DOI: https://doi.org/10.24425/amm.2026.1974

DARIUSZ KUC[1*], IWONA BEDNARCZYK[1], MARIA SOZAŃSKA[1]

EFFECT OF DEFORMATION MODE ON MICROSTRUCTURE EVOLUTION AND PLASTIC DEFORMATION BEHAVIOR OF AZ61 MAGNESIUM ALLOY

The present study investigates the influence of deformation mode on the microstructure evolution and plastic deformation behavior of AZ61 magnesium alloy. The material was processed using conventional extrusion and complex KoBo extrusion, resulting in different initial microstructures. Compression tests were performed at elevated temperatures and various strain rates to determine the flow stress behavior and plasticity characteristics of the alloy. The obtained stress-strain curves revealed significant differences in deformation behavior depending on the deformation mode and the initial microstructure. The material processed by the KoBo method exhibited lower flow stress and reduced peak stress compared to the alloy obtained by conventional extrusion. This behavior is associated with grain refinement and the enhanced activation of softening mechanisms during deformation. The results indicate that the refined microstructure accelerates the kinetics of dynamic recrystallization and improves the plastic deformation capability of AZ61 magnesium alloy.

Keywords: AZ61 magnesium alloy; hot deformation, microstructure evolution, flow stress, grain refinement

1. Introduction

Magnesium and its alloys are widely used in the metalworking industry due to their low density and favorable mechanical and physical properties, which make them particularly attractive for lightweight structural applications. With a density of approximately 1.74 g/cm^3, the use of magnesium alloys allows for a reduction in component weight of up to 30%, which is of great importance in modern engineering applications [1,2].

However, the wider application of magnesium alloys is still limited by several disadvantages, including relatively low corrosion resistance, flammability, limited strength, high processing costs, and poor formability at low temperatures [3-5]. In particular, the hexagonal close-packed (HCP) crystal structure restricts the number of available slip systems, which results in low plasticity at ambient temperature.

Despite these limitations, magnesium alloys remain the subject of intensive research due to their high potential for weight reduction and performance improvement. Numerous studies have focused on enhancing their mechanical properties and deformability through both conventional and advanced deformation methods. In particular, the refinement of microstructure to the ultrafine or nanocrystalline scale has been shown to significantly improve strength and ductility.

Among various grain refinement techniques, severe plastic deformation (SPD) methods have attracted considerable attention. These include high-pressure torsion (HPT), equal channel angular pressing (ECAP), multiaxial forging (MAF), accumulative roll bonding (ARB), and cyclic extrusion and compression (CEC) [6,7]. Although these methods are effective in producing ultrafine-grained materials, their application in large-scale industrial production remains limited due to technological complexity.

Recently, increasing attention has been paid to alternative processing routes that enable significant grain refinement in a single deformation step. High-ratio extrusion methods have been shown to be effective in producing ultrafine-grained magnesium alloys with improved mechanical properties. Most studies have focused on AZ31, AZ80 and AZ91 alloys, while relatively less attention has been given to AZ61.

One of the promising unconventional deformation methods is the KoBo process, which combines extrusion with reversible torsion of the die. This method enables the introduction of complex strain paths and promotes intense plastic deformation, leading to significant microstructural refinement [12-14]. The

1 SILESIAN UNIVERSITY OF TECHNOLOGY, FACULTY OF MATERIALS ENGINEERING AND INDUSTRIAL DIGITALIZATION, DEPARTMENT OF MATERIALS TECHNOLOGY, 8 KRASIŃSKIEGO STR., 40-019 KATOWICE, POLAND

* Corresponding author: dariusz.kuc@polsl.pl

KoBo method allows deformation to be performed at reduced temperatures or even at room temperature without prior heating, due to the activation of viscoplastic flow mechanisms. Additionally, it enables high deformation degrees to be achieved with relatively low forming forces.

Recent studies indicate that KoBo processing can lead to the formation of ultrafine-grained structures and improved mechanical properties compared to conventional deformation methods [8-14]. However, the influence of deformation conditions, such as temperature and strain rate, on the mechanisms of plastic flow, dynamic recrystallization, and deformation kinetics in AZ61 alloy requires further investigation. The flow stress behavior of AZ61 magnesium alloy during hot deformation is strongly dependent on strain rate and temperature and is closely associated with the evolution of dynamic recrystallization, which governs the transition from work hardening to steady-state flow [15,16].

Therefore, the aim of the present study is to evaluate the hot deformation behavior of AZ61 magnesium alloy processed by conventional direct extrusion (CDE) and the KoBo method, with particular emphasis on flow stress behavior, strain rate sensitivity, activation energy, and dynamic recrystallization kinetics.

2. Experimental procedure

The investigated material was AZ61 magnesium alloy belonging to the Mg-Al-Zn alloy system. The nominal chemical composition of the alloy contains approximately 6 wt.% Al and 1 wt.% Zn, with magnesium as the balance.

Prior to extrusion, the billets were annealed at 400°C for 40 min in order to homogenize the cast microstructure, promote partial dissolution of the β-$Mg_{17}Al_{12}$ phase and improve the workability of the alloy during subsequent plastic deformation.

Severe plastic deformation was performed using a horizontal hydraulic press operating according to the KoBo method (KoBo). The AZ61 alloy was extruded at room temperature without prior heating. The process was carried out with a die oscillation angle of ±8°, oscillation frequency of 5 Hz and a punch speed of 0.33 mm/s. Both CDE and KoBo processing resulted in rods with a diameter of 8 mm. The extrusion ratio λ was equal to 25. During the process the material was intensively cooled with water at the press outlet.

For comparison, conventional direct extrusion (CDE) was performed at a temperature of 300°C using a Hydromet press, producing rods with a diameter of 8 mm. The application of different extrusion methods resulted in materials with significantly different initial grain sizes, enabling investigation of the influence of the initial microstructure on deformation behavior and dynamic recrystallization.

