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DRAWABILITY STUDIES OF MAGNESIUM ALLOY SHEETS AT ELEVATED TEMPERATURE

BADANIA TŁOCZNOŚCI BLACH ZE STOPÓW MAGNEZU W PODWYŻSZONEJ TEMPERATURZE

Abstract: The paper presents the results of a study of drawability of thin AZ31 magnesium alloy metal sheets. These studies are a continuation of experiences in presenting the characteristics of technological plasticity of strips made of magnesium alloy which have been cast between rolls in vertical and horizontal systems called 'twin-roll casting'. In the context of previous experiments conducted at the Institute of Material Technology of the Silesian University of Technology in cooperation with the Technical University – Bergakademie Freiberg (Germany), drawability of these strips at elevated temperatures has been comprehensively defined while using forming limit curves. Due to low formability of magnesium alloys at ambient temperature, formability tests – including cup forming tests presented in this paper – have been carried out in heated dies at temperature range of 200°C to 350°C. A modern AutoGrid digital local strain analyzer has been used in the examinations and the method of image analysis of deformed coordination nets has been applied. Quantitative and qualitative impact of deformation temperature upon the drawability effects of AZ31 magnesium alloys products have been evaluated.

Keywords: drawability at elevated temperature, local strain distribution measurements, forming limit curve, AutoGrid strain analyzer, thin sheet metals, magnesium alloys, AZ31, cup forming test.

W pracy przedstawiono rezultaty badań tłoczności blach cienkich ze stopu magnezu AZ31. Badania te są kontynuacją doświadczeń w zakresie sporządzania charakterystyk technologicznej plastyczności blach taśmowych ze stopów magnezu odlewanych między walcami w układach pionowych i poziomych, tzw. metodą „twin roll casting”. W ramach wcześniejszych doświadczeń prowadzonych w Instytucie Technologii Metali Politechniki Śląskiej i we współpracy z Technical University – Bergakademie Freiberg (Germany), przy zastosowaniu granicznych krzywych tłoczenia określono kompleksowo tłoczność tych blach w podwyższonej temperaturze. Z uwagi na niską odkształcalność magnezu w temperaturze otoczenia próby tłoczności, w tym prezentowaną w niniejszym opracowaniu próbę miseczkowania, wykonano w podgrzewanych matrycach w zakresie 200°C do 350°C. W badaniach wykorzystano nowoczesny, cyfrowy analizator odkształceń lokalnych AutoGrid oraz metodę analizy obrazu odkształconych siatek podziałowych. Oceniono ilościowy i jakościowy wpływ temperatury odkształcenia na efekty tłoczenia wyrobów ze stopu magnezu AZ31.

1. Introduction

The application of plastic working methods of light metal alloys for aircraft industry is concerned mainly with semi-finished materials such as strips and sheets. Magnesium alloys which are light metal alloys, are the basic constructional materials required for producing construction elements of aircrafts because of their low density, high relative strength and vibration damping properties. Thin-walled sheathing elements are produced by charge forming which are in the form of sheets or strips, whereas thick-walled elements are produced by forging, extrusion or casting. The example of element which was formed from magnesium alloy has been presented in Fig. 1a and the one which was cast has been presented in Fig. 1b.

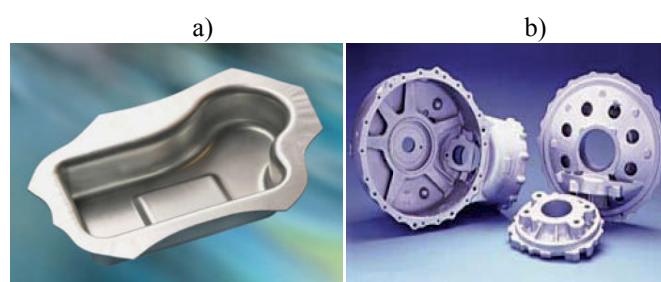


Fig. 1. Elements made of magnesium alloys: a) by stamping, b) by casting

Obtaining strips and sheets of defined formability properties from magnesium alloys, applying plastic working requires the application of special technology for making such type of semi-finished products. The new technology of strip

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casting from magnesium alloys between rolls in vertical or horizontal systems, called the 'twin roll casting' method (Fig. 2) [1] made it possible to obtain charges for producing sheets and strips and processing them by methods of stamping.

