

Mechanical Evaluation of 6060 Aluminum Alloy under Elevated Extrusion Ram Speed Using Liquid Nitrogen Die Cooling

E. Giarmas^{1,2,a}, E. Tzintzimis^{1,b}, K. Tsongas^{3,c}, D. Tzetzis^{1,d}

¹Digital Manufacturing and Materials Characterisation Laboratory, International Hellenic University, School of Science and Technology 14th km Thessaloniki-Moudania, 57001 Thermi, Greece

²Alumil S.A., Production Division, 611 00 Kilkis, Greece

³Advanced Materials and Manufacturing Technologies Laboratory, Department of Industrial Engineering and Management, International Hellenic University, 57400, Thessaloniki, Greece;

^av.giarmas@alumil.com, ^bm.tzintzimis@ihu.edu.gr, ^ck.tsongas@ihu.gr,

*Correspondence: ^dd.tzetzis@ihu.edu.gr

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Abstract. This study investigates the influence of increased extrusion ram speed, achieved through die cooling with liquid nitrogen, on the mechanical behaviour of 6060 aluminum alloy profiles for two ageing temperatures of 160 °C and 180 °C. Mechanical properties were evaluated through tensile testing and nanoindentation, with the latter also used to examine the alloy's creep response. The findings show that although higher ram speed has only a minor effect on Ultimate Tensile Strength (UTS) and Yield Tensile Strength (YTS), it leads to a notable improvement in elongation. In addition, the results demonstrate a clear effect of ram speed on creep displacement, as the dislocations generated at higher deformation rates appear to enhance the material's resistance to creep for both the selected temperatures.

1. Introduction

Aluminum profiles are widely employed as lightweight structural components across numerous industries owing to their low density, excellent recyclability, high specific strength, and superior corrosion resistance [1–3]. Among these materials, the 6xxx series aluminum alloys constitute the most extensively used extruded products worldwide [4]. These commercial alloys typically contain Mg, Si, Fe, and Cu as principal alloying elements, with Mg and Si playing key roles in strengthening through the precipitation of intermetallic phases during appropriate heat-treatment processes [5].

Given the broad application of aluminum extrusions, extensive research has been dedicated to evaluating their mechanical behavior. Zang et al. [6] examined the precipitation characteristics of 6xxx alloys aluminum alloys with elevated Mg/Si ratios and increased Cu content under various aging conditions, employing Vickers hardness tests, tensile characterization, differential scanning calorimetry (DSC), and transmission electron microscopy (TEM). Dariusz et al. [7] proposed a method to simulate welding conditions within extrusion die welding chambers for 6xxx alloys and assessed weld integrity using tensile testing. Similarly, Hannard et al. [8] utilized tensile experiments to determine the hardening and fracture behavior of three 6xxx series alloys subjected to different heat-treatment conditions.

In the context of mechanical assessment, Mróz et al. [9] analyzed the influence of aging on the dynamic stability of thin-walled aluminum extrudates. Their results indicated that the extruded sections exhibited high strength and dynamic stability according to the applied criteria; however, the specific dynamic response varied with the alloy temper. From a processing standpoint, heat treatment serves as an effective approach to tailor the strength of aluminum extrusions and may provide the only feasible means of adjustment when constraints on weight and cross-sectional geometry preclude dimensional modifications.

Additional studies have explored how extrusion speed affects the microstructure and mechanical properties of various alloys. Investigations on Mg–Ca binary alloys demonstrated that extrusion speed

induces notable changes in both microstructure and mechanical performance, underscoring the need for optimized processing parameters. Research on AA2024 similarly showed that ram speed influences surface quality and mechanical behavior, revealing a critical trade-off between extrusion rate and material performance. Work on Mg–Al–Ca–Sn alloys further highlighted the role of extrusion speed in governing microstructural evolution and resultant strength. Moreover, studies on continuous extrusion of 6063 aluminum alloy using double billets indicated that extrusion speed affects weld quality, suggesting opportunities for process improvement. Collectively, these findings reinforce the importance of controlling extrusion speed to enhance the mechanical performance and overall quality of aluminum and magnesium alloys [10–13].

The implementation of liquid nitrogen systems to regulate extrudate exit temperatures plays a critical role in extending die life, mitigating quality defects, and improving overall process productivity during aluminum alloy extrusion. Effective temperature monitoring is essential, and various approaches have been developed to manage thermal conditions throughout the process. Over the past decade, die cooling with liquid nitrogen has become one of the most widely adopted techniques. In response to the increasing demand for aluminum extruded products and the need to achieve high quality at competitive costs, liquid nitrogen–based cooling systems have gained prominence as an efficient solution. In addition, liquid nitrogen is considered an environmentally favorable option for enhancing extrusion productivity due to nitrogen’s natural abundance and negligible ecological footprint. The primary safety consideration associated with its use is ensuring adequate ventilation, as evaporated nitrogen can displace oxygen in confined spaces. Although optimizing die design also contributes to improved process efficiency, thermal management challenges—particularly at elevated ram speeds—persist. Within this context, liquid nitrogen offers an effective means of heat control and supports higher throughput [14–19].

Concerning the mechanical performance of aluminum alloys, nanoindentation testing has also been extensively utilized in several cases. Kim et al. [20] employed nano- and micro-indentation along with nano scratch testing, complemented by optical microscopy and atomic force microscopy (AFM), to investigate the mechanical and tribological characteristics of 6061 aluminum alloy, comparing their findings with Vickers hardness measurements. Peng et al. [21] generated a hardness distribution map across the cross-section of 6061–5A06 aluminum alloy joints using nanoindentation with a total of 700 indents. Additionally, Ogura et al. [22] applied nanoindentation to analyze the mechanical properties of interfacial reaction layers in dissimilar joints between 6000 series aluminum alloys and steel, demonstrating the technique’s effectiveness for characterizing such interface.

Previous studies have examined the influence of ageing temperature and the use of liquid nitrogen on the nanoindentation creep behavior of 6060 aluminum alloy [23,24]. The referred previous studies have examined a wide range of ageing temperatures and durations, including an ageing temperature of 180 °C. In the present work, an ageing temperature of 160 °C was additionally selected to enable future investigation of potential mixed ageing cycles, along with the temperature of 180 °C that was determined to provide the most advantageous performance. For this reason, both temperatures were adopted for detailed evaluation in the current study.

