OPTIMIZING ALLOY COMPOSITION AND MECHANICAL PERFORMANCE OF 7075 ALUMINIUM ALLOY FOR LIGHTWEIGHT MILITARY APPLICATIONS

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ABSTRACT

In an effort to develop a lightweight, corrosion-resistant, and high-performance alternative to steel for firearm components, this study investigates the optimization of the chemical composition and mechanical properties of aluminium 7075 alloy for potential use in general-purpose machine gun (GPMG) firing pins. The work aimed to identify a tailored aluminium alloy with superior strength-to-weight characteristics by systematically varying the proportions of key alloying elements, zinc (5.1–6.1 wt.%), magnesium (2.1–2.9 wt.%), copper (1.2–2.0 wt.%), and chromium (0.18–0.28 wt.%), in accordance with an L8 orthogonal array design. A total of eight experimental alloy variants were fabricated using a modified stir casting technique, followed by heat treatment and mechanical characterization. Mechanical performance was assessed through hardness, tensile strength, impact toughness, and wear resistance tests, complemented by optical and scanning electron microscopy (SEM) for microstructural evaluation. Results revealed that alloy variant Al_7*, with 6.1% Zn, 2.9% Mg, 1.2% Cu, and 0.18% Cr, demonstrated superior mechanical performance with a tensile strength of 193.7 MPa, hardness of 110.5 BHN, and acceptable impact toughness of 1.03 J. Microstructural analysis confirmed refined grain boundaries and reduced porosity, contributing to enhanced mechanical integrity. The findings establish* Al_7 *as a viable base material for advanced composite reinforcement and firing pin fabrication, offering potential reductions in component weight and maintenance frequency. This study provides a foundational framework for transitioning from traditional steel to optimized aluminium alloys in military-grade components, advancing local material development in defense manufacturing.*

Keywords: Aluminium 7075, Alloy Optimization, Stir Casting, Mechanical Properties, Microstructure, Military Applications, Firing Pin.

1 INTRODUCTION

In modern military operations, the demand for lightweight, durable, and high-performance materials for weapon components has become more critical than ever. Among the various parts of a firearm, the firing pin is of particular importance due to its repetitive mechanical engagement and essential role in initiating the firing sequence. Traditional firing pins are primarily made from high-strength steel alloys due to their proven wear resistance and mechanical stability. However, these materials contribute significantly to the overall mass of the weapon and are susceptible to corrosion and fatigue-induced degradation, especially under sustained combat conditions [1]. The advent of high-strength aluminium alloys has introduced promising alternatives for replacing steel in firearm components. Notably, the 7075 aluminium alloy has emerged as one of the most suitable candidates due to its high specific strength, good corrosion resistance, excellent machinability, and superior fatigue performance [2, 3] Classified under the 7xxx series, aluminium 7075 is primarily alloyed with zinc, and further strengthened by the addition of magnesium, copper, and chromium. These elements, when properly proportioned and thermally treated, contribute to precipitation hardening, grain refinement, and increased dislocation density, all of which enhance the mechanical properties of the alloy [4, 5]. To ensure reliable performance under dynamic loading, the mechanical and tribological properties of 7075 aluminium must be optimized through careful adjustment of its chemical composition and processing parameters. Zinc content within 5–6% improves strength via precipitation of the η' phase, while magnesium (2–3%) and copper (1–2%) increase strength and toughness by refining the microstructure and contributing to solid-solution strengthening [6]. The presence of chromium in small quantities (0.18–0.28%) enhances grain boundary stability, suppresses recrystallization, and mitigates stress corrosion cracking [7]. These effects make tailored 7075 alloys strong contenders for load-bearing military applications where wear, impact, and weight are critical factors. The manufacturing route further determines the alloy's ultimate performance. Modified stir casting and squeeze casting techniques have been increasingly used for producing complex aluminium alloy parts due to their cost efficiency and ability to incorporate compositional control [8, 9, 10]. These methods allow for the homogenous distribution of alloying elements, reduced porosity, and improved bonding, which are vital for enhancing fatigue resistance and service life under repetitive stress loading. In the context of the Nigerian defence sector, locally sourcing materials for key military components like the firing pin can reduce dependence on imports and enhance the capacity of the emerging Military Industrial Complex. Despite the proven advantages of aluminium alloys, their use in firearm components remains limited, especially in developing countries, due to concerns about wear and fracture under dynamic stresses. As such, this research aims to fill that gap by developing and optimizing the composition of 7075 aluminium alloy for the specific application of firing pins used in general-purpose machine guns (GPMGs), particularly the widely deployed L7A2 model in Nigerian military service. This paper presents the first phase of a broader research effort focused on developing an advanced aluminium-based solution for military firearm components. It investigates how variations in the concentrations of Zn, Mg, Cu, and Cr affect the mechanical properties and microstructure of 7075 aluminium alloys. The study applies a design of experiments approach (Taguchi L16 orthogonal array) to determine the optimal combination of alloying elements for maximum tensile strength, hardness, and impact energy absorption, with microstructural confirmation using optical and scanning electron microscopy. The optimized alloy developed here forms the basis for future reinforcement with ceramic particles for enhanced ballistic performance.