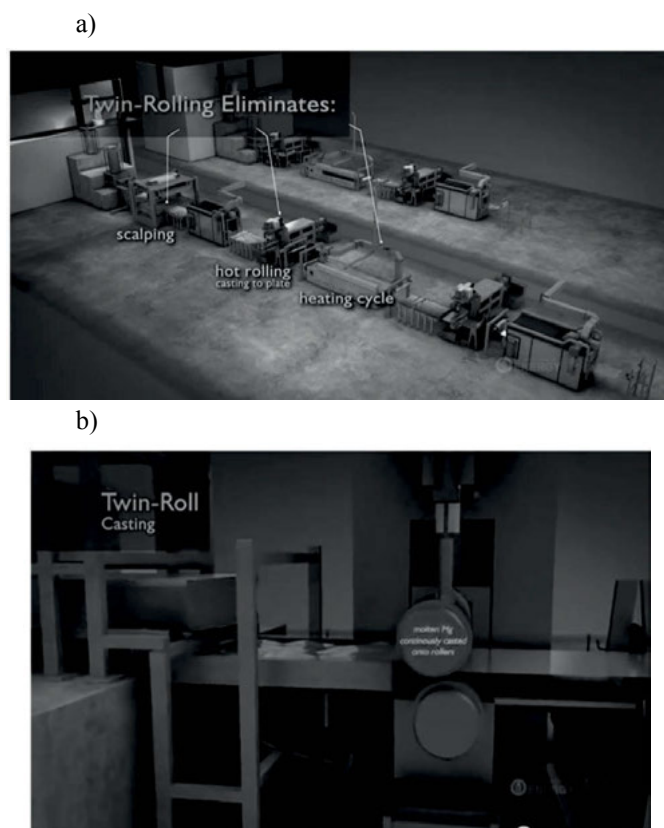


Fig. 2. Diagram of a line for rolling the sheets made of magnesium alloys: a) comparison of conventional line with the 'twin-roll casting' line, b) 'twin-roll casting line'. [2]

Conventional rolling of magnesium alloys ingots demands intermediate annealing which is expensive and time-consuming, whereas modern technology makes it possible to reduce the number of rolling operations. Hot rolling is the only way to process the strips made of Mg alloys and the temperature range depends on the contents of alloy additives. Selection of the appropriate temperature is determined by the requirements regarding the range of the level of mechanical properties which can provide the right formability of these rolled semi-finished products in subsequent processing, e.g. stamping methods. Such flexibility can be defined by evaluating drawability of these charge materials. The results of drawability examinations of thin sheets made of AZ31 magnesium alloy and formed at different temperature ranges in the process of hot plastic working have been presented in the paper. Advanced AutoGrid local strain analyzer has been used in the carried out examinations [11].

2. Magnesium alloys

Magnesium alloys feature low formability in ambient temperature due to their hexagonally compact crystallographic structure (A3) since the slip is only possible in one plane {0001}. At temperatures above 225°C the additional slipping systems

are activated and this guarantees very good formability. Alloy additives provide very good cold formability by changing crystal lattice or fine grain [7-10].

