Heat Treatment Analysis on Microstructure and Mechanical Properties of Thixoformed Aluminium Alloys

Nuramieza Norizan[1], Mohd Shukor Salleh[1*], Muhammad Hisyam Abdul Aziz[2]

[1]Fakulti Teknologi dan Kejuruteraan Industri dan Pembuatan, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia

[2]Chery Corporate Malaysia Sdn. Bhd. No.1 (2-21), Jalan SU5, Lion Industri Park, Taman Perindustrian Subang, Seksyen 22, 40300 Shah Alam, Selangor Malaysia

[*]Corresponding Author

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ABSTRACT

This study investigates the combined effects of magnesium (Mg) content and artificial aging duration on the microstructural evolution and mechanical properties of thixoformed A356 Al–Si–Mg alloys. Magnesium additions of 0.1, 0.3, and 0.5 wt.% were introduced into A356 alloy, followed by thixoforming and T6 heat treatment with artificial aging at 180 °C for 1, 3, and 5 hours. A Taguchi L9 orthogonal array was employed to systematically evaluate the influence of process parameters on yield strength (YS), ultimate tensile strength (UTS), elongation to fracture, and Vickers hardness. The results demonstrate that increasing Mg content and aging duration significantly enhance YS, UTS, and hardness, attributed to precipitation strengthening by Mg_2Si phases and refinement of spheroidized α-Al globules. However, a reduction in ductility was observed with higher Mg levels and prolonged aging. The findings provide an optimized processing window for achieving a balance between strength and ductility in thixoformed A356 alloys, offering practical implications for automotive and lightweight structural applications.

Keywords: A356 Alloy; Thixoforming; Magnesium content; Artificial aging; Mechanical properties; Taguchi method

INTRODUCTION

Al–Si–Mg alloys are widely used in automotive and aerospace industries due to their excellent strength-to-weight ratio, good castability, and favorable response to heat treatment (A. Megalingam et al., 2024). Among these alloys, A356 has attracted considerable attention for manufacturing lightweight structural components where mechanical performance and dimensional precision are critical. The incorporation of magnesium plays a vital role in enhancing mechanical properties through precipitation of Mg_2Si phases during aging heat treatment (Abdelgnei et al., 2022).

Thixoforming, a semisolid metal processing technique, has emerged as an effective route to improve the microstructural uniformity and mechanical behavior of aluminum alloys. By processing the alloy in its semisolid state, thixoforming promotes the formation of spheroidized αAl grains and a more homogeneous distribution of eutectic silicon, resulting in reduced porosity and improved strength–ductility balance (Abdelgnei et al., 2020). Previous studies have shown that combining thixoforming with T6 heat treatment can significantly improve tensile strength and hardness of Al–Si–Mg based alloys, although excessive Mg addition may lead to reduced ductility due to the formation of brittle intermetallic phases (Alhawari et al., 2017).

Despite extensive studies on Al–Si–Mg alloys, systematic investigations focusing on the combined effects of Mg content and artificial aging duration on thixoformed A356 alloys remain limited. Optimization of these parameters using a statistical design approach is still underexplored. Therefore, the present study aims to evaluate the influence of varying Mg content and aging time on the microstructure and mechanical properties of thixoformed A356 alloy using the Taguchi method. The outcomes of this work are expected to provide useful guidelines for optimizing heat treatment parameters in industrial thixoforming applications.

Although considerable research has been conducted on Al–Si–Mg alloys, most studies have focused on the effects of magnesium addition, semisolid processing, or heat-treatment parameters independently. Previous studies reported that magnesium content significantly influences the microstructural evolution and mechanical properties of semisolid processed aluminium alloys through the formation of Mg-containing phases and modification of eutectic silicon morphology (Alhawari et al., 2017). More recently, Carolina Barbosa et al. (2023) demonstrated that solidification and heat-treatment conditions play a crucial role in determining the tensile properties of Al–Si–Mg alloys through precipitation strengthening and microstructural refinement. Furthermore, A. M. Aziz et al. (2024) reported significant improvements in the microstructural characteristics and tensile behaviour of thixoformed Al–Si–Cu–Mg alloys subjected to T5 and T6 heat treatments. Despite these advances, limited studies have systematically investigated the combined effects of magnesium content and artificial aging duration on the microstructural evolution and mechanical properties of thixoformed A356 alloys using a statistical optimization approach. In particular, the relationship between magnesium addition, precipitation strengthening, microstructural refinement, and the resulting strength–ductility balance in thixoformed A356 alloys remains insufficiently understood.

Therefore, the novelty of the present work lies in the systematic evaluation of the combined influence of magnesium content and artificial aging duration on the microstructure and mechanical properties of thixoformed A356 alloys using the Taguchi design of experiments. Unlike previous studies that primarily focused on individual processing variables, the present study establishes a comprehensive relationship between Mg content, aging duration, microstructural evolution, tensile properties, and hardness. The scientific contribution of this work is the identification of optimum processing conditions for enhancing mechanical performance while providing further insight into the strength–ductility trade-off associated with precipitation hardening in thixoformed A356 alloys. The findings provide practical guidelines for optimizing magnesium additions and heat-treatment parameters in thixoformed A356 alloys for lightweight structural and automotive applications.

MATERIALS AND METHODS

Material Preparation

The base material used in this study was a commercial A356 aluminum alloy, supplied in ingot form. Prior to casting, the chemical composition of the base alloy was verified to ensure compliance with the standard A356 composition range. Magnesium was subsequently added to the molten alloy to achieve target Mg contents of 0.1, 0.3, and 0.5 wt.%, respectively.

The alloy was melted in an electric resistance furnace using a graphite crucible at a temperature of approximately 720–750 °C. Once fully molten, the melt was held for sufficient time to ensure chemical homogeneity. The required amount of magnesium was then added in the form of pure Mg lumps and gently stirred to promote uniform dissolution while minimizing oxidation losses. To reduce hydrogen porosity and non-metallic inclusions, a degassing process was carried out using a commercial degassing tablet prior to casting.

After melting treatment, the alloy was poured into a preheated permanent steel mold to produce cylindrical billets suitable for subsequent thixoforming. The mold was preheated to approximately 200–250 °C to promote uniform solidification and reduce thermal shock. Gravity casting was employed, and care was taken to ensure a stable and continuous pour to minimize turbulence and oxide entrainment. The cast billets were allowed to solidify under ambient conditions before being removed from the mold.

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This controlled casting route was selected to ensure consistent initial microstructure and chemical composition across all samples prior to semisolid processing and heat treatment. By maintaining identical melting and casting conditions for all Mg levels, the influence of casting related variables on the subsequent thixoforming and mechanical properties was minimized.