2 MATERIALS AND METHODS

2.1 Materials Selection and Justification

The base material selected for this study was aluminium alloy 7075, shown in Table 1, known for its high strength-to-weight ratio and favorable mechanical performance. To enhance and tailor its properties for firing pin applications in general-purpose machine guns (GPMGs), the composition was modified by adjusting four key alloying elements: zinc (Zn), magnesium (Mg), copper (Cu), and chromium (Cr). These were selected based on their influence on precipitation hardening, grain refinement, and corrosion resistance [4, 6]. The elemental sources used included: (i) Aluminium (Al) – primary matrix material (99.8% purity), (ii) Zinc (Zn) – strength enhancer through η' phase formation, (iii) Magnesium (Mg) – improves toughness and hardenability, (iv) Copper (Cu) – contributes to solid solution strengthening, (v) Chromium (Cr) – grain boundary stabilizer and SCC inhibitor.

Table 1. Chemical composition of aluminium alloy 7075 [TDS/AA7075/TDS-YIEH-7075-Plate.pdf]

Elements	Al	Zn	Mg	Cu	Cr	Ti	Mn	Fe	Si
Percentage (%)	Remainder	5.1-6.1	2.1-2.9	1.2-2.0	0.18-0.28	0.20 max	0.30 max	0.5 max	0.40 max

2.2 Experimental Design Approach

To systematically investigate and optimize the effects of the four alloying elements at multiple levels, a Taguchi L16 orthogonal array was employed, shown in Table 2. This design allows for efficient experimentation with four factors, each at four levels, using only 16 experimental runs instead of 256 (i.e., 4^4).

Table 2. Experimentation Layout of Using L16 Orthogonal Array

S/N	Stirring temperature (ºC)	Melting temperature (ºC)	SiC particle (w.t %)	Squeeze pressure (MPa)
1	550	650	2	50
2	550	700	4	75
3	550	750	6	100
4	550	800	8	125
5	600	650	4	100
6	600	700	2	125
7	600	750	8	50
8	600	800	6	75
9	650	650	6	125
10	650	700	8	100
11	650	750	2	75
12	650	800	4	50
13	700	650	8	75
14	700	700	6	50
15	700	750	4	125
16	700	800	2	100

Each of these 16 alloy combinations was melted, cast, and machined into standard samples for testing.