There are casting alloys and alloys for plastic working within the group of magnesium alloys. Magnesium casting alloys can be divided into two groups according to their chemical constitution [3]. In the first group there are alloys with Al content of 3-10% with Zn and Mn additives: Mg-Al-Mn (AM50, AM60), Mg-Al-Zn (AZ91), Mg-Si (AS21 and AS41), Mg-Al-RE (AE42 and AE44), Mg-Al-Sr (AJ52 and AJ62). In the second group there are alloys which contain many elements (it is usually Zn, RE, Y and Th) but there is always Zr: Mg-Zn-Zr (ZK51 and ZK61), Mg-RE-Zn-Zr (ZA62 and ZRE1), Mg-Ag-RE-Zr (QE22 and MSR-B), Mg-Y-RE-Zr (WE 43 and WE54), Mg-Nd-Gd-Zr (Elektron 21). However standard alloys used for plastic working contain 8% of Al and Mn additive (>2%), Zn (about < 1.5%), Si (about 0.1 %) and minute quantities of Cu, Ni and Fe (the less Fe, the better since Fe is corrosive). There are three groups of alloys used for plastic working [3]. The first one contains the alloys with Al, Zn and Mn: Mg-Mn (M1 and M2), Mg-Al-Zn (AZ21, AZ31, AZ61, AZ80), Mg-Zn-(Mn, Cu) (ZM21, ZC71). In the second group there are alloys mainly with Zn, RE, Y, Zr and Th: Mg-Zn-Zr (ZK30, ZK40, ZK60), Mg-Zn-RE (ZE10), Mg-Y-RE-Zr (WE43, WE54), Mg-Th (HK31, HM21, HZ11). In the third group there are ultra-light alloys with Li: Mg-Li-Al (LA141). The material obtained by adding alloy additives to magnesium features considerably higher strength properties as compared to those of pure metal. The following elements are added: aluminum, zinc, manganese, silicon, zirconium, lithium and lanthanides, however the main alloy components are: the first three ones, i.e. Al, Zn, Mn. Aluminum is the most frequently used alloy additive and it is a component of the majority of magnesium alloys. The contents of Al in cast alloys can be as high as 11% whereas in alloys for plastic working it only can be 8% [4]. Aluminum improves strength and elongation up to about 6%. At such quantity of Al, strength grows up by 50% and elongation by 100%. High contents of Al causes a rapid drop of alloy plasticity but it improves alloy castability [5]. Zinc, in the same way as aluminum, has the impact upon alloy properties, it increases hardness, strength, alloy elongation and improves castability. The alloy with about 5% of Zn has the maximum values [4]. Contents of manganese in alloys do not exceed 1.5%. It only slightly improves the mechanical properties of alloys but makes them corrosion resistant and they can be welded [4].

3. Drawability research

The aim of the research works was to analyze the impact of the parameters of strain process upon the properties of AZ31 alloy and to evaluate the quality of the produced sheets after the process of stamping. The following range of examinations have been carried out: fractography examinations of fractures, stable tensile tests and the evaluation of drawability. The examination results which have been presented in the paper refer mainly to the assessment of drawability properties for two different values of forming temperature of AZ31 alloy: 250°C and 300°C. The evaluation tests of drawability have

been carried out in dies heated up to 250°C and 300°C because of low formability of magnesium at ambient temperatures. A spherical punch of 60 mm diameter and a set of samples which has been prepared as presented in Fig. 3b have been used in the examinations. A modern AutoGrid local strain analyzer and a method of image analysis of the deformed parting grids with mesh parameter of 1 mm diameter have been used for quantitative evaluation of drawability of AZ31 alloy sheets. Hot stamping has been performed at a work stand (Fig. 3a) at TU Bergakademie Freiberg, Germany.