The hot deformation behavior was investigated using a Gleeble 3800 thermomechanical simulator. Cylindrical specimens with dimensions of 8 mm in diameter and 10 mm in height were subjected to uniaxial compression tests. The compression tests were performed at temperatures of 200, 225, 250, 300 and 350°C and strain rates of 0.01, 0.1 and 1 s^{-1}. The specimens were compressed to a true strain of $\varepsilon = 1$ and subsequently water quenched to preserve the deformation microstructure. For each deformation condition, one representative compression test was generally performed. In cases where technical problems occurred during testing, such as thermocouple detachment, or when the recorded flow curve suggested a possible experimental disturbance, the test was repeated. The stress-strain curves presented in this study correspond to correctly performed tests and were used for further analysis. The mechanical response was additionally verified by corresponding microstructural observations after deformation. For selected deformation conditions, the tests were interrupted at predefined strain levels to investigate the evolution of microstructure and dynamic recrystallization with increasing strain.

Based on the obtained stress-strain curves, the peak stress values were determined. These values were used to calculate the apparent activation energy for hot deformation and to analyze the kinetics of dynamic recrystallization as a function of the Zener-Hollomon parameter.

The apparent activation energy value Q [$J \cdot mol^{-1}$] in hot forming is a key material constant, needed e.g. for the calculation of the temperature compensated strain rate represented by the Zener-Hollomon parameter Z [s^{-1}]:

$$Z = \dot{\varepsilon} \exp\left(\frac{Q}{RT}\right) \tag{1}$$

where: Z – the Zener-Hollomon parameter, $\dot{\varepsilon}$ – is the strain rate, R = 8.314 $J \cdot mol^{-1} \cdot K^{-1}$, the universal gas constant and T – temperature

The relationship between strain rate, flow stress and temperature was described using the Arrhenius-type constitutive equation [17]:

$$\dot{\varepsilon} = C \exp\left(-\frac{Q}{RT}\right)\left[\sin h\left(\alpha\sigma_{pp}\right)\right]^n \tag{2}$$

where: C [s^{-1}], n [-] and α [MPa^{-1}] are other material constants, and σ_{pp} [MPa] is the flow stress corresponding to the peak stress on stress-strain curve.

The strain rate sensitivity coefficient (m) was evaluated based on the flow stress values obtained from compression tests carried out at strain rates of 0.01, 0.1 and 1 s^{-1}. The m parameter was calculated according to the following relationship:

$$m = \frac{\partial \ln \sigma}{\partial \ln \dot{\varepsilon}} \tag{3}$$

where σ denotes the flow stress and $\dot{\varepsilon}$ is the strain rate. The calculations were performed at a peak stress.

Compression specimens were machined from the extruded rods with their axis parallel to the extrusion direction (ED), and the compression tests were performed along ED. To reveal the microstructure, the polished samples were etched using a solution containing 4.2 g picric acid, 70 ml ethanol (95%), 10 ml distilled water and 10 ml acetic acid. Microstructure observations were performed using an Olympus GX50 optical microscope in bright and dark field mode. Quantitative microstructural analysis was carried out using the area method implemented in the Met-Ilo image analysis software. For each investigated condition, approximately 300 grains were analyzed. The average grain size was expressed as the equivalent grain diameter calculated from the measured grain cross-sectional area. The heterogeneity of the grain size distribution was evaluated using the coefficient of variation (v), calculated according to the following equation:

$$v(d) = \frac{s(d)}{\bar{d}} \times 100\% \qquad (4)$$

where $s(d)$ is the standard deviation of the equivalent grain diameter and $\bar{d}$ mean equivalent grain diameter. Thus, higher $v(d)$ values indicate a more heterogeneous grain size distribution.

3. Results and discussion

3.1. Initial state after extrusion

The representative microstructure of the AZ61 alloy in the annealed condition prior to extrusion is shown in Fig. 1a. The microstructure consists of coarse α-Mg grains and secondary phase particles located predominantly along grain boundaries, likely associated with the β-$Mg_{17}Al_{12}$ phase. This morphology is typical of homogenized AZ – series magnesium alloys and served as the initial state for both extrusion routes. The microstructures of the AZ61 alloy after conventional direct extrusion (CDE) and processing by the KoBo method (KoBo) are presented in Fig. 1b, c. The material processed by CDE exhibits a moderately refined microstructure, with an average grain size of approximately 17.3 μm. The grain size distribution is characterized by a high coefficient variation of about 123%, indicating significant microstructural heterogeneity and the presence of grains with a wide range of sizes. In contrast, the alloy processed using KoBo reveals a markedly refined microstructure. The average grain size is reduced to approximately 7.1 μm, while the coefficient of variation decreases to about 98%, suggesting a more homogeneous grain size distribution.

3.2. Deformation state

Based on previous investigations [18], it was established that deformation at temperatures below 200°C results in cracking samples, both after conventional direct extrusion (CDE) and KoBo processing. Increasing the deformation temperature to 200°C enables plastic deformation of the alloy up to a strain of $\varepsilon = 1$ in the case of KoBo-processed material, which is not observed for the material after conventional direct extrusion (CDE).

The results of compression tests performed on samples after CDE and KoBo processing at temperatures of 200 and 225°C and a strain rate of 0.1 s^{-1} are presented in Fig. 2. The evolution of flow stress differs for the two material conditions. In the case of KoBo-processed samples, a significantly lower level of flow stress is observed. Furthermore, the maximum flow stress for conventionally extruded samples is attained at higher strain values compared to the KoBo-processed material.

A representative microstructure of the AZ61 alloy after deformation at 200 and 225°C is shown in Fig. 3. Under these deformation conditions, a bimodal microstructure is observed, consisting of ultrafine dynamically recrystallized (DRX) grains and elongated primary grains (PG). Deformation twins can still be observed in the microstructure, although their role appears secondary to the dynamic recrystallization process. The DRX grains form characteristic necklace-type structures surrounding the PG and are also observed along twin boundaries (TB) formed at earlier stages of deformation.

Non-recrystallized regions are clearly visible in dark-field images as darker areas (Fig. 3c). It can be concluded that under these conditions the deformation process remains unstable, leading to crack formation (Fig. 3d). In addition, strain localization regions are observed, in which the recrystallization process proceeds with higher intensity.

