Comparison of the effects of isothermal equal channel angular pressing and multi-directional forging on mechanical properties of AM60 magnesium alloy

M.A. Salevati a, F. Akbaripanah a,⁎, R. Mahmudi b, K.H. Fekete c,d, A. Heczel e, J. Gubicza e

a Department of Mechanical Engineering, Faculty of Engineering, Malayer University, Malayer, Iran
b School of Metallurgical and Materials Engineering, College of Engineering, University of Tehran, Tehran, Iran
c Department of Physics of Materials, Faculty of Mathematics and Physics, Charles University, Prague, Czech Republic
d Nuclear Physics Institute of the CAS, Rez, Czech Republic
e Department of Materials Physics, Eötvös Loránd University Budapest, P.O.B. 32, H-1518, Hungary

ARTICLE INFO

Keywords:
AM60 alloy
Equal channel angular pressing
Multi-directional forging
Microstructure
Mechanical properties

ABSTRACT

This study investigates the correlation between the microstructure and the mechanical strength of AM60 magnesium alloy processed by equal channel angular pressing (ECAP) and multi-directional forging (MDF) at a constant temperature of 220 °C. The maximum number of passes was six for both severe plastic deformation (SPD) techniques. The minimum achievable grain size was ~1.9 μm for ECAP while it was only ~2.7 μm for MDF. Despite the monotonous reduction of the grain size, the yield and the ultimate tensile strength values decreased for high equivalent strains which was attributed to the decrease of the dislocation density. The maximum achievable strength was higher for ECAP than that for MDF mainly due to the higher dislocation density. Both ECAP and MDF processing led to an improvement of ductility. Based on the strength results, it is evident that the ECAP process is more effective in improving the mechanical properties of AM60 alloy at 220 °C, compared to the MDF process.

1. Introduction

In recent years, ultrafine-grained (UFG) materials processed by severe plastic deformation (SPD) are in the focus of materials science. These materials exhibit high mechanical strength, therefore, they have a high potential for using as structural components in various practical applications [1]. The most frequently used SPD methods are equal channel angular pressing (ECAP), multi-directional forging (MDF), accumulated roll bonding (ARB) and high-pressure torsion (HPT) [2]. In these processes, the material is subjected to severe strains in several steps, leading to the reduction of the grain size to submicron or even nano-metric levels [3]. Since dimensional changes during the processing of materials may hinder their broad practical applications, the majority of SPD methods are designed in such a way that the sample dimensions remain practically unchanged during the process. UFG materials processed by SPD usually have equiaxed grains and a large fraction of high angle grain boundaries [4]. The presence of large quantities of high angle grain boundaries makes it easier to achieve the desired properties [5]. SPD of magnesium (Mg) alloys is often carried out at temperatures higher than 200 °C due to their low room-temperature ductility [6].

ECAP is the first SPD method which was introduced in 1981 [7,8]. The sample is mainly deformed by shear when crossing the junction of the two ECAP channels. Since the dimensions of the sample remain constant, it is possible to reuse the same sample to create severe strains. By rotating the sample in subsequent passes, it is also possible to apply different shear forces [9]. The final grain size obtained by ECAP depends on the deformation temperature, the route, the number of passes, the angle between the two channels (ψ), the angle describing the outer arc of curvature (φ) and the strain rate. The most homogenous structures are produced using route B C [10,11]. Former studies have shown that ECAP processing through route B C can lead to an enhancement of homogeneity of grain structure and a reduction of grain size [12–14], an increased surface hardness [6,12] and improvement of tensile and shear properties [6,12,14].

The microstructural refinement, obtained by SPD, has been found to be beneficial for increasing both ductility and strength of Mg alloys.
However, the specific texture formed by employing route B of ECAP also influences the mechanical properties of Mg alloys [15]. The tensile yield strength measured in the direction of the longitudinal axis of the billet was reduced after 2 ECAP passes even if the grain size decreased below 1 μm [15]. It was shown that after several ECAP passes, the normal of the basal planes inclined by ~50° from the ECAP direction due to texture development [16]. The formation of this texture component, attributed to the activation of the basal slip system during the ECAP processing [16], was reported in AZ61 [17], AZ31 [15,16] and AE21 Mg alloys [18]. However, the effect of c/a ratio on the different texture development was also reported [18,19]. Therefore, the softening effect of the texture developed during ECAP processing could be suppressed by an appropriate tailoring of the c/a ratio [18].