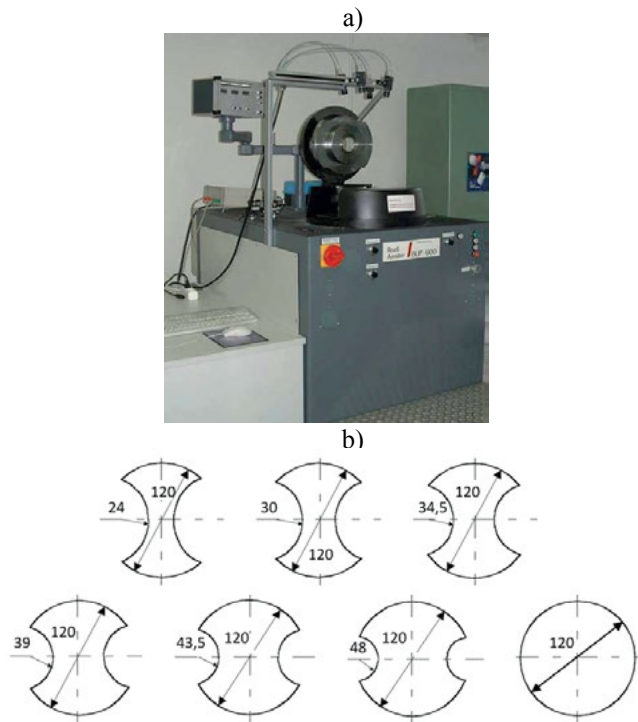


Fig. 3. a) Laboratory stand for hot stamping with AutoGrid local strain analyzer, b) set of test samples – sample dimensions

The photographs of drawpieces coming from stamping process at 250°C and 300°C have been shown in Fig. 4.

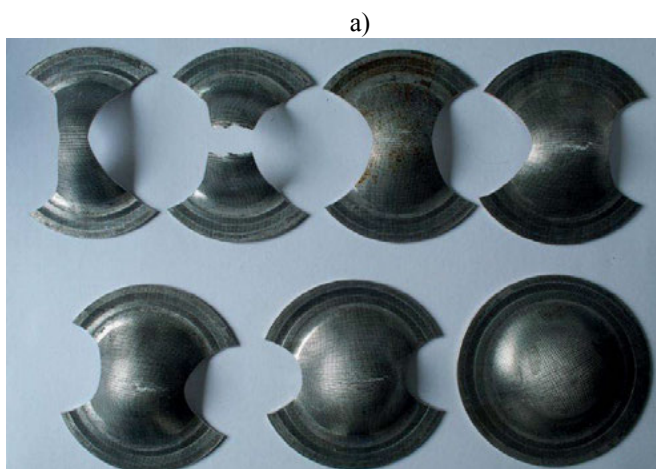


Fig. 4. Results of AZ31 alloy pressing at elevated temperatures: a) 250°C, b) 300°C – set of samples to determine FLCs

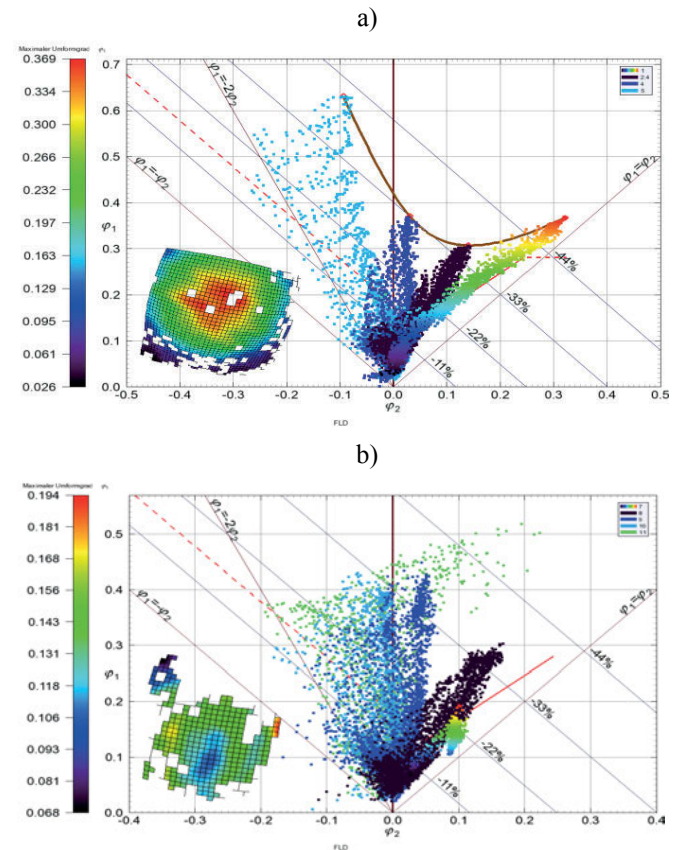


Fig. 5. Comparisons of measurements of local strain distributions for the samples after stamping test at a) 250°C, b) 300°C to calculate FLCs

The comparison of a forming limit curve of the examined sheet made of AZ31 magnesium alloy at elevated temperature (experimentally only for 250°C) together with the obtained results based on reference literature [12] (temperature range from 150° to 350°C) have been presented in Fig. 6.