The comparison of compression test results for samples after conventional direct extrusion (CDE) and KoBo processing at a temperature of 250°C and strain rates of 0.01 and 0.1 s^{-1} is presented in Fig. 4. The evolution of flow stress differs between the two material conditions. A significantly lower level of flow stress is observed for the KoBo-processed samples. Furthermore, the maximum flow stress for conventionally extruded samples (CDE) is attained at higher strain values (ε) compared to the

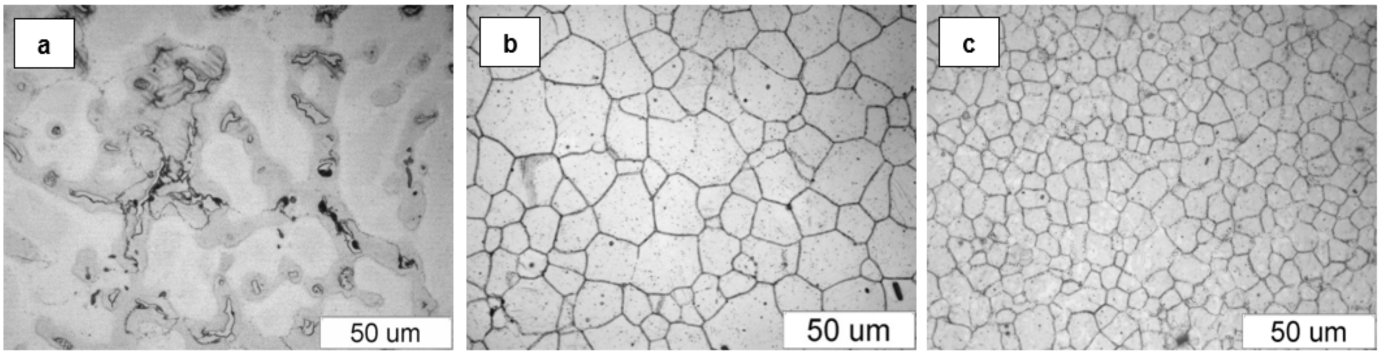

Fig. 1. Representative microstructures of AZ61 alloy: (a) annealed condition prior to extrusion, (b) after conventional direct extrusion (CDE), and (c) after KoBo extrusion. The extruded rods had a diameter of 8 mm

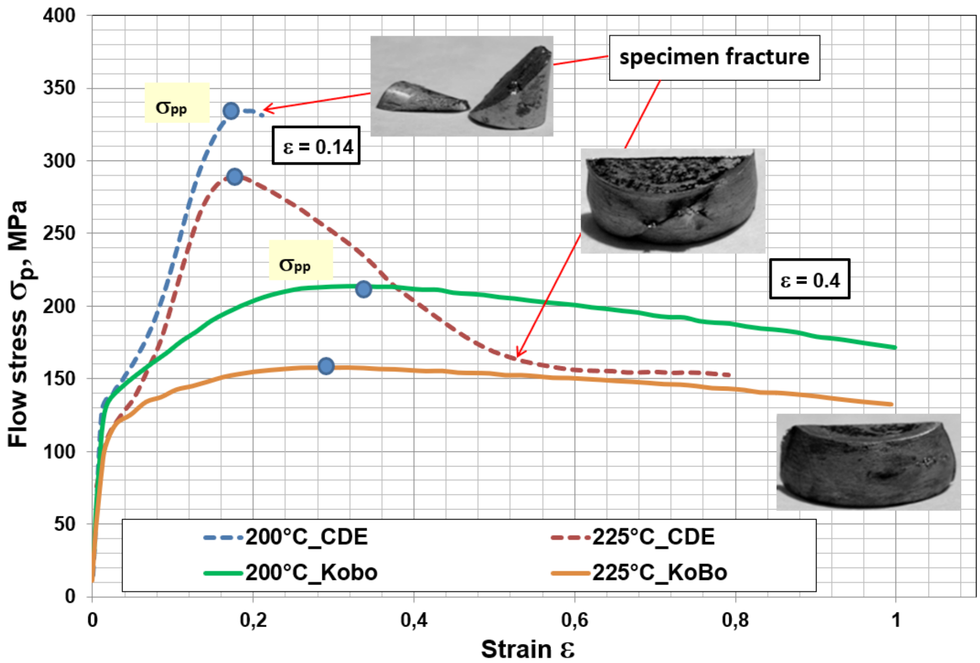

Fig. 2. Flow stress-strain curves for samples after conventional direct extrusion (CDE) and KoBo extrusion, obtained in compression tests at temperatures of 200 and 225°C

