

M. MITKA^{1*}, W.Z. MISIOŁEK², K. LIMANÓWKA¹, M. LECH-GREGA¹, R. SKRZYŃSKA¹, W. SZYMAŃSKI¹**CRYSTALLOGRAPHIC ORIENTATION, RECRYSTALLIZATION, AND TEXTURE DEVELOPMENT IN AZ91 MAGNESIUM ALLOY RODS FABRICATED BY CONTINUOUS ROTARY EXTRUSION (CRE)**

The magnesium alloy AZ91 is widely used in the aviation and automotive industries, where high mechanical properties combined with low density are required. Searching for new, advanced deformation methods in these industries is also essential. Therefore, the presented fundamental research is applied to the continuous rotary extrusion (CRE) process of AZ91 alloy, which is being introduced to industrial applications as a wrought alloy. In this process, magnesium alloy rods were continuously extruded using two types of dies, and their physical properties were examined and compared to rods extruded using the traditional direct extrusion (DE) method. The results indicate changes in the crystallographic orientation, texture, and degree of recrystallization of rods extruded in the CRE process to rods directly extruded from the AZ91 alloy. Significant changes in crystallographic orientation, surface texture, and crystallographic texture asymmetry for rods extruded with both types of CRE dies have been observed compared to the DE rods. The share of the recrystallized grain fraction for the CRE rods obtained using two kinds of dies was relatively uniform on the rod's cross-section. In contrast, in the case of DE rods, the differences between the surface and the center of the rod were more visible. The obtained results indicate different local deformation conditions within the processed material.

Keywords: AZ91 magnesium alloy; CRE; EBSD; Conform[®]

1. Introduction

The magnesium alloy AZ91 contains 9% aluminum by weight, the maximum value for wrought AZ series alloys. AZ91 is widely used in industry, especially in the aviation and automotive industries, mainly as cast products. Its high aluminum content results in excellent castability, making it widely used as a casting alloy, especially for die casting to produce complex thin-walled parts [1-3].

Although the AZ91 alloy is one of the most frequently used magnesium alloys in castings, it is being introduced in metal forming processes. The presented initial research results, among others, show the influence of deformation temperature on the properties of extruded products. A decrease in ductility with the increased temperature of the extrusion process of the AZ91 alloy is explained by the presence of coarse-grained precipitates of the Mg₁₇Al₁₂ phase, which propagate cracking in the material. There is also a significant increase in the average grain size with temperature increase and its impact on the texturing of the material, where at lower temperatures, a much weaker texture was observed [4].

At ambient temperature, the deformability of magnesium and its alloys is very limited due to the type of crystallographic lattice, which is a hexagonal close-packed crystal structure (HCP). The plasticity requirement consistent with Von Mises' theory is unmet for the HCP crystal lattice. According to von Mises' theory, five independent slip systems must operate in the polycrystalline material for uniform deformation without defects (cracks) at the grain boundaries [3,5]. For magnesium, there are only two independent slip systems. Due to this limitation, magnesium and its alloys can be deformed in metal-forming processes at temperatures above 200-225°C. Above these temperatures, additional slip planes are activated, which significantly improves the formability of magnesium and its alloys [3,5-7].

The plastic forming of magnesium alloys is mainly carried out using traditional methods, such as extrusion, rolling, forging, and stamping of sheets obtained in the rolling process. However, the transportation industry's requirement for high mechanical properties combined with low density requires searching for new materials and plastic deformation methods. The manufacturability of the proposed continuous rotary extrusion (CRE) process of AZ91 magnesium alloy will be evaluated later in the studies

¹ LUKASIEWICZ RESEARCH NETWORK/INSTITUTE OF NON-FERROUS METALS/LIGHT METALS CENTER, SKAWINA, POLAND

² LEHIGH UNIVERSITY/LOEWY INSTITUTE, BETHLEHEM, PA, USA

* Corresponding author: monika.mitka@imn.lukasiewicz.gov.pl



when physical properties and potential industrial applications are known and well understood. At that point, the economic aspects of the CRE process, based on its applications, will need to be evaluated based on the industrial sector. There are very different quality requirements, defined by various mechanical properties, for aerospace, medical, transportation, or structural applications. At that point, specific recommendations will be made about tooling geometry and materials and process parameters for particular materials to be used.

