

MECHANICAL PROPERTIES OF TWIN-ROLL CAST ALUMINUM SHEETS AFTER CONSTRAINED GROOVE PRESSING

BAJER Jan ¹, CIESLAR Miroslav ¹, ŠLAPÁKOVÁ Michaela ¹, ZIMINA Maria ¹, ZRNÍK Josef ²,
MATERNA Aleš ³

¹Charles University in Prague, Faculty of Mathematics and Physics, Prague, Czech Republic, EU

²COMTES FHT, Dobřany, Czech Republic, EU

³Czech Technical University in Prague, Faculty of Nuclear Sciences and Physical Engineering,
Prague, Czech Republic, EU

Abstract

Severe plastic deformation methods preserve dimensions of the material and reduce the grain size down to submicrometer scale. Twin-roll cast strips prepared from AA 3003 aluminum alloy (in wt.%) with 1 % Mn, 0.2 % Fe, 0.5 % Si, 0.2 % Cu and small additions of zirconium (0.2 %) and chromium (0.1 %) were subjected to deformation by Constrained Groove Pressing (CGP). The microhardness distribution along the strip cross-section reflects an inhomogeneous distribution of total equivalent strain simulated by finite element method only for one CGP cycle. Subsequently, after third CGP cycle, microhardness saturates and its distribution becomes more homogenous. Evolution of microstructure and mechanical properties during subsequent annealing was studied by transmission electron microscopy and electron backscatter diffraction. Inhomogeneous recovery of dislocation structure and recrystallization were observed during this annealing.

Keywords: Al-Mn-Zr alloy, twin-roll casting, CGP, recrystallization, electron microscopy

1. INTRODUCTION

Increasing demands on the price and the environment lead to a combination of unconventional materials and new casting and forming methods. Established sheet and strip-production technologies have to be revised in order to fulfill demands on formability, hardness, high temperature resistance and other characteristics of the material.

Twin-roll casting (TRC) allows production of sheets and strips of a required thickness avoiding subsequent homogenization or cropping known from ingot casting methods. High cooling rate during TRC produces supersaturated solid solution, fine grains and finely dispersed primary particles. On the other hand, inhomogeneities such as central segregations and grains inclined to the center of the strip can be found in TRC strips. Therefore TRC alloys have to be subjected to additional processing if their full potential has to be exploited. These include heat treatment, severe plastic deformation or a combination of both. Constrained groove pressing (CGP) is one of a few methods which preserve original thickness of the sheet material and does not produce grain structure elongated in a rolling direction. Although CGP imposes partially inhomogeneous strain into the material resulting in an inhomogeneous microhardness distribution, it seems to be one of the most promising SPD methods producing sheet materials. One CGP cycle consist of 4 steps (see **Figure 1**): 2 corrugations and 2 straightenings which can together apply effective strain 1.16 per each cycle [1, 2]. Khodabakhshi et al. [2] tested this method on various materials such as copper, nickel, low-carbon steel, pure titanium, aluminum and aluminum alloys, and received also a significant grain size reduction from 30 μm to 350 nm and microhardness increase in AA3003 alloy. Aluminum alloys AA3003 are commonly used in the industry. Addition of small amount of Zr to Al alloys enhances the microstructure stability. Zr forms coherent Al_3Zr precipitates after suitable heat treatment. These precipitates ping grain boundaries and thus recrystallization can be shifted to higher temperatures. [3-8]. AA 3003 alloys processed by ECAP recrystallize below 400 °C while in a Zr-containing alloy the recrystallization is shifted by more than 50 °C to higher

annealing temperatures [8]. The present work is focused on a study of an annealing response of the same Zr-containing alloy after CGP.