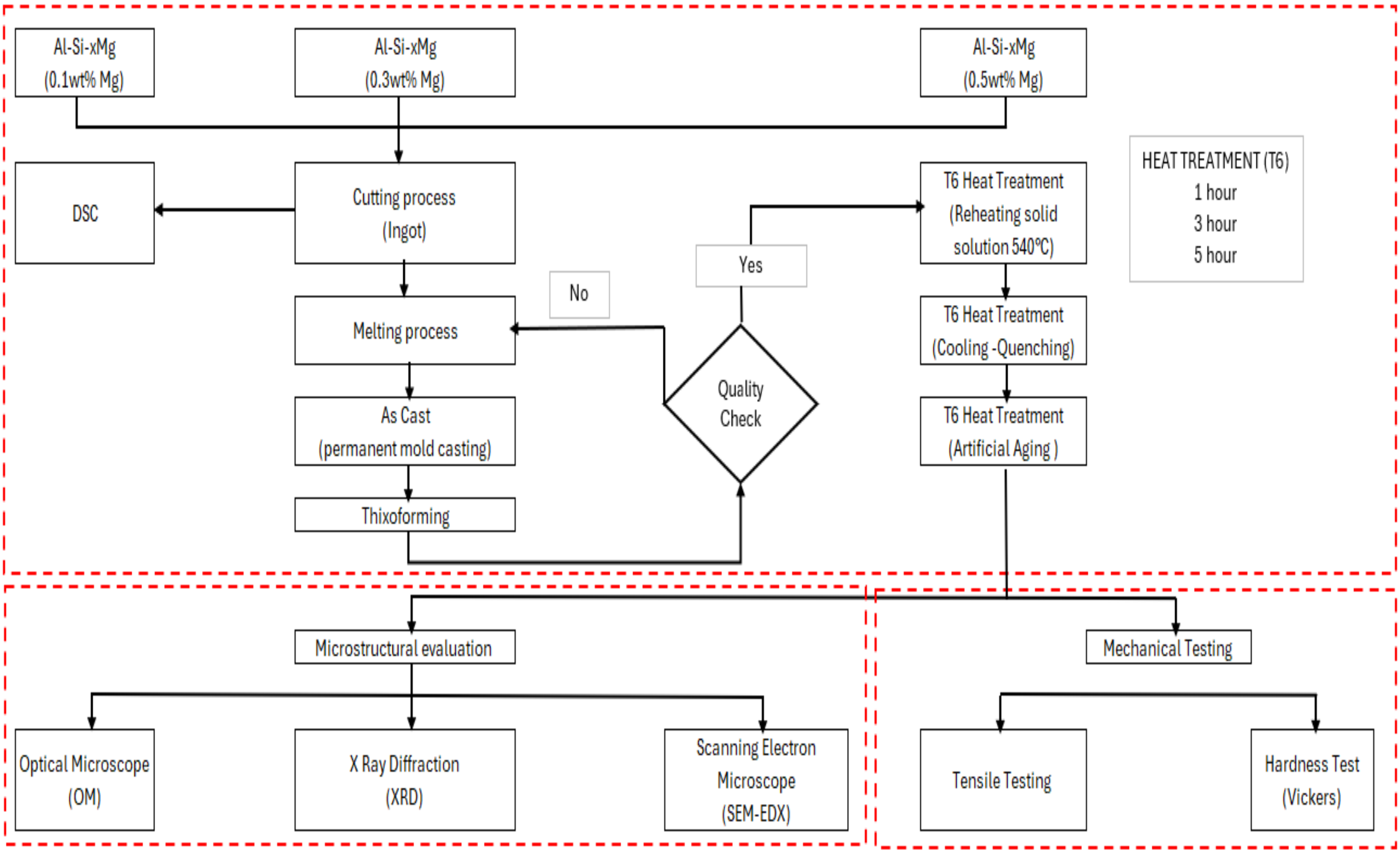

Figure 2.1.1: Flow chart on Al-Si-Mg alloying with different amounts Mg using casting mold and Thixoforming process

Figure 2.1.2: Aluminum Ingot (A356)

Figure 2.1.3: Aluminum ingot insertion into crucible

Thixoforming and Heat Treatment

Following casting, the billets were prepared for thixoforming by reheating of the semisolid temperature range. The reheating temperature was selected based on Differential Scanning Calorimetry (DSC) analysis to obtain a suitable solid–liquid fraction for semisolid processing. Based on the DSC-derived liquid fraction profile, a reheating temperature of approximately 583 °C was selected, corresponding to a liquid fraction of approximately 40%. This condition was chosen to promote thixotropic behaviour and to facilitate the formation of a non-dendritic semisolid microstructure suitable for thixoforming. Similar semisolid processing conditions have been reported by Salleh et al. (2015), where liquid fractions of approximately 40–45% were found suitable for producing globular microstructures in thixoformed aluminium alloys.

The reheated semisolid billets were transferred into a steel die and thixoformed to produce near-net-shaped specimens. During thixoforming, the dendritic structures were broken down and transformed into spheroidized α-Al grains surrounded by a liquid eutectic phase. This microstructural transformation is beneficial for reducing porosity, improving phase distribution, and enhancing the mechanical response of the alloy.

After thixoforming, all specimens were subjected to a T6 heat-treatment cycle consisting of solution treatment, quenching, and artificial aging. Solution treatment was conducted at 580 °C for 8 h to dissolve soluble Mg- and Si-containing phases into the aluminium matrix and promote chemical homogenization. The specimens were then immediately quenched in water at room temperature, approximately 23–25 °C, to retain a supersaturated solid solution. Artificial aging was subsequently performed at 180 °C for 1, 3, and 5 h to promote precipitation hardening through the controlled formation of β-Mg_2Si precipitates. This heat-treatment sequence was applied to evaluate the influence of aging duration on the microstructure and mechanical properties of the thixoformed A356 alloys.

