Development of a Medium-Strength Al-Mg-Si Alloy with Optimised Zirconium Addition

Kola Immanuel Raju[1], Viswanath Ammu[2], R. Anil Kumar[3], R. N. Chouhan[4] and Anupam Agnihotri[5]
1, 3. Scientist
2. Senior Scientist
4. Senior Principal Scientist
5. Director
Jawaharlal Nehru Aluminium Research Development & Design Centre, Nagpur, India
Corresponding author: immanuelkola@jnarddc.gov.in
https://doi.org/10.71659/icsoba2025-ch012

Abstract

Al-Mg-Si (6xxx series) aluminium alloys are widely used in extrusion due to their excellent balance of strength, toughness, and extrudability. The industry is increasingly shifting toward lightweight, medium to high-strength materials, particularly for automotive and defence applications, where aluminium extrusion alloys are favoured for their high strength-to-weight ratio and recyclability. Among aluminium alloys, the 6xxx series accounts for nearly 90 % of all extrusion products, as they offer superior extrusion speeds and surface quality compared to other extrudable alloy series. However, its strength limits its applicability, requiring improvements in mechanical properties for more demanding applications.

This study focuses on modification of a medium-strength Al-Mg-Si (AA6082 based) alloy with 0.4–0.5 wt.% zirconium (Zr) addition. The influence of Zr on grain refinement, precipitation behaviour, and mechanical property enhancement was investigated using microstructural characterization techniques such as optical microscopy, scanning electron microscopy, and phases formed using X-ray diffraction. Pilot-scale billet casting and extrusion of a 60 mm tube, followed by T6 heat treatment, demonstrated the effectiveness of Zr addition. The modified composition achieved an ultimate tensile strength (UTS) of 354 MPa and an elongation up to 16 %. This study highlights the potential of Zr addition in improving the performance of 6xxx series alloys, making them suitable for medium-strength, lightweight applications in various industries.

Keywords: Aluminium, 6xxx alloy, Extrusion, Lightweighting, Zr addition.

1. Introduction

6xxx series Aluminium alloys, comprising of Al-Mg-Si system are commercially popular in the automotive and construction industries. Owing to their favorable properties, they are now gaining traction in the defense and aerospace sectors as well [1–2]. Among the 6xxx series aluminium alloys, AA6082 is widely preferred for high-strength applications. This alloy contains magnesium and silicon, which enable precipitation hardening by forming Mg_2Si precipitates (β' and β''), while manganese and chromium contribute to dispersoid strengthening by forming α-Al (Mn, Cr) Si dispersoids. The final properties of the alloy are influenced by its chemical composition, casting conditions, and subsequent forming processes. Extrusion of Aluminium alloys is a high temperature forming process in which recrystallization of the microstructure is an inherent and essential part of the operation. Recrystallized microstructures tend to reduce the mechanical properties of Aluminium alloys. However, transition elements like zirconium and scandium are used as high-temperature recrystallization inhibitors by forming Al_3(Sc, Zr), aiding in grain refinement and enhancing the alloy performance.

Scandium, being a rare and expensive element, limits its widespread use. Consequently, zirconium (Zr) has been more extensively utilized, though typically restricted to a maximum of 0.3 wt.%. In this study, we explored the effects of adding over 0.4 wt.% Zr to the commercially available AA6082 alloy, aiming to investigate microstructural refinement and potential improvements in mechanical properties. In cast aluminium alloys, higher Zr additions are known to refine microstructure and improve properties. Building on this, we added over 0.4 wt.% Zr to wrought AA6082 to explore similar benefits. Jan et al. showed that 0.4–0.6 wt.% Zr in Al-Ni cast alloys promoted Al_3Zr nucleation, followed by dendritic α-Al growth [3]. Feng et al reported that the interatomic spacing values of interatomic spacing misfit and interplanar mismatch between Al_3 Zr and Al are very small, implying high grain refining efficiency of Al_3Zr in Al [4].

Birol et al. reported that the simultaneous addition of 0.13 wt.% Zr and 0.15 wt.% Cr enhances recrystallization resistance, which is attributed to the formation of Al (Cr, Mn, Fe) Si and (Al, $Si)_3Zr$ dispersoid particles [5]. Similarly, Schmid et al. observed that the addition of 0.2 wt.% Zr to the AA6082 alloy resulted in a 45 MPa increase in ultimate tensile strength (UTS), primarily due to suppressed recovery and recrystallization processes, owing to a higher dispersoid density [6].

Rakhmonov et al. [7] reported that the presence of a large volume of β″ precipitates, a smaller quantity of β′ precipitates, and fine dispersoids in the alloy containing 0.5 wt.% Mn led to a significant increase in yield strength at ambient temperature by 65–75 MPa under the T5 condition compared to the base alloy lacking dispersoids.

In the present study, Mn, Si, and Zr are incorporated to introduce additional strengthening mechanisms beyond conventional Mg_2Si precipitation hardening. The combined effect of these alloying elements and the associated strengthening mechanisms is evaluated through the tensile properties of the developed alloy. The objective is to synergize dispersoid and precipitate strengthening contributions from these additions to achieve a tensile strength exceeding 350 MPa.