Among various SPD methods, MDF processing has gained increased popularity because it is capable of producing large parts and does not require complicated equipment [20]. The MDF process is based on repeated compressions along the different axes of the billet. For the MDF-processed materials, a decreased grain size [21], an increased hardness and strength [22,23] and an improved superplastic behavior [24] were reported. Studies on Mg alloys processed by MDF have shown that the grain size distribution at the primary stages of MDF process is inhomogeneous, thus, the microstructure contains fine grains between 1 and 2 μm and coarse grains in the order of tens of micrometers [25]. The microstructure becomes more homogeneous, containing equiaxed fine grains, with the increasing number of MDF passes. According to studies on AZ-type Mg alloys, both the yield and ultimate tensile stress values were improved compared to the extruded samples [26-29].

Despite the numerous studies on SPD-processed Mg alloys, a complex analysis of the difference between the mechanical properties of Mg alloys processed by different SPD techniques is missing from the literature. In this study, the microstructures and the mechanical behaviors of the technically important AM60 Mg alloy processed by ECAP and MDF are compared. Both SPD processes are performed at 220 °C due to the poor workability of AM60 alloy at room temperature. The microstructure and the tensile performance are studied by electron backscatter diffraction (EBSD) and uniaxial tension, respectively. The dislocation density was determined formerly by X-ray line profile analysis [30] and now the results are used for the explanation of the strength variation due to SPD. The different evolutions of the mechanical properties for ECAP and MDF processed materials are related to the difference in the grain size and the dislocation density.

2. Materials and methods

The studied material was an AM60 (Mg-6 wt% Al-0.35 wt% Mn) alloy, produced from high purity (>99.9%) Mg, Al, and Mn. The melting process was carried out in a graphite crucible in an electrical furnace at 750 °C using the Foseco Magrex 36 covering flux to protect melt against oxidation. The melt was then poured by tilting technique into a cylindrical steel die with a diameter of 44 mm which was preheated up to 150 °C. The as-cast billets were extruded into 13 mm × 13 mm rectangular bars with an extrusion ratio of 6.73 at 380 °C in order to achieve a homogeneous recrystallized microstructure before ECAP and MDF processes. Using wire cut machining, billets with dimensions of 13 mm × 13 mm × 100 mm and 13 mm × 13 mm × 20 mm were cut from these bars for ECAP and MDF, respectively.

The ECAP processing was carried out at a constant temperature of 220 °C and a speed of 10 mm/min, using a die with an internal angle of ϕ = 90° between the two ECAP channels and ψ = 20° for the outer curve of channel intersection. The samples were subjected to 2, 4 and 6 passes, and the billets were rotated by 90° in the same sense between the consecutive passes following route B. These conditions result in an equivalent strain of about one for each pass [31]. To reduce friction and prevent the formation of surface cracks, a MoS₂ spray was used as a lubricant. The ECAP die and the coordinate system attached to the as-processed samples are shown in Fig. 1. MDF was also carried out for 2, 4 and 6 passes at the same constant temperature of 220 °C. For MDF processing, samples were forged by repeated pressing after changing the loading direction by an angle of 90° and each pass yielded an equivalent strain of 0.5. A schematic in Fig. 1b shows the MDF die and the sequence of the consecutive passes of MDF-processing. The billets were covered with Teflon tape which acted as a lubricant for the reduction of friction forces between the billets and the die.

The microstructure of the extruded (initial) specimen and the SPD-processed samples was studied on the surface lying perpendicular to the longitudinal axis of the specimens. For the extruded and the ECAP-processed specimens, this axis was parallel to the extrusion direction and the pressing direction in the output channel of the last ECAP pass, respectively. The longitudinal axis of the ECAP-processed billet is denoted as X as shown in Fig. 1a. For MDF, the coordinate system attached to the samples is shown in Fig. 1b. Here, the longitudinal axis is also parallel to direction X at the end of the passes. For microstructure investigation, the sample surfaces were ground by SiC papers and subsequently polished by diamond paste with a particle size decreasing down to 0.25 μm. Prior to EBSD measurements, the surface of the samples was finally ion beam polished using a Leica EM RES102 system. The EBSD experiments were conducted in a scanning electron microscope (type: FEI Quanta) at a working distance of 13 mm with a step size of 0.1 μm and an acceleration voltage of 15 kV. The orientation maps obtained by EBSD were evaluated for the grain size using the OM software. The grains were considered as the regions in the EBSD images bounded by high-angle grain boundaries (HAGBs) with misorientations higher than 15°. The area-weighted average grain size was determined from the EBSD images for the studied samples.