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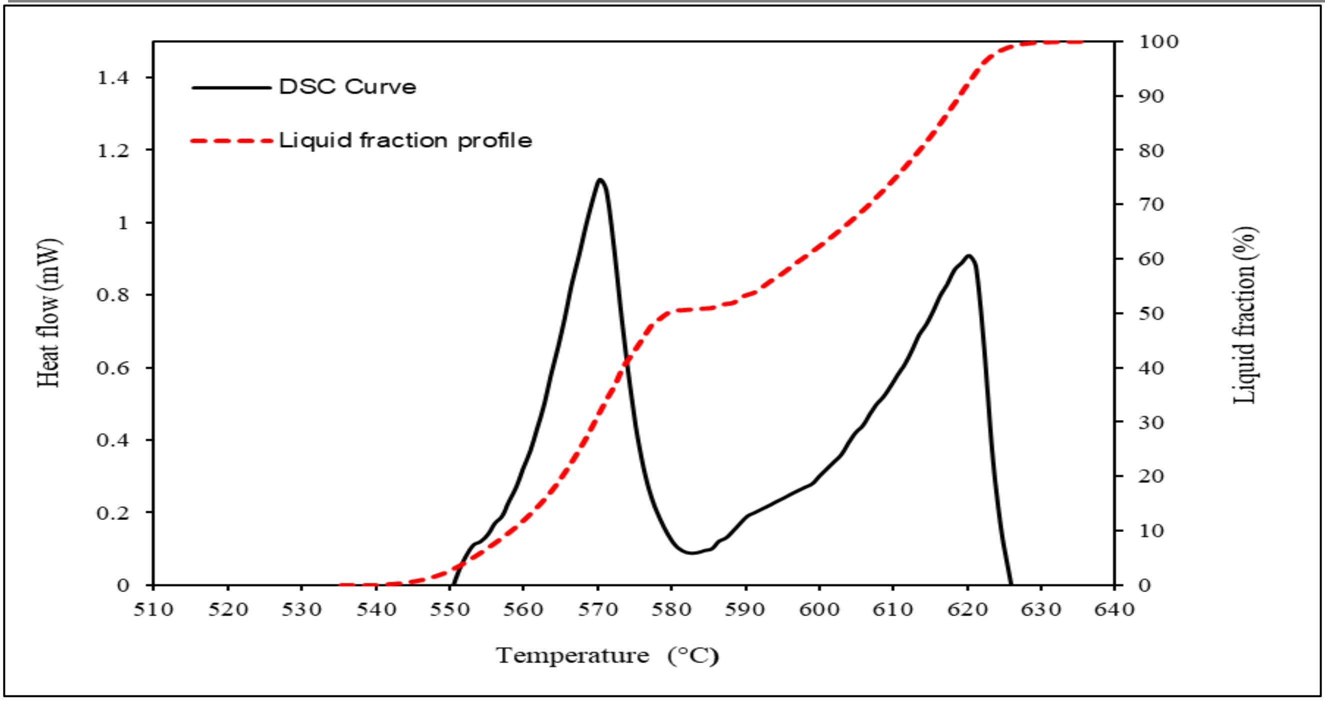

Figure 2.2.1: DSC heating flow and liquid fraction curves for A356 alloy

Figure 2.2.2: Thixoforming process

Experimental Design

A Taguchi design of experiments approach was employed to systematically evaluate the influence of magnesium content and artificial aging duration on the mechanical properties of thixoformed A356 alloys. A two-factor, three-level Taguchi L9 orthogonal array was selected to minimize the number of experimental runs while maintaining sufficient statistical reliability.

The two control factors investigated were Mg content (0.1, 0.3, and 0.5 wt.%) and artificial aging duration (1, 3, and 5 h). The response variables included yield strength, ultimate tensile strength, elongation to fracture, and Vickers hardness. This experimental design enabled the identification of dominant factors affecting mechanical performance and facilitated optimization of processing parameters with reduced experimental cost and time.

Table 2.3: Design summary method of Taguchi method

# Run (Code)	Magnesium amount addition (wt%)	Artificial Aging duration (ºC) at 180 ºC
1	0.1	1 hour
2	0.1	3 hour
3	0.1	5 hour
4	0.3	1 hour
5	0.3	3 hour
6	0.3	5 hour
7	0.5	1 hour
8	0.5	3 hour
9	0.5	5 hour

Characterization

Microstructural characterization was performed using Optical Microscopy (OM) and Scanning Electron Microscopy (SEM) to examine grain morphology, eutectic silicon distribution, and precipitate formation. Specimens for metallographic examination were sectioned, ground, polished, and etched using Keller's reagent to reveal the aluminum matrix and microstructural features. Energy Dispersive X-ray (EDX) analysis was employed to identify elemental distribution and confirm the presence of Mg-containing phases.
Mechanical characterization was carried out through tensile testing and hardness measurements. Tensile tests were conducted in accordance with ASTM E8/E8M standards using a universal testing machine, and key parameters such as yield strength, ultimate tensile strength, and elongation to fracture were recorded. Vickers microhardness measurements were performed following ASTM E92 using an appropriate load and dwell time. Multiple measurements were taken for each condition to ensure repeatability, and average values were reported for analysis.
The experimental results were analyzed statistically using signal-to-noise (S/N) ratios to evaluate the influence of process parameters and determine optimal conditions.

RESULTS AND DISCUSSION

Microstructural Characterization

Optical Microstructure

The microstructural evolution of the thixoformed A356 alloys with different Mg contents was investigated using optical microscopy, scanning electron microscopy (SEM), and energy-dispersive X-ray spectroscopy (EDS). The microstructural characteristics are summarized in Table 3.1.

The as-cast alloy exhibited a coarse dendritic α-Al matrix accompanied by plate-like eutectic silicon particles distributed within the interdendritic regions. Such a microstructure is generally associated with high stress concentration and limited ductility. Following thixoforming and T6 heat treatment, significant changes in the α-Al grain morphology and eutectic silicon distribution were observed. The addition of Mg promoted microstructural refinement and improved phase homogeneity.

At 0.1 wt.% Mg, the α-Al grains became partially globular, while the eutectic silicon particles showed a more spheroidized morphology compared with the as-cast condition. Increasing the Mg content to 0.3 wt.% resulted in a highly refined globular α-Al structure accompanied by fine spheroidized eutectic silicon particles that were uniformly distributed throughout the matrix. This condition exhibited the highest degree of microstructural homogeneity and is considered the optimum microstructure among the investigated compositions. In contrast, the alloy containing 0.5 wt.% Mg exhibited less uniformity, characterized by localized clustering and the coexistence of spheroidized eutectic silicon with coarser primary silicon particles. The presence of these coarse particles may increase concentration of local stress and adversely affect ductility.

Overall, the optical microscopy observations indicate that Mg addition plays a significant role in modifying the α-Al grain morphology, refining eutectic silicon particles, and improving phase distribution. The alloy containing 0.3 wt.% Mg exhibited the most favourable microstructure due to its refined globular grains and homogeneous phase distribution.

