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OPTIMIZATION OF SQUEEZE CASTING PROCESS PARAMETERS ON AA8011 BASED HMMCS UNDER NaCl ENVIRONMENT

The present research computes the impact of process parameters of squeeze casting on AA8011/Si_3N_4/ZrO_2 Hybrid Metal Matrix Composites (HMMCs). The melting temperatures (700 to 800°C), Si_3N_4 + ZrO_2 (5 to 15 wt.%) and stirring speed (550 to 750 rpm) were selected as parameters for input. The AA8011 HMMCs were fabricated as per the combination of L_9 input parameters, and they were subjected to Energy Dispersive X Ray Analysis (EDAX) and Scanning Electron Microscope (SEM) tests to compute the presence of wt.% of matrix and reinforcements and to confirm the uniform distribution of Si_3N_4 + ZrO_2 in matrix AA8011. Besides, fabricated composites were subjected to tensile and micro hardness test after subjecting to Salt spray test (3.5% NaCl, 120 hours exposing duration and 1.2 kg/cm^2 spray pressure) for computing the Ultimate Tensile Strength (UTS) and micro hardness. The Grey Relational Analysis (GRA) was employed for optimizing process parameters of squeeze casting on AA8011 based composites. The EDAX test results confirms that the increasing wt.% of silicon nitride and zirconium dioxide reinforcements enhances the presence of elements such as Si, N, Zr and O in manufactured composites. The higher dense reinforcements are uniformly distributed in the matrix AA8011 at the blend of input parameters of AA8011 composite. Based on the Taguchi approach, the medium level of melting temperature (750°C), higher level of wt.% of Si_3N_4 and ZrO_2 reinforcements (15 wt.%) and higher level for speed of stirring (750 rpm) is the optimized combination parameters of squeeze casting for UTS and microhardness are identified. Based on the GRA technique, the influencing sequence are identified for squeeze casting process parameters are wt.% of Si_3N_4 + ZrO_2 reinforcements, stirring speed and melting temperature for both UTS and Micro hardness. The contribution percentage of melting temperature, wt.% of reinforcements and stirring speed are 20.26%, 48.102% and 29.23% respectively. The confirmation test was done for optimized input parameters and it exhibit 56% higher UTS and 48.2% higher micro hardness of than AA8011 matrix material.

Keywords: AA8011; ZrO_2, Si_3N_4; Squeeze casting; UTS; Micro hardness

1. Introduction

Aluminium alloy has become the material of choice for many different industrial and engineering applications in the last few decades because of its remarkable intrinsic properties [1,2]. HMMCs have developed into superior materials, particularly for applications related to transportation, thermal, and structural factors. These materials have proven to be an effective substitute for ferrous-based components in applications where the highest level of wear resistance is required [3-5]. Aluminum composite materials are significantly appreciated for their exceptional resistance to corrosion and lightweight characteristics, making them useful in a variety of automotive and aerospace applications. The production of fan blades, cylinder blocks, brake linings, aircraft engines, pistons, clutches and brake drums are all included in these applications [6,7]. The size of reinforcement particles, bonding strength and bond potency are some of the factors that affects the wear resistance in the automotive application. The properties of AMCs have been improved through a sustained and continuous effort in recent years. In order to maximize the effectiveness, different strengthening particles, such as Zirconium Dioxide (ZrO_2), Aluminium Oxide (Al_2O_3), Titanium Carbide (TiC), Chromium Oxide (Cr_3C_2) and Boron Carbide (B_4C) [8-13] are incorporated. HMMCs based on aluminum are produced using a variety of fabrication techniques. Common methods used are squeeze, stir casting, and spray deposition. The mechanical properties are improved to a great extent by the chosen fabrication techniques. However, problems with uneven particle dispersion, porosity, and poor wettability have plagued conventional fabrication techniques, negatively impacting HMMC performance [14-15]. Based on the components that go into their alloying, a variety of aluminum alloys, ranging from