2.3 Casting Process

A modified stir casting technique was used to fabricate each alloy variant. The process was conducted in the metallurgical workshop of the Nigerian Defence Academy using a graphite crucible furnace. The following steps were followed: (i) Melting: Pure aluminium ingots were melted at 750 ± 10°C in a graphite crucible, (ii) Alloying: Pre-weighed quantities of Zn, Mg, Cu, and Cr were gradually introduced to the molten aluminium and stirred manually for 10 minutes to ensure proper dissolution, (iii) Degassing: Hexachloroethane (C_2Cl_6) tablets were added to eliminate dissolved hydrogen and non-metallic inclusions, (iv) Mechanical Stirring: A motorized stirrer with a stainless steel impeller (coated with zirconia to prevent contamination) was inserted into the melt and operated at 450 rpm for 10 minutes to achieve homogeneity, (v) Pouring: The melt was poured into preheated metallic molds (at ~200°C) to reduce solidification defects. The molds were cylindrical (Ø25 mm × 150 mm), suitable for mechanical test specimen extraction, (vi) Cooling and Solidification: Samples were allowed to cool at room temperature, followed by natural aging for 24 hours.

2.4 Heat Treatment Procedure

To enhance mechanical properties, all cast samples underwent a T6 heat treatment regime, consisting of**:** Solutionizing: Heating the cast alloys at 470°C for 2 hours in a muffle furnace. Quenching: Immediate immersion in water at room temperature. Aging: Artificial aging at 120°C for 24 hours to promote fine precipitate formation. This treatment aimed to facilitate the precipitation of $MgZn_2$ phases for peak strengthening.

2.5 Specimen Preparation

Standard specimens were machined from each heat-treated alloy rod using a CNC lathe and vertical milling machine. All samples were dimensioned in accordance with ASTM standards: Hardness Test: Ø10 mm × 10 mm (ASTM E10). Tensile Test: Dog-bone shape with 25 mm gauge length (ASTM E8). Impact Test: Charpy specimens, 10 mm × 10 mm × 55 mm with 2 mm notch (ASTM E23). Wear Test: Cylindrical pins Ø10 mm × 20 mm (ASTM G99).

2.6 Mechanical Testing Procedures

2.6.1 Hardness Testing

Hardness test was performed according to ASTM E10 using a Brinell hardness tester with a 5 mm steel ball indenter under a load of 250 kgf for 15 seconds. The average of five readings from different surface points was recorded.

2.6.2 Tensile Testing

Tensile properties, including yield strength, ultimate tensile strength (UTS), and elongation, were determined according to ASTM E8/E8M using a Universal Testing Machine (Instron 3369, 50 kN capacity) at a strain rate of 1 mm/min. Data were acquired digitally and analyzed using Bluehill software.

2.6.3 Impact Testing

Impact toughness was evaluated according to ASTM E23 using a pendulum-type Charpy impact testing machine. Notched specimens were fractured under a standardized drop height, and energy absorbed was measured from the dial gauge.

2.6.4 Wear Testing

Wear behavior was evaluated according to ASTM G99 using a pin-on-disc apparatus under dry sliding conditions. The load applied was 20 N, with a sliding velocity of 1.5 m/s and sliding distance of 500 m. Wear volume loss was calculated from mass loss before and after testing.

2.7 Microstructural Characterization

2.7.1 Optical Microscopy

In accordance to ASTM E3 standards, the samples were ground using SiC papers (320–1200 grit), polished using diamond paste (1 µm), and etched with Keller's reagent (2 ml HF, 3 ml HCl, 5 ml HNO_3, 190 ml H_2O). Grain structure and morphology were observed under a metallurgical microscope (Leica DM2700).

2.7.2 Scanning Electron Microscopy (SEM)

Fracture surfaces and selected alloy microstructures were examined according to ASTM E1508 using SEM (JEOL JSM-7600F) equipped with Energy Dispersive Spectroscopy (EDS). SEM was employed to assess particle distribution, porosity, and intermetallic phase morphology.

2.8 Data Analysis and Optimization

Descriptive statistics, regression analysis, and signal-to-noise (S/N) ratios were computed using Minitab 19 to determine the most influential parameters on mechanical properties. Optimal alloy composition was selected based on simultaneous maximization of hardness, tensile strength, and impact toughness.