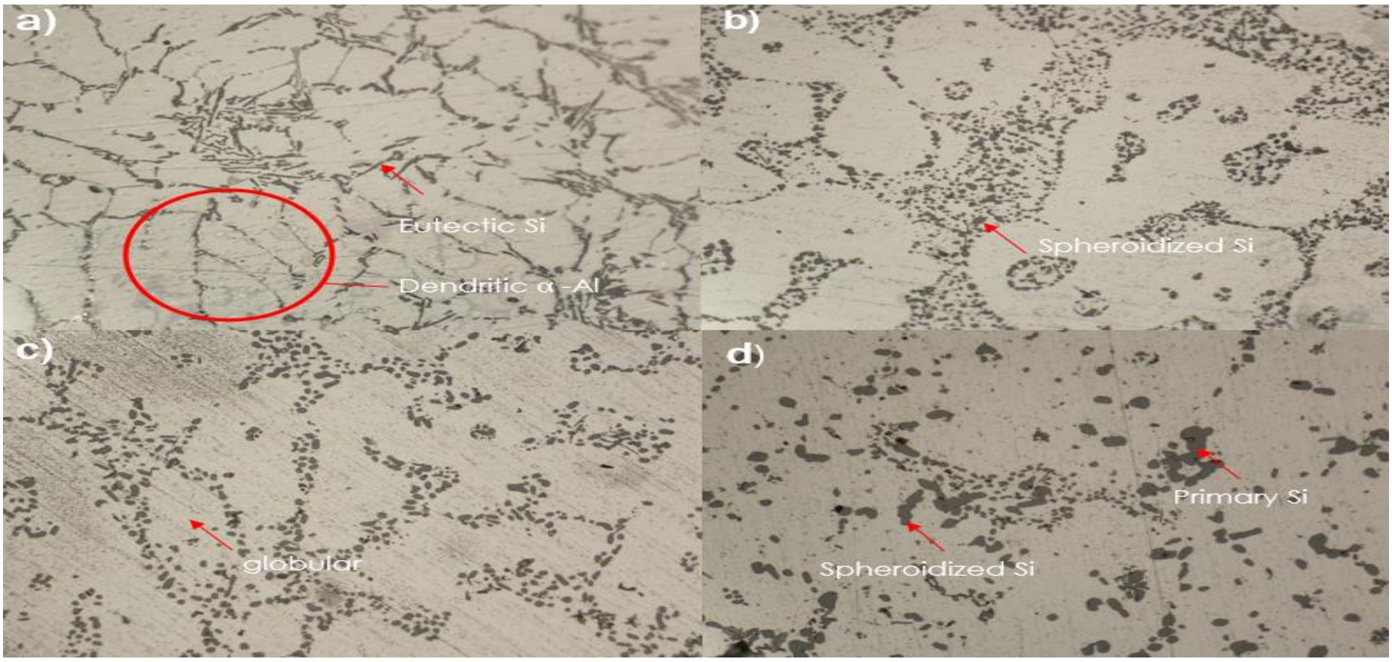

Figure 3.1.1: Optical microstructures of the Al–Si–Mg alloy with different Mg contents: (a) as cast condition showing dendritic α-Al structure with acicular eutectic Si; (b) 0.1 wt.% Mg exhibiting partial spheroidization of eutectic Si particles; (c) 0.3 wt.% Mg showing a more refined and globular eutectic Si morphology with improved distribution; (d) 0.5 wt.% Mg characterized by well-spheroidized Si particles with the presence of primary Si embedded in the α-Al matrix.

Table 3.1: Summary of qualitative microstructural evolution of thixoformed A356 alloys with different Mg contents.

Mg Content	α-Al Grain Morphology	Eutectic Silicon Morphology	Phase Distribution and Homogeneity	Microstructural Implication
As-cast	Coarse dendritic α-Al matrix	Plate-like / needle-like eutectic Si	Non-uniform; Fe-rich intermetallics along interdendritic regions	High stress concentration, poor ductility, typical cast structure
0.1 wt % Mg	Partially globular α-Al grains	Spheroidized and finer eutectic Si	Improved distribution with reduced segregation	Initiation of grain refinement and silicon modification

0.3 wt% Mg	Highly refined, uniform globular α-Al	Fine, uniformly distributed spheroidized Si	Homogeneous microstructure with optimal phase spacing	Optimal condition for balanced strength and ductility
0.5 wt% Mg	Less uniform α-Al structure	Coexistence of spheroidized Si and coarse primary Si	Localized clustering and phase coarsening	Excess Mg causes segregation and reduced microstructural stability

SEM Analysis

The SEM micrographs provide further evidence of the influence of Mg content on the eutectic silicon morphology. The as-cast alloy exhibited coarse and elongated silicon particles distributed along the interdendritic regions. With the addition of Mg, the eutectic silicon particles became progressively shorter and more spheroidized. The alloy containing 0.3 wt.% Mg showed the finest and most uniformly distributed silicon particles, indicating effective microstructural refinement during thixoforming and subsequent T6 heat treatment.

However, further increasing the Mg content to 0.5 wt.% resulted in the appearance of coarser silicon-rich particles within the microstructure. This suggests localized phase coarsening and segregation at higher Mg concentrations. Such coarse particles may act as preferential crack initiation sites during tensile loading, which explains the reduction in ductility despite improvements in strength and hardness. Therefore, the SEM observations confirm that 0.3 wt.% Mg provides the most favourable balance between microstructural refinement and phase homogeneity.