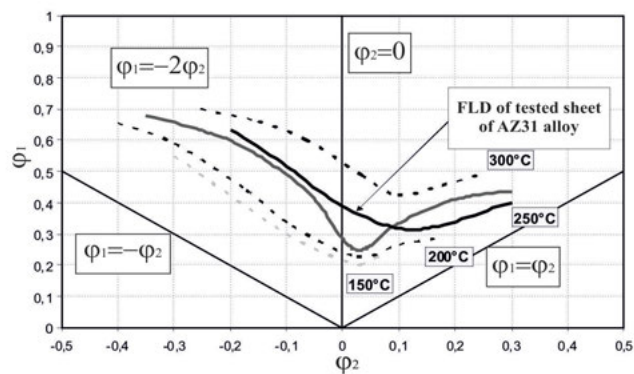


Fig. 6. Comparison of the forming limit curve of the examined AZ31 magnesium alloy sheet at elevated temperature 250°C with the results from reference literature [12]

4. Forming tests at elevated temperature – cupping test

Drawability of the examined sheet at 200°C, 250°C, 300°C and 350°C has been evaluated in order to examine formability of AZ31 magnesium alloy sheets produced in the process of twin-roll casting. Cupping test, using a punch of 40 mm diameter at a constant pressure force of 7 kN and punch shift velocity of 1 mm/sec has been performed. Additionally, heat treatment prior to the forming process has been carried out to make the mechanical properties of a sheet more homogeneous and to increase the range of plastic characteristics. The process of heat treatment was carried out for 1 h at 400°C. Disks made of AZ31 magnesium alloy sheets were 2 mm thick and the initial diameter of a charge disk was 66 mm.

TABLE 1
List of process parameters for cupping tests of AZ31 alloy sheets samples at the tested range of forming temperature

| Temperature [°C] | Sample number | Distance [mm] | Forming force F_m [kN] |
|------------------|---------------|---------------|--------------------------|
| 200 | MG_200_b | 14,28 | 18,27 |
| 200 | MG_200_c | 14,62 | 19,59 |
| 200 | MG_200_d | 14,40 | 23,63 |
| 250 | MG_250_a | 13,95 | 15,70 |
| 250 | MG_250_c | 14,36 | 15,61 |
| 250 | MG_250_d | 14,04 | 16,35 |
| 300 | MG_300_a | 14,24 | 12,67 |
| 300 | MG_300_b | 14,37 | 12,22 |
| 300 | MG_300_c | 15,36 | 12,31 |
| 350 | MG_350_a | 15,43 | 10,13 |
| 350 | MG_350_b | 15,30 | 10,17 |
| 350 | MG_350_c | 14,04 | 9,90 |

The comparison of registered parameters for the performed cupping test carried out in a selected range of temperature has been presented in Table 1 and the photographs of drawpieces produced in the process of cupping tests have been shown in Fig. 7. Special back-up plates made of teflon and plastic have been used in the forming process because of AZ31 alloy properties at elevated temperature (Fig. 7).