The dislocation density in the samples was determined by X-ray line profile analysis (XLPA). The X-ray diffraction patterns were measured by a MultiMax-9 rotating anode diffractometer (manufacturer: Rigaku, Japan) using CuKα radiation (wavelength: 0.15406 nm). The diffraction patterns were evaluated by the Convolutional Multiple Whole Profile (CMWP) fitting procedure [32,33].

The crystallographic texture of the extruded specimen and the samples processed by ECAP and MDF was examined by X-ray diffraction pole figure analysis. The pole figures were measured on the plane lying perpendicular to the longitudinal axis of the specimen using a Smartlab X-ray diffractometer (manufacturer: Rigaku, Japan) with CuKα radiation (wavelength: λ = 0.15418 nm) and parallel-beam optics.

The uniaxial tensile testing was performed by an Instron 8516 mechanical testing machine at room temperature and a constant cross-head velocity of 1.6 × 10⁻² mm s⁻¹ which corresponded to an initial strain rate of 2 × 10⁻³ s⁻¹. The loading was parallel to the longitudinal axis of the specimens. The gauge length, the width and the thickness of the specimens were 8, 4 and 1 mm, respectively. At least three tensile specimens were tested for each condition, and the average values of the mechanical characteristics (such as yield strength) obtained from the different measurements will be reported in the following section.

3. Results and discussion

3.1. Microstructure development during ECAP and MDF

The EBSD images in Fig. 2 show the evolution of the microstructures of the AM60 alloy processed by ECAP and MDF up to 6 passes. The grain size distributions extracted from the EBSD images for the initial (extruded) sample and the specimens processed by ECAP and MDF are shown in Fig. 3. It was revealed that after 2 passes of ECAP and MDF small and large grains coexist in the microstructure. However, with increasing number of passes, the microstructure became more homogeneous. The area-weighted mean grain sizes were determined from the distributions and are listed in Table 1. As can be seen, the average grain size of the extruded sample was about 16 μm which was reduced gradually to ~1.9 and ~2.7 μm after six passes of ECAP and MDF processes, respectively.
The co-existence of small and large grains at the beginning of ECAP and MDF deformation of Mg alloys is in agreement with the results obtained formerly by Figueiredo et al. [34]. In their study, it was found that the formation of bimodal microstructures during SPD depends on the grain size of the initial material. If the average grain size before SPD processing is higher than a critical grain size, the grain refinement started inhomogeneously with the formation of fine grains at the grain boundaries. Thus, finer and coarser grains coexisted in the...
The critical grain size for the development of such a bimodal size distribution was found to be between 3 and 9 μm for AZ31 alloy processed by ECAP at room temperature. If we consider this value as the critical grain size for the SPD-processed AM60 alloy too, the development of the bimodal grain size distributions in the initial stage of ECAP and MDF processing can be explained by the relatively large grain size of the initial material (~16 μm). It should be noted that dynamic recrystallization (DRX) has an important role in the initiation of grain refinement at the grain boundaries and its spreading into the grain interiors during SPD of pure Mg and its alloys [34,35].

For the comparison of the ECAP and MDF processes, the evolution of the microstructural parameters is investigated as a function of the equivalent strain in this study. Thus, the grain size of the ECAP- and MDF-processed AM60 alloy samples is plotted as a function of the equivalent strain in Fig. 4. For both techniques, the grain size decreased with increasing strain which is in accordance with the results of former studies performed on other Mg alloys [36–38]. It is revealed that the grain size versus the equivalent strain data for ECAP and MDF exhibit a common trend and the minimum grain size measured for MDF is close to the values obtained for ECAP at similar strains. The smaller minimum grain size for ECAP processing (~1.9 μm) compared to MDF (~2.7 μm) can be attributed to the higher equivalent strain after 6 passes.