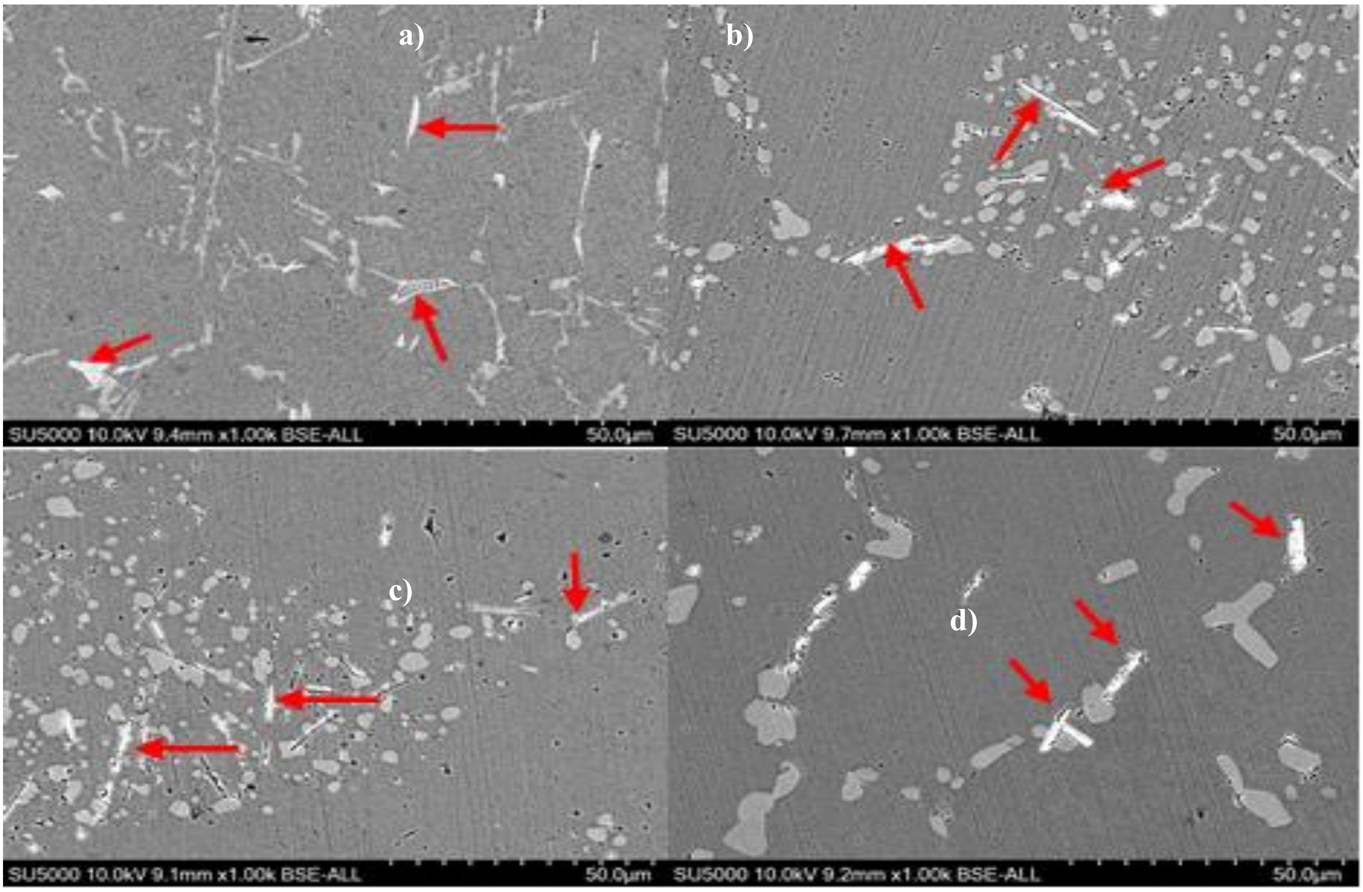

Figure 3.1.2: SEM images of Al–Si–Mg alloys in (a) as-cast, (b) 0.1 wt.% Mg, (c) 0.3 wt.% Mg, and (d) 0.5 wt.% Mg conditions, illustrating the evolution of eutectic Si morphology and intermetallic distribution with increasing Mg content.

SEM EDS Analysis

SEM-EDS elemental mapping confirms the distribution of the major alloying elements within the thixoformed A356 alloy. Aluminium was uniformly distributed throughout the matrix, indicating a homogeneous α-Al phase. Silicon was concentrated within the secondary particles observed in the SEM micrographs, corresponding to eutectic silicon and silicon-rich phases. Magnesium was detected in regions associated with silicon-rich particles, suggesting the formation of Mg-containing precipitates, particularly Mg_2Si, during the T6 heat-treatment process.

The relatively uniform elemental distribution indicates that the combination of thixoforming and T6 heat treatment promoted improved phase homogeneity within the alloy. The formation of Mg_2Si precipitates contributes to precipitation strengthening by restricting dislocation movement within the α-Al matrix. Consequently, the observed microstructural refinement and precipitation hardening mechanisms are consistent with the improvements in tensile strength and hardness obtained for the Mg-containing alloys. Among the investigated compositions, the alloy containing 0.3 wt.% Mg exhibited the most homogeneous microstructure and is therefore expected to provide the best combination of strength and ductility.

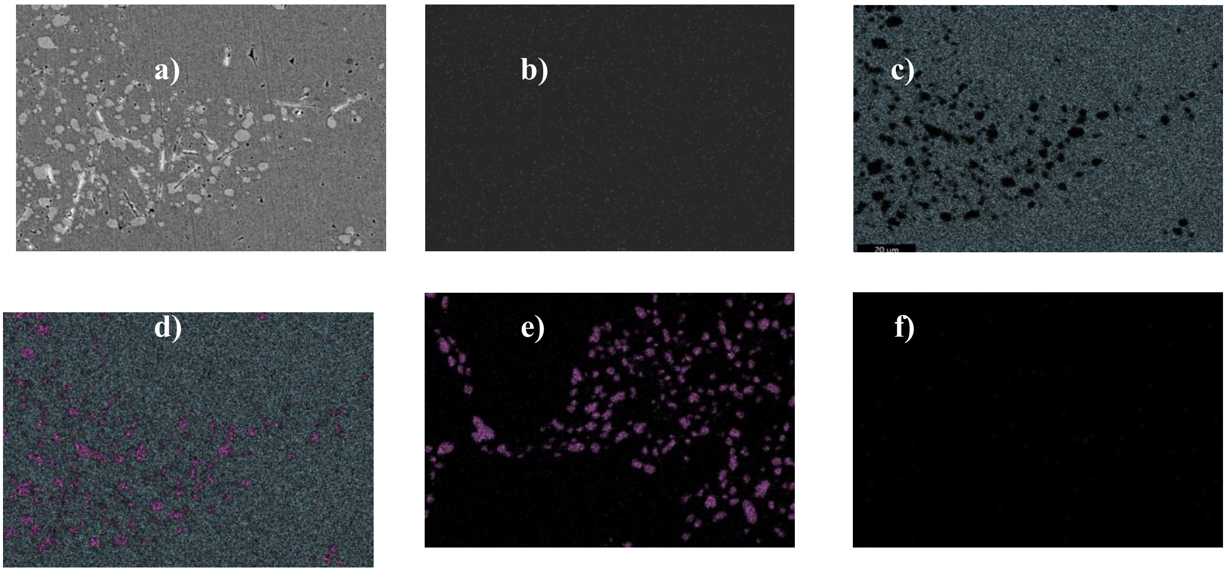

Figure 3.1.3: FESEM-EDS elemental mapping of the thixoformed A356 alloy showing (a) FESEM micrograph, (b) Mg distribution, (c) Al distribution, (d) combined elemental distribution, (e) Si distribution, and (f) Fe distribution. The elemental maps indicate a uniform distribution of Al within the matrix and the localization of Si-rich particles associated with eutectic silicon and Mg-containing phases.

Effect of Mg Content and Aging Duration on Tensile Properties

The tensile properties of the thixoformed A356 alloys with varying Mg contents and aging durations are summarized in Table 3.2. In general, both yield strength (YS) and ultimate tensile strength (UTS) increased with increasing Mg content and aging duration, whereas elongation exhibited a decreasing trend. Similar behaviour has been widely reported in Al–Si–Mg alloy systems and is commonly associated with precipitation hardening during artificial aging, where Mg_2Si precipitates contribute significantly to strength enhancement (Alhawari et al., 2017; Carolina Barbosa et al., 2023).