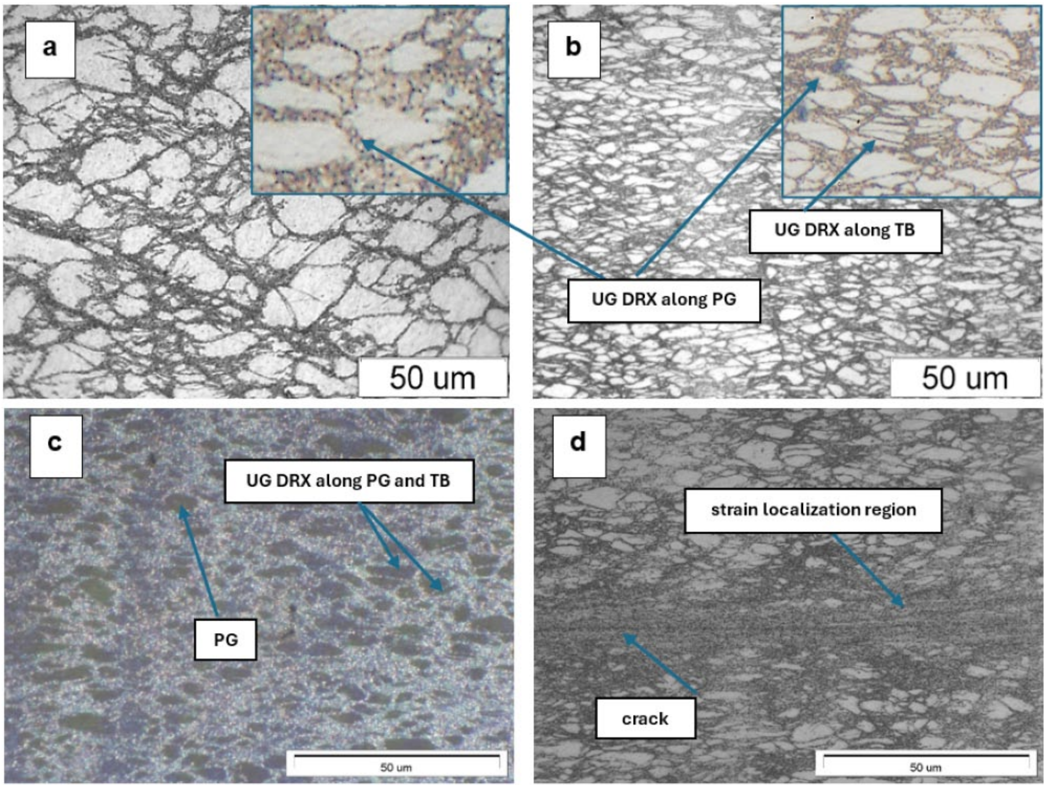

Fig.3. Microstructure of AZ61 alloy after deformation at 200°C: (a) conventional direct extrusion (CDE), (b, c) KoBo extrusion. Ultrafine dynamically recrystallized grains located along twin boundaries are indicated. Regions of strain localization and crack formation are marked in (d). DRX – dynamically recrystallized grains, UG – ultrafine grains, TB – twin boundaries, PG – primary grains

KoBo-processed material. The corresponding microstructures are also presented in Fig. 4. Increasing the deformation temperature to 250°C leads to an intensification of the dynamic recrystallization (DRX) process. However, the microstructures indicate that recrystallization remains incomplete under these conditions. The presence of elongated, non-recrystallized grains alongside fine DRX grains suggests a partially recrystallized microstructure. Moreover, an increase in strain rate results in a reduction of the DRX fraction, indicating a lower intensity of recrystallization due to the limited time available for nucleation and growth processes.

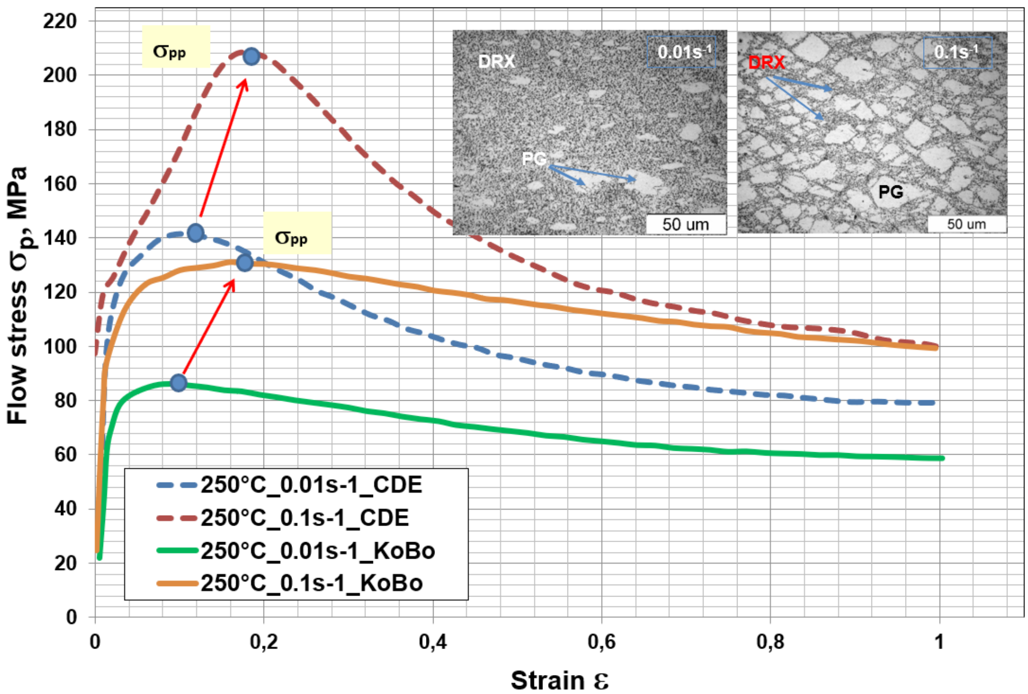

Fig. 4. Flow stress-strain curves for samples after conventional direct extrusion (CDE) and KoBo extrusion, obtained in compression tests at temperature of 250°C

The comparison of compression curves for samples after conventional direct extrusion (CDE) and KoBo processing at 300°C and strain rates of 0.01 and 0.1 s^{-1} is presented in Fig. 5. The overall character of the flow curves is like that observed at lower temperatures. In all cases, a rapid increase in flow stress is observed at the initial stage of deformation, followed by a distinct peak stress (σ_{pp}), and subsequent softening leading to a steady-state flow stress (σ_s).

Significant differences between the CDE and KoBo-processed materials are observed in the initial stage of deformation. The CDE samples exhibit a higher peak stress and a more pronounced work hardening effect, particularly at the higher strain rate (0.1 s^{-1}). In contrast, the KoBo-processed material is characterized by a lower σ_p and a more gradual transition to the steady-state regime.

At higher strains, the flow stress values for both material conditions become comparable, indicating the establishment of a dynamic equilibrium between work hardening and dynamic softening processes. This behavior suggests that dynamic recrystallization (DRX) plays a dominant role in controlling the deformation process at 300°C. Similar effects are observed at 350°C (Fig. 5), where comparable steady-state flow stress values are also obtained for both material conditions.

The effect of strain rate on microstructure evolution at 300°C is clearly observed in Fig. 6. At the lowest strain rate of 0.01 s^{-1}, a nearly fully recrystallized microstructure is obtained, characterized by fine, equiaxed grains uniformly distributed throughout the observed area.