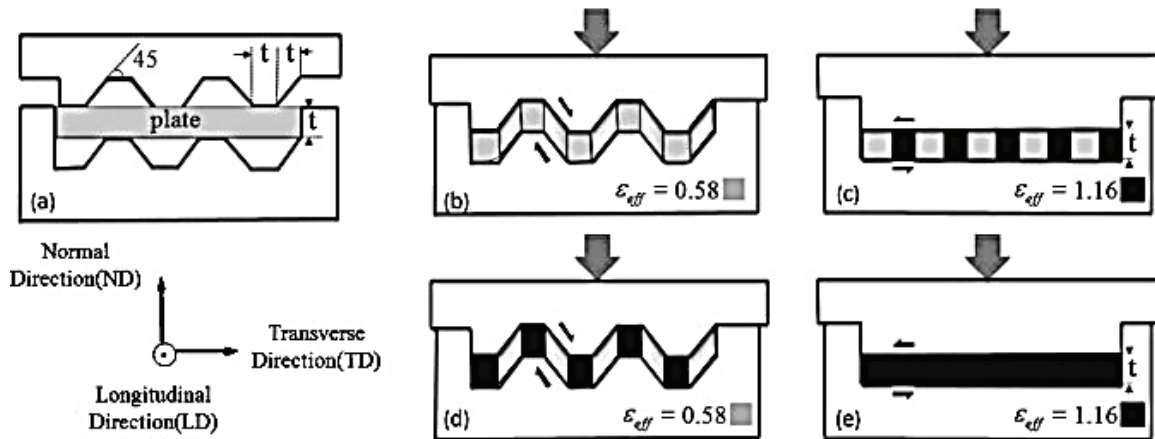


Figure 1 Schematics of one CGP cycle b) [1]

2. EXPERIMENTAL PART

A TRC alloy (a modified AA 3003 aluminum alloy with 0.17 wt. % of Zr addition) with a composition shown in **Table 1** was studied. The industrially prepared material was cut into samples with dimensions 60x80x8mm³. These samples were deformed by CGP method with grooves of dies parallel to the rolling direction using three CGP cycles. In order to investigate the changes of mechanical properties and microstructure at elevated temperatures samples were annealed in an air furnace and quenched after each annealing. Annealing was carried out using step-by-step isochronal heating scheme up to 550 °C with steps of 50 °C/50 min. Vickers microhardness measurements HV 0.1 with the load of 100 g were done after each step. In order to detect changes in microhardness distribution on cross-section, measurements were done on a large area of 20x6 mm² with more than 1000 indents per sample and annealing step. Electron back-scatter diffraction (EBSD) in scanning electron microscope FEI Quanta FEG200 and in-situ heating in transmission electron microscope (TEM) JEOL JEM 2000FX with the same heating scheme as the one employed during isochronal annealing, were used for the material characterization. Specimens for electron microscopy were electro-polished in 30 % HNO₃ solution in methanol.

Table 1 Nominal composition of studied Al alloy in wt. %

Al	Mn	Fe	Si	Cu	Zr	Cr
Balance	1.0	0.2	0.5	0.2	0.2	~0.1

3. RESULTS

Three CGP cycles have a significant influence on the microhardness of the material, which rises from the initial 55 to 81 HV_{0.1} (see **Figure 2**). Such an increase is slightly lower than the one observed by Šlapáková et al. [9] after four ECAP passes. The distribution of the microhardness is inhomogeneous reflecting the geometry of grooves (**Figure 3a**). No significant changes of microhardness were observed below 250 °C. Above this annealing temperature slight microhardness decrease connected with the microhardness equalization occurs (**Figure 3b**). Above 450°C the microhardness significant drop is accompanied by an increase of microhardness inhomogeneities, and at 550°C the initially harder parts (areas with higher microhardness after CGP) of the deformed specimens are significantly softer than parts exhibiting initially lower microhardness (**Figure 3c, 3d**).

Figure 4 shows EBSD orientation maps of originally harder (left) and softer (right) parts of the specimen in the initial state and after annealing. A pronounced fragmentation of original grains is observed after the CGP straining in both parts of the material, with more pronounced features of dynamic recovery in the initially harder one. At 350°C this recovery prevails in both parts resulting in a formation of well-defined subgrains. Full recrystallization is observed in the originally harder parts of the material at 550 °C, while only a partial recrystallization occurs in the initially softer parts leaving a significant volume fraction of the material in a well-recovered state.

Figure 5 shows the evolution of microstructure during in-situ heating observed by TEM. An area between harder and softer parts was chosen for this observation. This observation confirms substantial fragmentation of original grain into numerous subgrains. They reflect a high degree of strain imposed by CGP and contain a high density of dislocations (**Figure 5a**). With increasing annealing temperature an improvement of the subgrain structure proceeds resulting in a massive annihilation of dislocations (**Figure 5b**). Moreover, a formation of Mn and Si-rich particles observed also by Šlapáková et al. [10] and known as α -Al(Mn,Fe)Si cubic phase occurs above 400 °C (**Figure 5c**). Full recrystallization and grain growth occurs above 550 °C (**Figure 5d**).