Fig. 7. Photograph of drawpieces made of AZ31 magnesium alloy sheets 2.0mm thick after cupping test by a cylindrical punch of 40 mm diameter

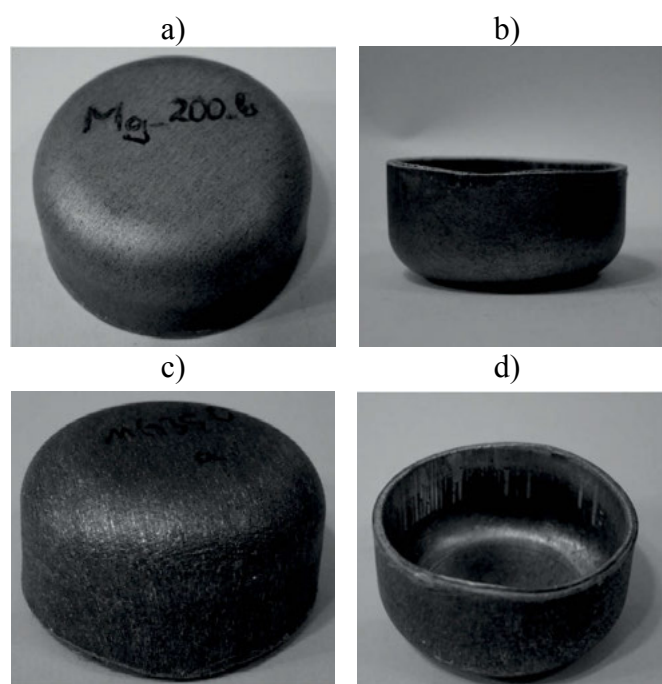


Fig. 8. Comparison of cupping test results at the following temperatures: a) and b) 200°C, c) and d) 350°C

Samples for investigating the microstructure have been taken from drawpieces made of AZ31 alloy sheets (Fig. 7 and Fig. 8). These samples have been taken from the most deformed zone of a drawpiece cross-section, i.e. cup bottom changing into the zone of lateral faces (see Fig. 8). Material microstructure of AZ31 alloy sheet and drawpieces formed at different temperature is presented on Fig. 9.

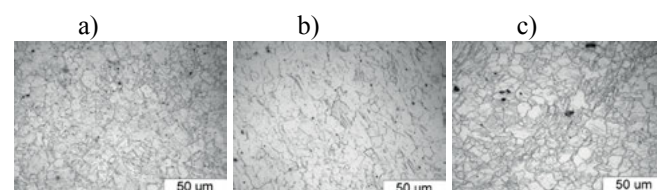


Fig. 9. Material microstructure of AZ31 alloy sheet at an initial state (a). Material microstructure at a drawpiece cross-section in the zone of cup corner after forming at temperature of: b) 200°C and c) 350°C

It is a typical feature in the examined alloy that there is the grain growth together with the temperature growth. There are also twinned zones in the form of lenses in AZ31 alloy

microstructure which seem to be quite characteristic [7-11] and they can be clearly seen in the samples taken after forming at the temperature of 300°C (Mg 300 sample). The microstructure of AZ31 alloy after the forming process at the temperature of 250°C has been dominated by twinning whereas the microstructure of AZ31 alloy after forming at 350°C has been dominated by numerous slip bands. Mg17Al12 is the eutectic which is present in the type of AZ31 alloys.

In order to present the impact of forming temperature upon the quality of the surface of a formed product, profilographometric examinations have been carried out and surface roughness (Fig. 10) as well as a wavy finish (Fig. 11) of the initial sample surface and after the process of forming at a given temperature have been evaluated.

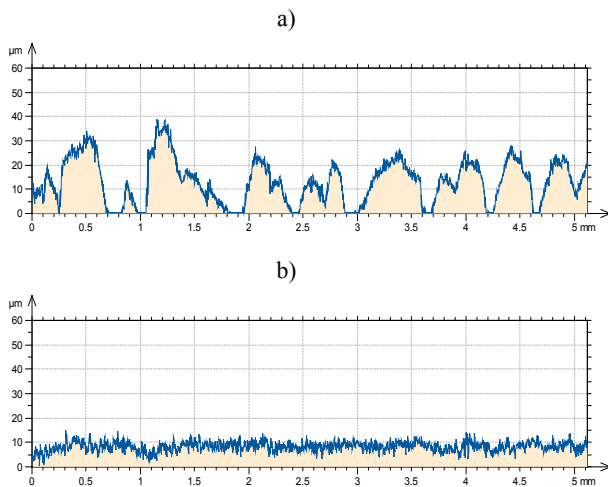


Fig. 10. Roughness distribution of the selected section of a sample taken from a cup formed at temperature of a) 200°C, b) 350°C