With increasing strain rate to 0.1 s^{-1}, the microstructure becomes partially recrystallized. A bimodal structure

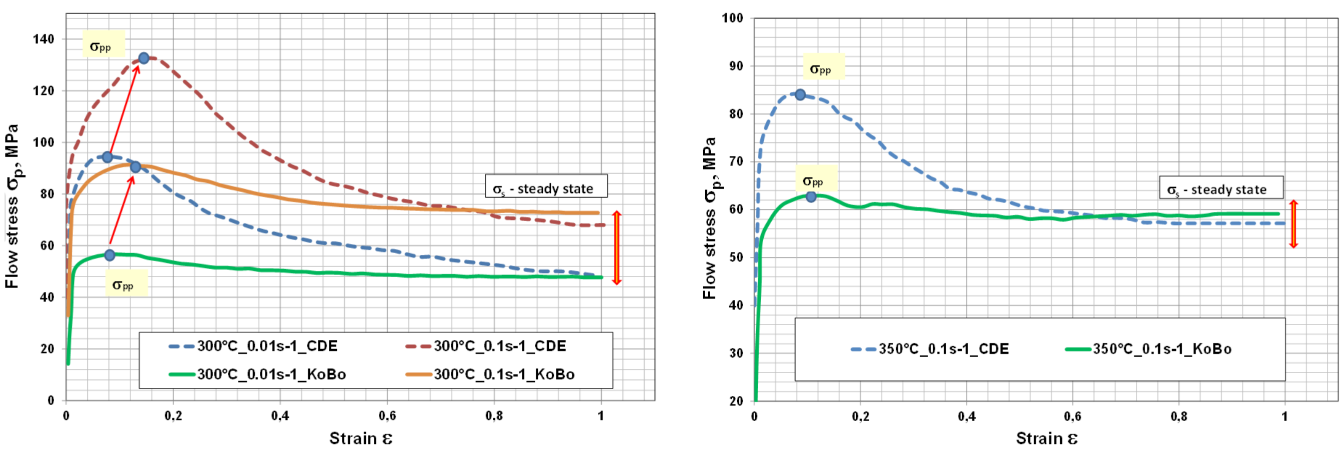

Fig. 5. Flow stress-strain curves for samples after conventional direct extrusion (CDE) and KoBo extrusion, obtained in compression tests at temperatures of 300 and 350°C

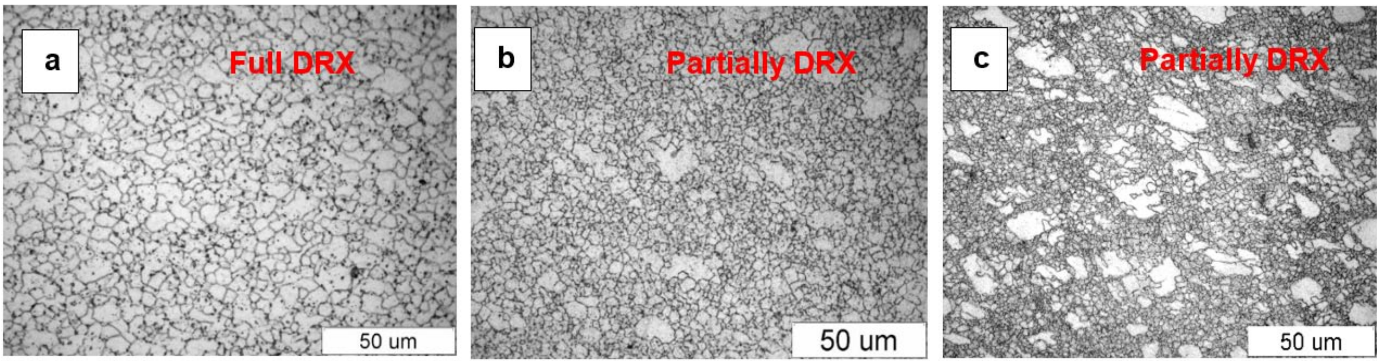

Fig. 6. Influence of strain rate on microstructures of AZ61 alloy deformed at 300°C. A transition from fully recrystallized to partially recrystallized microstructure with increasing strain rate is observed

is observed, consisting of recrystallized grains and elongated, non-recrystallized regions. The fraction of dynamically recrystallized (DRX) grains is reduced compared to the lower strain rate condition. At the highest strain rate of 1 s^{-1}, the extent of recrystallization is further limited. The microstructure consists of numerous non-recrystallized regions, with clearly visible elongated grains. The presence of these unrecrystallized areas indicates insufficient time for the development of DRX during deformation. This behavior confirms that decreasing the strain rate at 300°C promotes dynamic recrystallization due to the higher accumulated strain, which facilitates the nucleation and growth of recrystallized grains.

It should be noted that, in addition to grain refinement, texture modification may also contribute to the lower flow stress observed in the KoBo-processed material. Previous studies have shown that severe plastic deformation processes involving complex strain paths may weaken the basal texture of magnesium alloys, thereby facilitating plastic deformation. However, detailed texture characterization was beyond the scope of the present work and requires further EBSD investigations.

The kinetics of dynamic recrystallization (DRX) was evaluated based on the analysis of the recrystallized volume fraction as a function of true strain, as shown in Fig. 7. The DRX fraction was estimated using the commonly applied approach based on the flow stress curves. The obtained results indicate that the KoBo-processed material exhibits a faster progression of DRX compared to the conventionally extruded (CDE) material. For a given strain level, a higher recrystallized fraction is observed in the KoBo condition, which suggests an accelerated nucleation and growth of recrystallized grains. The difference is particularly pronounced in the initial stage of deformation, where the onset of DRX occurs at lower strain values for the KoBo-processed material. With increasing strain, both materials approach a fully recrystallized state; however, the KoBo material reaches this condition earlier.