The improvement in tensile strength can be attributed to the combined effects of precipitation hardening and microstructural refinement. During T6 heat treatment, fine Mg_2Si precipitates are formed within the α-Al matrix, which effectively hinder dislocation movement and increase resistance to plastic deformation. In addition, as discussed in Section 3.1, Mg addition promoted the formation of a refined globular α-Al structure together with a more homogeneous distribution of eutectic silicon particles. These microstructural modifications improve load transfer within the matrix and reduce localized stress concentration, resulting in enhanced yield strength and ultimate tensile strength.

However, the increase in strength was accompanied by a reduction in elongation. This strength–ductility trade-off is commonly observed in precipitation-hardened Al–Si–Mg alloys due to the increased density of strengthening precipitates and harder secondary phases, which restrict plastic deformation (Carolina Barbosa et al., 2023; Jin, 2022). Overall, the tensile behaviour observed in this study is consistent with the microstructural evolution presented in Section 3.1, indicating that the combination of thixoforming, Mg addition, and T6 heat treatment effectively improved the mechanical performance of the A356 alloy.

Table 3.2: Tensile properties evaluation for Aluminum alloy sample A356 with various Mg addition and various Artificial Aging duration

Run	Mg content (wt%)	Aging duration (Hours)	Yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation to fracture (%)	Hardness (HV)
1	0.1	1	235.02	284.60	7.02	111.43
2	0.1	3	240.85	291.42	6.53	116.09
3	0.1	5	263.45	310.99	6.03	122.13
4	0.3	1	265.82	335.18	5.74	125.79
5	0.3	3	276.00	342.80	5.65	129.01
6	0.3	5	261.21	345.71	5.51	130.01
7	0.5	1	263.19	321.56	4.74	127.43
8	0.5	3	290.74	370.09	4.57	137.56
9	0.5	5	300.74	375.87	4.34	140.00

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Effect of Mg Content and Aging Duration on Hardness

The hardness values of the thixoformed A356 alloys with different Mg contents and aging durations are presented in Table 3.2. Like the tensile property results, hardness increased with increasing Mg content and aging duration. The lowest hardness value of 111.43 HV was recorded for the alloy containing 0.1 wt.% Mg aged for 1 h, whereas the highest hardness value of 140.00 HV was achieved by the alloy containing 0.5 wt.% Mg aged for 5 h. This corresponds to an increase of approximately 25.6%, demonstrating the significant influence of Mg addition and artificial aging on the hardness response of the alloy.

The improvement in hardness is primarily attributed to precipitation hardening associated with the formation of Mg_2Si precipitates during the T6 heat-treatment process. As the Mg content increased from 0.1 wt.% to 0.5 wt.%, a greater volume fraction of strengthening precipitates was formed within the α-Al matrix, increasing resistance to localized plastic deformation during indentation. In addition, the refined microstructure observed in Section 3.1, particularly the formation of globular α-Al grains and spheroidized eutectic silicon particles, further contributed to the enhancement in hardness.

The effect of aging duration was also evident. For the alloy containing 0.1 wt.% Mg, hardness increased from 111.43 HV after 1 h of aging to 122.13 HV after 5 h of aging. Similarly, the hardness of the alloy containing 0.3 wt.% Mg increased from 125.79 HV to 130.01 HV as the aging duration increased from 1 h to 5 h. A comparable trend was observed for the alloy containing 0.5 wt.% Mg, where hardness increased from 127.43 HV after 1 h of aging to 140.00 HV after 5 h of aging. These results indicate that prolonged aging promoted the formation and growth of strengthening precipitates, thereby increasing the hardness of the alloy.

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Overall, the hardness behavior is consistent with the tensile property trends discussed in Section 3.2. The observed hardness enhancement was strongly influenced by the combined effects of microstructural refinement and precipitation strengthening mechanisms discussed in Section 3.1.

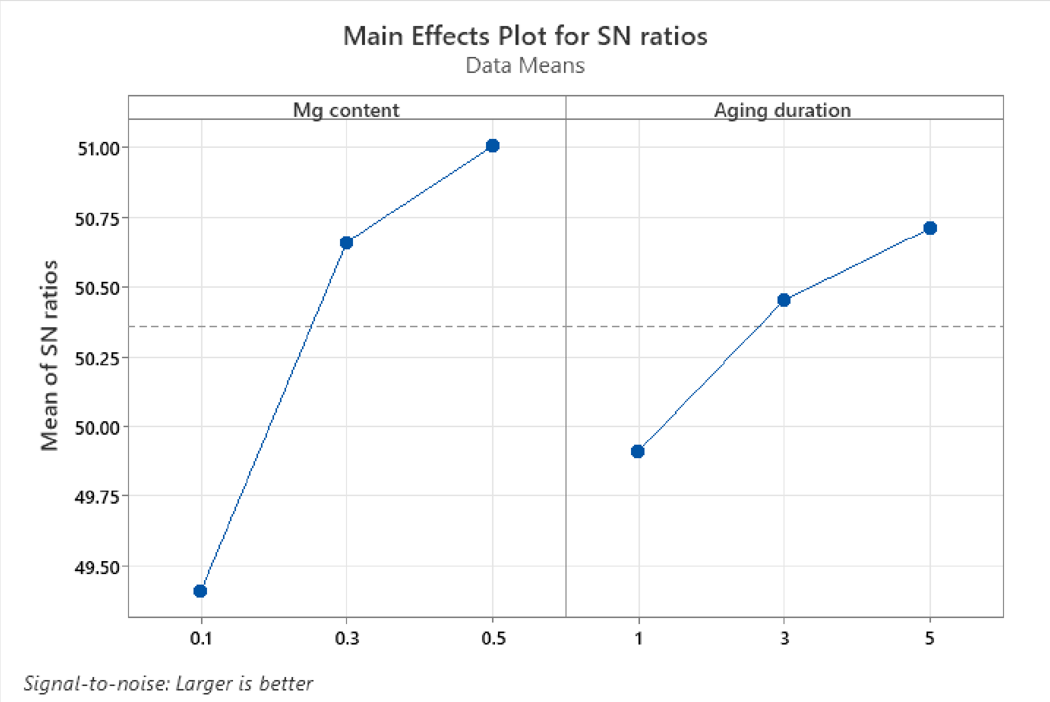
Optimization Using Taguchi Analysis

Based on the signal-to-noise (S/N) ratio analysis, the optimal processing condition for maximizing both tensile strength and hardness was determined to be 0.5 wt.% Mg combined with 5 hours of artificial aging. This parameter combination yielded the highest S/N ratio, indicating superior performance stability and reduced variability in mechanical properties. The improved strength and hardness under this condition can be attributed to the effective precipitation of fine and uniformly distributed Mg_2Si phases, which enhance dislocation resistance without excessive precipitate coarsening. The ranking analysis presented in Tables 3.4.1 and 3.4.2 indicates that Mg content consistently exhibited the highest Delta values and was therefore identified as the most influential factor affecting the investigated mechanical properties, followed by aging duration.