2. Methodology

2.1 Materials and Sample preparation

The material examined in this study is the 6060 aluminum alloy, whose elemental composition is presented in Table 1. Chemical analysis was performed using a Hitachi FOUNDRY MASTER COMPACT Optical Emission Spectrometer (OES). Test specimens were produced by extruding the alloy with a 37.5 MN Danieli Breda extrusion press. The extrudate exit temperature was consistently maintained at 520 °C for all ram speeds. This uniformity was achieved by closely controlling the billet preheating temperature and employing liquid nitrogen as a cooling medium to stabilize the exit temperature, even under elevated ram speeds. The operation was supported by the N5NITROGEN software from ATIEUNO in conjunction with the press’s SCADA system, ensuring stable process control.

Following extrusion, the material was aged at 160 °C and 180 °C for 1 h, 4 h, and 8 h, respectively. The design of cooling channels within aluminum extrusion dies is largely guided by empirical principles, as the complexity of multiphase flow and variable heat-transfer calculations poses significant challenges. To simplify the design process and minimize computational uncertainties, industry practice often relies on practical, experience-based guidelines that offer a cost-effective means of producing efficient cooling channel systems. Figure 1 illustrates the nitrogen cooling channel configuration used in the extrusion die from which the specimens in this study were produced. In this cooling system, liquid nitrogen enters at point (A), is distributed through the outer ring at (B), passes into the cooling channels at (C), and is delivered to the injectors at (D). The layout of the channels is determined by factors such as profile symmetry, the number of cooling holes, and structural limitations of the die. Although initial designs may require iterative adjustments, applying established design guidelines can greatly streamline the development of effective cooling systems. Specimens used for nanoindentation and tensile testing were prepared from the extrudates produced using the process described above.

Table 1. Elemental composition of the investigated alloy [28].

Alloy	Mg	Si	Fe	Mn	Cu	Cr	Zn	Ti
6060	0,38	0,5	0,23	0,019	0,021	0,005	0,061	0,014



Fig. 1. Liquid nitrogen channels at the aluminum extrusion die

2.2 Tensile tests

Tensile testing evaluates a material's ability to resist uniaxial tensile loads by applying a controlled stretching force to the specimen. In this study, tensile tests were performed using a universal testing machine (M500-50AT, Testometric, Lincoln, UK). The specimens were prepared in accordance with EN ISO 6892-1:2019, with a gauge length of 50 mm and a rectangular cross-section measuring 12.5 mm (± 1 mm) in width and a thickness of 1.63 mm, corresponding to the geometry of the extrudates. A crosshead speed of 5 mm/min was employed for all tests. To ensure statistical reliability and capture representative mechanical behavior, five specimens were tested for each experimental condition.

2.3 Nanoindentation testing

Nanoindentation experiments were carried out using a DUH-211S Shimadzu instrument (Kyoto, Japan) with a load resolution of 0.196 μN . Tests were performed at room temperature using a Berkovich diamond indenter, characterized by its three-sided pyramidal geometry, a 65° included angle, and a tip radius of 100 nm. A maximum load of 800 mN was applied to the surface and cross-section of the specimens and held for 3 seconds. This load level was selected to ensure sufficient penetration into the aluminum, thereby minimizing the influence of surface irregularities. At the

selected indentation depth, a larger volume of precipitates is engaged, enabling a more accurate representation of the bulk mechanical response. Indentation depth was continuously recorded as a function of the applied load, after which the indenter was unloaded to zero load. During the creep hold period, the peak load was maintained. The average of ten indents was used to determine the elastic modulus and hardness of the material.

2.4 Fractographic and Metallographic Characterization

A detailed fractographic analysis was conducted on the selected 6060 aluminum alloy following extreme ageing treatments (one hour at 180 °C and eight hours at 180 °C). This investigation employed Phenom ProX scanning electron microscopy (SEM) to characterize the effects of the different ageing conditions on the alloy's microstructural and fracture features. Complementary metallographic analysis was also performed. Sample preparation for metallography followed a systematic procedure: the specimens were first mounted using cold-curing resins, then ground with silicon carbide (SiC) papers of progressively finer grit sizes (320, 800, and 1200). Polishing was subsequently carried out using soft cloths and diamond suspensions of 3 µm and 1 µm for a total duration of six minutes. Final polishing was completed using an Oxide Polishing Suspension (OPS) for four minutes.

3. Results and Discussion

3.1 Production Data

Figure 2 presents the evolution of the average ram speed and the corresponding exit temperature of the extrudates. A total of twenty-five billets were processed for this experiment. Table 2 summarizes the billet lengths and temperature parameters pertinent to the study. Zones 1 through 3 represent the first three measurement locations along the billet, where temperatures were recorded to facilitate thermal control during extrusion. Liquid nitrogen cooling was initiated starting with the tenth billet. As shown in Figure 2, the substantial increase in ram speed did not influence the exit temperature of the extrudates, owing to the effectiveness of the liquid nitrogen cooling system. The introduction of liquid nitrogen enabled a 15.25% increase in average ram speed, from 9.31 mm/s to 10.73 mm/s.

Table 2. Billet length and Temperatures during the experiment

Billet length (mm)	Temp. at zone1 (°C)	Temp. at zone2 (°C)	Temp. at zone3 (°C)
1000	470	450	430

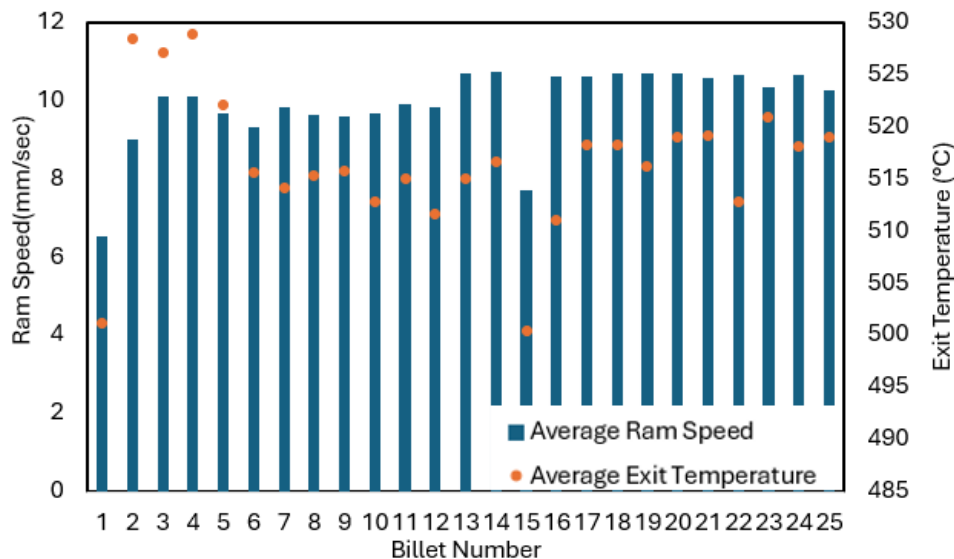


Fig. 2. Average ram speed and exit temperature evolution for the extrudates [24].