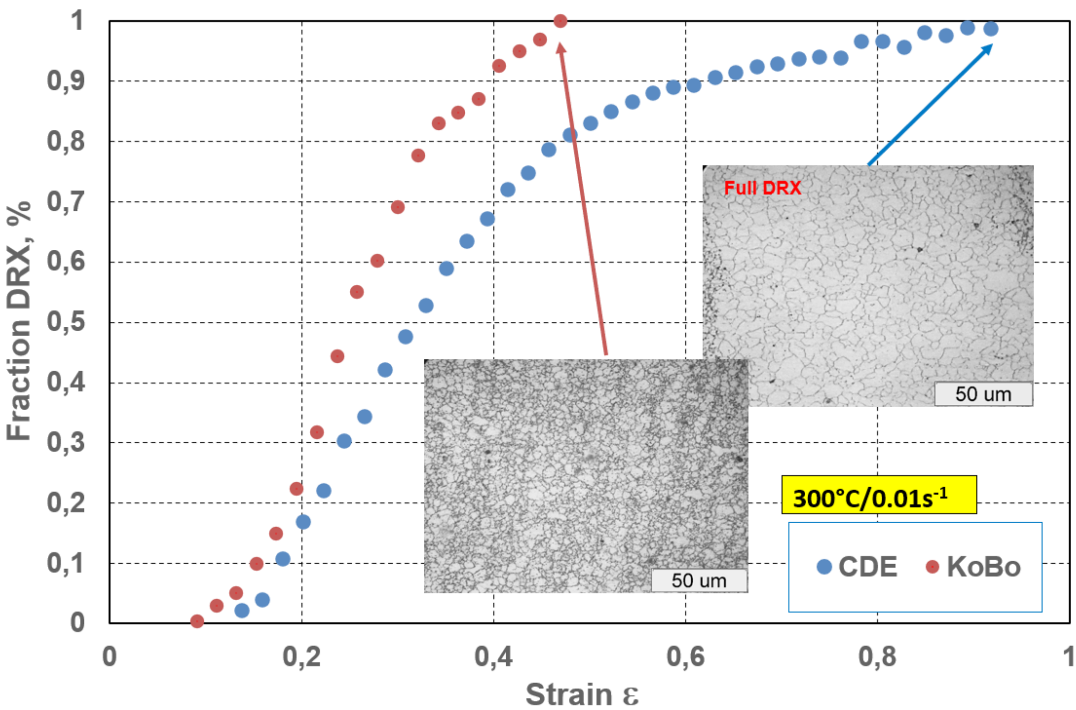

Fig.7. Evolution of the dynamically recrystallized fraction (DRX) as a function of true strain (ε) for CDE and KoBo-processed samples at 300°C, illustrating differences in recrystallization kinetics

This behavior is consistent with the refined initial microstructure and higher density of defects introduced during KoBo processing, which promote DRX kinetics.

The strain rate sensitivity coefficient (*m*) determined at 250 and 300°C is presented in Fig. 8. The strain rate sensitivity coefficient (*m*) increases with deformation temperature from 250°C to 300°C for both processing routes. For samples processed by KoBo, the m value rises from approximately 0.13 to 0.20, while for conventionally extruded (CDE) material it increases from about 0.09 to 0.17.

At both temperatures, slightly higher m values are observed for the KoBo-processed material compared to the CDE condition, although the difference is not significant. The increase in m with temperature indicates enhanced sensitivity of the material to strain rate, which is associated with the activation of thermally assisted deformation mechanisms, such as dynamic recrystallization (DRX).

The relatively higher m values obtained at 300°C suggest more stable plastic flow conditions and a greater contribution of DRX processes, particularly in the KoBo-processed material.

The activation energy for hot deformation, determined based on Eq. (2), was found to be slightly higher for the KoBo – processed material (180 kJ/mol) than for the CDE condition (174 kJ/mol).

Both activation energy values obtained in this study are consistent with literature data reported for AZ-series magnesium alloys. For AZ61-based alloys, Q values ranging from about 150 to above 200 kJ/mol have been reported, depending on the initial microstructure, alloying additions and deformation conditions [15,19,20]. Although the KoBo-processed material exhibited lower flow stress values, its apparent activation energy was found to be slightly higher than that of the CDE material. This indicates that the activation energy should be interpreted as an apparent parameter reflecting the combined contribution of several thermally activated mechanisms, including dislocation slip, dynamic recovery, grain boundary migration and dynamic recrystallization (DRX), rather than a single rate-controlling process. The slightly higher Q value obtained for the KoBo-processed material may be associated with its refined grain structure and the enhanced contribution of grain-boundary-related processes during hot deformation. It should also be noted that the apparent activation energy depends on the temperature and strain-rate ranges used for its determination. In the present study, the constitutive analysis was performed using data obtained up to 350°C, whereas some literature studies include higher deformation temperatures. Consequently, direct comparison of Q values should be made with caution, since differences in the experimental range may affect the calculated activation energy.

The relationship between the Zener-Hollomon parameter (*Z*) and peak flow stress (σ_{pp}) is shown in Fig. 9. For both material conditions, σ_{pp} increases with increasing *Z*, following an exponential-type relationship. The KoBo-processed material exhibits lower σ_{pp} values over the entire *Z* range, indicating improved deformability compared to the conventionally extruded (CDE) material.

It should be noted that, besides grain refinement, texture modification and the stored deformation energy introduced during KoBo processing may also contribute to the lower flow stress and accelerated dynamic recrystallization observed in the investigated alloy. However, a detailed assessment of these effects would require EBSD characterization, including orientation mapping, grain boundary analysis and KAM measurements. Such investigations are planned for future work.