An unconventional metal processing method is continuous rotary extrusion (CRE), a.k.a. the Conform® process [8]. The CRE is becoming increasingly popular due to its continuity, constant deformation conditions, high efficiency, and uniform mechanical properties of products.

In the CRE process, the feedstock material is fed between the rotating clamping wheel and moved to the deformation zone due to friction between the material and the wheels (Fig. 1). As a result of friction and deformation heating, the tools and the feedstock material achieve an appropriate temperature for extrusion. Due to the change in the deformation path and the relatively low temperatures of the deformation process, it is possible to obtain fine-grained materials with a homogeneous structure and, therefore, with high tensile strength [8-10].

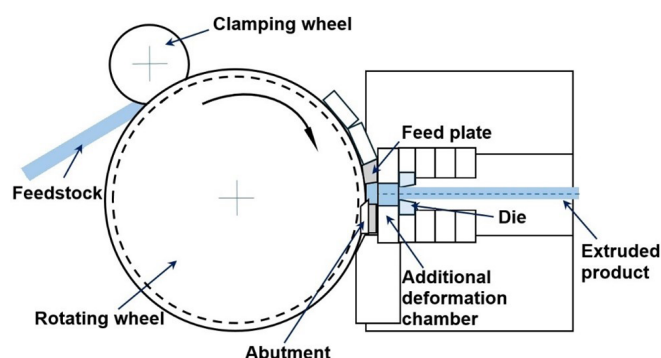


Fig. 1. Continuous rotary extrusion scheme

Continuous rotary extrusion of magnesium alloys, primarily focused on the industrial process, needs to be sufficiently understood and is described in a limited way in the literature. So far, very few results have been reported for the continuous rotary extrusion of the AZ31 magnesium alloy [11,12] and the AZ61 magnesium alloy [13].

For the AZ31 alloy, an intense internal shear band was found in the deformation area, which, combined with a lower deformation temperature, favors grain twinning and the propagation of dynamic grain recrystallization. It was also found that the stresses obtained during a static tensile test of CRE rods made of the AZ31 alloy are lower than for rods extruded using the traditional method. Despite the fine-grained structure of CRE rods, their tensile strength and yield strength are lower than in the case of the direct extruded rods. The authors explain the situation by the texture's softening caused by the crystal's changing orientation during the Conform® process. An increase in elongation was also observed for the CRE rods, which may

be related to the more uniform, fine-grained microstructure of these rods. The summary of the research results concluded that continuous rotary extrusion can be successfully used for the AZ31 magnesium alloy [11, 12].

Studies of the CRE process for AZ31 alloy performed at different process speeds showed a more fine-grained structure in the center of the cross-section of the rods obtained at lower speeds, which is probably caused by dynamic recrystallization in this area. At the edge of the same rod, the authors observed both grains remaining in their original state and the fine grains dynamically recrystallized, which is probably related to the deformation path in the Conform® process [12].

There were also trials of CRE extrusion of the AZ61 alloy, where the feedstock was a smaller diameter than the obtained rod. In this trial, a particular shape of the deformation chamber was used – an inverted cone with the apex directed towards the material feeding direction. This shape of the chamber application, combined with the increase in temperature during the process, resulted in strong plastic deformation, affecting the grain refinement of the obtained rods [13]. The observations of the microstructure of the rod received in the CRE process showed a parabolic distribution of the microstructure along the extrusion direction. Significantly refined grains were observed in the center of the rod than at the edge, where overgrown or secondary recrystallized coarser grains occurred. A change in the grain's preferred orientation toward the edge of the rod was also noticed. It was also found that different dynamic recrystallization behaviors during the CRE process significantly impacted crystallographic texture evolution [13].

Mitka et al. conducted preliminary studies on the extrusion of the AZ91 alloy in an actual CRE process. They confirmed that magnesium alloy AZ91 can be extruded using the Continuous Rotary Extrusion process. They noticed a very strong correlation between the extrusion speed (rotary wheel speed) and process temperature [14].

Due to insufficient literature data, the magnesium CRE process requires more understanding and detailed engineering knowledge. Deformation processing of hard deformable magnesium alloys using the CRE method cannot use the results of processing highly deformable materials such as Al or Cu alloys, for which extensive research has been carried out, and a lot of process and material data is available.

Therefore, the present study applied the continuous rotary extrusion process to AZ91 magnesium alloy rods and examined their physical properties.