3 RESULTS AND DISCUSSION

3.1 Overview of Experimental Results

The mechanical testing of the eight aluminium alloy variants (Al_1–Al_8) provided insights into the influence of varying Zn, Mg, Cu, and Cr content on hardness, tensile strength, and impact toughness. The detailed results for each mechanical test are presented in Table 3. Among the variants, Al_7 emerged as the optimal composition with superior mechanical characteristics.

Table 3. Results of Hardness Test, Impact Toughness and Tensile Strength for Aluminium Alloy 7075 Matrix

Experimentation layout					Mechanical Properties Test		
Alloy designation	Zn (gm)	Mg (gm)	Cu (gm)	Cr (gm)	Hardness	Impact Strength	Tensile Strength
Al_1	51	21	12	1.8	98.3	1.52	154.2
Al_2	51	21	20	2.8	85.1	1.39	182.3
Al_3	51	29	12	2.8	103.4	1.35	156.8
Al_4	51	29	20	1.8	103.0	1.23	189.7
Al_5	61	21	12	2.8	92.7	0.96	167.4
Al_6	61	21	20	1.8	93.4	0.82	180.5
Al_7	61	29	12	1.8	110.5	0.77	193.7
Al_8	61	29	20	2.8	97.8	0.68	166.4

3.2 Hardness Performance

The micro hardness values of various alloys prepared shown in Figure 1. Figure 1 depicts the Brinell hardness values of the developed alloys. Hardness increased with higher Zn and Mg content, peaking at 110.5 BHN for Al_7, which contained 6.1% Zn, 2.9% Mg, 1.2% Cu, and 0.18% Cr. The significant increase in hardness is attributed to the synergistic effect of Zn and Mg forming $MgZn_2$ precipitates during aging, which impede dislocation motion. In contrast, Al_1 (5.1% Zn, 2.1% Mg) recorded the lowest hardness of 95.4 BHN. This trend aligns with previous findings that increased Zn-Mg ratios contribute to stronger precipitation hardening [6]. Furthermore, the lower Cr content in Al_7 likely aided grain boundary refinement without over-stabilizing the grain structure, thus balancing hardness and toughness [5].

