Materials Research Proceedings 44 (2024) 736-743 https://doi.org/10.21741/9781644903254-78

The continuous rotary extrusion (CRE) process of the AZ31 magnesium alloy with various deformation zone geometry

MITKA Monika[1,a *], MISIOLEK Wojciech Z.[2,b], LECH-GREGA Marzena[1,c], LIMANÓWKA Kamila[1,d] and SZYMAŃSKI Wojciech[1,e]

[1]Łukasiewicz Research Network - Institute of Non-Ferrous Metals, Skawina Division, Piłsudskiego 19 Street, 32-050 Skawina, Poland

[2]Loewy Institute, Lehigh University, Bethlehem, PA 18015, USA

[a]monika.mitka@imn.lukasiewicz.gov.pl, [b]wzm2@lehigh.edu, [c]mlgkrk@gmail.com, [d]kamila.limanowka@imn.lukasiewicz.gov.pl, [e]wojciech.szymanski@imn.lukasiewicz.gov.pl

Keywords: AZ31 Magnesium Alloy, CRE, Conform®, Δ Parameter, Mechanical Properties, EBSD

Abstract. The presented studies are focused on the continuous rotary extrusion (CRE) process, also known in the literature under the Conform® name. The CRE process is commonly used for aluminum and copper alloys but is new for magnesium alloys. A broader understanding of the application of the CRE process and the input material, the AZ31 magnesium alloy, enables the combination of a new, economical method of plastic deformation of the material with the desired final properties. The main aim of the presented work was to analyze how different deformation zone geometry influences the quality of the extruded AZ31 magnesium rods. Additionally, the properties of the CRE extruded rods were compared to the traditionally directly extruded (DE) rods. The research was conducted to analyze the impact of the CRE process parameters on the mechanical properties of the obtained rods, as well as on changes occurring in grain size, texture, and the level of recrystallization.

Introduction

Due to its attractive specific mechanical properties, the AZ31 magnesium alloy is a promising candidate for replacing certain aluminum alloys and steels in engineering applications, especially in the aviation and automotive industries [1].

Because of the hexagonal crystal structure with a limited number of slip systems, AZ31 alloy is difficult to deform at room temperature, and the deformation parameters must be carefully selected. The alloy formability increases as the deformation temperature increases. Magnesium and its alloys can be deformed in metal-forming processes at temperatures above 200-225°C when subsequent slip systems are activated, significantly improving magnesium's formability and its alloys [2]. However, the plastic processing temperature of such difficult-to-deform alloys should be controlled due to its increase related to the work of deformation and friction and the possibility of forming low-melting eutectics at specific temperatures on the other hand [2]. Additionally, the mechanical properties of the processed alloy could be improved and controlled by proper selection of the plastic deformation process parameters. Therefore, new methods of plastic deformation are being sought. A new, unconventional method of plastic processing for magnesium alloy is continuous rotary extrusion (CRE).

The CRE process is commonly used for well-deformable metals and their alloys due to its advantages, such as constant deformation conditions related to the continuous process, high efficiency, and uniform mechanical properties of the products [3].

In the CRE process, friction between the material and the tooling causes the material to move towards the deformation chamber, which gradually heats the material through its contact with the tooling. This way, the appropriate extrusion temperature is achieved [4, 5]. The same phenomenon occurs in the continuous rotary extrusion (CRE) of the AZ series of magnesium alloys [6].

Material and experimental methods

Rods of 10 mm in diameter made from commercial AZ31 magnesium alloy (chemical composition shown in Table 1) were obtained in direct extrusion (~400°C) and used as feedstock material for the CRE process using the MC-260 Conform-type device. During the CRE process, the speed of the rotary wheel was controlled, and the die temperature was measured when the process was stabilized.

Table 1. The chemical composition of the AZ31 alloy used in the presented work.