2. Test material and methodology

Rods with a diameter of 10 mm, extruded in the direct extrusion (DE) process from the AZ91 magnesium alloy, were used as feedstock for the continuous rotary extrusion process (TABLE 1). During the DE process, the rods were extruded through a 3-orifice die. The process temperatures were approximately 400°C, and the extrusion ram speed was 0.5 mm/s.

TABLE 1

Chemical composition of the AZ91 magnesium alloy used in the extrusion processes

Element content wt. %									
Al	Zn	Mn	Cu	Ni	Fe	Si	Be	Ca	Mg
8,98	0,59	0,23	0,005	0,002	0,014	0,046	0,001	0,001	bal.

The CRE process used two types of dies, 9 mm in diameter, with a sharp and rounded edge of die-bearing land (see Fig. 2). No additional deformation chamber was used in the deformation zone in the CRE process.

The processing speed was 3 rpm, and at this speed, the CRE process temperature generated for extrusion with a rounded edge of die-bearing land was close to the temperature obtained during the direct extrusion of AZ91 alloy (approx. 400°C). At 3 rpm, the CRE process temperature with the sharp edge of die-bearing land was lower, at 350°C.

The extrusion ratio for the CRE process was small: $R = 1.2$, while for the direct extrusion process, it was $R = 33$.

Changes in crystallographic orientation, texture, and degree of recrystallization of rods extruded via the CRE process were analyzed and compared to rods extruded using the traditional direct extrusion method. The tests were conducted using the Electron Backscattered Diffraction (EBSD) technique, using a FEI INSPECT F50 scanning electron microscope equipped with an EDAX Velocity PRO EBSD camera. The investigations of the material's microstructure were based on one cross-section sample from the rod obtained from the steady-state process conditions where no changes in temperature of the die-bearing land were observed.

The (EBSD) tests were performed on cross-sections of rods in two areas: in the center and at the edge (approx. 300 μm from the

surface of the rod) of the extruded rod at 1000 $\times$ magnification. The same test conditions were used for each analyzed rod; the analysis area was 320 $\times$ 250 μm . The EBSD analysis aimed to determine the general characteristics of the grains, and it was performed for a magnesium matrix. Due to the uniform distribution and morphology of the precipitates, they were not analyzed during EBSD.

The crystallographic orientation maps, which included grain size measurements, texture measurements, and GOS (grain orientation spread) index calculations, were obtained using the EDAX OIM Analysis 8 program.

The GOS index analysis assumed that grains with a GOS orientation dispersion of less than or equal to 1° are dynamically recrystallized grains. In contrast, the grains are deformed for GOS > 1° [15,16].

Fig. 3 shows the magnesium elementary triangle, texture levels chart, and GOS legend used for OIM analysis.

3. Results and discussion

TABLE 2 presents the results of grain size measurement and crystallographic orientation analysis of AZ91 alloy rods extruded by both methods.

Fine grains of relatively uniform size were observed in particular cross-section areas in the CRE process's direct extruded feedstock rods from the AZ91 magnesium alloy. A slightly larger grain was measured at the edge of the rod's cross-section than at its center.

For CRE rods extruded using a die with a sharp bearing land, a similar dependence is observed, while for the CRE rod extruded using a die with a rounded edge of the bearing land, the grain size on the cross-section of the rod is more uniform

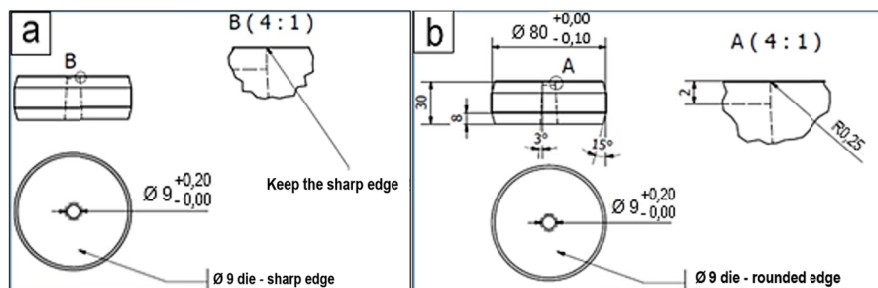


Fig. 2. Sketches of the dies used in the CRE process: a) with a sharp edge and b) with a rounded edge of the die-bearing land