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1xxx to 8xxx are fabricated. AA8011, which includes Al-Fe alloys, has become a vital material for structural applications in modern engineering applications [16]. Incorporating B_4C into the AA8011-1.5% nano B_4C composite leads to enhanced hardness, tensile strength, and fatigue resistance in comparison to the unalloyed matrix [17]. As the proportion of TiO_2 particles increased, there was a simultaneous widening of the full width at half maximum of XRD peak, accompanied by enhancements in microhardness, ultimate tensile strength, and yield strength of the composite [18]. The inclusion of 1 wt.% graphene and 6 weight percent B_4C reinforcements in the AA8011 Aluminum alloy matrix led to notable improvements in the tensile strength (19.8%), hardness (36.1%), and wear resistance (50.9%) of the composite specimens [19]. The results suggest that the sample reinforced with 20 weight percent of cow horn displayed the most significant enhancements in yield strength, ultimate tensile strength (UTS), and hardness, with improvements of 57%, 52.6%, and 54.4%, respectively. Additionally, the sample reinforced with 15 wt% cow horn demonstrated a 52.6% increase in hardness compared to the control sample, while a 10 wt.% cow horn reinforcement led to a 61% enhancement. These findings underscore the significant contribution of utilizing agro-waste materials in composite development, as validated by the results presented [20]. According to the test outcomes, the AA8011 composite with 0.5 weight percent graphene exhibited enhanced mechanical characteristics, specifically in terms of hardness and tensile strength, surpassing those of the pure AA8011 matrix [21]. Employing a liquid metallurgy technique, a series of five steps were undertaken to fabricate hybrid composites featuring varied particulate compositions ranging from 0% to 20%. Comparative analysis against the unreinforced AA8011 revealed a more significant enhancement in both hardness and ultimate tensile strength of the composite [22]. The in-situ formed TiB_2 reinforcements showcased peak hardness at 55.03 HV and maximum tensile strength at 158.2 MPa when incorporated at 8 weight percent. Conversely, a percentage of elongation 7.2% was observed with 4 weight percent of TiB_2 [23]. The mechanical performance of the silicon nitride and zirconium dioxide reinforced hybrid composites, encompassing wear resistance and microhardness, is evaluated. Optimal conditions for minimum wear and enhanced microhardness are observed at a reinforcement percentage of 6, stir speed of 400 rpm, stir time of 30 minutes, and molten temperature of 900°C. Wear analysis indicates that the percentage of reinforcement contributes significantly (7.06%) to wear properties. In contrast, the molten temperature parameter is identified as the most influential factor (11.15% contribution) in the analysis of microhardness [24]. The findings of this investigation reveal that machining 17-4 PH stainless steel with a 0.4 mm cutting nose radius, in comparison to a 0.8 mm cutting nose radius, leads to reductions of 2.35%, 28.89°C, and 1.18% in average cutting force, cutting temperature, and tool wear values, respectively. Moreover, increasing the cutting tool's nose radius yields an average improvement of 47.48% in surface quality. Through multi-response optimization, the optimal milling parameters for multiple output parameters are identified as 0.8 mm cutting nose radius, 70 m/min cutting speed, and 0.06 mm/tooth [25]. After conducting the experiments, an analysis was performed on vibration, noise radious, cutting temperature, and surface roughness values, revealing that the PVD-coated cutting tool exhibited the most favourable performance. Furthermore, Taguchi optimization was employed to scrutinize the experimental results, determining the turning parameters associated with the lowest Ra value. Additionally, ANOVA analysis was utilized to identify the turning parameters and effect ratios that exerted the most significant influence on Ra [26]. By employing analysis of variance (ANOVA) alongside the experimental data, the impact levels of the control factors on surface roughness were determined. Additionally, Taguchi analysis revealed that employing a wet cooling technique and a cutting speed of 120 m/min yielded the most favorable outcomes concerning surface roughness [27]. Determined the sequence of important parameters for process of heat treatment that affect microhardness and wear resistance by utilizing GRA method [28]. The coefficient of friction (COF) and Wear Rate (WR) of the AA8011 composites were predicted using a Taguchi combined with TOPSIS approach. According to the experimental results, sliding velocity and applied load contributed 12.84% and 26.32% respectively to COF and WR while the reinforcement content had the largest impact, accounting for 55.06% of the total [29]. In the micro hardness test of AA8011 based composites, the volume fraction of hybrid ZrB_2-Si_3N_4 particulates and hardness are positively correlated [30].

From the earlier research, it is confirmed that no research has been done on the optimization on squeeze casting process parameters of AA8011 based composites and also no investigation was made to study the behavior of AA8011 based composites under corrosive environments.The main difference from earlier research on AA8011-based composites lies in the specific scope and focus of this study. While prior studies might have examined diverse topics such as applications, fabrication techniques, and material properties of AA8011 composites, they often overlooked the influence of specific environmental factors like NaCl. Therefore, this research likely represents a novel or more targeted investigation within the broader field of AA8011-based composite material research. In this research, optimization on squeeze casting process parameters of AA8011/Si_3N_4/ZrO_2 HMMC by accounting UTS and YS under NaCl environment with the help of GRA technique.

2. Materials and methods

2.1. Materials

In this research, AA8011 was selected as material because of its higher corrosion resistance, UTS, hardness and high S/W ratio for fabricating the components for automobile, aerospace and marine applications. The AA8011 was acquired from Chennai Metals and Powders Company, Trichy, Tamil Nadu, India in the form of round rod and its chemical composition is displayed in TABLE 1.

TABLE 1

Chemical composition of AA8011

Si	Mg	Cu	Mn	Ti	Na	Zn	Fe	Pb	B	Al
0.46	0.47	0.14	0.09	0.01	0.01	0.22	0.61	0.01	0.01	97.86

The Silicon Nitride and Zirconium Dioxide were selected as reinforcements due to their higher UTS, corrosion resistance and hardness. Incorporating ZrO_2 and Si_3N_4 into the aluminium matrix enhances the composite material's hardness due to their high hardness values. Their exceptional wear resistance attributes contribute to improved wear resistance in the composite, making it suitable for applications where wear is a concern. Silicon nitride, in particular, stands out for its significant strength and toughness, bolstering the overall strength and durability of the composite material. Both ZrO_2 and Si_3N_4 exhibit strong thermal stability, rendering them suitable for applications involving elevated temperatures. Furthermore, their chemical inertness enables them to endure corrosive substances and harsh environments while retaining their properties. The ZrO_2 and Si_3N_4 reinforcements were procured from Sigma Aldrich through Subra Scientific Company, Chennai, Tamil Nadu. The reinforcements were purchased in the form of powder with an average particle size of 10 µm. The AA8011, ZrO_2 and Si_3N_4 were purchased with the purity 99.8%, 99.9% and 99.9% respectively. The properties of matrix and reinforcements are displayed in TABLE 2.

The SEM image of ZrO_2 and Si_3N_4 is displayed in Fig. 1. The average particle size of ZrO_2 and Si_3N_4 reinforcements was confirmed with the usage of Particle Size Analyzer.

2.2. Fabrication of composites

Squeeze casting is a casting process that combines elements of both casting and forging processes, offering advantages over traditional casting methods such as gravity casting or pressure die casting. Squeeze casting involves injecting molten metal into a preheated die cavity and applying high pressure (usually through hydraulic force) during solidification. This pressure helps to eliminate porosity and improve material density, resulting in higher mechanical properties compared to traditional casting methods. In contrast, other casting processes like gravity casting rely solely on gravity to fill the mold cavity, while pressure die casting uses high pressure to force molten metal into the mold cavity. Squeeze casting results in finer grain structure and reduced porosity compared to conventional casting methods. This leads to improved mechanical properties such as higher strength, better fatigue resistance, and improved dimensional accuracy in the final product. The application of pressure during squeeze casting ensures uniform distribution of reinforcing materials within the metal matrix, leading to improved mechanical properties and enhanced performance of the composite material.