3.2 Tensile test Results

Tensile test results at an ageing temperature of 160 °C show that the application of liquid-nitrogen cooling does not produce any substantial change in yield stress as depicted in Figure 3. Ageing for 4 hours and 8 hours at 160 °C leads to increases in YTS of 53.15% and 49.89%, respectively, for specimens extruded at lower ram speeds, while the corresponding increases for higher ram speeds are 47.84% and 43.74%. Ageing for 4 hours and 8 hours results in UTS increases of 22.25% and 18.21% for the lower ram-speed condition, whereas the increases measured for the higher ram-speed condition are 17.48% and 17.49%. When directly comparing the two processing routes, only a marginal UTS increase of 0.57% is observed after 8 hours of ageing at 160 °C under liquid-nitrogen cooling and elevated ram speed. Figure 4 presents the tensile test results, indicating that the use of liquid nitrogen as a cooling agent had no substantial influence on the yield stress at an ageing temperature of 180 °C. Ageing for 4 hours and 8 hours at 180 °C leads to increases in YTS of 53.15% and 49.89%, respectively, for specimens extruded at lower ram speeds, while the corresponding increases for higher ram speeds are 63.86% and 12.69%. Ageing for 4 hours and 8 hours results in UTS increases of 25.13% and 15.67% for the lower ram-speed condition, whereas the increases measured for the higher ram-speed condition are 33.22% and 8%. A marginal increase in UTS of 0.20% was recorded after 8 hours of ageing at 180 °C under liquid nitrogen cooling and increased ram speed.

By comparing the YTS, UTS and strain at UTS for the ageing temperature of 180 °C, it is evident that for the ageing duration of 1 hour the YTS and UTS are reducing by 20.76% and 7.91% respectively, while the strain at UTS is increasing by 36.89%. For both ageing temperatures the use of liquid nitrogen exhibited a more pronounced effect on the strain (%) at UTS. This behavior can be attributed to the increased dislocation density generated by the higher ram forces, which promotes greater plastic deformation within the aluminum matrix. Under shorter ageing conditions, these dislocations contribute to reduced mechanical performance during tensile tests; however, at longer ageing durations, the formation of precipitates effectively restricts dislocation motion, thereby reducing the impact of this mechanism. As ageing progresses, this effect diminishes, likely due to the accelerated development of larger Mg₂Si precipitates, which further impede dislocation mobility. Specifically, elevated ram speeds achieved through liquid nitrogen cooling resulted in increases in strain at UTS of 17.9% and 20.78% for ageing durations of 4 hours and 8 hours at 160 °C, respectively. Moreover, elevated ram speeds achieved through liquid nitrogen cooling resulted in increases in strain at UTS of 36.9%, 14.6%, and 12.1% for ageing durations of 1 hour, 4 hours, and 8 hours at 180 °C, respectively. These results indicate that while strength parameters remained relatively unchanged, ductility improved significantly. Overall, the findings suggest that liquid nitrogen cooling can effectively tailor mechanical performance (particularly ductility) without compromising material strength. Additional microstructural characterization would help clarify the mechanisms responsible for this improvement.

