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# THE USE OF UFG METALS OBTAINED IN SPD PROCESSES IN THE SHEET METAL MICROFORMING

The paper presents the process of preparing UFG metal in the form of 0.2 mm thick foil made of 6060 aluminium alloy, intended for micro-forming operations. The material was obtained in a hybrid SPD process involving ECAP (Equal Channel Angular Pressing), multi-upsetting and rolling. In addition, a selected batch of material was subjected to supersaturation before ECAP. A method for determining formability in the conditions of the sheet metal forming process was proposed, including micro-drawing with the preceding preform preparation process in the micro-blanking process. Noticeable differences were found for different series of the prepared material after the upsetting process, however, the effect of supersaturation before the ECAP process on the formability in the conditions of the sheet metal microforming process was not observed.

*Keyword:* UFG metals; aluminium 6060; hybrid SPD; microforming

## 1. Introduction

The miniaturization of devices [1], which has been progressing for several decades, imposes the miniaturization of the parts used for their production, which are largely produced by metal forming technology [1-3]. Reducing the dimensions to about one millimeter causes a change in the dominant physical phenomena. This manifests itself in the incompatibility of the previously used calculation principles and methods with the technological reality. Its expression is the so-called scale effects. They concern all elements of the technological process: material [4], contact conditions [5], tools [6,7], instruments [8,9] and machines [10], and even sequences of operations [11]. Difficulties in the accurate design of technological processes for miniature parts, combined with the growing demand for them, led to the separation of a relatively new branch of metal forming, which is microforming [12-15]. The main reasons for this state are the natural granularity of the polycrystalline materials used [16,17] and the surface layer treated as an area with a certain thickness, mainly dependent on the structure of the material [18-20] The share of both of these features increases as the product becomes smaller, the material of which can no longer be considered uniform throughout its volume. The proposed avoidance of many of the unfavorable scale effects is the concept of using ultrafine grain metals (UFG) [21-23]. Positive effects of such a strategy have been observed, for example, in the UFG brass microforming process [24]. Within the presented work, the field of interest was narrowed down to sheet metal microforming processes. As a method of obtaining ultra-fine grain, the ECAP process was adopted on the stand used in previous works [25]. The selected material for the tests is aluminium alloy 6060, which was chosen because of its high (in the group of aluminium alloys) strength properties.

The main purpose of the work was to develop a research method allowing for the assessment of the possibility of using this alloy with the UFG structure obtained by the ECAP method for sheet metal microforming processes. It should be noted that the UFG materials obtained from the ECAP process are in the form of rods that must undergo further deformations [26], so that the final effect is a foil with a UFG structure. The influence of the technological path of preparing foil with a thickness of 0.2 mm made of aluminium alloy 6060 on the possibility of sheet metal microforming was initially examined. The process of free micro-drawing was adopted as the verification process. It was chosen because of the simplicity of implementation, which favours further miniaturization and reduces the number of process parameters in research. Due to the difficult formability of the selected material discussed in the literature, it was decided to use heat treatments to improve this feature.

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## 2. Formability of UFG 6060 aluminium alloy