TABLE 2

Properties of AA8011, Si_3N_4 and ZrO_2

Material properties	AA8011	Si_3N_4	ZrO_2
Melting temperature °C	675	1900	2715
Tensile strength MPa	115	700	711
Poisson's ratio	0.33	0.28	0.3
Specific heat J/g °C	0.9	0.71	0.42
Young's modulus GPa	69	297	200
Density g/cm^3	2.8	3.44	5.68
Thermal conductivity W/cm/ °C	2.1	0.032	0.017
Hardness VHN	87	653	1350

The choice of the squeeze casting process for manufacturing the AA8011/ZrO_2 and Si_3N_4 Hybrid Metal Matrix Composites (HMMCs) was based on its ability to ensure a uniform distribution of reinforcements and minimize porosity. The corrosion resistance, mechanical and properties of squeeze casted composites were mainly depending on the selection of process parameters of squeeze casting. Hence, the use of well-tailored squeeze casting parameters results in composites displaying optimal mechanical and corrosion properties and so the use of well-tailored squeeze casting parameters is needed for fabricating AA8011. The melting temperature (700, 750 and 800°C), stirring speed (550, 650 and 750 rpm) and wt.% of Si_3N_4 + ZrO_2 (5, 10 and 15) were selected as input parameters [31-33].

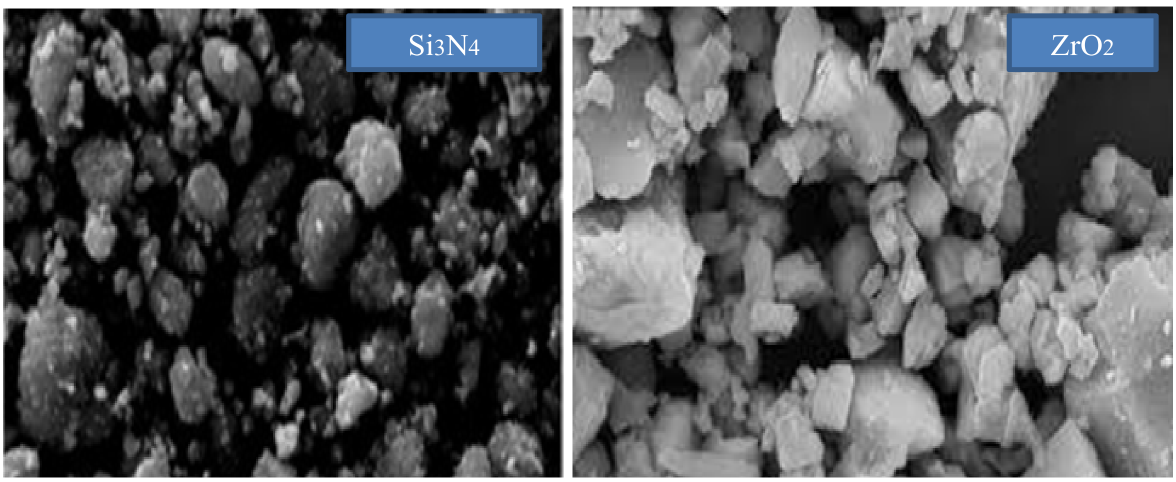

Fig. 1. SEM image of Si_3N_4 and ZrO_2 with 1 µm

An equivalent ratio was employed for adding Si_3N_4 and ZrO_2 reinforcements. Selecting the right melting temperature (such as 700°C, 750°C, or 800°C) is crucial for fine-tuning the squeeze casting process parameters for AA8011 HMMCs. This choice is essential to attain the desired material properties and enhance manufacturing efficiency. Key factors affected by this selection encompass flow ability, interfacial bonding, energy consumption, and process stability. To optimize the squeeze casting process parameters for AA8011 HMMCs and attain the desired material properties and manufacturing efficiency, selecting the suitable stirring speed (e.g., 550 rpm, 650 rpm, or 750 rpm) is crucial. This choice guarantees homogeneity, correct particle distribution, interfacial bonding, fluidity, energy efficiency, and process stability. The weight percentage of Si_3N_4 + ZrO_2 directly influences the volume fraction of reinforcing particles in the composite material. Higher weight percentages result in increased concentrations of reinforcement, potentially improving mechanical properties such as stiffness and strength. Moreover, the weight percentage of reinforcement can affect the interaction between the matrix alloy and the reinforcing particles. Proper weight percentages promote strong interfacial bonding, encouraging good wetting and bonding between the two phases, ultimately leading to enhanced mechanical properties. The UTS and micro hardness were selected as response parameters. The L_9 OA with parameters for input of squeeze casting was designed by using Taguchi approach and it is displayed in TABLE 3.