Element content, weight %									
Al	**Zn**	**Mn**	**Cu**	**Ni**	**Fe**	**Si**	**Be**	**Ca**	**Mg**
2,99	0,84	0,33	0,001	0,001	0,003	0,015	0,001	0,001	balance

During the CRE process, the process parameters, including different speeds of the rotating wheel and three variations of the deformations zone geometry, were used. A 9 mm diameter die with a rounded edge on the entrance to the die-bearing land was used for every variation. Fig. 1 shows the scheme of the CRE process and a description of the deformation zone. The deformation zone was defined by the feed plate in front of the additional deformation chamber on top of the extrusion die. The feed plate was added for metal flow control in front of the extrusion die.

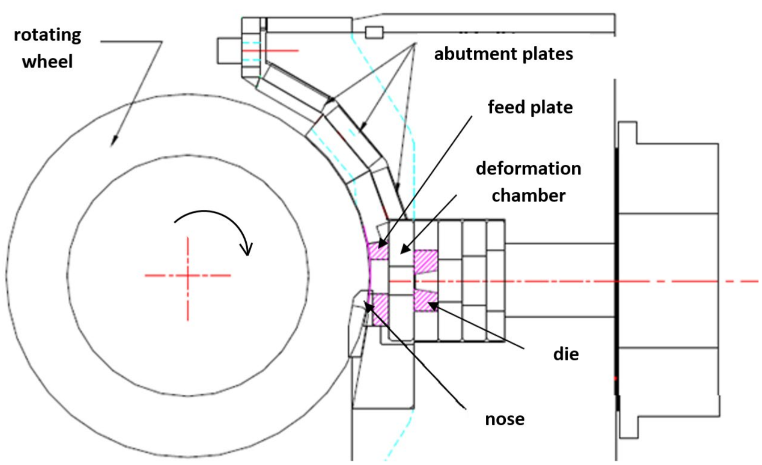

Fig. 1. CRE scheme with a description of the tooling in the deformation zone.

Providing some adjustments to the deformation zone geometry through tooling modifications it is critical to be able to describe these changes quantitatively. For each variation of the deformation zone geometry, the parameter Δ was calculated to allow better comparison of the deformation conditions. Parameter Δ (Eq. 1) is defined as the value of the average height of the deformation zone perpendicular to the deformation direction (H_{av}) divided by the total length ($L_{tot.}$) of the deformation zone measured in the direction parallel to the deformation direction [7]. Its value tells us how optimal the deformation zone geometry is and what the contributions are associated with the energy needed to overcome the friction work and related to the redundant work.

$$\Delta = H_{av.}/L_{tot.} \quad (1)$$

In the case of the continuous rotary extrusion process, determining the Δ parameter is more complicated due to the use of a deformation chamber in front of the extrusion die. Using a feed plate (pre-chamber) also complicates the geometry of the die set. As a result of these tooling changes, it is more complicated to define the parameters of the deformation zone, including the calculation of the Δ parameter. Therefore, the Δ parameter calculations considered the contribution of individual tools and their heights (feed plate, deformation chamber, and extrusion die) in the die set. The weighted average of the heights H was used. The weighted average is based on the percentage contribution (percentage share of the H total) of the height of a given tool (H_1, H_2, H_3) into the entire extrusion tooling (Fig. 2). Detailed data for Δ parameters calculations are presented in Table 2.

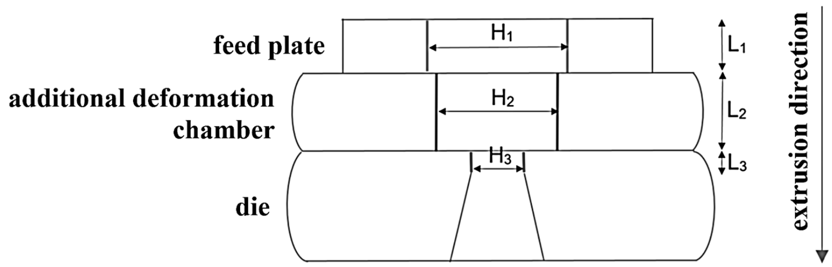

Fig. 2. Scheme of a die set used in the CRE process.