Formability is a property of a material that refers to the ability to undergo plastic deformation. Formability is influenced by many factors, which can be divided into material and external factors, related to the deformation process itself. In the case of material factors, such parameters as crystallographic texture or grain size have an impact. The reduction of the average grain size causes a significant reduction in the plasticity of the material, which leads to a reduction in the formability of UFG materials compared to CG materials [27]. The main feature of the UFG microstructure limiting ductility is the inability to accommodate plastic deformation, which leads to rapid deformation localization, rapid necking and fracture. Precipitation strengthening also affects the forming ability [28]. This treatment consists of two processes, supersaturation and ageing. During supersaturation, the precipitates are dissolved in a solid solution and then rapidly cooled, resulting in non-equilibrium material. Further ageing causes precipitation processes to take place. Natural ageing, i.e. at ambient temperature, is a slow process, while artificial ageing, i.e. at elevated temperature, results in a faster precipitation of second phase particles. Aging increases the strength of the material, but at the same time reduces the ductility. Thus, the material shows higher plasticity immediately after supersaturation. As shown in [29] for the AA 6063 aluminum alloy, natural ageing resulted in the highest elongation values. This was due to the presence of clusters in the microstructure, which over time transform into Guinier-Preston (GP) zones. In the case of accelerated ageing, larger, semi-coherent and coherent β'' and β' precipitates are formed. The increase in the size of the precipitates changes the mechanism of interaction of dislocations with precipitates from shear to the Orowan mechanism. This affects the strength and ductility of the material. In the work [30], the formability of the AA 6061 alloy was investigated immediately after supersaturation and subsequent ageing. The best results were obtained after supersaturation alone, which was correlated with the highest plasticity. Ageing worsen the formability, which was caused by the presence of precipitates strengthening the material. On the basis of this analysis, it was decided to check the influence of the supersaturation process before the ECAP on the broadly understood ability to form the sheets metal of the UFG 6060 aluminium alloy obtained by the ECAP method, under the conditions of microforming.

## 3. Foil preparation

The extended UFG metal fabrication process with the ECAP main operation was used in the work to prepare 0.2 mm thick 6060 aluminium foil. Three variants of the material preparation process were carried out in order to verify its impact on the possibility of forming micro-products. Three series of material in the form of 0.2 mm foil, marked respectively with the symbols CG (material not subjected to ECAP), UFG F (material subjected to ECAP in the delivery condition) and UFG G (material supersaturated before ECAP) were punched with a 4 mm diameter punch. Then, the obtained discs were used to carry out the micro-drawing operation.

The hot-extruded bar EN AW-6060 ø50 was used as the initial material. The chemical composition of the material is shown in TABLE 1 and its mechanical properties is shown in TABLE 2 (CG as delivered). The bar was divided into billets with dimensions of 8×8×45 mm by milling according to the scheme shown in Fig. 1a.

TABLE 1

Chemical composition % of used material

| Fe | Si | Cu | Zn | Ti | Mn | Mg | Ni | Cr | Pb |
|---|---|---|---|---|---|---|---|---|---|
| 0.19 | 0.43 | 0.006 | 0.009 | 0.005 | 0.004 | 0.57 | 0.004 | 0.008 | 0.002 |

Part of the billets obtained in this way were subjected to supersaturation (annealing for 2 hours at 525°C, cooling in water). These billets were used to prepare a series of UFG G material. Then, a two channel turns mtECAP (2×110°) was performed six times at 150°C (Fig. 1b). The temperature of 150°C was selected on the basis of previous work of the research team. This temperature allowed to avoid cracking of 6060 aluminium and it was not too high to observe grain growth. ECAP was performed for a batch of supersaturated material (UFG G) and as delivered (UFG F). The rods obtained in this way were subjected to free upsetting (Fig. 2a) at 150°C, obtaining plates with a thickness of 1 mm. In addition, identical upsetting was applied to the billets that were not subject to the ECAP. The diagram of the upsetting operation with the selected coordinate system is shown in Fig. 2b. The obtained material was mainly subjected to natural ageing, however, the use of elevated temperature in the ECAP and upsetting operations meant that the material stayed in total

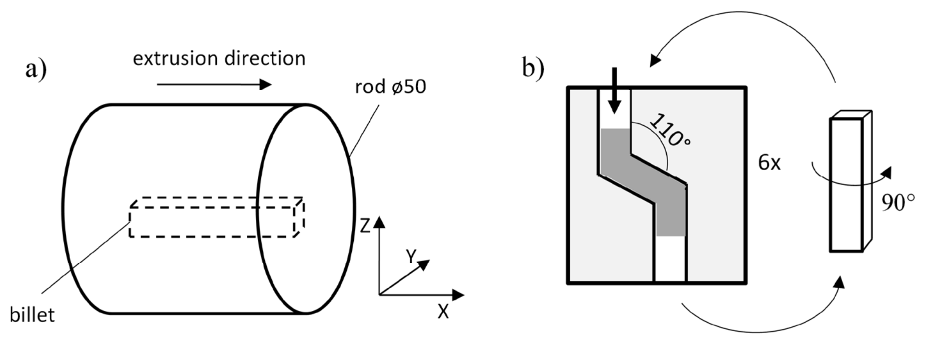


Fig. 1. Scheme of orientation of the taken billets in relation to the ø50 bar (a) and scheme of ECAP operation (b)