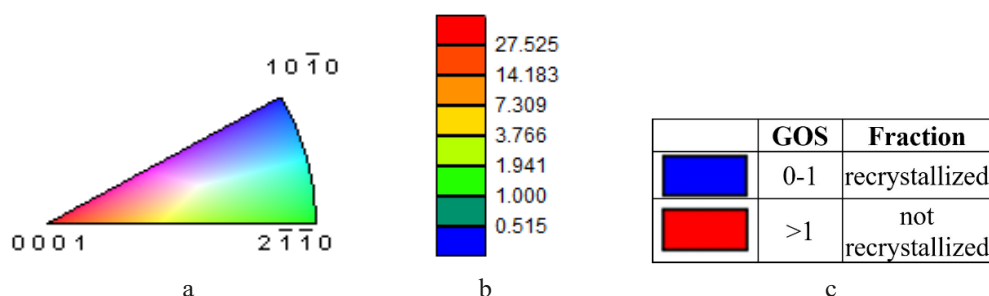
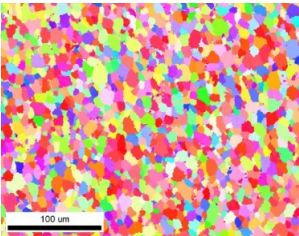
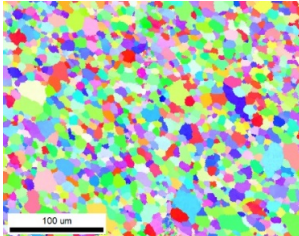
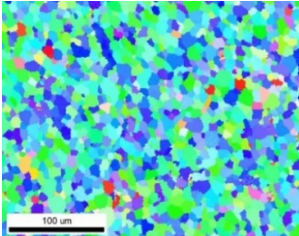
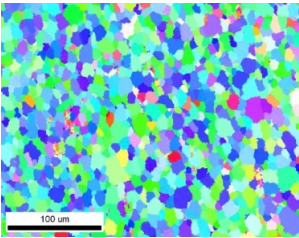
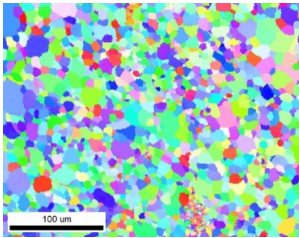
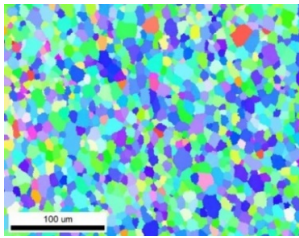


Fig. 3. The elementary triangle for magnesium [001] (a) texture levels, (b) GOS legend, and (c) results of the OIM analysis of extruded AZ91 alloy rods

TABLE 2

Results of EBSD analysis of AZ91 rods extruded in direct and CRE extrusion – IPF maps with grain size measurements results [μm]

Cross section area	CRE die bearing land edge				DE	
	Sharp		Rounded			
	Grain size [μm]	Standard deviation	Grain size [μm]	Standard deviation	Grain size [μm]	Standard deviation
Center						
	5,07	3,76	6,18	3,65	6,97	3,67
Edge						
	6,89	4,36	6,13	3,89	7,84	3,73

(Fig. 4a). This indicates a positive effect of the die rounding on higher uniformity of local extrusion parameters in the area of the extruded material.

Compared to the direct extrusion (DE) process, the CRE process resulted in a finer grain microstructure for both dies used, which may be associated with additional shear deformation in the deformation zone.

The crystallographic orientation analyzed in the cross-section of the direct extruded rods indicates the dominance of the $[10\bar{1}0]$ and $[21\bar{1}0]$ directions.

Compared to the DE rods, the grains within the rods obtained in the CRE process change their crystallographic orientation, especially in the center area. A more significant change in orientation is visible, especially in the center of the rod extruded in the CRE process with the sharp edge of the die-bearing land, where the $[0001]$ orientation dominates.

No grain twins were observed during EBSD analyses for rods extruded in the CRE and DE processes. This indicates that during the CRE and DE process, the deformation of AZ91 magnesium alloy occurs only by slip mechanism, which is typical for magnesium alloys deformed at elevated temperatures [5-6].

TABLE 3 and Fig. 4b show the texture of rods extruded in the CRE process. The DE rods' texture was fibrous, typical for rods extruded by this method, with visible texture heterogeneity in the rod cross-section. A lower level of texturing was analyzed for the center of the rod than at its edge.