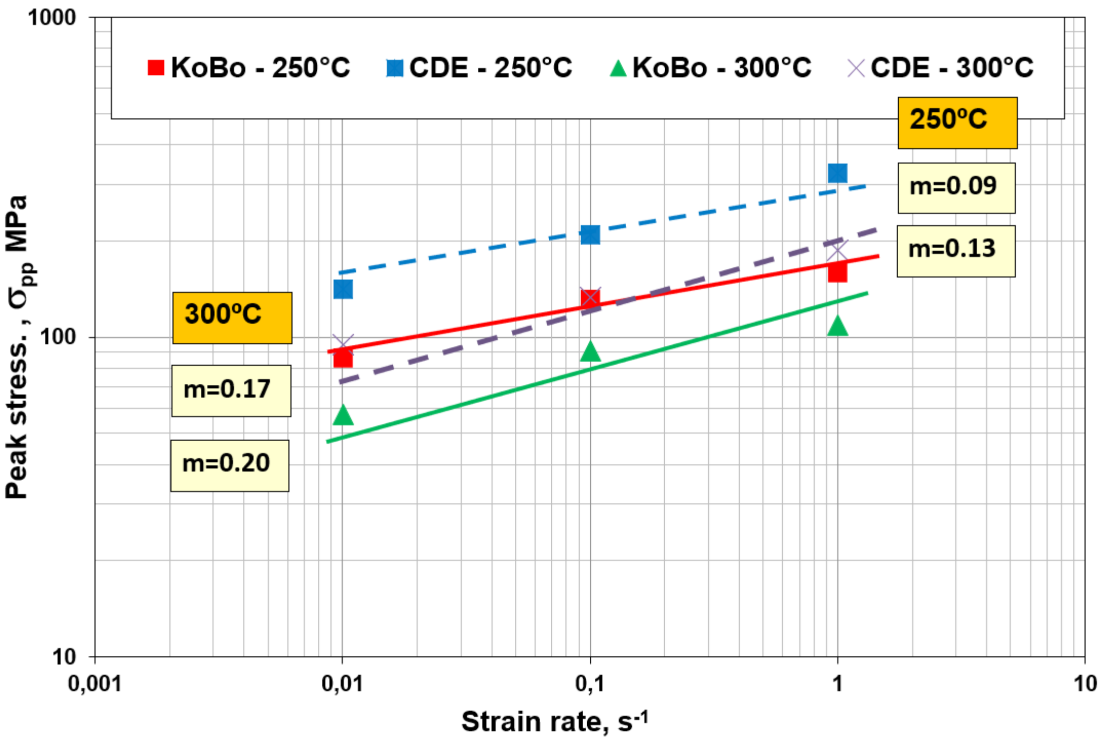

Fig. 8. Strain rate sensitivity coefficient (*m*) as a function of strain rate at 250 and 300°C for AZ61 alloy processed by CDE and KoBo methods

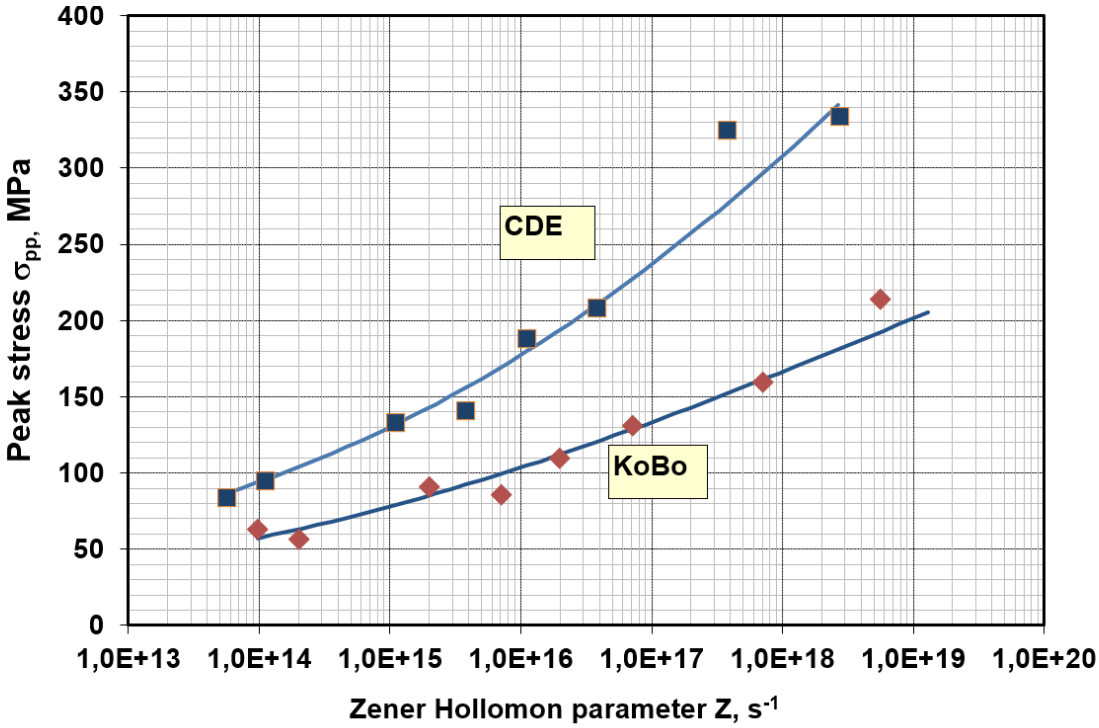

Fig. 9. Relationship between the Zener-Hollomon parameter and peak flow stress for AZ61 alloy processed by CDE and KoBo methods

4. Summary and conclusions

The obtained results allow the following conclusions to be drawn:

1. The application of the KoBo method leads to significant grain refinement of the AZ61 alloy, resulting in a more homogeneous microstructure compared to the conventionally extruded material.
2. The KoBo-processed material exhibits lower flow stress and reduced peak stress values over the entire range of deformation conditions, indicating improved plastic deformability in comparison with the CDE condition.
3. The deformation behavior of the alloy strongly depends on temperature and strain rate. Increasing the deformation temperature promotes dynamic recrystallization (DRX), while increasing the strain rate limits its development.
4. At temperatures of 200 250°C, the microstructure is partially recrystallized and characterized by a bimodal grain structure consisting of ultrafine DRX grains and elongated primary grains. Under these conditions, deformation instability, strain localization and crack formation may occur.
5. At 300°C and above, dynamic recrystallization becomes the dominant softening mechanism. At low strain rates, a nearly fully recrystallized microstructure is obtained, whereas higher strain rates result in a reduced DRX fraction and the presence of non-recrystallized regions.
6. The KoBo-processed material shows accelerated DRX kinetics compared to the CDE material, which is associated with the refined initial microstructure and higher defect density introduced during KoBo processing.
7. The strain rate sensitivity coefficient (*m*) increases with increasing temperature and is slightly higher for the KoBo-processed material, indicating more stable plastic flow conditions and a greater contribution of thermally activated mechanisms.
8. The activation energy for hot deformation is slightly higher for the KoBo-processed material (180 kJ/mol) than for the CDE condition (174 kJ/mol), suggesting a greater contribution of thermally activated mechanisms associated with dynamic recovery and recrystallization.
9. The relationship between the Zener-Hollomon parameter (*Z*) and peak flow stress follows an exponential trend for both material conditions. Lower σ_{pp} values for the KoBo-processed material confirm its enhanced deformability.