for almost an hour at a temperature close to 150°C, which could initiate the processes related to artificial ageing.

In the next stage of the process, the obtained plates were cut into 6 mm wide strips, which were rolled to a thickness of 0.2 mm at room temperature to obtain a foil intended for micro-forming. The method of taking strips from plates and the 0.2 mm foil obtained are shown in Fig. 3.

The diagram of the carried out variants of the process, in which three series of material in the form of a foil with a thickness of 0.2 mm were obtained, is shown in Fig. 4.

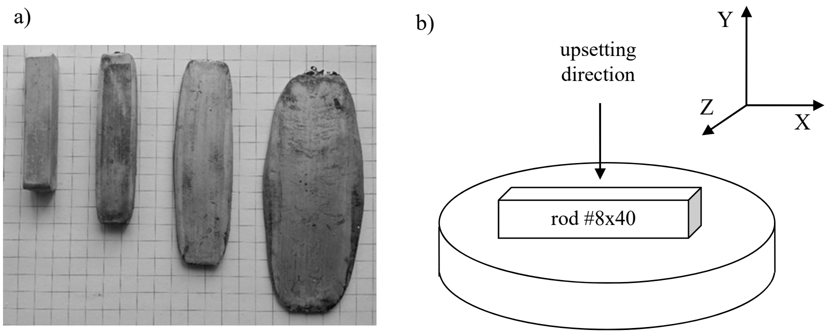


Fig. 2. The result of subsequent upsetting operations at a thickness of ≈5, 3 and 1 mm (a) and the scheme of upsetting operations with the coordinate system marked (b)

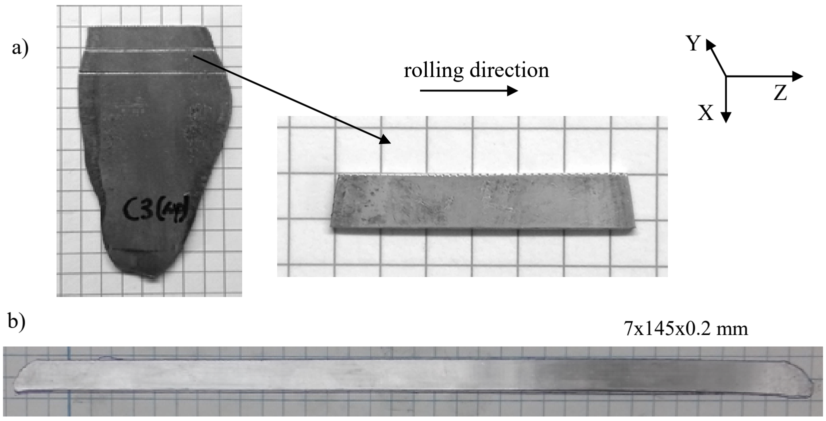


Fig. 3. Preparation of metal strips for the rolling process (a), obtained 0.2 mm foil (b)