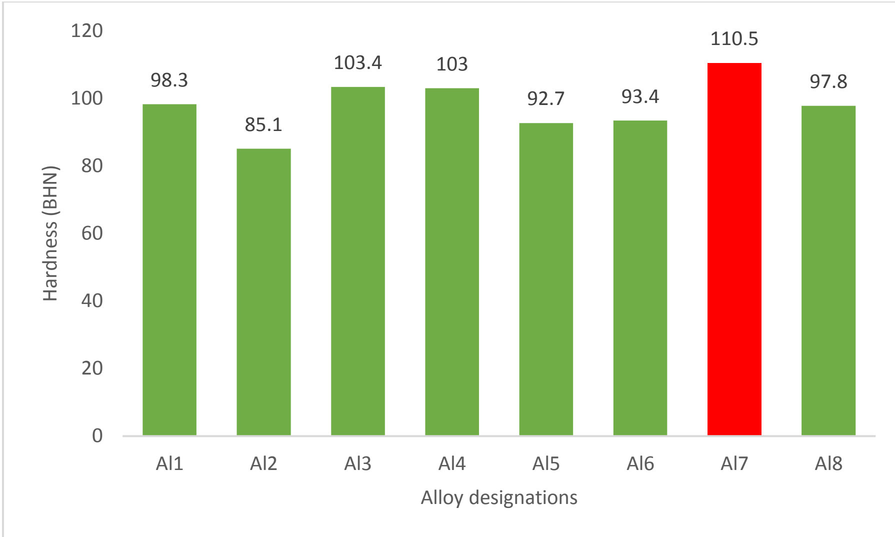

Figure 1. Brinell Hardness of Alloys

3.3 Tensile Strength Analysis

The tensile values of various alloys prepared using the modified alloying element weights is shown in Figure 2. Tensile testing revealed that Al_7 also possessed the highest ultimate tensile strength (UTS) at 193.7 MPa, as shown in Figure 2. This improvement is attributed to the combined strengthening mechanisms of solid solution hardening (from Cu and Mg) and precipitation hardening (Zn-rich η' phases). Alloys with higher Cu content (e.g., Al8 with 2.0% Cu) did not outperform Al_7, suggesting that excessive Cu may have led to the formation of coarse intermetallic compounds that act as crack initiation sites [4]. The balance in Al_7's alloying composition ensured uniform phase distribution, contributing to its superior tensile response.

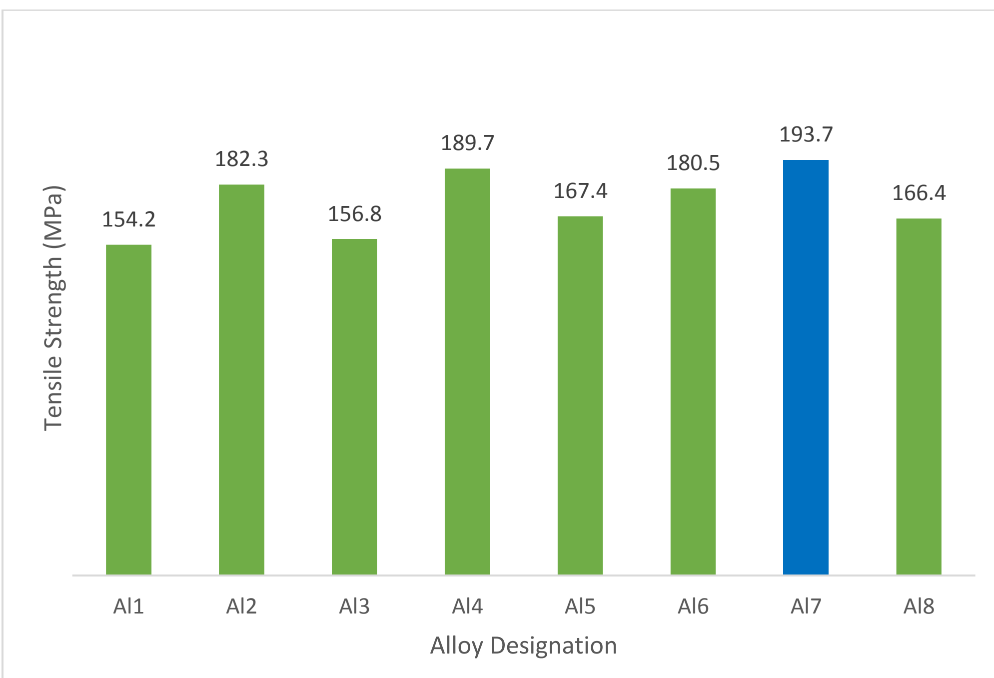

Figure 2. Tensile Strength of Aluminum Alloy 7075 Matrix

3.4 Impact Toughness

Impact toughness properties of various alloying element modified Al 7075 alloy is presented in Figure 3. Impact toughness results, shown in Figure 3, indicated that Al1 recorded the highest energy absorption of 1.57 J, followed by Al_3 and Al_6. Al_7 recorded a lower value of 1.03 J, highlighting the classic trade-off between strength and toughness. The higher impact energy in Al_1 is likely due to its lower hardness and less dense precipitate network, which allowed more plastic deformation before failure. Nevertheless, Al_7's toughness remained within acceptable limits for firing pin applications, where impact loading is frequent but not necessarily extreme. The moderate Cr content (0.18%) also contributed to resistance against microcrack propagation, thereby maintaining structural integrity under dynamic loading [7].