Table 2. Δ parameters calculations for each variation of deformations zone geometry.

Variation Number	Detailed data						Δ= $H_{av.}/L_{tot.}$
I	$H_{1,2,3}$ height [mm]	H_1	H_2	H_3	$H_{tot.}$	H_{av}	**1,840**
		32	0	9	41	26,951	
	$H_{1,2,3}$ weight [%]	78,049	0,000	21,951	100		
	$L_{1,2,3}$ lengths [mm]	L_1	L_2	L_3	$L_{tot.}$		
		12,9	0	1,75	14,650		
II	$H_{1,2,3}$ height [mm]	H_1	H_2	H_3	$H_{tot.}$	H_{av}	**0,815**
		32	30	9	71	28,239	
	$H_{1,2,3}$ weight [%]	45,070	42,254	12,676	100		
	$L_{1,2,3}$ lengths [mm]	L_1	L_2	L_3	$L_{tot.}$		
		12,9	20,0	1,75	34,65		
III	$H_{1,2,3}$ height [mm]	H_1	H_2	H_3	$H_{tot.}$	H_{av}	**1,355**
		32	40	9	81	33,395	
	$H_{1,2,3}$ weight [%]	39,506	49,383	11,111	100		
	$L_{1,2,3}$ lengths [mm]	L_1	L_2	L_3	$L_{tot.}$		
		12,9	10,0	1,75	24,65		

Table 3 presents the variations of used tooling geometries in the CRE process for which AZ31 alloy rods were obtained and the Δ parameters calculated.

Table 3. The deformations zone geometries, CRE process parameters, and the Δ parameters.

Variation Number	Additional deformation chamber	Process speed [rpm]	Process temperature [°C]	Δ
I	not used	3	400	1,840
		4	415	
		4,5	420	
		5	425	
II	H_2 = 30 mm L_2 = 20 mm	2,5	370	0,815
		3	380	
		3,5	400	
III	H_2 = 40 mm L_2 = 10 mm	3	390	1,355
		4	395	
		5	400	
		6	415	

The rods extruded in direct extrusion, and the CRE processes were evaluated in the static tensile test, where the hardness measurements were performed. The rods were also analyzed for grain size, texture, and level of recrystallization using the EBSD method. The level of recrystallization was calculated based on the Grain Orientation Spread (GOS) index. For AZ31 alloy, it was assumed that grains with the GOS orientation dispersion of less than or equal to 1° are dynamically recrystallized grains, while for GOS>1°, grains are deformed [8].

EBSD investigations were performed on cross-sections of extruded rods in the middle of the cross-section and at the edge (approx. 300 µm from the surface of the rod).

Experimental Results

The die temperature generated at a given process speed was monitored during the CRE process. The process speed was experimentally adjusted according to the temperature target. Fig. 3 shows the dependence of the achieved process temperatures on the process speed for each variation of deformations zone geometry used. Variant III showed the lowest process temperatures; however, the strongest relationship between the process temperature and speed.

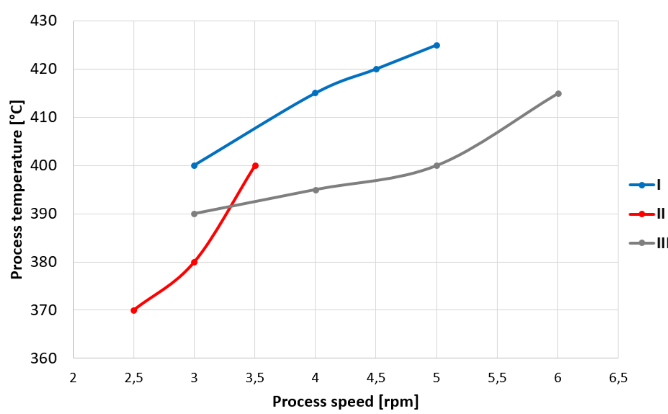

Fig. 3. CRE process temperature vs process speed relationship for different die designs marked as I, II, and III.