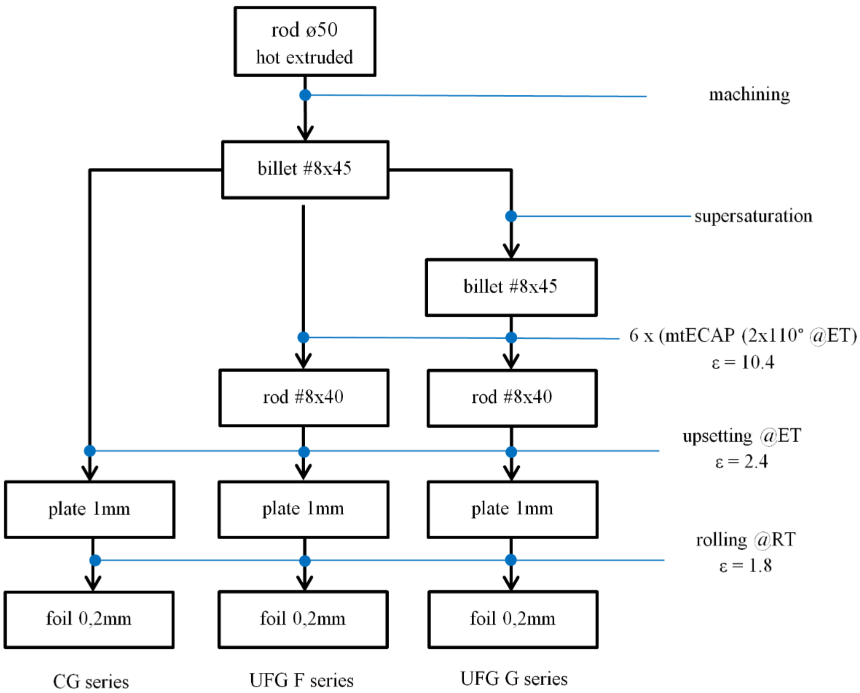


Fig. 4. Variants of the 0.2 mm foil preparation process

## 4. Strength tests before the foil rolling process

In order to verify the effect of supersaturation on the material properties after the ECAP, a standard uniaxial tensile test was performed, in which the yield strength $R_{p0.2}$, tensile strength $R_m$ and elongation $A$ were determined. These parameters were determined for the material immediately after the ECAP process and after additional upsetting. TABLE 2 presents the obtained results and compares them with the parameters of the material as delivered.

TABLE 2

Values of $R_m$, $R_{p0.2}$ and $A$ for prepared series of material in two stages of the process

| | CG | UFG-F | | UFG-G | |
|---|---|---|---|---|---|
| | As deliver | ECAP | ECAP + upsetting | ECAP | ECAP + upsetting |
| $R_m$ [MPa] | 180 | 288 | 312 | 297 | 307 |
| $R_{p0.2}$ [MPa] | 60 | 270 | 293 | 257 | 290 |
| $A$ [%] | 18 | 11.9 | 8.5 | 10.5 | 10.3 |

### Structural studies of the obtained foil

The obtained 0.2 mm foils were subjected to structural analysis. Fig. 5 shows the microstructures of the the CG and UFG-F foil series in XY plane and the corresponding grain size distribution.

## 5. Analysis of test results

Data collected in TABLE 2 indicate a noticeable effect of supersaturation on the properties of the obtained material, however, this effect is different immediately after ECAP and after additional upsetting. The supersaturated material (UFG-G series) shows higher strength and lower plasticity after ECAP compared to the UFG-F series, however, after additional upsetting, this relationship is reversed and the UFG-G series shows lower strength and higher plasticity. This phenomenon may be caused by the influence of increased tamperture occurring during upsetting, which may partially eliminate the strengthening effects. Finally, a positive effect of supersaturation on the formability of the obtained UFG plates was observed.

Structural analysis of foils intended for sheet metal microforming leads to the conclusion that the ECAP process unifies the structure of the material in the entire volume of the obtained foil. The foil made of the CG material is characterized by a much greater grain size variation, despite the fact that the large ($\varepsilon = 14.6$) plastic deformation that took place during subsequent metal forming operations significantly fragmented the grains.

## 6. Formability determination – free micro-drawing

The process was carried out in the setup shown in Fig. 6a, consisting of a precise micro-device placed on the testing machine table. The micro-device ensured precise positioning of the tools. The dimensions of the tools are shown in Fig. 6b. Lubrication was applied with a lubricant based on $MoS_2$ from the die side and light oil from the punch side. The coefficient of extrusion in the process was 0.54. During the process, the force measured on the punch and its displacement were recorded.