The texture of rods extruded in the CRE process differs from that of feedstock rods extruded in the DE process. The blurring and asymmetry of the central area of the rods extruded in the CRE process are observed. This is due to the lower degree of deformation in the CRE process than in the DE process, so the

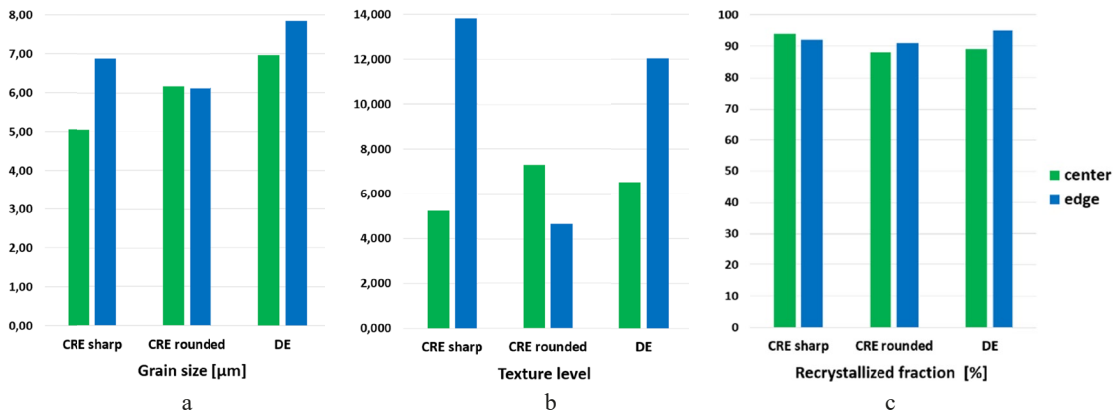


Fig. 4. Comparison of grain size (a), texture level (b), and recrystallized fraction (c) measured at the center and at the edge of the rod cross sections obtained for DE and CRE rods

TABLE 3

Results of EBSD analysis of AZ91 rods extruded in direct and CRE extrusion – pole figures and measured maximum texture level

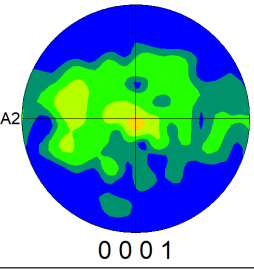
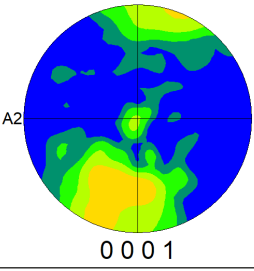
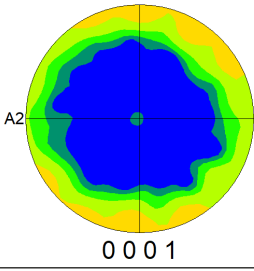
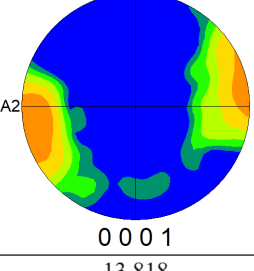
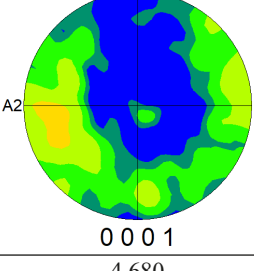
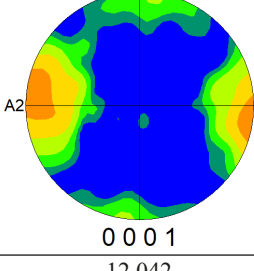
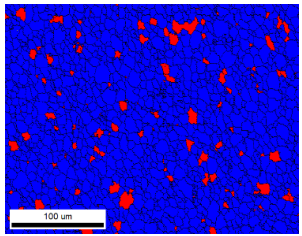
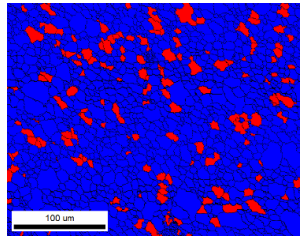
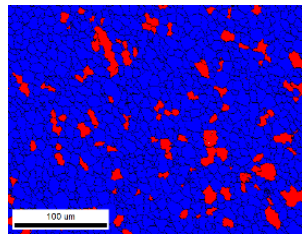
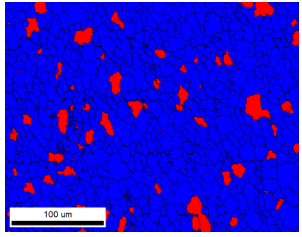
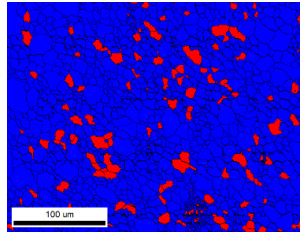
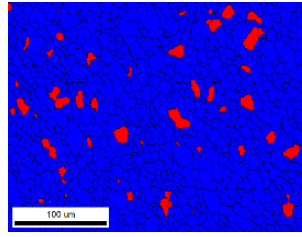
Cross section area	CRE die bearing land edge		DE
	Sharp	Rounded	
Center			
	0 0 0 1 5,241	0 0 0 1 7,291	0 0 0 1 6,506
Edge			
	0 0 0 1 13,818	0 0 0 1 4,680	0 0 0 1 12,042

