International Journal of Modern Manufacturing Technologies
ISSN 2067–3604, Vol. XVI, No. 1 / 2024
https://doi.org/ 10.54684/ijmmt.2024.16.1.7

EFFECTS OF PROCESSING AL-MG ALLOY BY SEVERE PLASTIC DEFORMATION: TENSILE PROPERTIES AT HIGH TEMPERATURES

Radu-Ioachim Comăneci[1]**, Vasile Damaschin**[2]**, Daniela-Lucia Chicet**[1]

[1]"Gheorghe Asachi" Technical University of Iasi-Romania, Faculty of Material Science and Engineering, D. Mangeron 41, 700050, Iasi, Romania
[2]Continental Automotive Romania SRL, Bd. Poitiers 6, 700671, Iasi, Romania

Corresponding author: Radu Ioachim Comăneci, radu-ioachim.comaneci@academic.tuiasi.ro

Abstract: Aluminum and wrought non age-hardenable such as Al-Mg alloys became interesting alternatives for various structural applications in spite of generally moderate strength, but relatively good formability and good corrosion resistance. Increasing overall strength while preserving or even improving ductility in special conditions without any any change in chemical composition that oppositely could alter other features of the material - such as weldability, becomes an objective worthy of research. A suitable way to increase the potential of Al-Mg alloys is the raising up the mechanical properties by structural refinement. Ultrafine grain size provides enhanced mechanical and/or physical properties such as strength and very good ductility – close to superplasticity at slightly higher strain rate and relatively lower temperatures – and better corrosion resistance. Well-known as one of the most encouraging and efficacious structure refining method amid other severe plastic deformation (SPD) techniques, equal channel angular pressing (ECAP) has been deeply investigated thanks to dramatic improvements in structure and therefore properties of bulk ultrafine grained/nanostructured materials. The aim of this study is to evaluate by tensile testing at higher temperatures the mechanical properties of an Al-3.4%Mg alloy previously processed by ECAP up to 8 passes, as a candidate for replacing AA5154 which contains different amounts of chromium. The tensile tests conducted at different temperatures using a computer-controlled testing machine with different strain rates showed in terms of engineering stress vs. engineering strain evolution that the ECAPed Al-3.4%Mg alloy have the potential to be used in technological processes at high temperatures, opening opportunities for industrial applications requiring high ductility.
Key words: severe plastic deformation, aluminum-magnesium, tensile, ductility.

1. INTRODUCTION

Widely used in the aerospace, automotive, electronics, solar and wind energy and electrotechnical industries, due to the advantageous strength-to-weight ratio and notable electrical and thermal conductivity or corrosion resistance, aluminum alloys imposed themselves as valuable structural materials [1]. With moderate strength, but relatively good formability and excellent corrosion resistance in fresh or salt natural waters or chemical media, Al-Mg alloys have gained increased interests in building construction, refrigeration technology, pressure vessels, chemical tankers, ships, automotive and aviation as pipes, rods, wires and free-form or drop-forged parts [2].

Containing Mg as main alloy element and small additive of manganese and/or chromium, Al-Mg alloys standardized as 5xxx series, are wrought non age-hardenable aluminum alloys whose properties cannot be improved by heat treatments but only by alloying and/or structural changes [3]. Alloying elements could act adversely by improving some properties but negatively affecting other properties. For instance, some alloying elements can alter some technological properties such as formability and/or weldability. Moreover, the presence of precipitates can change the subsequent behavior at high temperatures and pressures. The increase of precipitates leads to a decrease in creep or tensile strength.

Aluminum alloy AA5154 which contains on average 3.5% Mg and 0.25% Cr is commonly used in welded structures such as pressure vessels and tubes. Complex tube shapes with thin walls made from AA5154 are manufactured by unconventional methods such as Hot Gas Tube Hydroforming or Steam Hydroforming [4, 5] which involves higher plastic strain near too superplasticity to ensure a uniform thickness of the tubes. The effect of temperature and pressure/strain rate on thickness distribution of the final product were investigated. Chromium has a slow diffusion rate which doesn't support high strain at high temperatures and forms fine dispersed phases which lead to creep issues. Consequently, there is a general interest in replacing or reducing the amount of alloying elements such as chromium through appropriate structural changes as effects of processing processes.