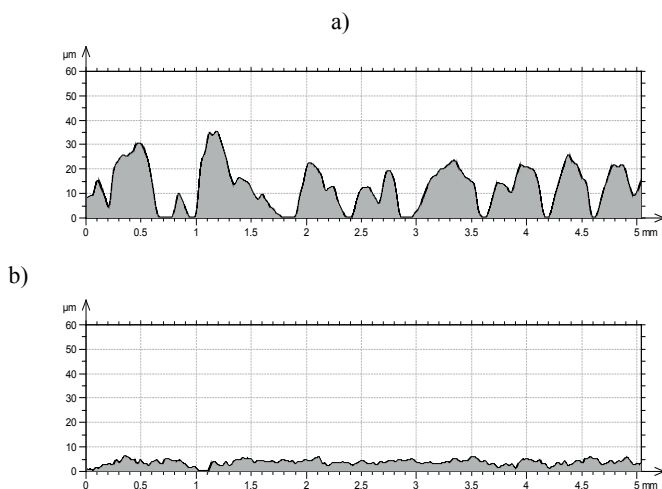


Fig. 11. Waviness of the selected section of a sample taken from a cup formed at temperature of a) 200°C, b) 350°C

Surface roughness (R_a – arithmetic mean deviation of the roughness profile) and wavy finish (W_{sm} – average width of profile elements wave) are described surface quality of magnesium alloy drawpiece after cupping. At temperature 200°C measured $R_a=0,925\text{mm}$ and $W_{sm}=0,687\text{mm}$,

while at temperature 350°C measured $R_a=0,876\text{mm}$ and $W_{sm}=1,09\text{mm}$. Comparison of the R_a and W_{sm} indicates that the smaller surface roughness and higher wavy finish values for drawpiece after forming at 350°C are not propitious. It is the result of drawpiece surface delamination and degradation grid mesh applied before cupping. Such surface quality disqualifies pressed product.

The samples formed at the temperature of 250°C feature the acceptable level of surface roughness. Higher temperature applied in the process of forming, changes the surface roughness considerably and provides favorable conditions for groove forming and stratification of a cup surface, particularly in the corner zones – lateral faces changing into the bottom of a sample.

5. Results

1. The carried out examinations fall within the scope of the research program - project Nr POIG.0101.02-00-015/08 - have revealed that the rolling process at the temperature range of 450°-300°C guarantees the production of sheets of the required quality which feature good press-formability. This is due to the high size reduction of grains which helps to activate the additional slip systems. The possibility of forming the elements at the temperature of 150÷200°C is limited. Increasing the temperature up to 250°C allows to achieve satisfactory results. The elements of more complicated shapes can be produced in forming processes thanks to a higher limiting formability without lowering the quality of a product.
2. Elevating the temperature up to 300°C increases the range of strain which can be applied but it can result in the changes of microstructure formed in the process of previous rolling and heat treatment. It was not possible to determine the strain limit curve because of methodological reasons for that value of temperature.
3. The obtained strain limit values at elevated temperatures make it possible to form the construction elements of the required quality from sheets produced from AZ31 alloy which have been processed in the worked out technology.
4. The decrease of forming temperature can lower the quality of the formed products. The increase of forming temperature of AZ31 alloy up to a maximum temperature of 250°C allows to get the products of a complex geometry, maintaining at the same time a good quality of the surface of the formed products.

Acknowledgements

The research has been conducted within the scope of the Project 'Advanced material technologies applied in the aircraft industry' Nr POIG.0101.02-00-015/08 in the Operational Program – Innovational ECONOMY (POIG). The project is co-financed by The European Union under The Regional Development Fund.

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Received: 15 September 2015.