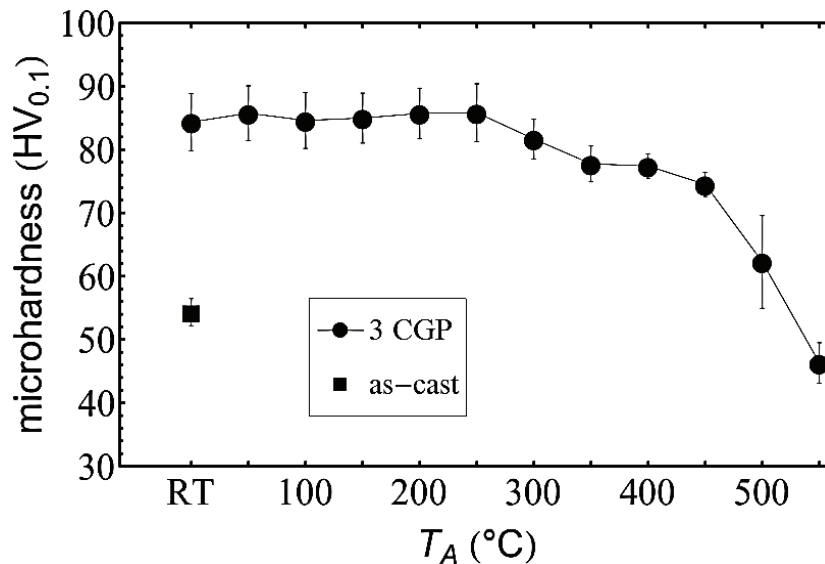


Figure 2 Room temperature microhardness evolution as a function of annealing temperature T_A

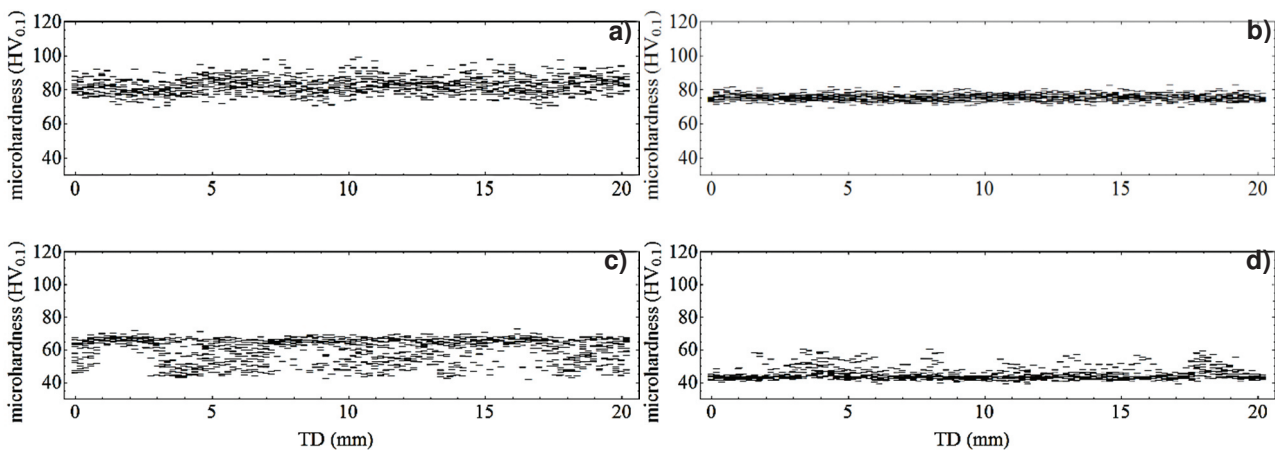


Figure 3 Microhardness distribution along transverse direction: a) initial state, b) after 400 °C annealing, c) 500 °C, d) 550 °C