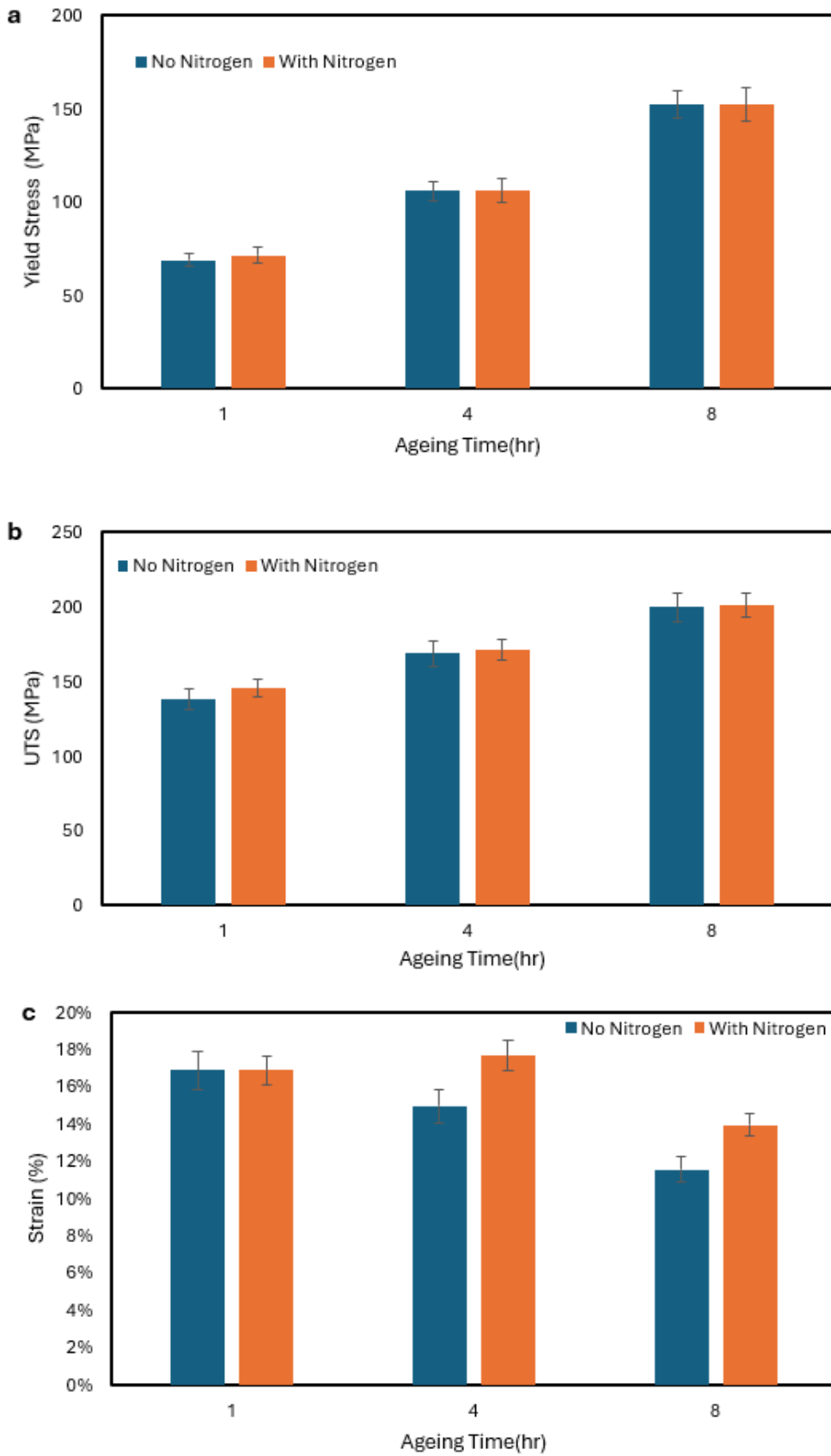


Fig. 3. a) YTS, b) UTS and c) strain (%) at UTS for ageing at 160°C for 1,4 and 8 hours

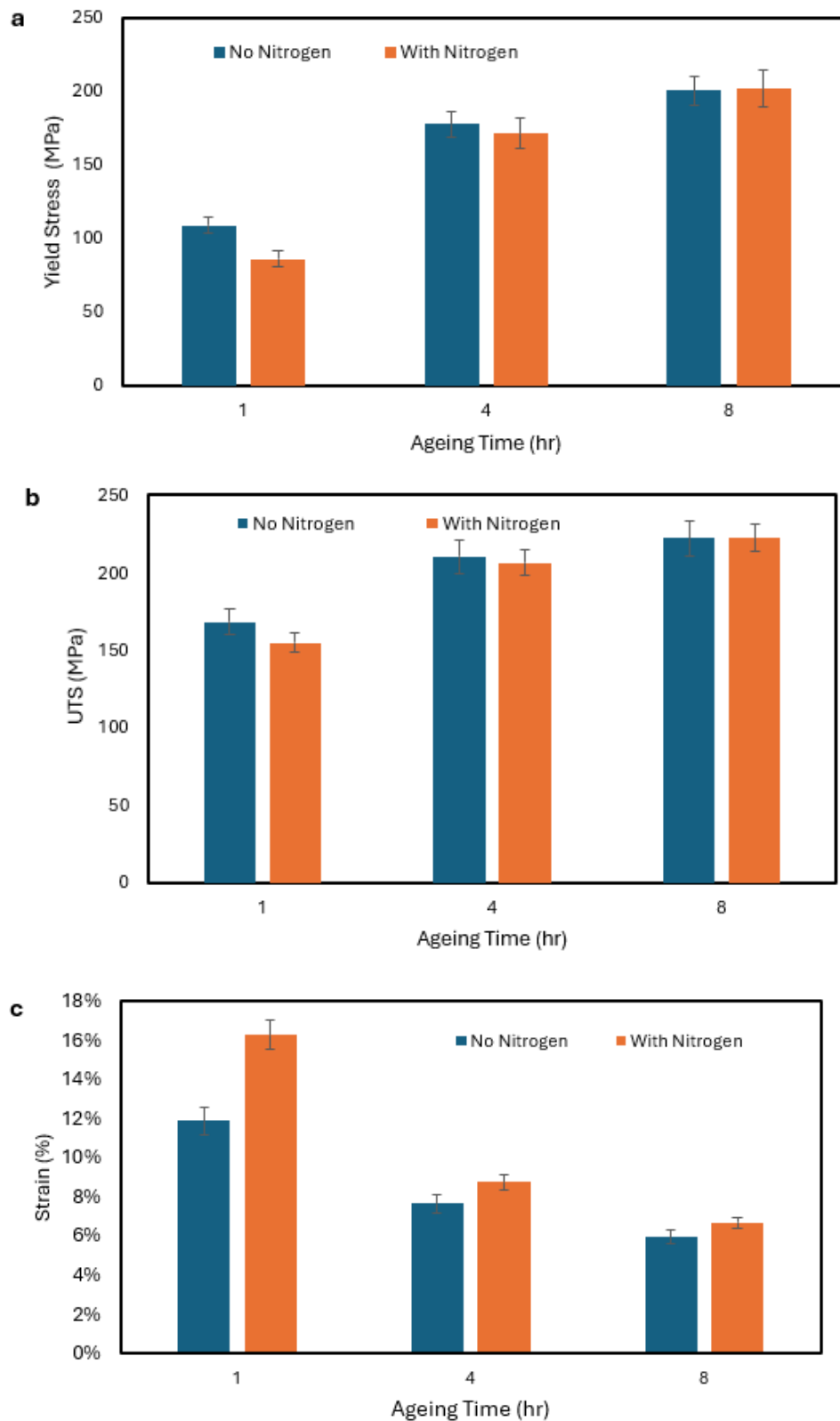


Fig. 4. a) YTS, b) UTS and c) strain (%) at UTS for ageing at 180°C for 1,4 and 8 hours [24].

3.3 Fractographic and Metallographic Characterization

A detailed fractographic analysis was performed on tensile specimens subjected to the maximum ageing conditions (1 hour at 160 °C and 8 hours at 180 °C). Figure 5a illustrates a typical ductile fracture, characterized by micro-void coalescence. With increasing ageing, the voids become fewer but larger compared to those observed in less-aged material. Additionally, the peak-aged specimen exhibits a greater number of dimpled regions on the fracture surface, likely due to the increased

presence of precipitates that promote dimple formation. Figure 5b highlights transgranular brittle fractures of surface particles, resulting in shallow dimples of varying sizes, which can be attributed to the higher material strength under these ageing conditions. Metallographic analysis was also conducted for both ageing states. Figure 6 provides a visual representation of the α -AlFeSi particles, which are more easily observed due to the stronger etching effect in more aged materials. This increased etching contrast arises because precipitation reduces the amount of solute in the α -Al matrix, making it closer to pure aluminum and therefore more responsive to the etching process.