TABLE 3

Squeeze casting input parameters combination as per L9 Orthogonal Array

Ex. No	Melting temperature (°C)	Wt.% of Si_3N_4 + ZrO_2	Stirring speed (rpm)
1	700	5	550
2	750	10	650
3	800	15	750
4	700	5	650
5	750	10	750
6	800	15	550
7	700	5	750
8	750	10	550
9	800	15	650

The AA8011 HMMCs were fabricated as per the designed L_9 Orthogonal Array combination of input parameters. The round rod AA8011 was made small enough to place into the crucible furnace. To remove moisture, enhance wettability, reduce oxidation, ensure even heating, and enhance process uniformity, the choice is made to preheat Si_3N_4 and ZrO_2 reinforcements in a muffle furnace at 350°C for 30 minutes [34]. This decision aims to optimize the squeeze casting process parameters for AA8011 HMMCs and enhance the properties of the composite material. The preheated Si_3N_4 and ZrO_2 reinforcements were fed into crucible furnace with required wt.% after melting. The stirring was done at different designed speed for 10 minutes. Achieving the best squeeze casting process parameters for AA8011 HMMCs involves stirring at different predetermined speeds for 10 minutes. This fosters homogenization, particle dispersion, interfacial bonding, degassing, temperature uniformity, and overall process control, leading to enhanced properties of the composite material. The 1 wt.% of Mg was included to enhance the wettability between AA8011 and Si_3N_4 and ZrO_2 reinforcements [35]. The die was preheated to 450°C to prevent crack, improve the flow and life. The selected die size was 150 mm length and 50 mm diameter. The molten AA8011/Si_3N_4/ZrO_2 HMMC was allowed to solidify under the axial pressure of 380 N/m^2 [36]. The optimization aims to improve the squeeze casting process parameters for AA8011 HMMCs and enhance the properties of the composite material. Preheating the die to 450°C serves to enhance surface finish, extend die lifespan, prevent cracking, and maintain process consistency. Ultimately, this optimization improves the squeeze casting process parameters for AA8011 HMMCs and elevates the quality of the cast parts. In order to tailor the process parameters of squeeze casting for AA8011 HMMCs to ASTM testing methods, a die size of 150 mm in length and 50 mm in diameter was selected. This decision guarantees conformity, compatibility, accuracy, validation, and comprehensibility of test outcomes within the ASTM standards. This pressure aids in achieving uniform solidification, minimizing porosity, enhancing mechanical properties, refining surface finish, ensuring process control, and upholding compatibility with the material system.

2.3. Testing on composites

The fabricated AA8011 HMMCs underwent to metallurgical examination for computing the metallurgical properties. The required size was obtained by wire cut EDM to avoid dislocation of particles while cutting by other methods. The EDAX and SEM test were conducted on AA8011 HMMCs to determine the added weight % of AA8011, Si_3N_4 and ZrO_2 and to examine the microstructure. The ASTM was utilized for various test to evaluate the properties AA8011 based hybrid composites. The ASTM E 1508 was employed for conducting EDAX and SEM test on AA8011 based hybrid composites.The Shimadzu SEM EDX equipment was utilized for conducting EDAX and SEM tests. The polishing of fabricated sample was carried out using sheets of abrasive grades uch as 600, 800, 1000 and 1200. The surface of sample was polished to attain 1 μm. The Mitutoyo SJ210 Surface Roughness Tester was employed to measure the roughness of polished AA8011 HMMCs. Three trails were made, and average roughness value had been taken. The Keller's reagent was employed on the exterior of the polished AA8011 HMMC to improve the contest. Keller's reagent is a mixture of 15% nitric acid and 5% hydrochloric acid in water.

The determined properties of fabricated composites generally vary, which is depends on the environment in which it is performing. So, it is necessary to determine the properties of fabricated composites under the condition of working environment. The manufactured AA8011 HMMCs were fed into NaCl environment while using in marine applications. Hence, the manufactured AA8011 HMMCs were subjected into SPT at the spray pressure of 1.2 kg/cm^2, 3.5% of NaCl and 120 hours of exposing duration [37]. The SPT was performed as per ASTM B117. After exposing to SPT, the samples underwent or experienced the specified test such as stensile test and micro hardness test to determine the UTS and microhardness. Each experiment was conducted through three trials and average value had been taken. The tensile test was executed on AA8011 HMMCs as per ASTM E08 and the AA8011 HMMCs were sized by the usage of wire cut EDM. The TTSH2000-IUTM was employed to conduct tensile test. The Vickers hardness test was conducted as per ASTM E384 to compute the micro hardness of AA8011 HMMC. The Metlab – 1000 Vickers Microhardness tester was utilized to conduct micro hardness test. The micro hardness was determined at the condition of 300 g load for the duration of 15 seconds.

The optimized UTS and micro hardness value for fabricated AA8011 HMMCs was determined by utilizing Taguchi with GRA technique. The Minitab 19 software was employed for optimization. The subsequent procedures were employed for implementing GRA and it is employed to transform single-response problem form a multi-response problem [38].

GRA is well-suited for optimization tasks involving complex or unclear relationships between variables, as it adeptly captures non-linear associations between input and output variables. With its flexibility, GRA proves effective in diverse problem domains, including multi-objective and multiple-input variable optimization. Its results are easily comprehensible and interpretable, enabling users to grasp the relationship between input variables and optimization criteria effortlessly. Moreover, GRA is particularly suitable for resource-constrained applications due to its modest computational requirements compared to alternative optimization methods.

The GRA (Grey Relational Analysis) technique was employed to optimize the parameters of the squeeze casting process for AA8011 HMMCs, considering variables like stirring speed, weight percentage of reinforcement, and melting temperature, offers numerous benefits and contributes significantly to research findings. GRA allows for the simultaneous evaluation of multiple process parameters, including stirring speed, weight percentage of reinforcement, and melting temperature. This multivariate approach enables researchers to comprehensively assess the combined impact of these factors on the efficiency of the squeeze casting process, providing insights into their interrelationships. Furthermore, GRA provides a numerical evaluation of each process parameter's relative significance to the intended result, such as mechanical or microstructure properties. Utilizing GRA simplifies the task of finding the optimal process parameter settings to achieve desired outcomes, such as maximizing mechanical properties or enhancing material characteristics. By analyzing the grey relational grades, researchers can pinpoint the combination of melting temperature, weight percentage of reinforcement, and stirring speed that yields the best performance. The step by step procedure of GRA is mentioned below.