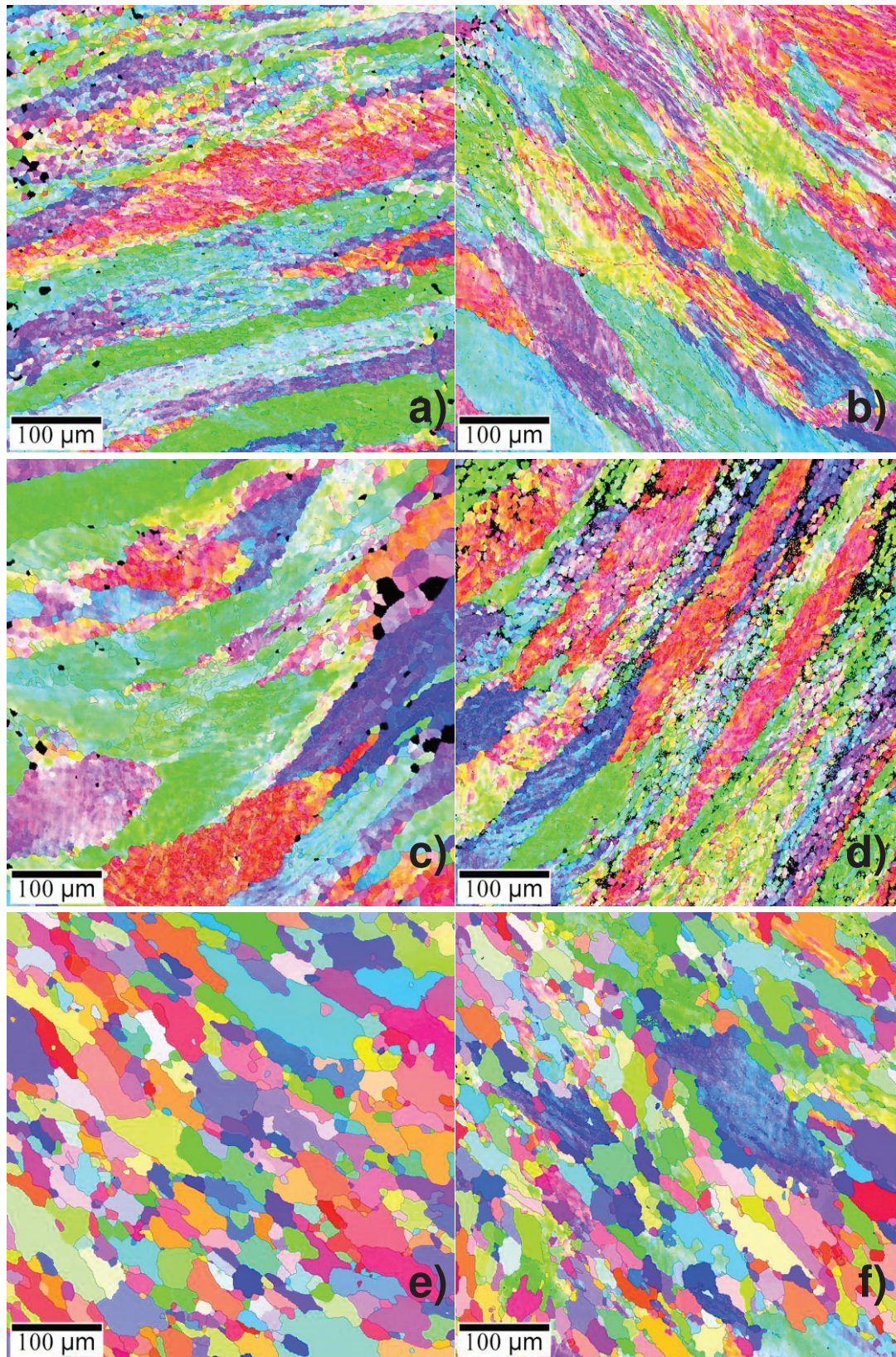


Figure 4 EBSD maps of C 471 alloy after 3 CGP cycles a), b) initial states; c), d) after 350 °C annealing step; e), f) after 550 °C annealing step; initially softer part of the sample on the right and initially harder one on the left