An option that does not include additions of alloying elements or heat treatments is the grain refinement by severe plastic deformation (SPD) which has proved as a suitable top-down method for grain refinement in bulk metals and alloys, down to submicron or even nanometric size. Among the benefits of grain refinement is increasing ductility at high temperatures. At these grain sizes, bulk deformation mechanisms occurring within each grain (i.e. dislocation creep) become secondary to the process of grain boundary sliding, involving the relative motion and reorientation of grains with respect to one another. In fine/ultrafine-grained materials the deformation mechanism at high temperature becomes grain boundary sliding which gradually replaces dislocation creep [6]. But for an effective accommodation of grain boundaries, diffusion is necessary and so, the very low strain rate is justified. At the same time, the very low strain rate delays the deformation itself prolonging the process. To shorten it, a way to increase the diffusion without increasing the temperature - which would lead to the growth of grains - must be found. The most convenient way is increasing boundaries in length by grain refinement down to ultrafine/submicronic scale. Ultrafine grain (UFG) size shows enhanced mechanical properties such as strength and ductility [7], superplasticity [8] (even at relatively low temperatures and high strain rates [9]), physical properties such as electric conductivity [10], and better corrosion resistance [11].

1.1 . Equal Channel Angular Pressing

Many procedures have been dedicated to grain refinement. Well-known as the most promising and effective structure refining method among other SPD techniques such as High Pressure Torsion [12], Multiaxial Forging [13], Cycling Extrusion Compression [14], Accumulative Roll Bonding [15], Equal Channel Angular Pressing (ECAP) has been intensively investigated due to spectacular improvements in structure and therefore in properties for bulk ultrafine grained/nanostructured materials [16 – 18].

ECAP is a discontinuous process capable of imparting high strain in materials through simple shearing. The sample is extruded through a die containing two identical cross-sectional channels (Figure 1). The two equal cross-sectional rectangular channels make between them a certain angle ϕ usually in the range of 90 - 150º. In the extrusion process, the billet crosses the area corresponding to the bisecting plane of the two channels being subjected to simple shearing [5]. The microstructure of the ECAPed material is strongly influenced by the die geometry and extrusion settings that govern the material behavior during shear deformation.

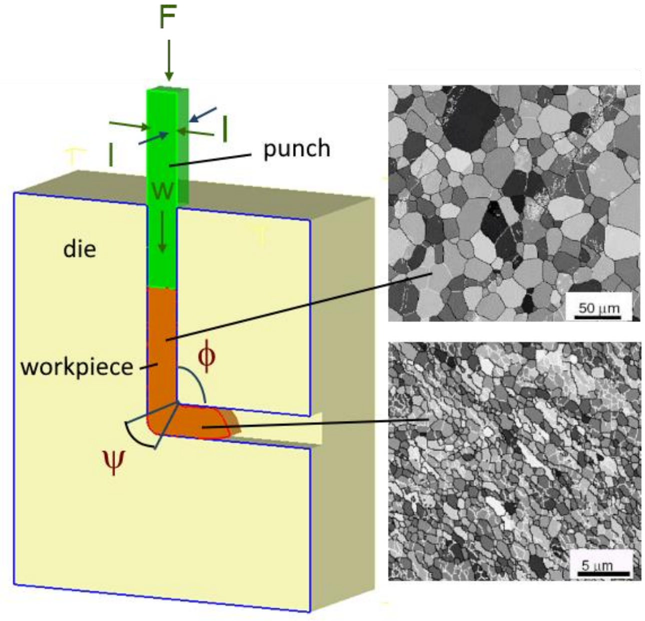

Fig.1. Schematic representation of ECAP and typical structural changes

Until the material reaches the critical zone near the intersection plane of the die’s channel, the billet moves in the inlet (usually the vertical one) channel like a rigid body without any plastic deformation. While crossing the area around the bisector plane of the two channels that defines the plastic deformation zone, the material undergoes simple shearing. Because the cross-sectional dimensions of the two channels are identical, the workpiece moves inside them with the same speed. But at the contact with the bisector plane, velocity suddenly changes direction which gives rise to a velocity discontinuity: when a grain already elongated in the direction of deformation crosses a velocity discontinuity surface along which tangential stress exceeds the strength in pure shear, the strength of the grain will be overcome, and the fragmentation starts [19]. To become more effective, grain refinement can be increased by rotating billet around its longitudinal axis. Four processing routes were initiated [20, 21]: route A - without rotation, route B_A and B_C - with alternating ±90° and same sense 90° rotations respectively, and route C

- with 180° rotations (Figure 2). ECAP can be easily resumed by reinserting the billet previously ECAPed and having obviously identical cross-sectional geometry and dimensions. The billet removal from the outlet channel (horizontal or inclined, depending on the angle ϕ) implies a new ECAP pass in which a new billet is inserted into the vertical channel, pushing out the previous deformed sample that can be thus reinserted for process resuming.