TABLE 4

Results of EBSD analysis of AZ91 rods extruded in direct and CRE extrusion – share of the recrystallized fraction based on GOS [%]

Cross section area	CRE die bearing land edge		DE
	Sharp	Rounded	
Center			
	94	88	89
Edge			
	92	91	95

strain level does not affect the grain refinement and the rotation of the slip planes to the same extent. Deformation in the CRE process is more localized on the surface of the extruded rods, which also may impact the texture evolution. In the edge area, there is also a visible difference in texture between rods obtained in the CRE process using different types of dies. For rods extruded with a rounded edge of the bearing land, the texture at the surface of the rod is weaker than for rods extruded with a sharp edge of bearing land. This confirms the influence of

the die rounding on the level of strain achieved in the vicinity of the surface area.

TABLE 4 and Fig. 4c present the results of the grain orientation spread GOS analysis and the percentage of recrystallized grains in the structure of rods extruded in the direct extrusion process and in the continuous rotary extrusion process from the AZ91 magnesium alloy.

The share of the recrystallized fraction in the structure obtained based on the GOS analysis indicates that the level of

recrystallization was about 7% higher at the surface of the DE rods than at the center of the rod. For the CRE rods obtained using both dies, the share of the recrystallized fraction was uniform on the whole cross-section.

This may indicate that, given the process temperature obtained, local differences in temperature changes occurring in the near-surface area of CRE rods do not significantly impact the degree of recrystallization. Also, local differences in temperature changes occurring in the CRE rods near-surface area do not significantly impact the degree of recrystallization in the face of the process temperature obtained. Also, rounding the die-bearing land to reduce static friction forces at the point of contact between the extruded material and the bearing land does not significantly impact temperature changes in the face of higher friction forces from the feed plate area. The weaker texture is slightly reflected in the higher share of recrystallized grains in individual areas of the CRE rods. It may also indicate non-uniform deformation conditions between rod cross-section areas for the CRE method.

4. Summary and conclusions

It can be concluded that obtaining rods in the CRE process from AZ91 magnesium alloy is possible, but it is more complicated than in the traditional direct extrusion process. In terms of technology and its economy, Special attention should be paid to the more complex set of tools in the CRE process, which requires the appropriate selection of both the process speed (and consequently its temperature) and the geometry of individual elements (especially a properly selected deformation chamber for a die set used). Inappropriate use of particular tooling members may result in damage due to feedstock material leaking and squeezing between the tooling elements under high deformation forces in the CRE process.

It is also clear that speed-temperature parameters for the same input materials differ depending on the geometry of the deformation zone (type of extrusion die).

However, the deformation mechanism for DE and CRE processes is the same, and deformation occurs mainly through slip.

The results indicate changes in the crystallographic orientation, texture, and degree of recrystallization of rods extruded in the CRE process to rods directly extruded from the AZ91 alloy, indicating different local deformation conditions within the deformed material. Moreover, the slightly higher degree of recrystallization for CRE rods extruded using a die with a sharp edge of the bearing land may indicate the occurrence of slightly higher redundant strain while this type of extrusion die is used.

The results indicate uneven deformation of extruded rods, varying regarding the applied extrusion method and the type and geometry of tooling used in the CRE process. A detailed investigation of this effect requires additional studies, including numerical modeling of the CRE process.

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