## 7. The course of the free micro-drawing process

Carrying out the drawing process requires a preliminary operation (Fig. 8), which is the preparation of the preform. In this

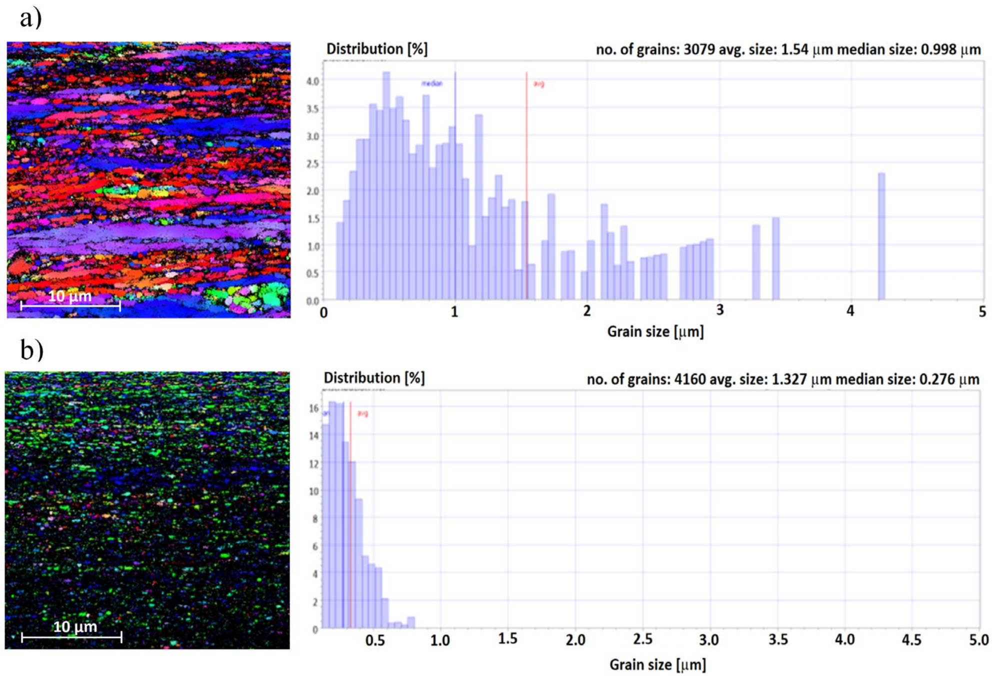


Fig. 5. Microstructure in XY plane and grain size distribution of the obtained 6060 aluminum foil for the CG (a) and the UFG-F (b) series

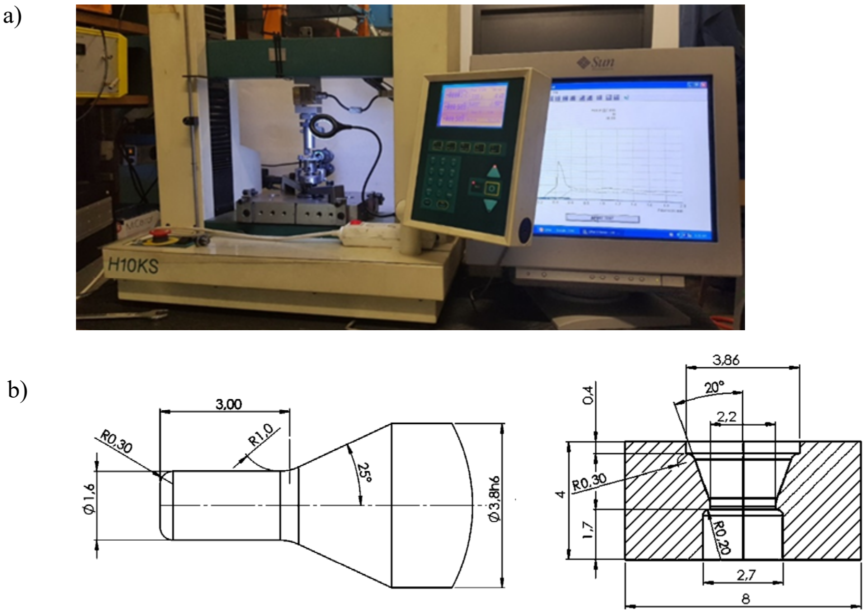


Fig. 6. Setup for micro-drawing (a) and dimensions of the tools used (b)