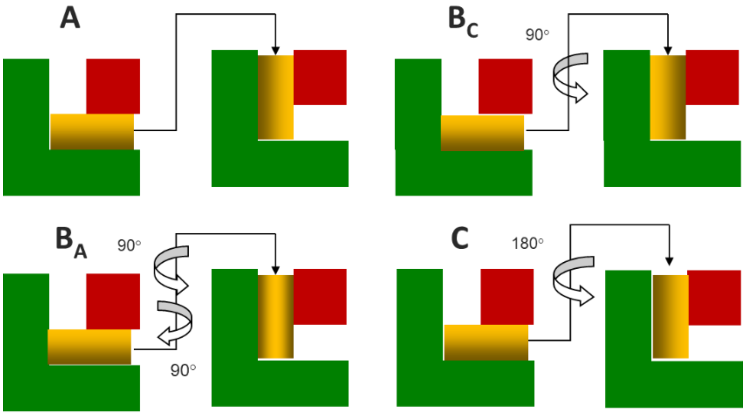

Fig. 2. Resuming ECAP and processing routes (A, B_A, B_C, C)

The aim of this work is to achieve uncommon strain for an unalloyed AA5154 Al-Mg alloy (i.e. without Cr) at high temperatures by stimulating specific conditions through grain refinement obtained by severe plastic deformation. Results show in terms of engineering stress vs. engineering strain evolution that the ECAPed Al-Mg alloys have the potential to become suitable candidates for specific manufacturing processes at high temperatures requiring high ductility.

2. MATERIALS AND METHODS

2.1. Experimental Al-3.4%Mg alloy

In this work, an experimental Al-Mg alloy (3.4% wt. Mg) whose chemical composition is shown in Table 1, containing a majoritar solid solution of Al(Mg) and an intermetallic phase $Al_{12}Mg_{17}$ (Figure 3) was involved.

Table 1. Chemical composition of designated Al-Mg alloy

Chemical composition, % wt.							
Mg	Si	Fe	Mn	Cr	Ni	Pb	Al
3.40	0.09	0.10	0.015	0.001	0.09	0.09	balance

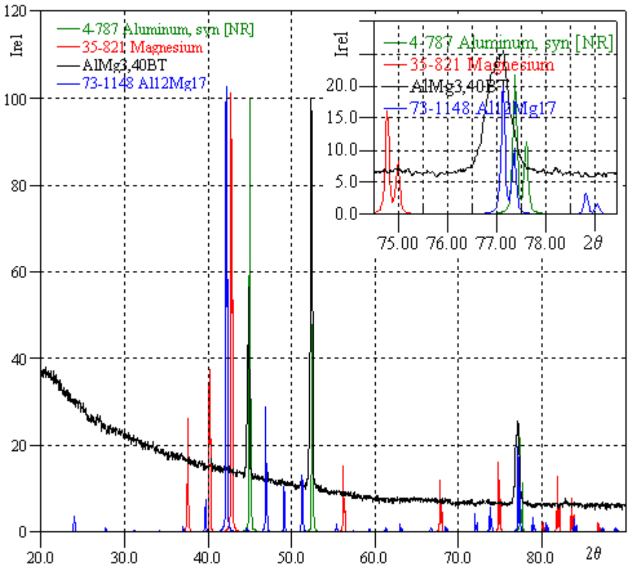

Fig. 3. X-ray Difraction of Al-3.4%Mg alloy

The alloy was cast in billets with dimensions of 24 x 24 x 180 mm subsequently homogenizated at 773 K for 24 h and then upset at 673 K down to cross-sectional dimensions of 18 x 18 mm. Billets with dimensions of 10 × 10 × 60 mm were machined and then annealed at 523 K for 3 h to discharge any effects of previous metal-working processes and gain suitable ductility. After this thermomechanical treatment grain size decreases from aproximately 102 μm to 24 μm.