Hardness was measured at three points near the center of the rod's cross sections, and the average hardness was calculated. Fig. 4 shows the hardness of CRE rods as a function of the process temperature. Hardness measured for the direct extruded rod is marked with a black line.

A static tensile test determined the tensile strength, yield strength, and elongation. Three samples were tested, and the average values were calculated. Fig. 5 shows the tensile strength, yield strength, and elongation depending on the process temperature. Values measured for the directly extruded rods are marked by a black line.

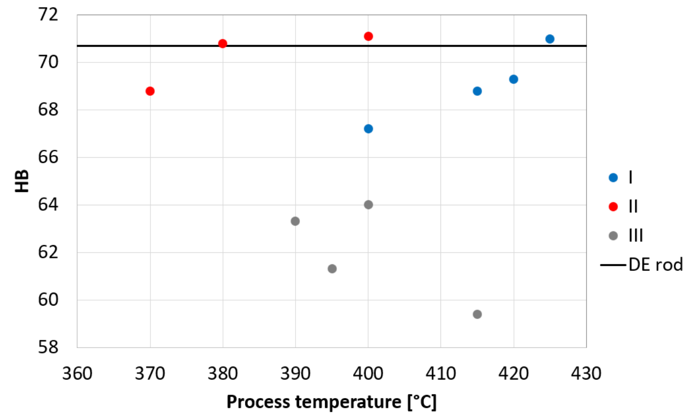

Fig. 4. Hardness of the CRE and DE rods vs process temperature.

For the CRE rods extruded at a speed of 5 rpm and at a temperature of 425°C with no additional deformation chamber, no tensile test was performed due to the deep surface tearing on the rods' surface.