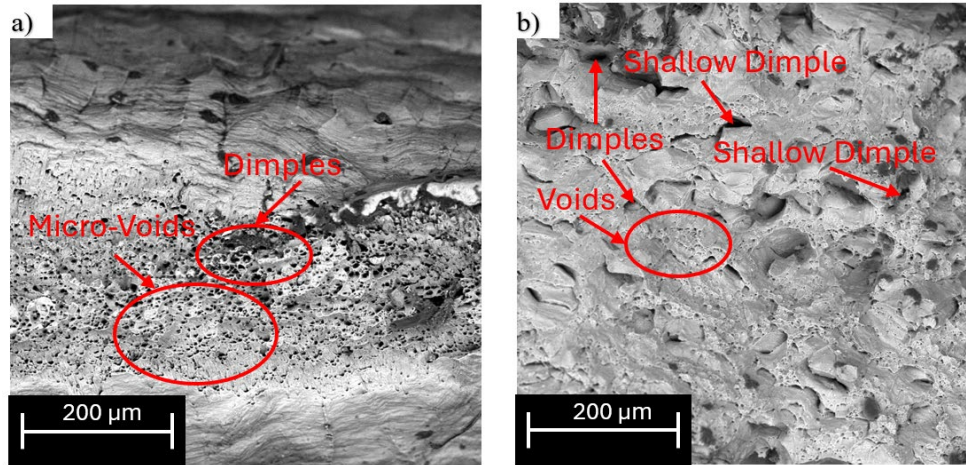


Fig.5. SEM images of fracture surface from tensile tests: a) ageing for 1 hour at 180 °C, b) ageing for 8 hours at 180 °C [24].

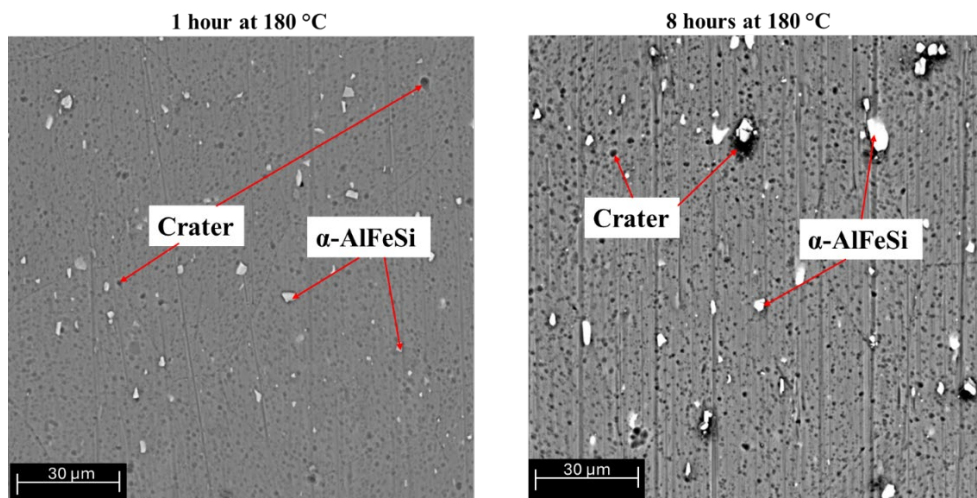


Fig. 6. Craters and α -AlFeSi particles for 1 hour at 180 °C and 8 hours at 180 °C after etching [24].

3.4 Nanoindentation Test results

3.4.1 Load-Depth Curves

Figure 7 displays the load–depth curves for specimens aged at 160 °C for three different durations, comparing extrudates processed at higher ram speeds with liquid-nitrogen cooling to those produced at lower ram speeds without cooling. The data show that hardness increases as ageing time increases, reflected by the reduced penetration depth. The nanoindentation results further demonstrate that higher ram speeds, enabled by liquid-nitrogen cooling, lead to a substantial rise in hardness after 1 hour and 4 hours of ageing, with only a slight increase after 8 hours. Extrudates processed at elevated ram speeds exhibited reductions in maximum indentation depth of 8.03%, 8.85%, and 0.81% for the 1-hour, 4-hour, and 8-hour ageing conditions, respectively. Figure 8 presents the load–depth curves for specimens aged at 180 °C for three different durations, comparing extrudates processed at higher ram speeds with liquid nitrogen cooling to those produced at lower ram speeds without

cooling. The results indicate that hardness increases with longer ageing time, as evidenced by the decreasing penetration depth. Additionally, the nanoindentation data reveal that higher ram speeds, facilitated by liquid nitrogen cooling, result in a slight reduction in hardness for the 1-hour and 4-hour ageing conditions, and a minimal reduction after 8 hours. Specifically, extrudates produced at elevated ram speeds exhibited increases in maximum indentation depth of 6.2% and 2% for the 1-hour and 4-hour ageing durations, respectively, while for the 8-hour ageing cycle, the increase was only 1%. The distinct behaviour of the studied alloy during ageing at 160 °C and 180 °C can be attributed to the increased dislocation density generated under higher deformation rates associated with elevated extrusion ram speeds. This enhanced dislocation density contributes to strengthening at lower ageing conditions. As ageing progresses and precipitation becomes the dominant hardening mechanism, the contribution of dislocation-related strengthening gradually diminishes. These figures provides a more detailed analysis of data reported in our previous study, while providing more data for another ageing temperature. [23].