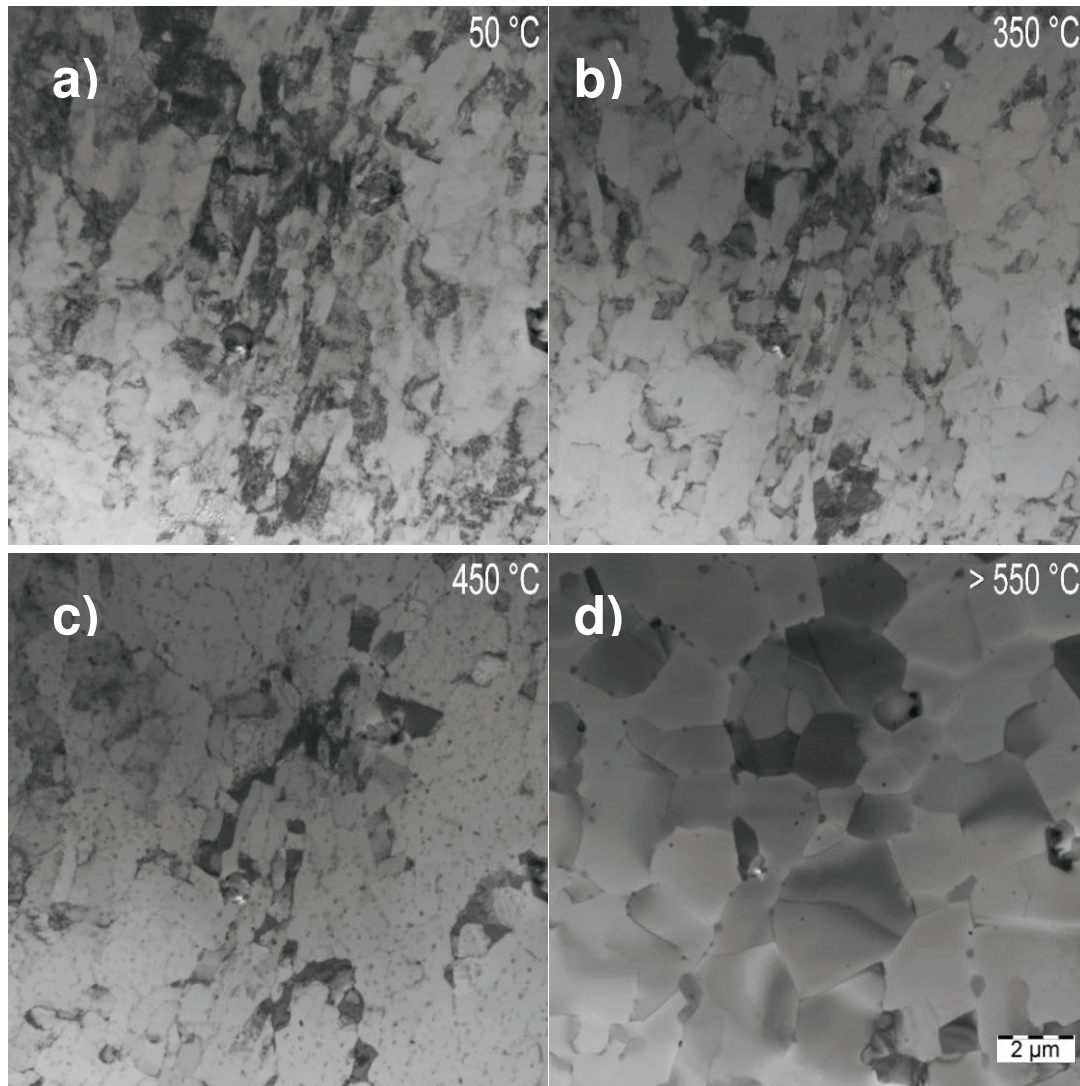


Figure 5 TEM images of the samples heated in-situ: a) 50 °C, b) 350 °C, c) 450 °C, d) > 550 °C