2. Materials and Methods

Table 1 presents the target chemical compositions of the developed alloys from previous studies. The base alloy was designed to contain Mg and Si to facilitate the formation of θ-type precipitates, while Mn and Cr were incorporated to promote the formation of α-AlMnSi dispersoids. Additionally, Zr was added to form Al_3Zr dispersoids, contributing to enhanced thermal stability and mechanical properties.

Table 1. Chemical composition of the alloys melted.

Alloys	Zr	Si	Mn	Mg	Fe	Cr	Al (Wt.%)
Wt.%	0.45	1.1	0.91	0.91	0.18	0.25	Remaining

The alloy was prepared using an Inductotherm induction furnace equipped with a 25-kg capacity crucible. High-purity Al (99.8 %) served as the base metal, and alloying elements were introduced using master alloys such as AlMn10, AlCu30, AlZr5, AlCr10, and AlSi50. Pure magnesium (99.1 %) was added towards the end of the melting process to minimize oxidation losses. The melt temperature was maintained at 700 °C during alloying and the pouring temperature is maintained at 760 °C.

Degassing tablets were used to eliminate dissolved gases, and glass fiber filter paper was placed over the mold to trap non-metallic inclusions. Grain refinement was not employed owing to Zr-induced poisoning, which adversely affects the nucleating efficiency of standard grain refiners. The molten metal was poured into a preheated crucible at approximately 750 °C. The resulting

The addition of excess zirconium resulted in the formation of DO23-type $(Al, Si)_3Zr$ precipitates, which are incoherent with the α-Al matrix. These dispersoids contributed to grain boundary pinning through the Zener drag effect, thereby enhancing the strength of the alloy. The excess addition of silicon (Si) and manganese (Mn) further enhanced the strength of the developed alloy through the formation of Mn-rich dispersoids and Mg_2Si precipitates via age hardening. These combined effects significantly contributed to both the strength and elongation of the alloy.

Extrusion of the developed alloy facilitated the breakdown of primary intermetallics formed during casting. Furthermore, Zr precipitates effectively suppressed high-temperature grain growth, leading to microstructural refinement and improved mechanical strength. Thermodynamic simulations were validated through experimental casting of the alloy, where the addition of zirconium resulted in a tensile strength improvement of approximately 50 MPa. It is anticipated that utilizing a proper direct chill (DC) casting facility will lead to further strength enhancements, which will be explored in future work.

5. References

1. Yi-Cheng Gao et al., Research progress, application and development of high performance 6000 series aluminium alloys for new energy vehicles, *Journal of Materials Research and Technology,* Volume 32, September–October 2024, 1868-1900. https://doi.org/10.1016/j.jmrt.2024.08.018
2. The Main 6xxx Aluminium Alloys in Aircraft Industry, https://www.aircraftaluminium.com/a/the-main-6xxx-aluminum-alloys-in-aircraft-industry.html (Accessed on 14 June 2024).
3. Jan Šmalc et al., The impact of small Zr addition to Al–Ni cast alloy for elevated temperature applications, *Journal of Materials Research and Technology, Volume 32,* September–October 2024*,* 1928-1936. https://doi.org/10.1016/j.jmrt.2024.08.029
4. Feng Wang et al., The grain refinement mechanism of cast aluminium by zirconium, *Acta Materialia,* Volume 61, Issue 15, September 2013, 5636-5645. https://doi.org/10.1016/j.actamat.2013.05.044
5. Yucel Birol, Effect of Cr and Zr on the Grain Structure of Extruded EN AW 6082 Alloy. *Journal of Metals and Materials International*, 2014, Volume 20, 727–732.
6. Florian Schmid et al., Synergistic alloy design concept for new high-strength Al–Mg–Si thick plate alloys, *Materialia*, Volume 15, March 2021, 100997.
7. Jovid Rakhmonov et al., Effects of Al (MnFe)Si dispersoids with different sizes and number densities on microstructure and ambient/elevated-temperature mechanical properties of extruded Al–Mg–Si AA6082 alloys with varying Mn content, *Journal of Alloys and Compounds,* Volume 861, 25 April 2021, 157937.
8. Franc Zupanič et al., Microstructure and Properties of a Novel Al-Mg-Si Alloy AA 6086, *Metals* 2021, 11(2), 368. https://doi.org/10.3390/met11020368.
9. Juan-Ricardo Castillo-Sánchez et al., Investigation of silicon sublattice substitution within (Al, Si)3 Zr intermetallic via DFT simulations, *2023 IOP Conf. Ser.: Mater. Sci. Eng.* 1281 012055. https://doi.org/10.1088/1757-899X/1281/1/012055
10. Xiaoming Qian, Nick Parson and X.-Grant Chen, Effects of Mn addition and related Mn-containing dispersoids on the hot deformation behaviour of 6082 aluminium alloys, *Journal of Materials Science and Engineering: A,* Volume 764, 9 September 2019, 138253. https://doi.org/10.1016/j.msea.2019.138253
11. L. Lityńska-Dobrzyńska et al., Structure and properties of Al-Mg-Si alloys with Zr and Sc additions produced by melt spinning and twin rolling casting techniques, *Kovove Mater.* 48, 2010, 9-15, https://doi.org/10.4149/km_2010_1_9.