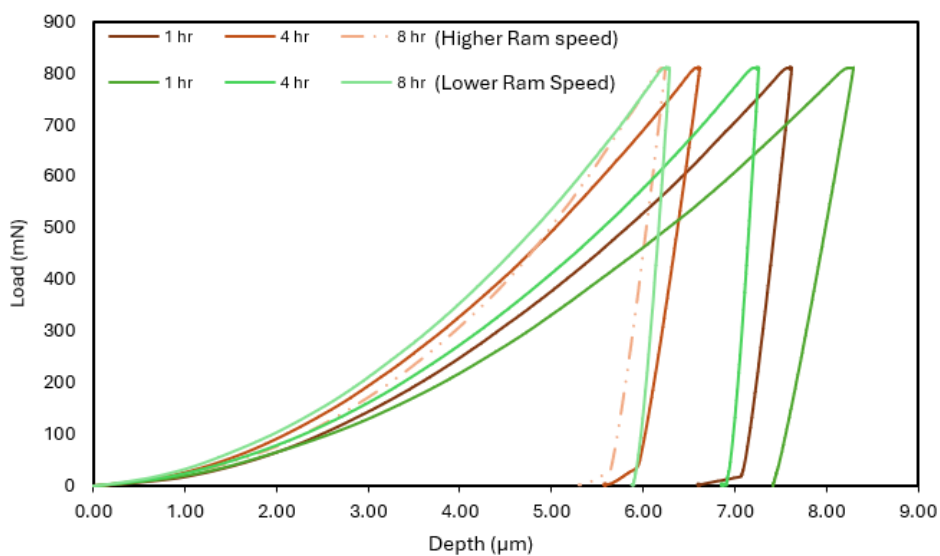


Fig. 7. Load-Depth curves for ageing at 160°C

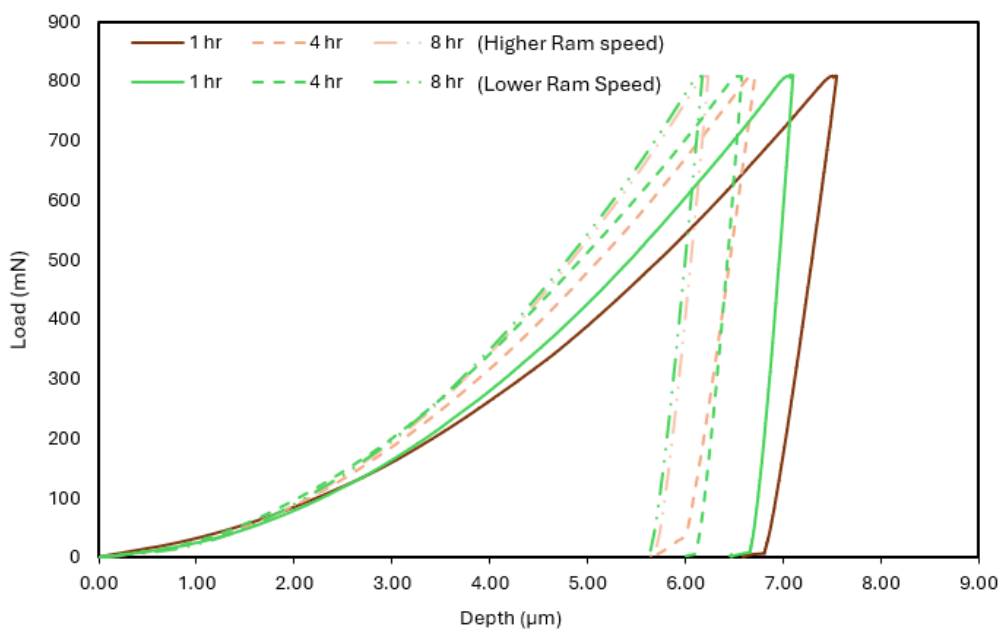


Fig. 8. Load-Depth curves for ageing at 180°C [24].

3.6 Nanoindentation creep behavior

To examine the creep behavior using nanoindentation tests, data collected during the holding stage of the experiment were analyzed. The experimental data during this stage were well-fitted with the following equation [25]:

$$h = h_i + a(t-t_i)^{1/2} + b(t-t_i)^{1/4} + c(t-t_i)^{1/8} \quad (\text{eq.1})$$

where h is the indenter displacement during the holding stage, t is creep time, and h_i , t_i , a , b and c are the best-fit parameters. Figure 9 illustrates the experimental data alongside the fitted creep displacement curve for a specimen aged at 180 °C for 1 hour during the nanoindentation holding stage. The red line corresponds to the curve fitted according to Eq. 1, while the blue dots represent the experimental measurements. The origin of the x-axis was set at the start of the holding stage to clearly define the temporal range of the observed creep behavior.

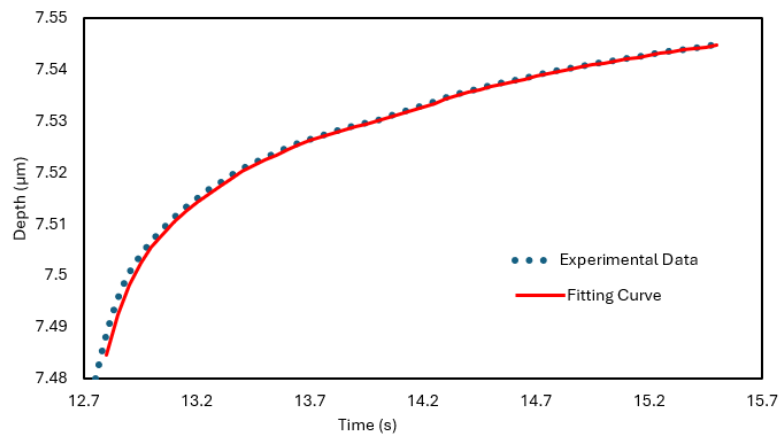


Fig. 9. Experimental and fitted creep displacement and time curve of ageing at 180 °C for 1 hour for the extrudates produced with higher ram speed (utilizing liquid nitrogen) [24].