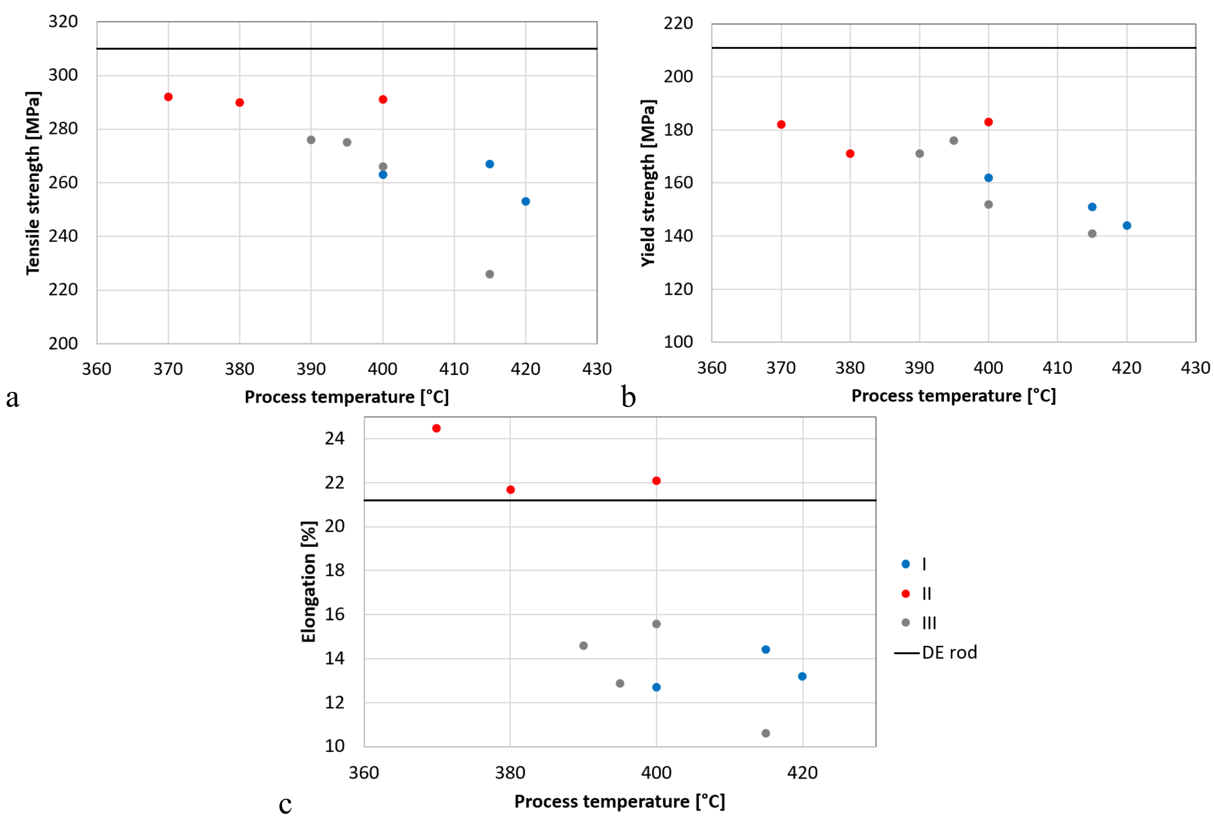

Fig. 5. Tensile strength (a), yield strength (b), and elongation (c) of the CRE and DE rods vs process temperature.

Grain size, texture level, and the share of recrystallized fraction were measured based on the Inverse Pole Figure (IPF) maps obtained by EBSD. The dependence of the grain size, texture level, and recrystallized fraction on the temperature of the CRE process for the center and edges of the rods is shown in Fig. 6. The black lines indicate the grain size of the DE rod.