2.2. Equal Channel Angular Pressing

ECAP was performed at ambient temperature with a speed of 10 $mm \cdot s^{-1}$, using a die consisting in two half-dies with 2 orthogonal channels and sharp inner angles of $\phi = 90°$. The two channels are outer interconnected by a radius of 2 mm which corresponds to a ψ angle of approximately 12° (see Figure 1). The die has a compressive reinforcement to absorb the elastic deformations during extrusion (Figure 4).

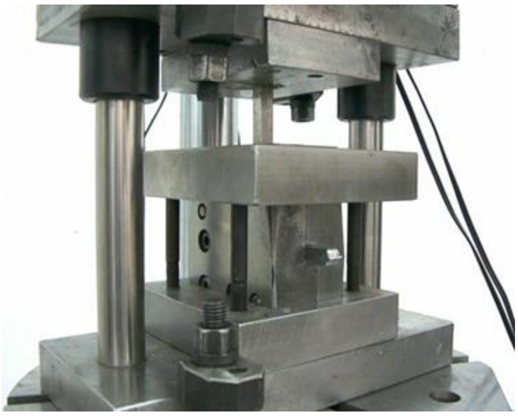

Fig. 4. ECAP die with the compressive reinforcement

Zinc stearate was used as a lubricant to reduce friction at the metal–tool interface. The material was extruded N = 8 passes route B_C through the die using a hydraulic press with a nominal load of 750 kN. Extruded specimens and the specific morphology are revealed in Figure 5. According to Iwahashi et al. [22] the accumulated effective strain and strain rate are depending on die geometry (ϕ and ψ):

$$\bar{\varepsilon}_N = \frac{N}{\sqrt{3}}\left[2ctg\left(\frac{\phi}{2}+\frac{\psi}{2}\right)+\psi cosec\left(\frac{\phi}{2}+\frac{\psi}{2}\right)\right] \tag{1}$$

$$\dot{\epsilon} = \frac{1}{\sqrt{3}}\left[2ctg\left(\frac{\phi}{2}+\frac{\psi}{2}\right)+\psi cosec\left(\frac{\phi}{2}+\frac{\psi}{2}\right)\right]\frac{l\sqrt{2}}{w\psi} \tag{2}$$

with terms revealed in Figure 1. For 8 passes, the effective strain was approx. 8.7 and strain rate (which is not dependent on number of passes) was 6.52 s^{-1}.

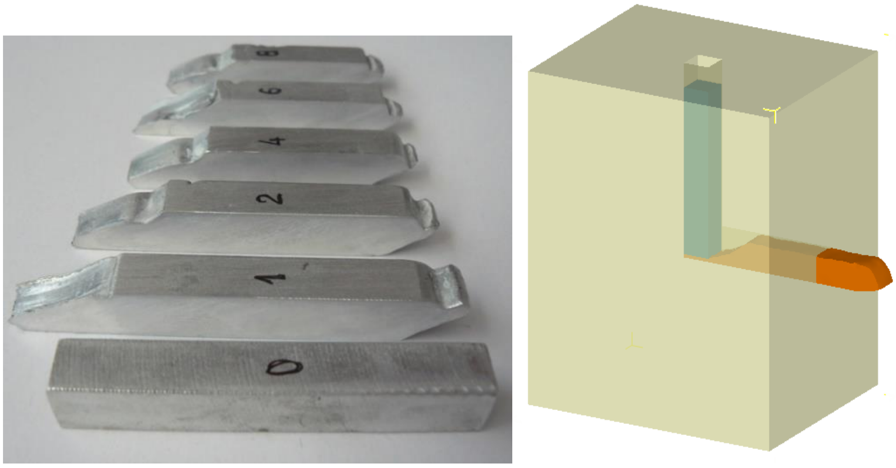

Fig. 5. Extruded specimens - 1, 2, 4, 6, 8 passes and schematic explanation of specific morphology

The samples get shorter with the increase in the accumulated effective strain because when resuming the process by re-introducing the previously deformed sample, its ends must be removed.

2.3. Tensile tests

To evaluate mechanical properties at high temperatures (tensile strength R_m and elongation at fracture A_t) of the Al-Mg alloy previously ECAPed, tensile tests were carried out according to ISO 6892-2: 2018. Test pieces with rectangular cross-section of 1.25 x 2.5 mm and gauge length of 7 mm were sampled from the extruded specimens by electro-discharge machining. The tensile tests were conducted at 483 K and 523 K respectively. The two testing temperatures were so chosen that the first value is at the lower limit of the solid solution (α) domain (for the nominal chemical composition of 3.4% Mg) and the second at the start of recrystalization range [23]. Tensile testing was performed using an Instron 3382 computer-controlled testing machine with the constant strain rates of 10^{-4} and 10^{-5} s^{-1}. A dedicated mounting device was used to fix the specimens between the grips, Figure 6.