Figure 10 illustrates the creep displacement–time response obtained from nanoindentation at an ageing temperature of 160 °C for three ageing durations, comparing extrudates processed at higher ram speeds with liquid-nitrogen cooling to those produced at lower ram speeds without cooling. Across all ageing conditions at 160 °C, specimens extruded at higher ram speeds consistently exhibit lower creep displacement throughout the entire holding period, demonstrating the suppressive effect of increased deformation rate and cryogenic cooling on time-dependent deformation. Moreover, Figure 11 presents the creep displacement–time curves obtained during nanoindentation at an ageing temperature of 180 °C for three different ageing durations, comparing extrudates processed at higher ram speeds with liquid nitrogen cooling to those produced at lower ram speeds without cooling. Unlike the load–depth behavior shown in Figure 8, the creep displacement data indicate that, for all ageing durations at 180 °C, higher ram speeds facilitated by liquid nitrogen result in reduced creep displacement throughout the entire holding period. As emphasized previously, for shorter ageing durations, the dislocations generated by higher ram speeds locally improve the creep resistance of the material. In contrast, for longer ageing times, precipitate formation effectively hinders dislocation motion, thereby diminishing the influence of this mechanism. Furthermore, it is evident that by increasing the ageing time the creep displacement is decreased. Based on the results presented, it is noteworthy that the use of liquid nitrogen as a cooling agent, which enables higher ram speeds, does not markedly affect the maximum indentation depth in nanoindentation tests. However, the data suggests that creep behavior may be influenced, as slightly reduced creep displacements were observed across all experiments. It is plausible that these effects could be more pronounced in stronger alloys, such as 6005 or 6082.

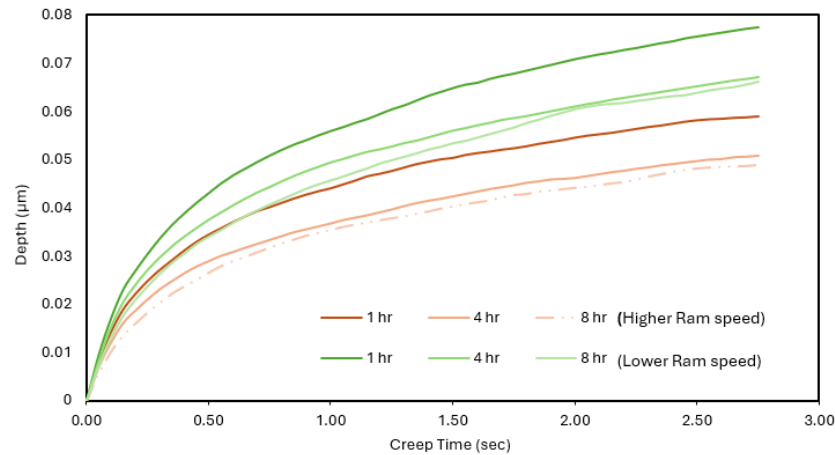


Fig. 10. Creep displacement-time curves for ageing at 160 °C

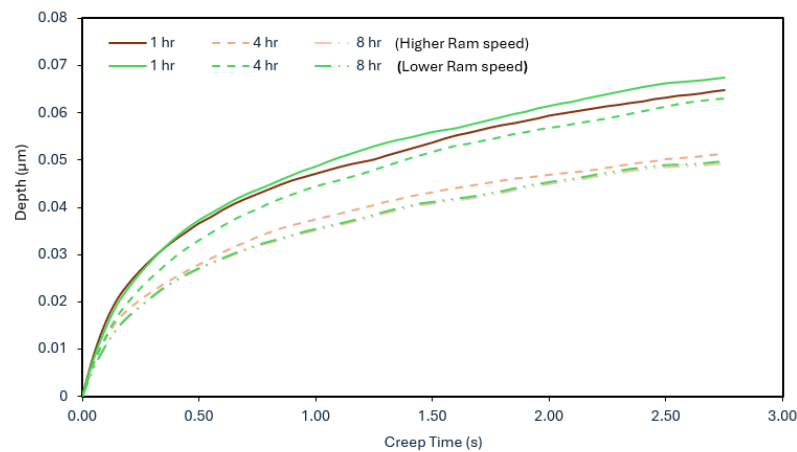


Fig.11. Creep displacement-time curves for ageing at 180 °C [24].

4. Conclusions

The present study employed the 6060 aluminium alloy to examine the influence of elevated extrusion ram speeds, achieved through the application of liquid nitrogen as a die cooling medium, on the alloy's mechanical performance. The mechanical response of the extruded profiles was characterized using tensile testing and nanoindentation techniques. In addition, creep behaviour was evaluated through nanoindentation.

Tensile testing at an ageing temperature of 160 °C showed that the application of liquid-nitrogen cooling, and the resulting increase in extrusion ram speed, did not produce any meaningful change in yield stress. Ageing for 4 or 8 hours at the same temperature similarly had no notable effect on yield stress. The ultimate tensile strength (UTS) was also largely unaffected by liquid-nitrogen cooling, with 4 hours of ageing showing no measurable variation. Only a marginal increase in UTS, equal to 0.57%, was observed after 8 hours of ageing under the higher ram-speed condition. Concerning the ageing at 180 °C for 4 hours, no significant effect on the ultimate tensile strength (UTS) or yield tensile strength (YTS) has been noticed. Similarly, the application of liquid nitrogen cooling during extrusion has only a marginal impact on UTS and YTS following 8 hours of ageing at 180 °C, with increases limited to 0.2% and 0.72%, respectively. In contrast, liquid nitrogen cooling markedly affects the strain at UTS under the same ageing conditions for both the selected temperatures, with higher ram speeds producing strain increases of 17.9% and 20.78% for ageing durations of 4 hours and 8 hours at 160 °C and 36.71%, 24.76%, and 16.94% for 1 hour, 4 hours, and 8 hours of ageing at 180 °C. This behaviour is particularly relevant to aerospace and automotive applications,

underscoring the need for further investigations into harder alloys such as 6063, 6005, and 6082 to determine whether comparable trends are observed.

Nanoindentation results reveal that hardness was found to increase with ageing duration at 160 °C, as indicated by the progressive reduction in penetration depth during nanoindentation. Specimens extruded at higher ram speeds with liquid-nitrogen cooling consistently exhibited greater hardness compared to those processed at lower ram speeds, particularly after 1 hour and 4 hours of ageing, while the effect became minimal after 8 hours. The corresponding reductions in maximum indentation depth were 8.03%, 8.85%, and 0.81% for the 1-hour, 4-hour, and 8-hour ageing conditions, respectively, confirming the strengthening influence of elevated ram speed under shorter ageing durations. Furthermore, the maximum indenter displacement decreases with prolonged ageing at 180 °C. The use of liquid nitrogen cooling does not significantly alter maximum displacement during these tests. However, higher ram speeds in conjunction with liquid nitrogen cooling lead to reduced creep displacement throughout the holding stage, while extended ageing further diminishes creep displacement. Overall, the findings confirm that increasing ageing time consistently reduces creep displacement.