Further studies involving EBSD characterization are required to clarify the role of texture evolution and stored deformation energy in the deformation ehavior of the KoBo-processed AZ61 alloy.

Acknowledgements

This work was supported by statutory research funds under project No. 11/030/BK_26/1250 (BK-222/RM3/2026) and by the Initiative of Excellence – Research University (IDUB) program under project No. 11/030/SDU/10-04-06.

REFERENCES

[1] E. Hadasik, D. Kuc, Plastic treatment of metals. Metal Forming **24** (2), 131-147 (2013).

[2] L.A. Dobrzański, T. Tanski, L. Cizek, J. Madejski, The influence of heat treatment on the microstructure and properties of Mg-Al-Zn based alloys. Arch. Mater. Sci. Eng. **36** (1), 48-54 (2009).

[3] I. Bednarczyk, A. Mrugała, A. Tomaszewska, Microstructure and properties of magnesium alloys. Arch. Metall. Mater. **61** (1), 389-392 (2016). DOI: https://doi.org/10.1515/amm-2016-0066

[4] M.W. Grabski, Nadplastyczność strukturalna metali. Wydawnictwo Śląsk, Katowice (1973).

[5] D. Kuc, E. Hadasik, G. Niewielski, A. Płachta, Structure and plasticity of the AZ31 magnesium alloy after hot deformation. J. Achiev. Mater. Manuf. Eng. **27**, 27-31 (2008).

[6] D. Kuc, E. Hadasik, A. Szuła, Plastyczność i struktura odkształcanego stopu magnezu AZ31 w stanie po odlaniu oraz po przeróbce plastycznej, Hutnik – Wiad. Hutn. **76** (8), 666-670 (2009).

[7] C. Zhang, H.Y. Wang, M. Zha, C. Wang, J.H. Li, Z.Z. Yang, Q.C. Jiang, Microstructure and tensile properties of AZ61 alloy sheets processed by high-ratio extrusion with subsequent direct aging treatment. Materials **11**, 895 (2018).
DOI: https://doi.org/10.3390/ma11060895

[8] K. Rodak, Structure and mechanical properties of Cu and Al formed by compression with oscillatory torsion method. Monograph, Silesian University of Technology, Gliwice (2012).

[9] R.Z. Valiev, R.K. Islamgaliev, I.V. Alexandrov, Bulk nanostructured materials from severe plastic deformation. Prog. Mater. Sci. **45**, 103-189 (2000).
DOI: https://doi.org/10.1016/s0079-6425(99)00007-9s

[10] Meng, H. Yu, S. Fan, Q. Li, S. Park, J. Suh, Y. Kim, X. Nan, M. Bian, F. Yin, W. Zhao, B. You, K. Shin, Recent progress in extrusion of rare-earth-free Mg alloys: A review. Acta Metall. Sin. (Engl. Lett.) **32**, 145-168 (2019).
DOI: https://doi.org/10.1007/s40195-018-0772-5

[11] M.M. Myshlyaev, H.J. McQueen, E. Konopleva, Microstructural development in Mg alloy AZ31 during hot working. Mater. Sci. Eng. A **337**, 121-127 (2002).
DOI: https://doi.org/10.1016/S0921-5093(02)00023-4

[12] W. Bochniak, A. Korbel, P. Ostachowski, S. Ziółkowski, J. Borkowski, Extrusion of metals and alloys by KoBo method. Metal Forming **24** (2), 83-94 (2013).

[13] W. Bochniak, Teoretyczne i praktyczne aspekty plastycznego kształtowania metali - metoda KoBo, AGH, Kraków (2009).

[14. A. Korbel, W. Bochniak, P. Ostachowski, L. Błaż, Visco-plastic flow of metal in dynamic conditions of complex strain scheme. Metall. Mater. Trans. A **42** (9), 2881-2897 (2011).
DOI: https://doi.org/10.1007/s11661-011-0704-2

[15] H.Y. Wu, J.C. Yang, F.J. Zhu, H.C. Liu, Hot deformation characteristics of as-cast and homogenized AZ61 Mg alloys under compression. Mater. Sci. Eng. A **550**, 273-278 (2012).
DOI: https://doi.org/10.1016/j.msea.2012.04.087.

[16] X. Xu, H. Nie, J. Zhou, Dynamic recrystallization and twinning behavior of magnesium alloy during hot tension. J. Mater. Res. Technol. **24**, (2023).
DOI: https://doi.org/10.1016/j.jmrt.2023.05.056

[17] C.M. Sellars, W.J. McG. Tegart. International Metallurgical Reviews **17** (1), 1-24 (1972).
DOI: https://doi.org/10.1179/imtlr.1972.17.1.1

[18] K. Kołdys, Comparison of Microstructure and Properties of AZ61 Magnesium Alloy after Conventional Direct and KoBo Extrusion. MSc thesis, Silesian University of Technology, Gliwice (2021).

[19] S.A. Aliakbari Sani, G.R. Ebrahimi, A.R. Kiani Rashid, Hot deformation behavior and dynamic recrystallization kinetics of AZ61 and AZ61 + Sr magnesium alloys. J. Magnes. Alloys **4**, 104-114 (2016).
DOI: https://doi.org/10.1016/j.jma.2016.05.00118

[20] H. Mirzadeh, Constitutive analysis of Mg-Al-Zn magnesium alloys during hot deformation. Mech. Mater. **77**, 80-85 (2014).
DOI: https://doi.org/10.1016/j.mechmat.2014.07.004