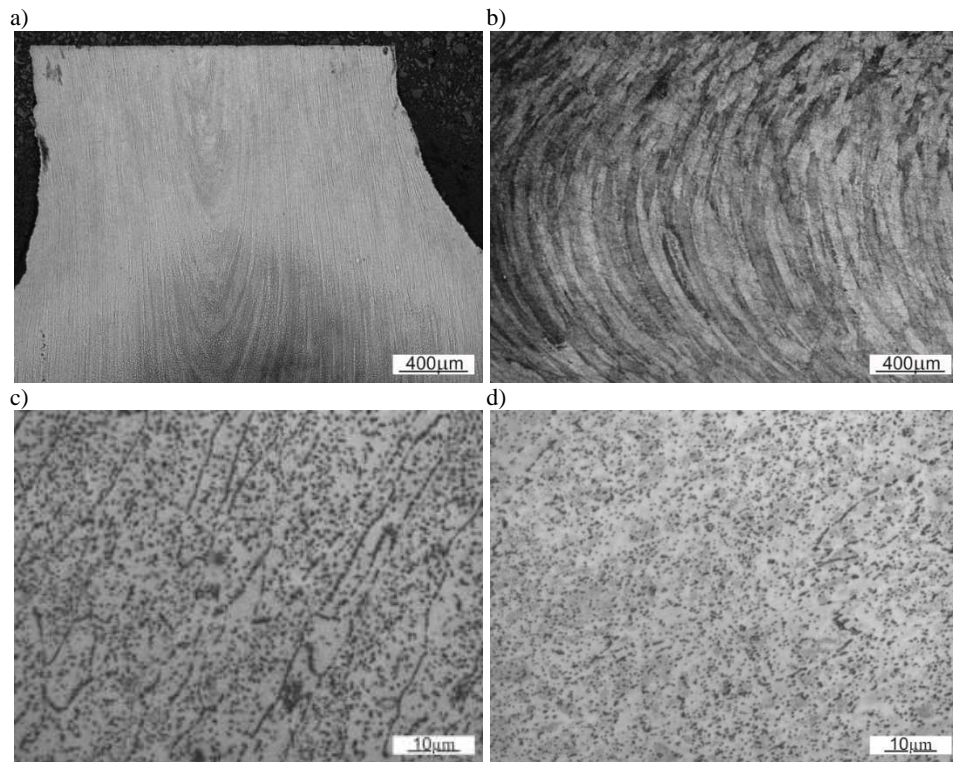


Fig. 10. Microstructure (LM) of the forged 2099 aluminium alloy: a) plastic flow bands, b) deformed and elongated grains of α (Al) phase, c, d) intermetallic phase precipitations

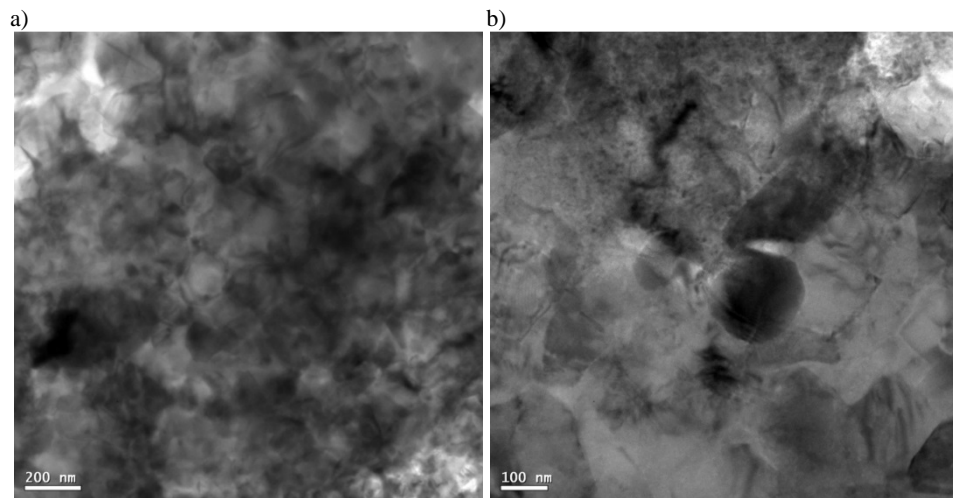


Fig. 11. Microstructure (TEM) of the ribbed plate: a) fine precipitations of intermetallic phases, b) spherical precipitates of the δ' phase

precipitation strengthening. The zirconium comprising β' phase does not dissolve during processing and effectively block the subgrains activity, raising the strength of the alloy. Another phase, consisted of manganese, are incoherent $\text{Al}_{20}\text{Cu}_2\text{Mn}_3$ precipitations formed on the boundaries that prevent grains growth. Moreover, both $\text{Al}_{20}\text{Cu}_2\text{Mn}_3$ and β' phases determine dynamic recrystallization process [8, 9].

Microstructure of the ribbed plate observed by the transmission electron microscope allowed to confirm the presence of ultrafine precipitation (Fig. 11a) and recognise dark spherical precipitates of the phase δ' (Fig. 11b).

4. Conclusions

Based on numerical and experimental analysis of isothermal forging process following conclusions can be formulated:

1. The findings from the analysis of the forging process confirmed that production of the ribbed plate is possible in a single forging operation. However, it is possible only when the chosen feed has an accurate excess of the material in order to allow complete filling of the blank matrix.

2. High quality of the forging is a result of the appropriate distribution of the stresses.

3. No cracks or other defects are found during the metallographic observations, which confirm proper selection of the process parameters.

4. The microstructure of the alloy after deformation is clearly fibrous. The grain size depends on the deformation direction, i.e. larger elongated grains are observed in the extrusion direction, while smaller grains are localised in the compression zone.

5. The homogeneity of alloy's microstructure in the forging indicate that the plastic deformation is undergone in steadily and stable conditions. The 2099 aluminium alloy demonstrates predispositions to conduct the process under isothermal conditions.

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Received in September 2016