case it was a disc with a diameter of 3.8 mm obtained in micro-blanking process with a blank holder, which in turn required preforms in the form of 10×7×0.2 mm strips. In this process, the same universal micro-device was used as in the case of drawing [31]. The disc micro-blanking operation was additionally used to analyze the technological variants of CG, UFG-F and UFG-G. The courses of forces were recorded (Fig. 7a), the cut strengths and the fill factors of the graph were determined (TABLE 3).

The following description of the process refers to the recorded force of micro-drawing (Fig. 7b). The disk is placed in the cavity of the matrix (Fig. 6b) enabling its precise positioning. The precisely guided punch presses centrally on the foil, the force of the process increases to the value of the first maximum. After reaching it, the edge of the disc begins to be drawn into the die, sliding on its conical surface. As the punch moves, the force decreases and reaches a minimum value, after which it increases again due to the strengthening of the material and the thickening of the edge of the cup. When the strengthening and thickening of the material is no longer able to compensate for the decreasing perimeter of the edge, the force of the process decreases until

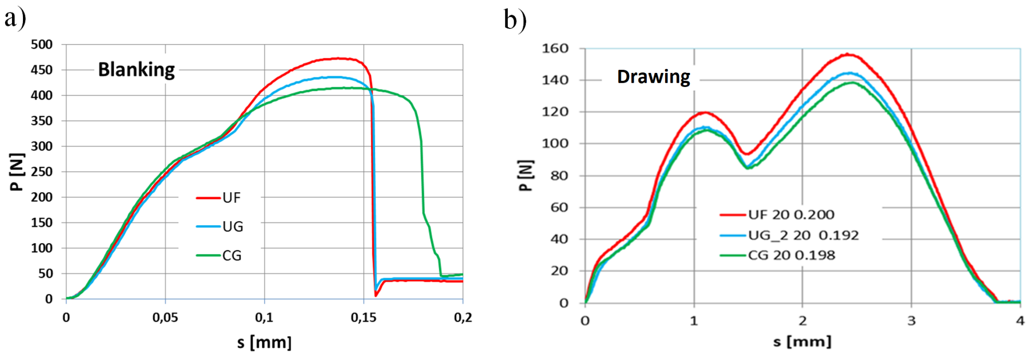


Fig. 7. Course of forces during micro-blanking (a) and micro-drawing (b) of 0.2 mm foil for three series of material

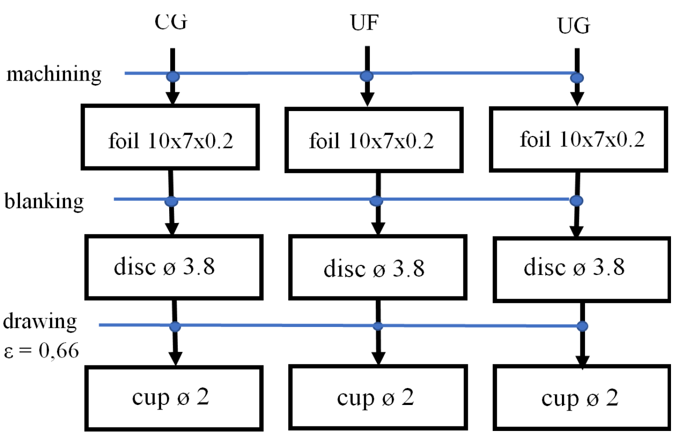


Fig. 8. Scheme of the micro-drawing preparation process

TABLE 3

Cut strength $R_t$ and graph fill factor $\lambda$ for three series of 0.2 mm foil

| | CG | UF | UG |
|---|---|---|---|
| $R_t$ [MPa] | 168 | 185 | 181 |
| $\lambda$ | 0.67 | 0.51 | 0.55 |