However, while this condition is optimal for achieving peak strength and hardness, it may not necessarily provide the best compromise between strength and ductility. Higher aging durations or Mg contents, although beneficial for hardness, can promote precipitate coarsening and increased matrix strengthening, which may reduce the alloy's ability to undergo plastic deformation. Consequently, intermediate Mg levels and aging durations offer a more balanced microstructural state, where sufficient precipitation strengthening is achieved while maintaining adequate ductility. Such trade-offs are particularly important for structural and automotive applications, where components are often subjected to combined loading conditions and require both high strength and reasonable formability.

Table 3.4.1: Main effects plot for S/N ratios of Aluminum alloy sample A356 with various Mg addition and various Artificial Aging duration

	Yield Strength (YS)		**Ultimate tensile strength (UTS)**	
Level	**Mg content (wt%)**	**Aging duration (Hours)**	**Mg content (wt%)**	**Aging duration (Hours)**
1	47.82	48.11	49.41	49.91
2	48.55	48.57	50.66	50.45
3	49.08	48.77	51.00	50.71
Delta	1.26	0.67	1.26	0.67
Rank	1	2	1	2



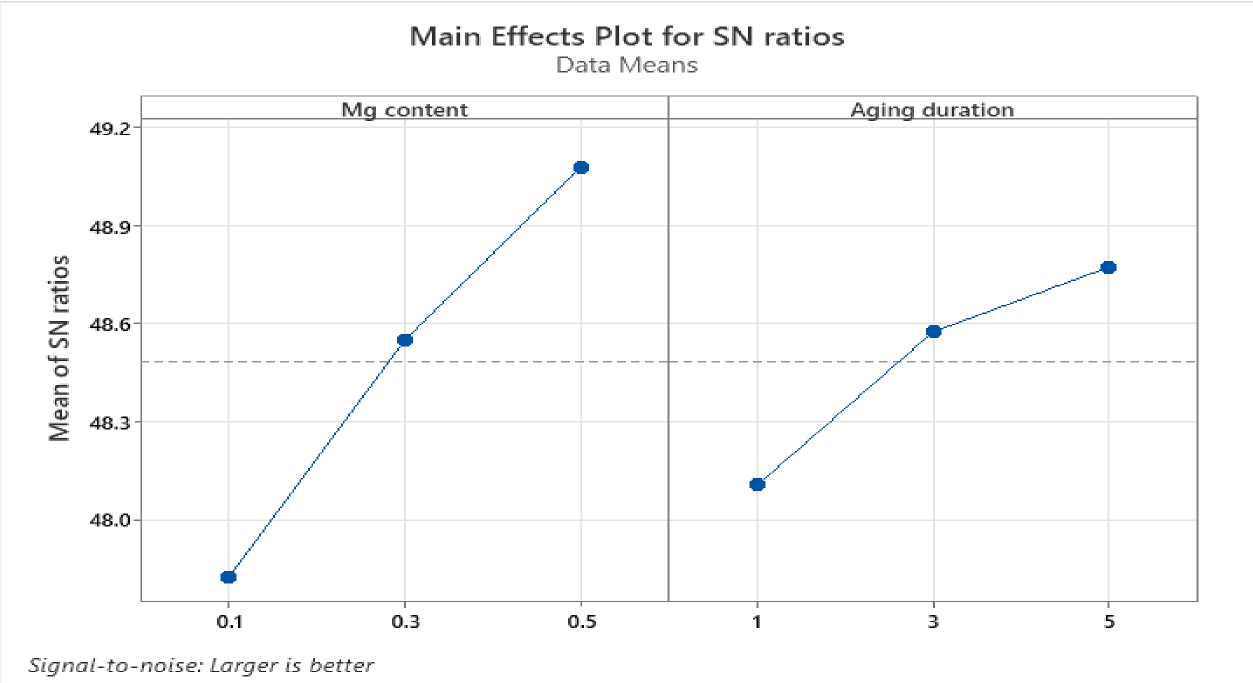


Figure 3.4.1: Main effects plot of control factors on the S/N ratio for (a) Yield Strength (YS), (b) Ultimate Tensile Strength (UTS)

Table 3.4.2: Main effects plot for S/N ratios of Aluminum alloy sample A356 with variousMg addition and various Artificial Aging duration

	Elongation (ETF)		Hardness	
Level	Mg content (wt%)	Aging duration (Hours)	Mg content (wt%)	Aging duration (Hours)
1	16.28	15.21	41.32	41.68
2	15.06	14.90	42.16	42.09

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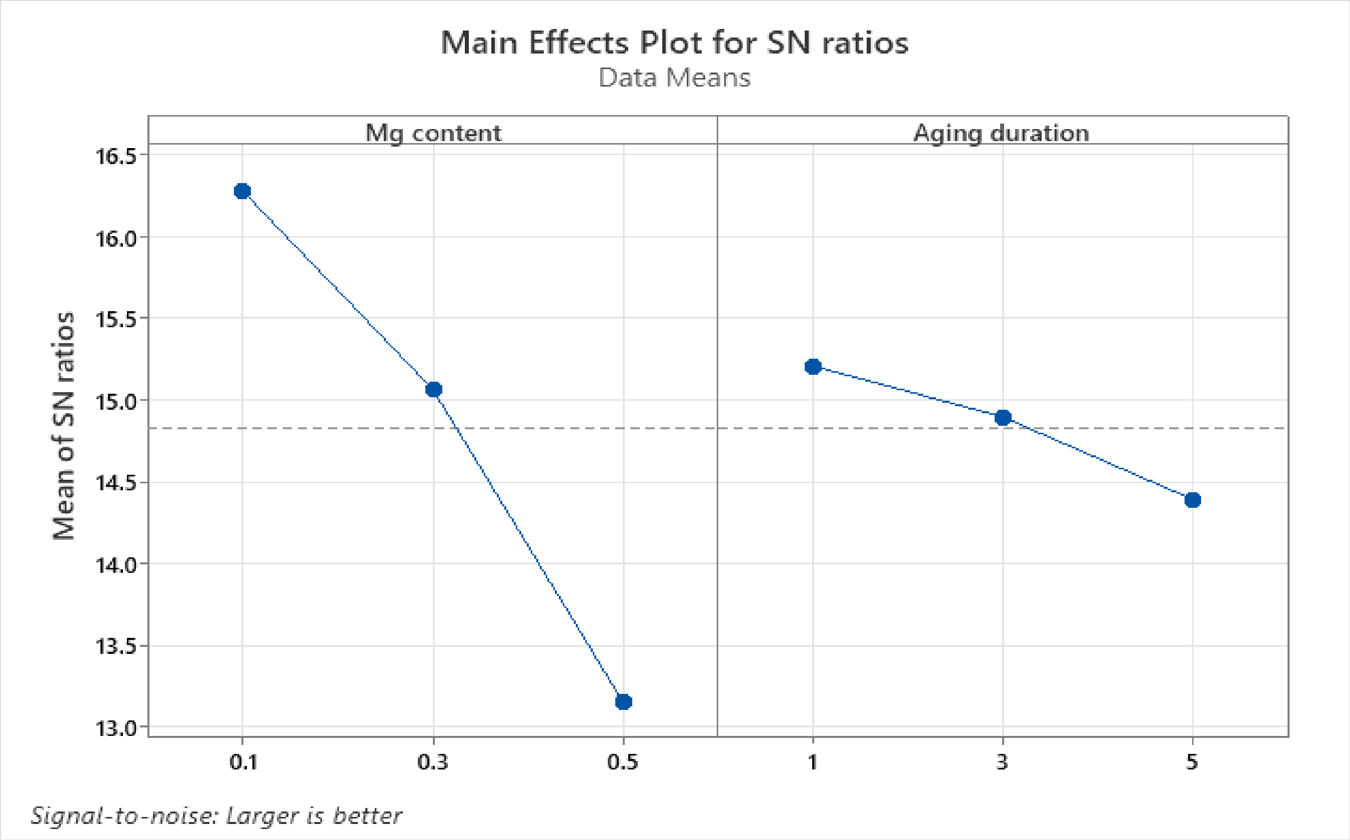
3	13.15	14.39	42.60	42.31
Delta	3.12	0.81	1.28	0.63
Rank	1	2	1	2