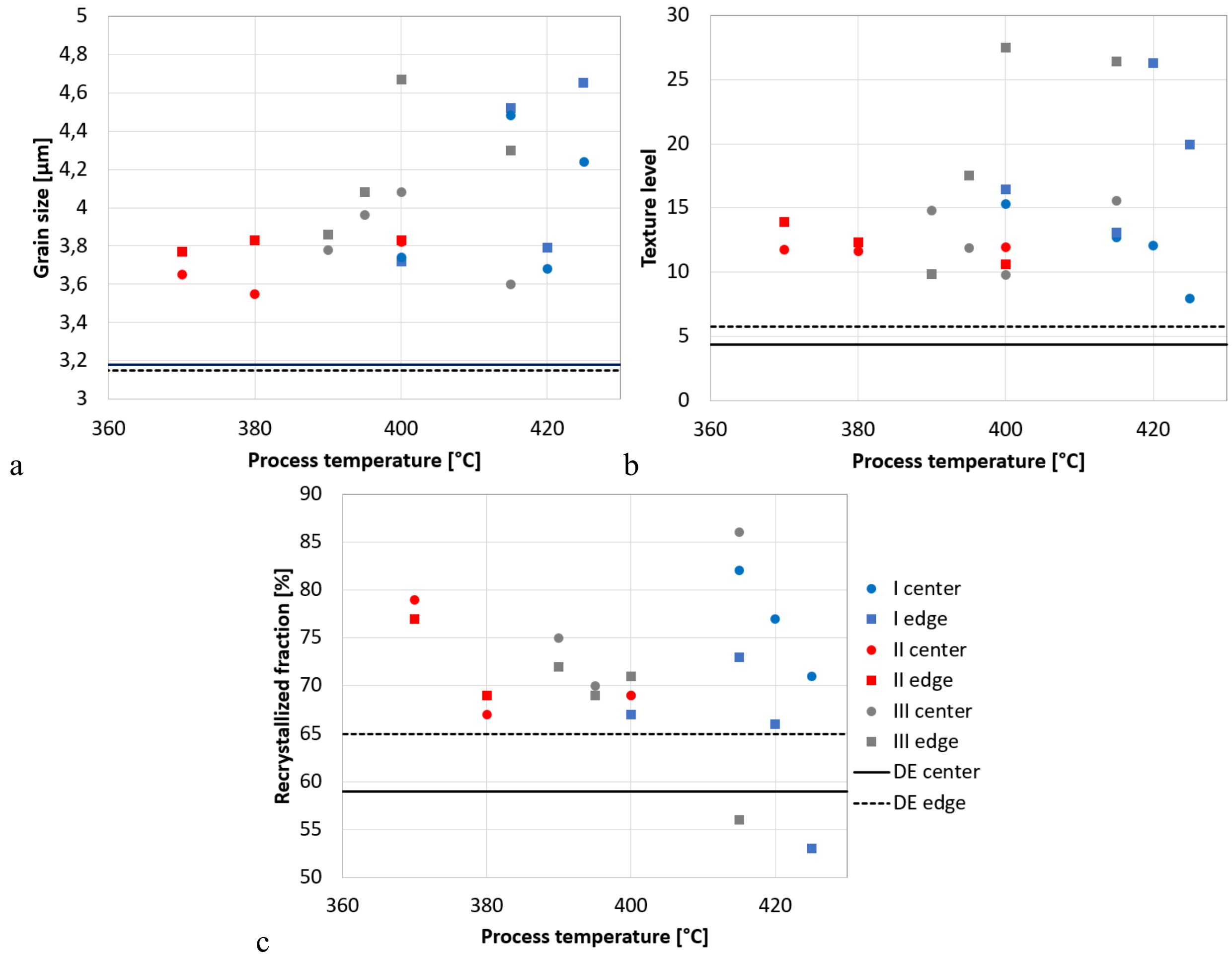

Fig. 6. Grain size (a), texture level (b), and the share of recrystallized fraction (c) for the CRE and DE rods vs process temperature.

Discussion of the Experimental Results

Each change in the geometry of the deformation zone resulted in a change in the deformation history and, consequently, a change in the parameters of the CRE process. It was found that by using variations of deformations zone geometries, it was possible to obtain different process outputs for the AZ31 alloy, measured by the process speed (Table 2).

During the CRE process, the process speed (rotary wheel speed) was correlated to the temperature obtained. For all variations of the deformation zone, an increase in process temperature was observed with an increase in speed. This was caused by the more intense friction phenomenon at higher speeds and the limited cooling of the extruded rod after the CRE process.

The use of various types of deformation zones affects the heat generated in the CRE process and, therefore, increases its temperature. Depending on the variation of the deformation zone, different process temperatures were obtained for the same process speeds.

It was also observed that the AZ31 alloy achieves lower process temperatures for the same speeds using both additional deformation chambers than CRE extrusion without additional tooling.

This is mainly related to different friction forces in the deformation zone when using different deformation chambers or the pre-chamber.

No rods with better mechanical properties than directly extruded rods were obtained for deformation zone variations labeled as I and III in the CRE process (Fig. 4 and 5).

Hardness measurements and static tensile tests of CRE rods indicate that better properties are obtained for extruded rods using an additional deformation chamber with dimensions H = 30, mm L = 20 mm (variation number 2). For this variation, higher values of hardness and elongation were obtained. Higher elongation values for variation II also indicate a better surface quality of the CRE rods extruded in this variant. This is the deformations zone geometry variant for which the Δ parameter is the highest, so the local deformation conditions in the deformation zone should be the most uniform. Better mechanical properties of CRE rods from variant II are also correlated with obtaining a smaller grain diameter in comparison to rods from variants I and III (Fig. 6a). The smaller grain size for variant II is the result of the lower temperature of the CRE process, which also affects the lower degree of recrystallization (Fig. 6c).

For variations I and III, higher process temperatures were achieved, which caused the material to tear at the surface. The presence of the surface cracks is responsible for lower values of both elongation and tensile strength (Fig. 5a, Fig. 5c).

Analyzing the results of mechanical properties, there is no clear dependence on the temperature of the CRE process. This means that the material in the deformation zone behaves differently for each variant of the deformation zone for different CRE process speeds. Significant fluctuations of mechanical properties for different speeds/temperatures of the CRE process are visible, especially for rods extruded in variant III, for which the Δ parameter is not the highest among those used.