Step 1

The normalizing of data was done based on "higher the better" by utilizing the following equation.

$$M_{ij} = \frac{N_{ij} - \min(N_{ij})}{\max N_{ij} - \min(N_{ij})}$$

where N_{ij} are initial data for a response j of experiment i M_{ij} is the order following data pre-processing; max (N_{ij}) is the highest numerical value of N_{ij}; and min (N_{ij}) is the minimum numerical value of N_{ij}.

Step 2

Grey Relational Coefficient (GRC) was computed based on normalized data by using the following equation.

$$\gamma\left(M_{0J}, M_{ij}\right) = \frac{\Delta_{\min} + \zeta\Delta_{\max}}{\Delta_{ij} + \zeta\Delta_{\max}}$$

where $\gamma(M_{0J}, M_{ij})$ is the GRC between M_{0J} and M_{ij} and the value of ζ is taken as 0.5.

Step 3

The Grey Relational Grade was computed by utilizing the following equation.

$$GRG\left(M_0, M_i\right) = \sum_{j=1}^{n} P_j \gamma\left(M_{0J}, M_{ij}\right)$$

where GRG (M_0, M_i) is the grade between comparability sequence M_i and reference sequence M_0. The weight of response j is P_j and typically relies on the judgement of decision-makers.

3. Results and discussion

3.1. Metallurgical examination

The metallurgical properties of AA8011 based HMMCs are analyzed by using EDAX and SEM test. The EDAX test was conducted for computing the presence of wt.% of matrix and reinforcements in manufactured composites. The EDAX test result is displayed in TABLE 4 and Fig. 2. The EDAX test results confirms that the increasing wt.% of silicon nitride and zirconium di oxide reinforcements enhances the presence of elements such as Si,N,Zr and O in manufactured composites. Zirconium dioxide (ZrO_2) and silicon nitride (Si_3N_4) contain elements such as Si, N, Zr, and O. As the weight percentage of these reinforcements increases, the overall concentration of these elements in the composite material rises. Higher weight percentages of Si_3N_4 and ZrO_2 in the AA8011 matrix alloy typically lead to improves the dispersion and distribution of reinforcing particles, resulting in a more uniform distribution of Si, N, Zr, and O elements throughout the composite material was achieved. The likelihood of interaction between the reinforcement particles and the matrix alloy during the manufacturing process also increases with the rising weight percentages of Si_3N_4 and ZrO_2.

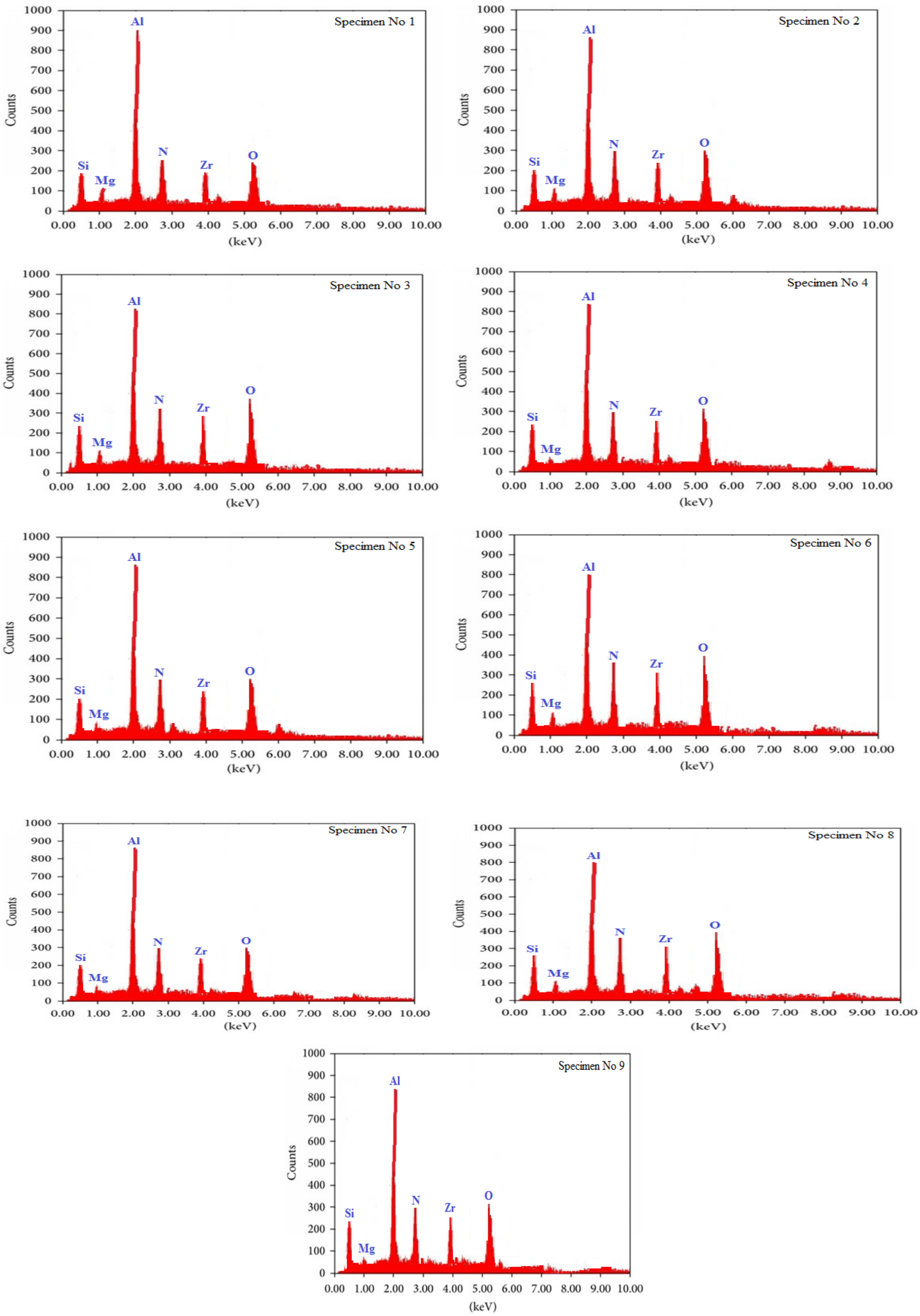

Fig. 2. EDAX test results of AA8011 based HMMCs fabricated as per L_9 OA combinations of squeeze casting input parameters