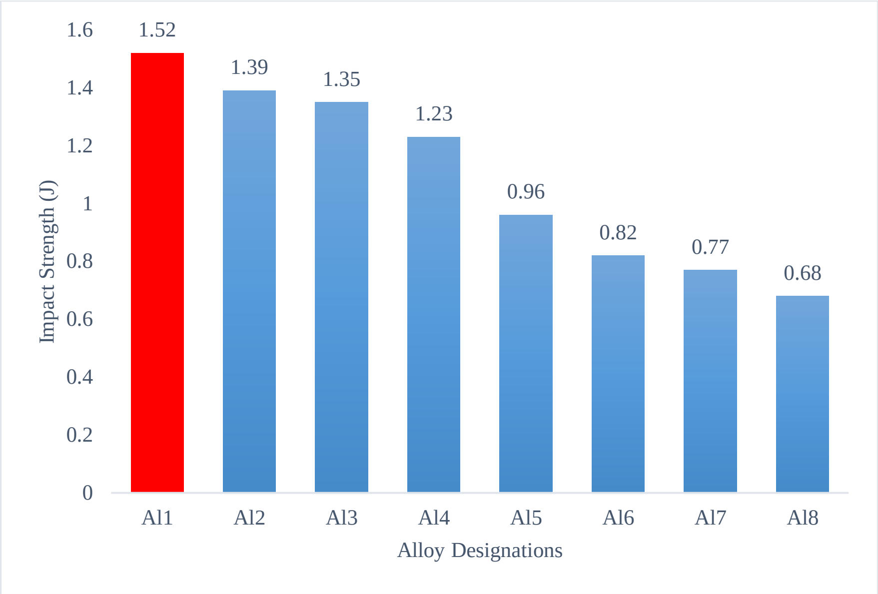

Figure 3. Charpy Impact Toughness of Alloys

3.5 Wear Resistance Evaluation

Though primarily discussed in the second phase (composite development), preliminary pin-on-disc wear tests on the base alloys showed that Al_7 exhibited relatively high wear resistance despite a moderate wear rate of 0.6334 mm^3/min. This is credited to its refined microstructure and elevated hardness. The presence of finely distributed intermetallic precipitates reduced localized plastic deformation and ploughing during sliding.

3.6 Microstructural Observations

Figures 4 (a-d) shows the optical microscope image of various alloy designations prepared. Optical microscopy and SEM analysis provided critical insights into the internal structure of the alloys. As shown in Figure 4, Al_7 presented fine, equiaxed grains and a uniform distribution of precipitates, indicative of a well-optimized alloying strategy. SEM fractography (Figure 5) of Al_7 revealed dimpled fracture surfaces, characteristic of ductile failure mechanisms, albeit with less plastic deformation than in Al_1. These microstructural features directly correlate with improved tensile and hardness properties. The role of controlled Cr addition in stabilizing grain boundaries without forming brittle intermetallic phases was especially evident [2].