4. DISCUSSION

CGP treatment creates a wavy grain structure with alternating harder and softer areas. This microhardness alternating is consistent with a FEM simulation of equivalent strain distribution after CGP [10], which predicts an inhomogeneous distribution of strain with periodic alternation of specimen parts with higher and lower imposed strain. As a consequence, a higher degree of a dynamic recovery is observed in parts with higher total equivalent strain. Surprisingly, in the area with higher degree of dynamic recovery, i.e. with a lower dislocation density and better defined subgrains, the microhardness exhibits higher values. Such an effect has been often observed in pure aluminium and some aluminium alloys after severe plastic deformation [9, 11], and generally is associated with difficulties of activation of new dislocation sources necessary for accommodation of strain during subsequent room temperature indentation. The equalization of microhardness in the range of annealing temperatures below 400 °C is a consequence of full recovery in both parts of the specimen, and reflects the inhomogeneous distribution of deformation energy stored during CGP. A formation of α -Al(Mn,Fe)Si cubic phase has only a moderate influence on mechanical properties and most probably is responsible for a faint microhardness increase observed near 400 °C. The following drop of microhardness above 400 °C is connected with a pronounced recrystallization, which again proceeds in a different manner in both parts of the specimen as a consequence of inhomogeneous distribution of the stored energy. Thus, in

accordance with EBSD observations, only a partial recrystallization in initially softer parts of the specimen is responsible for their less intensive softening leaving the final microhardness at 550 °C above the values observed in the rest of the material.

5. CONCLUSIONS

A modified AA3003 alloy was CGP treated. A significant hardening is, however, accompanied with a pronounced inhomogeneous distribution of microhardness. An equalization of mechanical properties along the specimen occurs during static recovery of the dislocation substructure. A final recrystallization at higher annealing temperatures re-evokes the mechanical inhomogeneity with an inverse profile, and originally softer parts of the specimen exhibit higher microhardness values in comparison with the rest of the specimen. Such a behavior is a consequence of inhomogeneous distribution of imposed equivalent strain due to the CGP.

ACKNOWLEDGEMENTS

The financial support of grant GAUK 134715 is gratefully acknowledged.

REFERENCES

- [1] MORATTAB, S., RANJBAR, K., REIHANIAN, M. On the mechanical properties and microstructure of commercially pure Al fabricated by semi-constrained groove pressing. *Materials Science and Engineering: A*, 2011, Vol. 528, pp. 6912-6918.
- [2] KHODABAKHSHI, F., HAGHSHENAS, M., ESKANDARI, H., KOOHBOR, B. Hardness–strength relationships in fine and ultra-fine grained metals processed through constrained groove pressing. *Materials Science and Engineering: A*, 2015, vol. 636, pp. 331-339.
- [3] BIROL, Y. Homogenization of a twin-roll cast thin Al-Mn strip. *Journal of Alloys and Compounds*, 2009, vol. 471, pp. 122-127.
- [4] BIROL, Y. Response to annealing treatment of a twin-roll cast thin AlFeMnSi strip. *Journal of Materials Processing Technology*, 2009, vol. 209, pp. 506-510.
- [5] HATCH, J. E. *Aluminum Properties and Physical Metallurgy*. American Society For Metals, 10th printing 2005.
- [6] NES, E. H., BILLDAL Non-equilibrium solidification of hyperperitectic Al-Zr alloys. *Acta Metallurgica*, 1977, vol. 25, pp. 1031-1037.
- [7] KNIPLING, K. E., DUNAND, D. C., SEIDMAN, D. N. Precipitation evolution in Al-Zr and Al-Zr-Ti alloy during aging at 450-600 °C. *Acta Materialia*, 2008, vol. 56, pp. 1182-1195.
- [8] MÁLEK, P., ŠLAPÁKOVÁ, M., CIESLAR, M. High temperature deformation of twin-roll cast Al-Mn-based alloys after equal channel angular pressing. *Materials*, 2015, no. 8, pp. 7650-7662.
- [9] POKOVÁ, M., CIESLAR, M. Recrystallization of AA3003 aluminum alloy after ECAP during isothermal annealing. In *METAL 2014: 23rd International Conference on Metallurgy and Materials*. Ostrava: TANGER, 2014, pp. 1039-1044.
- [10] MOU, X., PENG, K., ZENG, J., SHAW, L. L., QIAN, K.-W. The influence of the equivalent strain on the microstructure and hardness of H62 brass subjected to multi-cycle constrained groove pressing. *Journal of Materials Processing Technology*, 2011, vol. 211, pp. 590-596.
- [11] HUANG, X., TSUJI, N., HANSEN, N., MINAMINO, Y. Microstructural evolution during accumulative roll-bonding of commercial purity aluminum. *Material Science and Engineering A*, 2003, vol. 340, pp. 265-271.