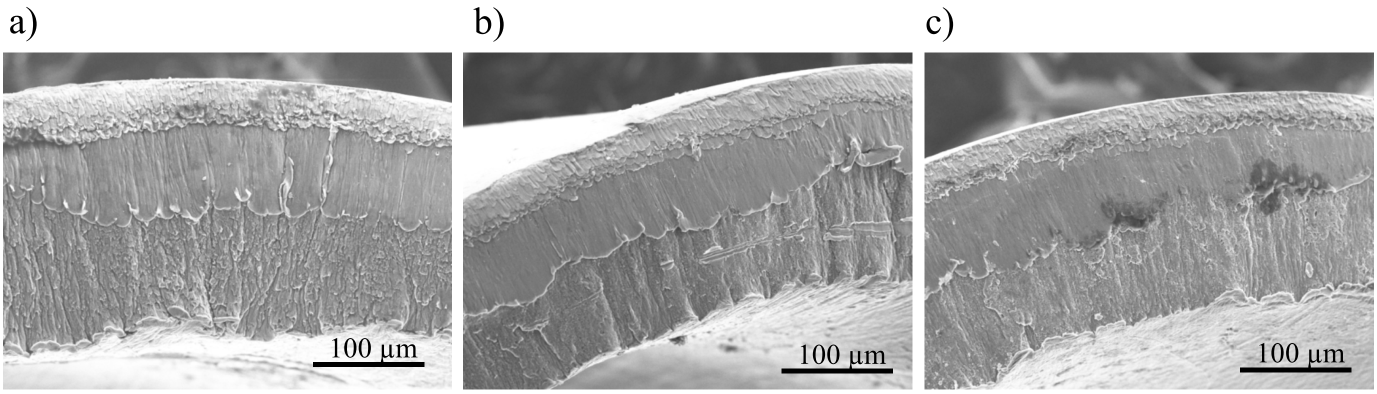


Fig 9. SEM images of the cut surface observed on the free edges of the caps: a) CG series, b) UG series, c) UF series

its full completion. The threat here is the possible cracking of the bottom, which is the main phenomenon limiting the process.

In addition, Fig. 9 shows a view of the cut surfaces observed on the free edges of the cup made.

## 8. Analysis of test results

Within the presented research only preliminary analyzes of the formability of the 6060 aluminium were carried out. This research should be considered as a preparation of a platform for the development of technologies enabling the use of UFG metals obtained by ECAP in sheet metal microforming, Conclusions were based on the analysis of force courses and random structural tests.

### Micro-blanking process

Despite the slightly higher cut strength (Fig. 7a) determined for the material from the UFG-F series, the effect of supersaturation before the ECAP on the process conditions and the image of the cutting zone of the 6060 UFG aluminum foil was not observed.

### Free micro-drawing process

An increase in the process force was observed in the case of the UFG-F material. With regard to the CG and UFG-G materials, slight differences in the force course were observed, requiring further research. The shape and appearance of the cups surface (Fig. 10) as well as the size of the lugs indicating the presence of flat anisotropy in the assessment of the image from the light microscope do not indicate significant differences in individual material series.