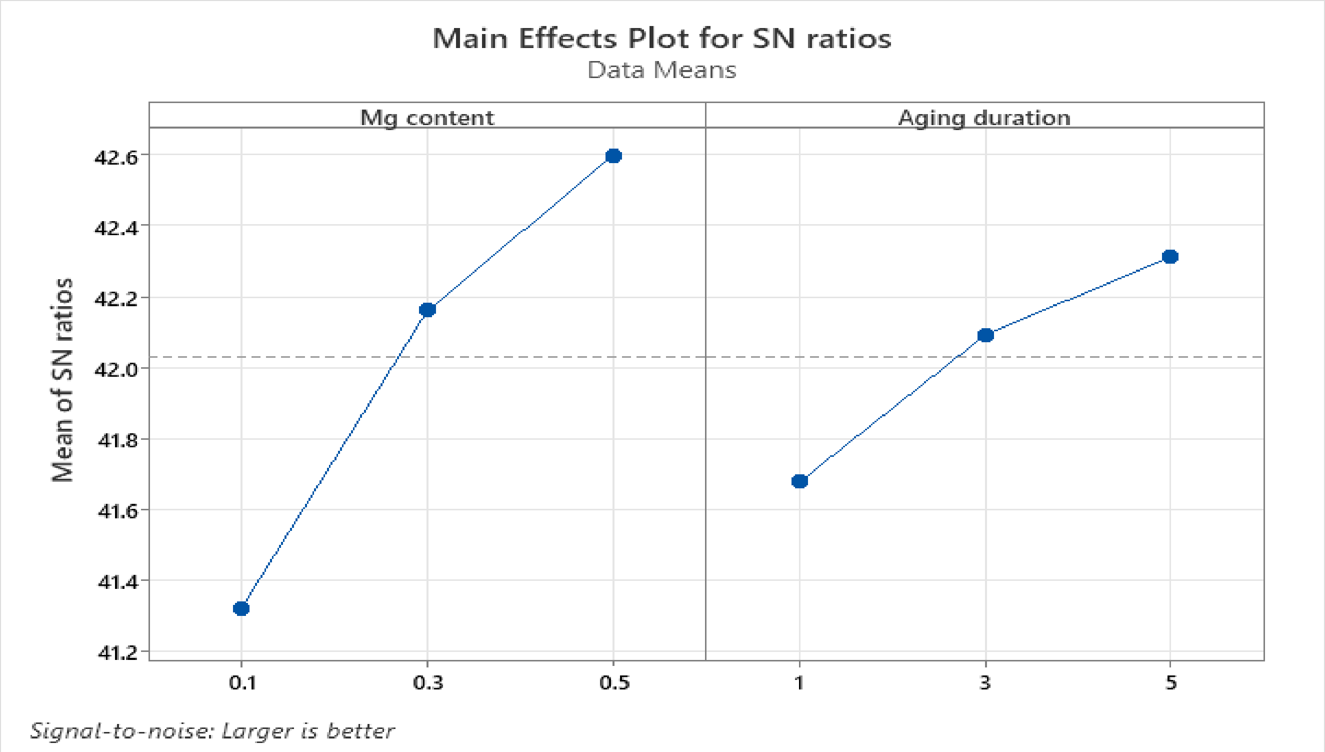


Figure 3.4.2: Main effects plot of control factors on the S/N ratio for (c) Elongation, and (d) Hardness

CONCLUSION

The effects of magnesium content and artificial aging duration on the microstructure and mechanical properties of thixoformed A356 alloys were successfully evaluated. Optical microscopy, SEM, and EDS analyses showed that Mg addition influenced the evolution of the α-Al matrix and eutectic silicon morphology after thixoforming and T6 heat treatment. A more refined and homogeneous microstructure was obtained with Mg addition, particularly at 0.3 wt.% Mg, where globular α-Al grains and uniformly distributed eutectic silicon particles were observed.

The mechanical properties improved with increasing Mg content and aging duration. The highest yield strength, ultimate tensile strength, and hardness values of 300.74 MPa, 375.87 MPa, and 140.00 HV, respectively, were obtained at 0.5 wt.% Mg after 5 h of artificial aging. These improvements are associated with precipitation strengthening by Mg_2Si phases and the refined microstructure produced through thixoforming. Nevertheless, the increase in strength and hardness was accompanied by a reduction in elongation, indicating the typical trade-off between strength and ductility observed in precipitation-hardened Al–Si–Mg alloys.

Based on the Taguchi analysis, Mg content was identified as the most influential factor affecting the mechanical performance of the alloy, followed by aging duration. The optimum parameter combination for achieving maximum strength and hardness was 0.5 wt.% Mg with 5 h of artificial aging. The results obtained in this work provide useful information for selecting suitable processing parameters for thixoformed A356 alloys and support their potential application in lightweight engineering and automotive components where high strength and hardness are required.

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