The dislocation density values determined by XLPA are listed in Table 1. For the extruded initial sample, the dislocation density cannot be determined since the measured diffraction peak width was practically the same as the instrumental broadening which indicated that in this sample the dislocation density was under the detection limit of the present XLPA method (<10¹³ m⁻²). The evolution of the dislocation density versus the equivalent strain is plotted in Fig. 5. Unlike the grain size evolution, the dislocation density showed different trends for ECAP and MDF. Namely, although a maximum of the dislocation density was
observed for both techniques, this maximum was higher for ECAP (~5.6 compared to MDF 

can yield a higher maximum dislocation density in AM60 alloy as 

to SPD-processing as it is revealed by the 100 and 002 X-ray diffraction 

decreasing grain size was caused by the change of the crystallographic texture. Similar results were reported for MDF-processed samples [45, 46]. For the present ECAP and MDF samples, the texture also varied due to SPD-processing as it is revealed by the 100 and 002 X-ray diffraction pole figures shown in Fig. 9. In the main texture component of the extruded material, the crystallographic direction <100> is parallel to the extrusion axis and the normal vector of the basal plane is almost perpendicular to this axis. Even after the first two passes of ECAP and MDF, considerably different texture can be observed (see Fig. 9). Similar SPD-induced changes in the texture was observed for other Mg alloys in the literature (e.g., for ECAP-processed AX41 alloy see Ref. [47]). The evolution of the texture in SPD-processed Mg alloys including AM60 has already been investigated and discussed in former papers [45–47]. The evolution of the texture in SPD-processed Mg alloys including AM60 has already been investigated and discussed in former papers [45–47]. Therefore, in this study only its effect on the yield strength is discussed in the next paragraphs. It is noted that in addition to the change of the texture, a significant reduction of the dislocation density also occurred at high equivalent strains for both ECAP and MDF which may also explain the observed decrease of the yield strength. Therefore, both effects must be considered in the study of the reasons of softening caused by ECAP and MDF at high equivalent strains. The combined effect of grain size, dislocation density and texture on yield strength can be taken into account by the sum of Hall-Petch and Taylor terms, and applying a correction factor for texture:

3.2. Mechanical properties obtained by tensile testing

Engineering stress-strain diagrams obtained by tensile testing at room temperature for the ECAP- and MDF-processed materials are shown in Fig. 6. The loading direction was parallel to the longitudinal axis of the specimens (denoted as axis X in Fig. 1), i.e., perpendicular to the surfaces shown in the EBSD images of Fig. 2. The diagrams in Fig. 6 reveal that both SPD processes improved the ductility of the extruded material. In addition, both the yield strength and the ultimate tensile strength values increased due to ECAP and MDF. The evolution of the yield strength and the ultimate tensile strength as a function of the equivalent strain are shown in Fig. 7a and b, respectively. There is a significant difference between the strength versus equivalent strain evolutions for ECAP and MDF which is not in accordance with the trend observed for the grain size (see Fig. 4). Therefore, this observation suggests that in addition to the grain size effect other factors such as the dislocation density also influence the strength evolution. Indeed, the strength values reached their maxima at the equivalent strains of ~2 and ~1 for ECAP and MDF, respectively, similar to the evolution of the dislocation density (see Fig. 5). In addition, the maximum values for both the yield strength and the ultimate tensile strength were higher for ECAP than for MDF.

In SPD-processed polycrystalline materials, the increase of the yield strength is often related solely to the decrease of the grain size using the well-known Hall-Petch equation in which the increase of strength varies linearly with the inverse square root of the grain size [43]. Fig. 8 shows the Hall-Petch plots for the ECAP- and MDF-processed samples. It can be seen that the data do not obey the Hall-Petch relationship since (i) two different curves were obtained for ECAP and MDF and (ii) for high equivalent strains (≥2) a softening was observed with decreasing the grain size for both ECAP and MDF. The latter trend resembles the inverse Hall-Petch behavior when the main deformation mechanism changes from dislocation glide to grain boundary sliding. However, except for very pure materials this transient occurs only when the grain size is in the nanocrystalline regime while in the present case the grain size is about ~2 μm. Therefore, the softening effect of grain boundary sliding can be ruled out. In a former study [44], Masoudpanah and Mahmudi also reported a limited validity of the Hall-Petch relationship for ECAP-processed AZ31 magnesium alloy. In that case, the softening with decreasing grain size was caused by the change of the crystallographic texture. Similar results were reported for MDF-processed samples [45, 46]. For the present ECAP and MDF samples, the texture also varied due to SPD-processing as it is revealed by the 100 and 002 X-ray diffraction pole figures shown in Fig. 9. In the main texture component of the extruded material, the crystallographic direction <100> is parallel to the extrusion axis and the normal vector of the basal plane is almost perpendicular to this axis. Even after the first two passes of ECAP and MDF, considerably different texture can be observed (see Fig. 9). Similar SPD-induced changes in the texture was observed for other Mg alloys in the literature (e.g., for ECAP-processed AX41 alloy see Ref. [47]). The evolution of the texture in SPD-processed Mg alloys including AM60 has already been investigated and discussed in former papers [45–47] therefore in this study only its effect on the yield strength is discussed in the next paragraphs. It is noted that in addition to the change of the texture, a significant reduction of the dislocation density also occurred at high equivalent strains for both ECAP and MDF which may also explain the observed decrease of the yield strength. Therefore, both effects must be considered in the study of the reasons of softening caused by ECAP and MDF at high equivalent strains.