The results of the grain size measurement, texture level, and degree of recrystallization also indicate non-uniform deformation conditions in the near-surface and central areas of rods extruded in the CRE process (Fig. 6). The Δ parameter lower than 1 in the extrusion process should indicate better uniformity of parameters in the deformation area. In the case of the extrusion variant II (Δ = 0.815) more uniform properties are visible when comparing the areas of the center and the edge of the rods, and the influence of lower Δ is visible.

However, for the deformation zone variations I and III, for which the Δ parameter is higher than 1, the differences in properties between the areas of the edge and the center of the rod are inadequate for the Δ parameter's value. For variation I, the Δ parameter is 1.840, which is higher than for variation III, where Δ is 1.355. Therefore, it can be expected that the differences for both rod areas would be more significant for variation I, while the results indicate greater differences for variation III.

It should also be noted that CRE rods with a process temperature similar to the direct extrusion process temperature (~400°C) were characterized by a higher degree of recrystallization than DE rods. This may indicate local changes in deformation conditions due to using a more complicated deformation path than in the traditional DE process.

Summary

Based on the experiments performed using the continuous rotary extrusion process, this technological process can extrude AZ31 magnesium alloy. However, it is more complicated than the traditional direct extrusion process, as it may be influenced by more process parameters.

The increased process temperature (measured in the area of the die-bearing land) was recorded for higher wheel speeds, and different properties of extruded rods were obtained for every variation of the extrusion tooling geometry. Based on the CRE trials, it was found that various levels of material flow heterogeneity took place in the deformation zone when additional deformation chambers were used. Results of mechanical properties and EBSD analysis indicate a more complicated deformation path in the CRE process, for which deformation conditions within the extruded metal are not uniform. This uniformity partially depends on the value of the Δ parameter.

However, the Δ parameter traditionally used in the direct extrusion process can be used in the CRE process as an approximate indicator due to less symmetric metal flow.

It was also found that the CRE process performed in our experiments at room temperature does not lead to material strengthening compared to the direct extrusion process.

A study of continuous rotary extrusion confirmed the ability of AZ31 magnesium alloy to be extruded. However, it showed the need for further research to better understand and optimize this material's deformation conditions.

References

[1] E. Friedrich, B. L. Mordike, Magnesium Technology. Metallurgy, Design Data, Applications. Springer Science & Business Media, Berlin Heidelberg, 2006.

[2] E. Hadasik, D. Kuc, Obróbka plastyczna stopów magnezu, Obróbka plastyczna metali 24 (2013) 131-146.

[3] M. Mitka, M. Gawlik, M. Bigaj, W. Szymański, The Effect of Extrusion Parameters on Possibility of Extrusion of Magnesium Alloys in Continuous Rotary Extrusion Process, Arch. Metall. Mater. 60 (2015) 2981-2984. https://doi.org/10.1515/amm-2015-0476

[4] J. Zasadziński, T. Knych, E. Dziedzic, Badanie procesu wyciskania metodą Conform w produkcji wyrobów i recyklingu aluminium i jego stopów, Rudy i Metale Nieżelazne R-52 (2007) 757-767.

[5] Y. Kim, J. Cho, H. Jeong, K. Kim, S. Yoon, A study on optimal design for CONFORM process, J. Mater. Process. Tech. 80-81 (1998) 671-675. https://doi.org/10.1016/S0924-0136(98)00173-3

[6] M. Mitka, M. Gawlik, M. Bigaj, W. Szymański, W.Z. Misiołek, Continuous rotary extrusion of AZ81 magnesium alloy, Procedia Manuf. 15 (2018) 257-263. https://doi.org/10.1016/j.promfg.2018.07.217

[7] W.F. Hosford, R.M. Caddell, Metal Forming. Mechanics and Metallurgy, Cambridge University Press, 2011.

[8] M. Nienaber, G. Kurz, D. Letzig, K.U. Kainer, J. Bohlen, Effect of Process Temperature on the Texture Evolution and Mechanical Properties of Rolled and Extruded AZ31 Flat Products, Crystals 12 (2022) 1307. https://doi.org/10.3390/cryst12091307