## 9. Summary and conclusions

The presented paper proposes a research method for selection of process parameters enabling the use of UFG materials obtained by the ECAP method for use in sheet metal microforming. The applied ECAP has been enriched with the process of

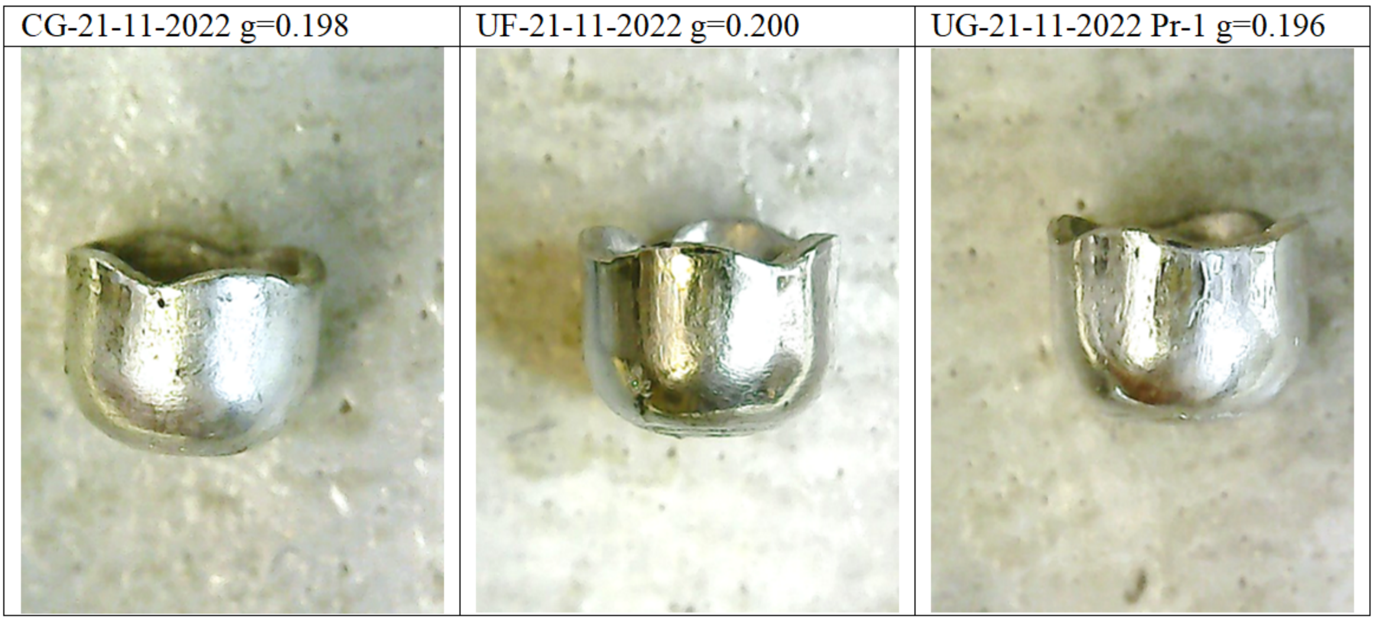


Fig. 10. Obtained micro cups for three series of material with information about the exact thickness *g* of the foil used

obtaining thin foils by initial multiple upsetting with the possibility of increasing the temperature and subsequent multiple rolling at room temperature. The obtained material in the form of a foil with a thickness of 0.2 mm made of aluminium alloy 6060 was then subjected to a micro-drawing operation recognized as a process determining the formability of the prepared materials in the conditions of sheet metal microforming. Necessary to prepare preforms for the micro-drawing process, the micro-blanking process was used to additionally compare the characteristics of foils from different series.

Based on the prepared research, it was found that:

- The obtained material in the form of a foil is characterized by a uniform structure and is consistent throughout its volume without structural defects and cracks.
- The ECAP process plays a key role in unifying the structure throughout the volume of the foil. Its omission results in a significant decrease in the homogeneity of the material, despite the large deformations to which the material is subjected during upsetting and rolling, which causes significant grain refinement comparable to ECAP.
- Despite the noticeable differences in strength properties occurring after the upsetting process for the supersaturated material and the material processed as delivered, no effect of supersaturation of the billets material before the ECAP process on formability was observed in the conditions of the sheet metal microforming. This may be due to partial natural ageing and an additional structural change in the rolling process which may have minimized the material differences between the UF and UG series. For a better distinction of the formability of the material there are planed extension of micro-drawing process in the next research.

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