References

- [1] F. Gagliardi, C. Ciancio, G. Ambrogio, Optimization of porthole die extrusion by Grey-Taguchi relational analysis, *Int. J. Adv. Manuf. Technol.* 94 (2018) 719–728.
- [2] T. Bakhtiani, H. El-Mounayri, J. Zhang, Modeling of extrusion process of a condenser tube for investigating the effects of mandrel geometry, *Int. J. Adv. Manuf. Technol.* 92 (2017) 3237–3252.
- [3] U.M. Iqbal, V.S.S. Kumar, S. Gopalakannan, Application of Response Surface Methodology in optimizing the process parameters of Twist Extrusion process for AA6061-T6 aluminum alloy, *Measurement* 94 (2016) 126–138.
- [4] Y. Wu, H. Liao, Corrosion Behavior of Extruded near Eutectic Al–Si–Mg and 6063 Alloys, *J. Mater. Sci. Technol.* 29 (2013) 380–386.
- [5] H. Zhan, J.M.C. Mol, F. Hannour, L. Zhuang, H. Terryn, J.H.W. De Wit, The influence of copper content on intergranular corrosion of model AlMgSi(Cu) alloys, *Mater. Corros.* 59 (2008) 670–675.
- [6] R. Zang, Y. Ning, L. Ding, Z. Jia, K. Xiang, Q. Liu, L. Cao, Y. Li, Study on properties and precipitation behavior of 6000 series alloys with high Mg/Si ratios and Cu contents, *Mater. Charact.* 194 (2022).
- [7] D. Lesniak, P. Gromek, Estimation of extrusion welding conditions for 6xxx aluminum alloys, *Procedia Manuf.* 47 (2020) 253–260.
- [8] F. Hannard, T. Pardoën, E. Maire, C. Le Bourlot, R. Mokso, A. Simar, Characterization and micromechanical modelling of microstructural heterogeneity effects on ductile fracture of 6xxx aluminium alloys, *Acta Mater.* 103 (2016) 558–572.
- [9] A. Mróz, R.J. Mania, The complex influence of aluminium aging on the dynamic response of the thin-walled AL-6060 alloy profil, *Thin-Walled Struct.* 79 (2014) 147–153.
- [10] V. Ammu, I. Raju, R.N. Chouhan, A. Agnihotri, Effect of ram speed on surface quality and mechanical properties during extrusion of AA2024 alloy, *Mater. Today: Proc.* 113 (2024) 258–263.
- [11] M. Zhang, C. Yang, Z. Li, S. Bao, P. Ye, Y. Chen, Effect of extrusion speed on microstructure and mechanical properties of Mg-Al-Ca-Sn alloy, *Mater. Res. Express* 9 (2022) 5. <https://doi.org/10.1088/2053-1591/ac6a47>.

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- [12] J. Li, A. Zhang, H. Pan, Y. Ren, Z. Zeng, Q. Huang, C. Yang, L. Ma, G. Qin, Effect of extrusion speed on microstructure and mechanical properties of the Mg-Ca binary alloy, *J. Magnes. Alloy.* 9 (2021) 1297–1303.
- [13] Y. Zhao, J. Pei, L. Guo, X. Yun, H. Ma, Effects of extrusion speed of continuous extrusion with double billets on welding performance of 6063 Al alloy, *Trans. Nonferrous Met. Soc. China* 31 (2021) 1561–1571.
- [14] P.K. Saha, *Aluminum Extrusion Technology*, ASM Int., OH, USA, 2000.
- [15] J. Zasadziński, W. Libura, J. Richert, Fundamentals of advanced aluminum extrusion processes, *Proc. 8th Int. Extrusion Technol. Sem.* 2 (2004) 391–397.
- [16] A. Klaus, How to benefit from isothermal extrusion, *Proc. 11th Int. Extrusion Technol. Sem.* 2 (2016) 215–220.
- [17] P. Stratton, Raising productivity of aluminum extrusion with nitrogen, *Int. Heat Treat. Surf. Eng.* 2 (2008) 105–108.
- [18] T.J. Ward, R.M. Kelly, G.A. Jones, J.F. Heffron, Effects of nitrogen – liquid and gaseous – on aluminum extrusion, *JOM* 36 (1984) 29–33.
- [19] D. Ruppin, K. Mueller, Influence of mandrel cooling in the direct extrusion of aluminum tubing using stationary or moving mandrels, *Aluminum Dusseldorf* 58 (1982) 402–406.
- [20] H.H. Kim, S.H. Cho, C.G. Kang, Evaluation of microstructure and mechanical properties by using nano/micro-indentation and nanoscratch during aging treatment of rheo-forged Al 6061 alloy, *Mater. Sci. Eng. A* 485 (2008) 272–281.
- [21] G. Peng, Y. Ma, J. Hu, W. Jiang, Y. Huan, Z. Chen, T. Zhang, Nanoindentation hardness distribution and strain field and fracture evolution in dissimilar friction stir-welded AA 6061-AA 5A06 aluminum alloy joints, *Adv. Mater. Sci. Eng.* 2018 (2018).
- [22] T. Ogura, K. Ueda, Y. Saito, A. Hirose, Evaluation of interfacial microstructures in dissimilar joints of aluminum alloys to steel using nanoindentation technique, *Mater. Trans.* 52 (2011) 979–984.
- [23] E. Giarmas, E. Tzimtzimis, D. Tzetzis, The influence of ageing conditions and liquid nitrogen cooling of extrusion dies on nanoindentation creep in 6060 aluminium alloy, *Int. J. Adv. Manuf. Technol.* 137 (2025) 6187–6205. <https://doi.org/10.1007/s00170-025-15529-4>.
- [24] E. Giarmas, E. Tzimtzimis, K. Tsongas, A. Korlos, C. David, D. Tzetzis, The Influence of Increased Extrusion Ram Speed through Liquid Nitrogen Cooling on the Mechanical Performance of 6060 Aluminum Alloy, *Metals* 15 (2025) 1136.
- [25] X. Liu, Q. Zhang, X. Zhao, X. Yang, L. Luo, Ambient-temperature nanoindentation creep in ultrafine-grained titanium processed by ECAP, *Mater. Sci. Eng. A* 676 (2016) 73–79.