The combined effect of grain size, dislocation density and texture on yield strength can be taken into account by the sum of Hall-Petch and Taylor terms, and applying a correction factor for texture: 

\[
\sigma = \sigma_0 + k_d \cdot \frac{1}{\sqrt{d}} + k_t \cdot \frac{1}{\sqrt{d}} + k_\text{corr} \cdot \frac{1}{\sqrt{d}}
\]

where \(\sigma_0\) is the yield strength at the initial grain size, \(k_d\) and \(k_t\) are the Hall-Petch constants for dislocation density and texture, respectively, \(d\) is the grain size, and \(k_\text{corr}\) is the correction factor for texture. This equation takes into account the combined effect of grain size, dislocation density, and texture on yield strength, allowing for a more comprehensive understanding of the deformation behavior of SPD-processed materials.
\[ \sigma_c = \sigma_0 + k d^{-1/2} + \alpha M_R G b \langle \rho \rangle^{1/2} \]

where \( \sigma_c \) is the calculated yield stress, \( \sigma_0 \) is the friction stress, \( d \) is the average grain size, \( k \) is Hall-Petch slope, \( \alpha \) is a parameter depending on the existing dislocation slip systems, \( G \) is the shear modulus, \( b \) is the average Burgers vector of dislocations and \( \rho \) is the dislocation density. For a texture-free AM60 alloy, the following values can be used in eq. (1): \( G = 17 \) GPa, \( \sigma_0 = 30 \) MPa and \( k = 159 \) MPa \( \mu m^{1/2} \) \[48,49\]. In SPD-processed AM60 alloy samples, most of the dislocations have \(<a>\) type Burgers vector \[30\], therefore \( b \) is taken as 0.32 nm (corresponding to lattice parameter \( a \)). The value of \( \alpha \) for Mg alloys varies between 0.2 and 1, depending on the types of the existing dislocation slip systems \[49,50\]. As the population of the different slip systems is not investigated, an average value of 0.6 was used for \( \alpha \). The influence of texture on the yield strength was taken into account by the factor \[M_T/M_R\] where \( M_R \) is the Taylor factor for random crystallographic orientation and \( M_T \) is the Taylor factor calculated on the basis of the texture in the studied specimens. The value of \( M_R \) is 4.5 \[49\] while \( M_T \) can be estimated as the reciprocal of the Schmid factor of the major slip systems \[50\]. This calculation is described in the next paragraph.

In Mg alloys, usually the basal dislocation slip system gives the main contribution to plasticity \[51\], therefore for simplicity only the occurrence of this deformation mode was considered in the calculation of \( M_T \). The Schmid factor of basal slip was determined using the formula \( m = \cos \beta \cos \gamma \) where \( \beta \) and \( \gamma \) are the angles between the surface normal (axis
X) and the directions corresponding to the high intensity spots in the pole Figs. 100 and 002, respectively. The former and the latter angles correspond to the angles between the tensile load and the dislocation Burgers vector, and the tensile load and the normal vector of the slip plane, respectively. If a pole figure contained more than one spot, the angles of the different high intensity spots were averaged and this average value was used for the calculation of $m$. This procedure resulted in a Schmid factor value of 0.27 for the extruded sample. The Schmid factor increased to 0.40 ± 0.03 after two passes of MDF and ECAP (corresponding to the equivalent strains of ~1 and ~2, respectively), and this value remained unchanged within the error when the equivalent strain increased during SPD. It is noted that although the texture differs considerably in the MDF- and ECAP-processed samples, only slight differences between the Schmid factors were observed for these specimens. The lower the Schmid factor, the more difficult the dislocation slip, i.e., the plastic deformation requires higher stress. Thus, the texture in the extruded sample has a higher strengthening effect than that in the SPD-processed specimens. The Taylor factor $M_T$ was calculated as the reciprocal of the Schmid factor and substituted into eq. (1) for the calculation of the yield strength.