The enhanced diffusion of Si, N, Zr, and O elements across the interface between the reinforcement and matrix phases, along with enhanced interfacial bonding, may result from this phenomenon. Elements such as Si, N, Zr, and O influence the microstructure of the composite material. Finer microstructural features generated by increased weight percentages of Si_3N_4 and ZrO_2 may further facilitate the presence and diffusion of these elements throughout the composite.

TABLE 4

EDAX test results of AA8011 based HMMCs fabricated as per L_9 OA combinations of squeeze casting input parameters

Specimen	AA8011 (wt.%)		Si_3N_4 (wt.%)		ZrO_2 (wt.%)	
	Al	Mg	Si	N	Zr	O
Specimen 1	93.58	0.42	1.1	1.9	1.2	1.8
Specimen 2	90.3	0.39	1.8	3.3	1.7	3.5
Specimen 3	82.99	0.41	2.9	5.2	2.9	5.6
Specimen 4	94.6	0.4	0.9	1.6	0.8	1.7
Specimen 5	89.28	0.42	1.8	3.3	1.7	3.5
Specimen 6	84.04	0.46	2.7	4.9	2.6	5.3
Specimen 7	94.55	0.45	0.9	1.6	0.8	1.7
Specimen 8	89.27	0.43	1.8	3.3	1.7	3.5
Specimen 9	84.09	0.41	2.7	4.9	2.6	5.3

Energy Dispersive X-ray Analysis (EDAX) is adept at discerning a material's elemental composition. EDAX analysis confirms the presence and distribution of Si, N, Zr, and O elements within the composite, with their detectability and quantifiability increasing as their concentration rises. The SEM test was conducted on AA8011 based HMMCs to study the microstructure through confirmation of uniform distribution of silicon nitride and zirconium dioxide in the AA8011 material. The SEM picture of AA8011 based HMMCs is displayed in Fig. 3. The SEM images proves that, the distribution of reinforcements is attained uniformly while increasing of stirring speed. The increasing of melting temperature from 700 to 750°C confirms the uniform distribution and at 800°C accumulation of reinforcements is attained [39]. Besides, enhancement of melting temperature maintains the consistency in the uniform existence of reinforcements in the manufactured composites and 750°C melting temperature easily allows the reinforcements to disperse uniformly because of density of molten AA8011 HMMCs is low. The increasing of stirring speed evenly distributes the reinforcements and hence 750 rpm stirring speed allows the uniform presence of reinforcements.Throughout the fabrication process, the stirring speed plays a pivotal role in enhancing the dispersion of reinforcement particles within the molten matrix. As the stirring speed escalates, the molten metal experiences heightened shear forces, thereby facilitating the dispersion and uniform distribution of reinforcement particles across the matrix. To achieve uniform distribution of reinforcement particles within the matrix, higher stirring speeds are beneficial for disintegrating particle agglomerates. Agglomeration may lead to localized regions of high reinforcement concentration, potentially causing irregular mechanical properties and defects in the final composite material. As per the statement, the optimal distribution is achieved at a stirring speed of 750 rpm, indicating its ability to ensure the uniform presence of reinforcements without adverse effects. The low melting temperature and higher stirring speed prevents the uniform presence of reinforcements due to inappropriate occurred densities. The higher dense reinforcements are uniformly distributed at the blend of input parameters such as higher stirring speed, medium melting temperature with high wt.% of silicon nitride and zirconium di oxide. The medium melting temperature avoids formation of porosity due to appropriate attained density. The increasing of stirring speed distribute the reinforcements uniformly in the AA8011 matrix material and high dense with uniform distribution is attained at 750 rpm stirring speed.

3.2. Optimization of Squeeze casting parameters by Taguchi technique

The effect of wt.% of reinforcements, speed of stirring and melting temperature on fabrication of salt spray tested AA8011 based HMMCs is determined by using Taguchi approach. TABLE 5 displays the input parameters of manufactured AA8011 HMMCs with their UTS and micro hardness responses under corrosion environment.

TABLE 5

L9 OA with squeeze casting input parameters with their responses under NaCl environment

Ex. No	Melting temperature (°C)	Wt.% of $Si_3N_4 + ZrO_2$	Stirring speed (rpm)	UTS (MPa)	Micro hardness HV
1	700	5	550	129.24	95
2	700	10	650	146.52	107
3	700	15	750	163.28	119
4	750	5	650	145.32	105
5	750	10	750	162.14	117
6	750	15	550	149.34	118
7	800	5	750	151.26	106
8	800	10	550	138.18	107
9	800	15	650	155.13	118

The Taguchi approach was used for optimizing the squeeze casting process parameters with the help of Minitab 19 software. TABLE 6 displays the response table for UTS and the influencing parameter. For squeeze casting, the medium level of melting temperature (750°C), higher level of wt.% of Si_3N_4 and ZrO_2 reinforcements (15 wt.%) and higher level for speed of stirring (750 rpm) is the optimized parameters for UTS.