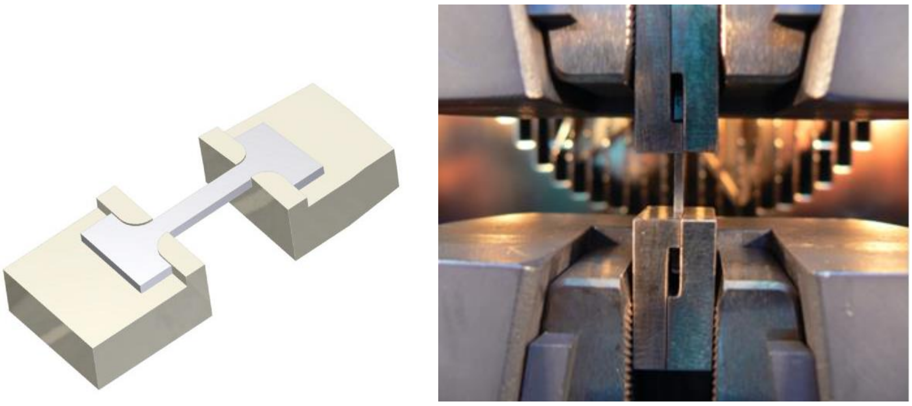
a) b)

Fig. 6. Schematic mounting device (a) and specimen during testing (b)

3. RESULTS AND DISCUSSION

Figures 7 and 8 show the engineering stress vs. engineering strain of Al-3.4%Mg alloy tensile tested at 483 and 523 K with designated strain rates of 10^{-3} and 10^{-4} s^{-1}.

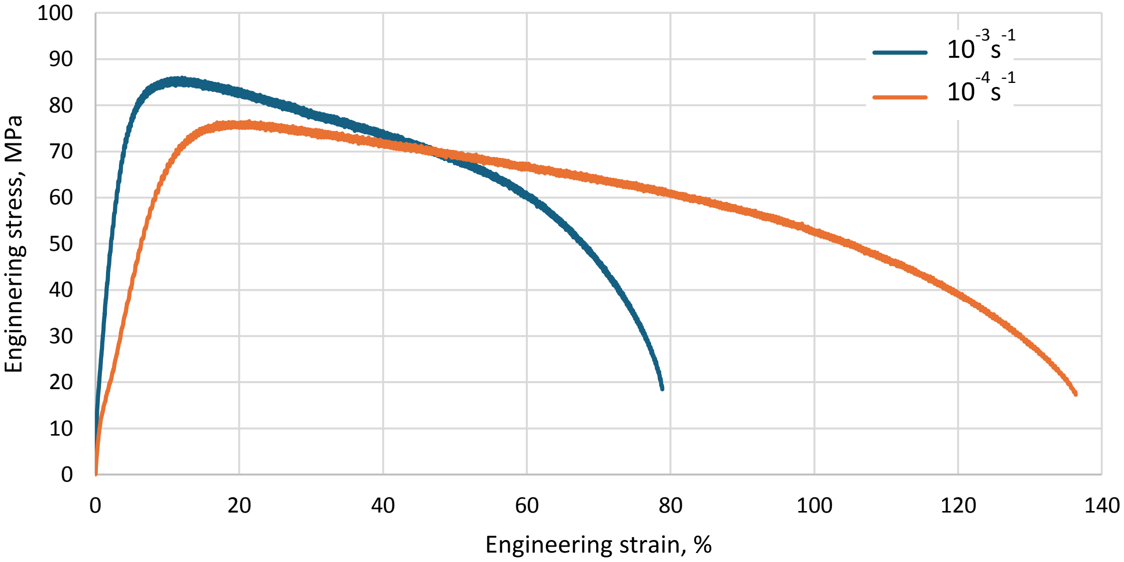

Fig. 7. Engineering stress vs. engineering strain (at 483 K) for Al-3.4%Mg 8 passes ECAPed

Testing begins with an extensive increase in tensile stress – especially for strain rate of 10^{-3} s^{-1} and 483 K – fully explainable by the increased yield stress given by grain refinement, according to Hall-Petch relation [24].