Fig. 10 shows the measured yield strength versus the values calculated from eq. (1). The relatively good agreement between the measured and calculated yield strength values suggests that eq. (1) gives a good approximation of the yield strength despite the applied approximations (e.g., linear additivity of Hall-Petch and Taylor terms). The differences between the calculated and the measured strength values observed for some samples can be explained by the simplified determination of $M_T$ since only the main basal dislocation slip was considered while most probably other slip systems also contributed to plasticity during tensile testing. Nevertheless, the most important conclusion drawn from Fig. 10 is that the inclusion of the strengthening effect of dislocations can solve the anomaly observed in the Hall-Petch behavior in Fig. 8. This means that the softening observed at the equivalent strains higher than ~1 and ~2 for MDF and ECAP, respectively, can be attributed solely to the decrease of the dislocation density since the Schmid factor for the SPD-processed samples did not change considerably in this strain regime. It should be noted that although there is a texture softening at the strains of ~1 and ~2 for MDF and ECAP, respectively, this effect was
overwhelmed by the strengthening effect of the increased dislocation density, resulting in a hardening as compared to the extruded state (see Fig. 7a).

The present study demonstrated the importance of the Taylor term in the description of the evolution of the yield strength for SPD-processed AM60 alloy. This is shown in Fig. 11 where the fraction of the Taylor term in the yield strength is plotted as a function of the equivalent strain. In the calculation of the Taylor term and the total yield strength, eq. (1) was used. For the SPD-processed samples, the contribution of the Taylor term to the strengthening varies between ~40 and ~80% which proves its significance in the evolution of the yield strength. For MDF, the contribution of the Taylor term to the strengthening saturated at a lower strain with a smaller value (about 65%) as compared to ECAP (~76%). These differences can be attributed to the different loading modes for the two SPD methods which is manifested e.g., in the different levels of non-monotony (see section 3.1).

4. Conclusions

Experiments were conducted to study the evolution of the microstructure and the mechanical behavior of an AM60 magnesium alloy processed by ECAP and MDF at 220 °C. The variation of the tensile yield strength was correlated to the change of the microstructure during SPD. The following results were obtained:

1. The microstructure was greatly refined due to SPD processing and at high equivalent strains ECAP and MDF processes resulted in a decrease of the average grain size from ~16 μm to ~1.9 and ~2.7 μm, respectively. The grain size versus equivalent strain data for ECAP and MDF follow the same trend and the smaller minimum grain size for ECAP can be attributed to the higher equivalent strain achieved.

2. In the beginning of SPD processing, the grain refinement was accompanied by strengthening. On the other hand, above the equivalent strains of about two softening was observed despite the grain refinement which indicated that the Hall-Petch formula solely is not enough for the depiction of the relationship between the strength and the microstructure. It was shown that an additional Taylor term in the description of the strength can explain the softening for high equivalent strains since the dislocation density decreased in this deformation regime.

3. It was found that the maximum strength was higher for ECAP compared to MDF, mainly due to the larger dislocation density. This difference can be explained by the higher equivalent strain, the larger strain rate and the higher level of non-monotony of ECAP processing. The tensile ductility of the AM60 alloy was improved as a result of SPD processing for both techniques.

Authors contributions section

M.A. Salevati: Methodology, Data processing, Original draft preparation, Investigation.
F. Akbaripanah: Conceptualization, Supervision, Validation, Writing- Reviewing and Editing.
R. Mahmudi: Conceptualization, Methodology, Validation, Reviewing and Editing.
K. H. Fekete: Methodology, Data processing.
A. Heczel: Methodology, Data processing.
J. Gubicza: Conceptualization, Methodology, Validation, Reviewing and Editing.

Data availability

The raw/processed data required to reproduce these findings cannot be shared at this time due to technical or time limitations.

Declaration of competing interest

None.

Acknowledgement

The authors thank the Iran National Science Foundation (INSF) for financial support of this work under Grant no. 94017499. KHF acknowledges the support of Operational Programme Research, Development and Education, The Ministry of Education, Youth and Sports (OP RDE, MEYS) [CZ.02.1.01/0.0/0.0/16_013/0001794]. JG thanks for the financial support of the Ministry of Human Capacities of Hungary within the ELTE University Excellence program (1783-3/2018/FEKUTSRAT).

References