TABLE 7 displays the response table for microhardness with its influencing parameters. The medium level of melting temperature (750°C), higher level of wt. % of Si_3N_4 and ZrO_2 reinforcements (15 wt.%) and higher level of stirring speed (750 rpm) is the optimized combination of squeeze casting influencing parameters for microhardness alone.

TABLE 6

Response Table for Means for UTS under NaCl environment

Level	Melting temperature (°C)	Wt.% of $Si_3N_4 + ZrO_2$	Stirring speed (rpm)
1	146.3	141.9	138.9
2	**152.3**	148.9	149.0
3	148.2	**155.9**	**158.9**
Delta	5.9	14.0	20.0
Rank	3	2	1

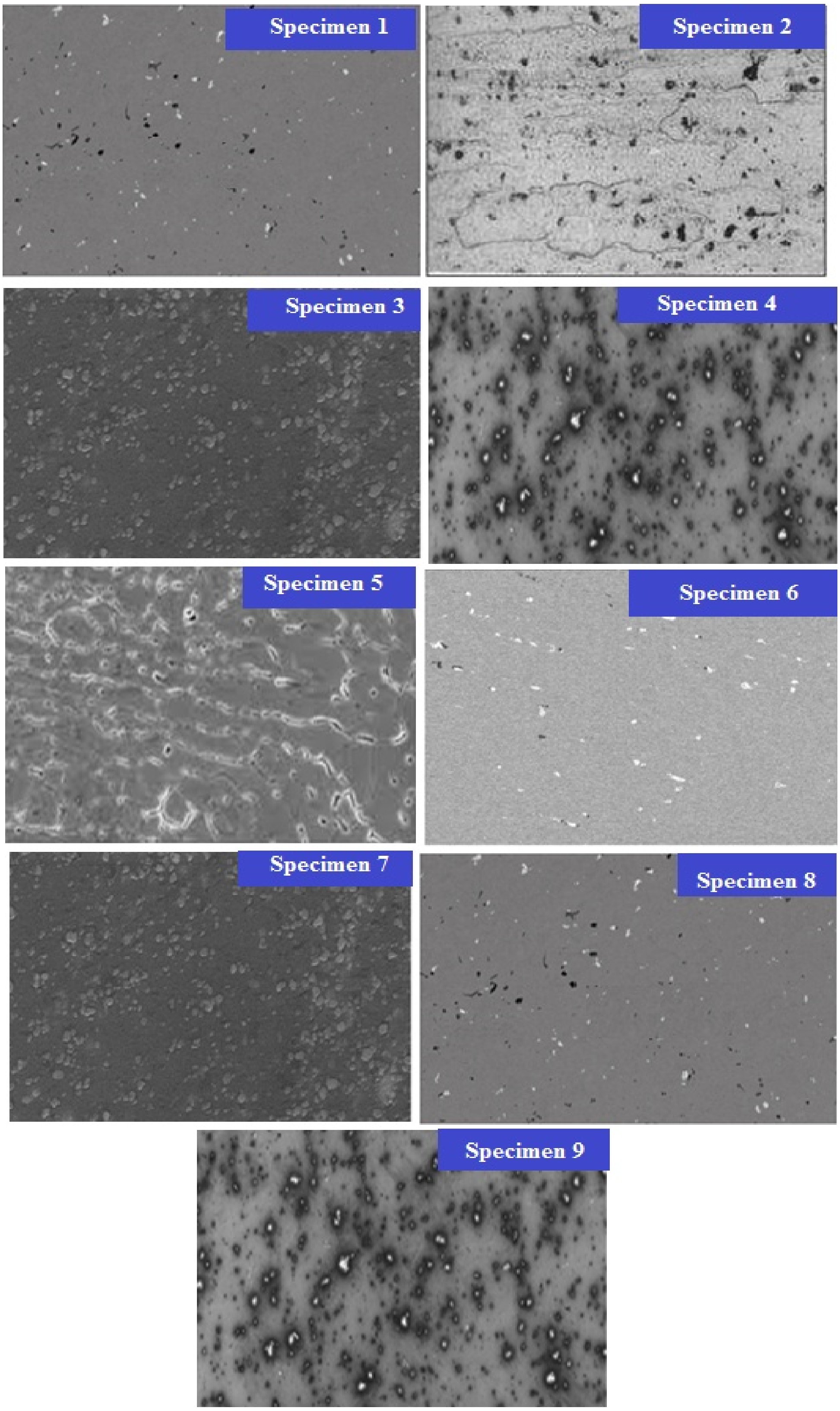

Fig. 3. SEM images of AA8011 based HMMCs fabricated as per L_9 OA combinations of squeeze casting input parameters with 200 µm

The factor information for ANOVA test on UTS and micro hardness is displayed in TABLE 8.

TABLE 9 displays the ANOVA test results for UTS. The selected parameters for input are significant because of their P value is smaller than 0.05 [40]. The contribution percentage of melting temperature, wt.% of reinforcements and stirring speed is 5.8%, 30.9% and 63.2% respectively.

The accuracy of the conducting experiment and the test is high because of adj R square value is 99.97% and it is displayed in TABLE 10.