When the strain rate decreases at 10^{-4} s^{-1} this tendency fades, the work hardening rate and strength decrease visibly which denotes that at lower temperature, in the absence of a significant caloric intake, time has a dominant position ruling the diffusion during hot deformation.

Not the same situation is recorded for the tensile test at 523 K when the evolution of the work hardening rate for the two designated strain rates is almost identical in the first part of the stage to the ultimate strength. After that the work hardening rate naturally slowly decreases towards the ultimate stress. The maximum ductility expressed as tensile strain was 191% for a strain rate of 10^{-4} s^{-1} at 523 K. These promising results can be achieved only for lower strain rate.

As could be observed, no steady-state flow range was noticed, not even at 523 K. That because, as can be seen from the shape of the deformed samples, there is not enough strain hardening to sustain a long uniform straining as occurs in the case of superplastic alloys. So, the strain hardening and strain hardening rate are capital features for a stable plastic deformation.

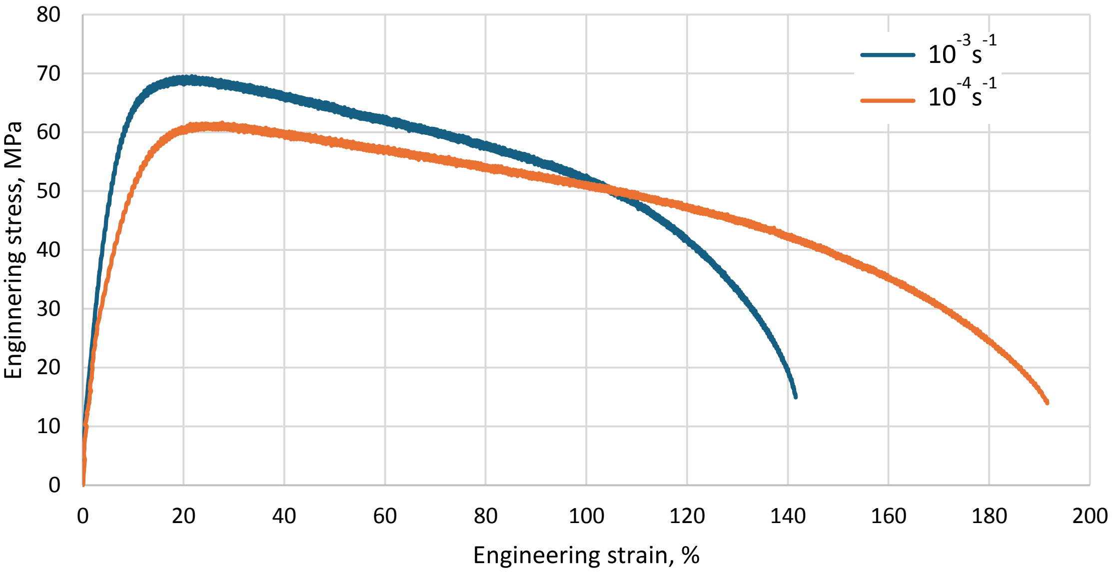

Fig. 8. Engineering stress vs. engineering strain (at 523 K) for Al-3.4%Mg 8 passes ECAPed

4. CONCLUSIONS

As a candidate for replacing AA5154, an Al-3.4%Mg alloy was processed by severe plastic deformation in order to achieve fine grain that contributes to the improvement of the conditions that lead to the increase of hot ductility. The material subjected to 8 passes ECAP at room temperature was then tensile tested at 483 K (the lower limit of the solid solution (α) domain) and 523 K (the start of recrystalization range) respectively, with two different strain rates of 10^{-3} and 10^{-4} s^{-1} using a computer-controlled testing machine which meet the requirements of the standard ISO 6892-2: 2018. The results in terms of engineering stress vs. engineering strain evolution showed maximum ductility at the lowest strain rate of 10^{-4} s^{-1} for the two designated temperatures. This shows that the material is capable to develop remarcable ductility when a proper processing like severe plastic deformation which creates suitable conditions for hot plastic deformation is applied.

Therefore, the Al-3.4%Mg alloy gets the potential to be used in specific technological processes such as tube hydroforming at high temperatures, opening opportunities for industrial applications requiring high ductility.

Funding: This paper has received no external funding.
Conflicts of Interest: There is no conflict of interest.

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Received: March 15th, 2024 / Accepted: June 15th, 2024 / Paper available online: June 20, 2024 © International Journal of Modern Manufacturing Technologies.