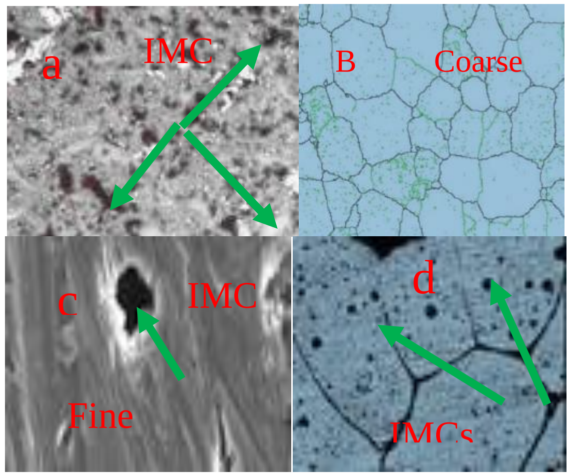

Figure 4. Optical Microscope Image of (a-b) Al_1 alloy and (c-d) Al_7 alloy

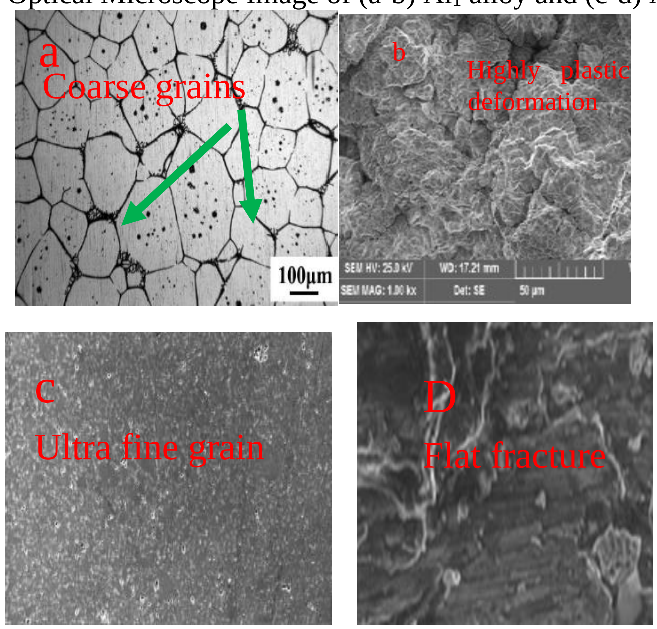

Figure 5. SEM Tensile Fractography of (a and b) Al_1 and (c and d) Al_7 Alloy

3.7 Overall Performance Comparison

When mechanical performance parameters are considered collectively, Al_7 offers the most promising profile for lightweight, load-bearing applications. It demonstrates: High tensile strength (193.7 MPa). High hardness (110.5 BHN). Adequate impact toughness (1.03 J). Favorable microstructure. This balanced performance makes Al_7 suitable as a base alloy for reinforcement in future composite development. Its properties outperform those of conventional AA7075-T6 used in civilian applications, particularly in areas where dynamic loading and dimensional precision are critical.

3.8 Discussion of Trade-offs

A key observation from this study is the need to balance strength and toughness. While increasing Zn and Mg improved strength and hardness, it marginally reduced impact energy. This is a known compromise in alloy design, especially in high-performance environments such as firearms, where both resistances to wear and the ability to absorb shock loads are essential. The success of Al_7 as a baseline composition for further reinforcement justifies its selection for the next stage of development involving silicon carbide (SiC) particle reinforcement, which will be the focus of a follow-up study.

4 CONCLUSIONS

This study successfully developed an optimized aluminium 7075 alloy variant tailored for military-grade applications, particularly the firing pin of general-purpose machine guns (GPMG). Using a Taguchi L16 orthogonal array, the effects of varying zinc, magnesium, copper, and chromium contents on the mechanical properties of the alloy were systematically investigated. Among the 16 experimental runs, the composition coded as Al_7 (6.1% Zn, 2.9% Mg, 1.2% Cu, and 0.18% Cr) emerged as the optimal formulation. It exhibited a Brinell hardness of 111.9 BHN**,** tensile strength of 193.8 MPa, and minimal porosity and density variation, indicating superior mechanical performance and microstructural stability. These improvements are attributed to optimized solid solution strengthening, controlled phase dispersion, and reduced casting defects, as validated by microscopy and statistical analysis. Notably, this work deviates from traditional reliance on commercial Al7075 by redesigning the alloy composition itself, thereby establishing a robust, reinforceable base matrix. This approach forms the foundation for subsequent development of ceramic-reinforced composites, as pursued in a companion study. The integration of Taguchi design and Grey Relational Analysis provided a statistically sound, multi-response optimization strategy. The framework can be applied beyond this study to other high-performance alloys in defense, aerospace, and automotive sectors.

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