TABLE 7

Response Table for Means for micro hardness under NaCl environment

Level	Melting temperature (ºC)	Wt.% of $Si_3N_4 + ZrO_2$	Stirring speed (rpm)
1	107.0	102.0	106.7
2	**113.3**	110.3	110.0
3	110.3	**118.3**	**114.0**
Delta	6.3	16.3	7.3
Rank	3	1	2

TABLE 8

Factor Information for UTS and microhardness under NaCl environment

Factor	Type	Levels	Values
Melting temperature (ºC)	Fixed	3	700, 750, 800
Wt.% of $Si_3N_4 + ZrO_2$	Fixed	3	5, 10, 15
Stirring speed (rpm)	Fixed	3	550, 600, 650

TABLE 9

Analysis of Variance for UTS under NaCl environment

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Contri-bution %
Melting temperature (ºC)	2	55.063	27.532	884.00	0.001	5.8
Wt.% of $Si_3N_4 + ZrO_2$	2	293.021	146.511	4704.23	0.000	30.9
Stirring speed (rpm)	2	598.415	299.207	9607.09	0.000	63.2
Error	2	0.062	0.031	—	—	0006
Total	8	946.562	—	—	—	100

TABLE 10

Model Summary for UTS NaCl environment

S	R-sq	R-sq(adj)	R-sq(pred)
0.176478	99.99%	99.97%	99.87%

TABLE 11 displays the ANOVA test for micro hardness and it reveals that the all selected input parameter are produces significant effect on microhardness because of P value of all input parameters is lesser than 0.05. The contribution percentage of melting temperature, wt.% of reinforcements and stirring speed on micro hardness is 11.09%, 73.93% and 14.787% respectively.

The accuracy of the conducting experiment and the test is high because of adj R square value is 99.84% and it is displayed in TABLE 12.

3.2.1. Effect of melting temperature on UTS and micro hardness

The impact of melting temperature on UTS and microhardness is displayed in Fig. 4 and Fig. 5.

TABLE 11

Analysis of Variance for microhardness under NaCl environment

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Contri-bution %
Melting temperature (ºC)	2	60.222	30.111	271.00	0.004	11.09
Wt.% of $Si_3N_4 + ZrO_2$	2	400.222	200.111	1801.00	0.001	73.93
Stirring speed (rpm)	2	80.889	40.444	364.00	0.003	14.787
Error	2	0.222	0.111	—	—	0.02
Total	8	541.556	—	—	—	100

TABLE 12

Model Summary for microhardness

S	R-sq	R-sq(adj)	R-sq(pred)
0.333333	99.96%	99.84%	99.17%

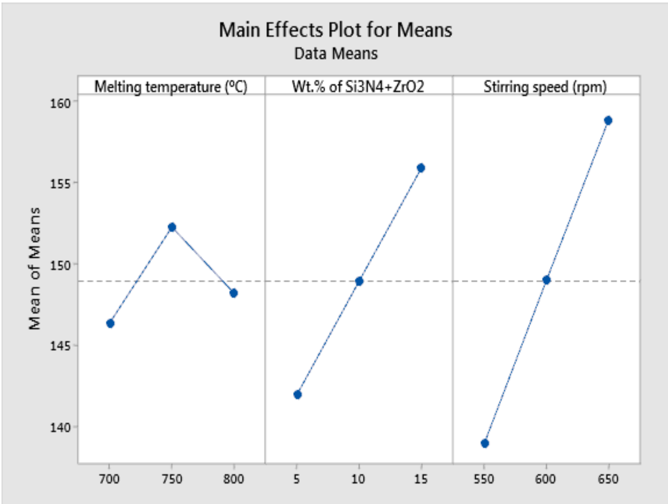

Fig. 4. Maineffect plot for UTS under NaCl environment

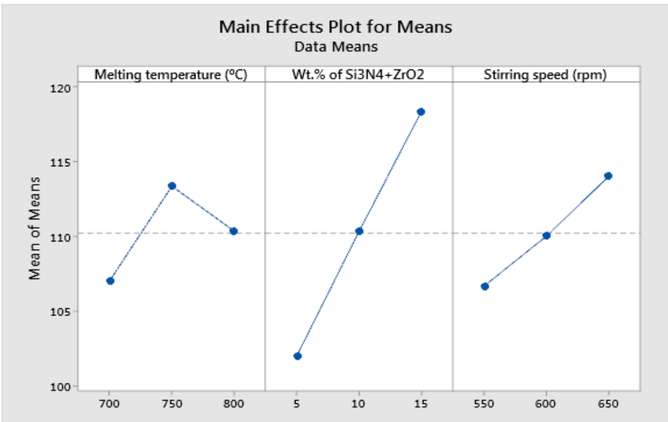

Fig. 5. Main effect plot for micro hardness under NaCl environment

The increasing of melting temperature from 700°C to 750°C enhances the UTS and micro hardness because of density of the molten AA8011 HMMCs is enhanced. The enhanced density of AA8011 decreases the defects such as porosity and accumulation of reinforcements [41]. Elevated melting temperatures promote improved mixing and dissolution of alloying elements and reinforcements, leading to a more uniform solid solution. The resultant homogeneous solid solution often correlates with increased ultimate tensile strength (UTS) and hardness. Higher temperatures also facilitate the diffusion of alloying elements and reinforcements within the molten metal, ensuring a more even distribution of these components in the microstructure. Higher temperatures lead to elevated atomic mobility due to the increased kinetic energy of atoms in the molten metal. This heightened mobility facilitates the diffusion of reinforcements and alloying elements throughout the molten metal. Diffusion, the movement of atoms or molecules from regions of high concentration to regions of low concentration, ensures the uniform distribution of reinforcements and alloying elements within the matrix material of composite materials. This, in turn, reduces the likelihood of element segregation during solidification, fostering a homogeneous composition throughout the material.

The rise in melting temperature can potentially affect the precipitation kinetics of strengthening phases in the alloy, potentially yielding finer and more dispersed precipitates that contribute to enhanced strength and hardness. Moreover, increased temperatures may improve the wetting and dispersion of Si_3N_4/ZrO_2 particles in the molten metal, promoting a more equitable distribution of reinforcing phases and overall improvement in mechanical characteristics. However, it's noteworthy that increasing the melting temperature from 750 to 800°C results in a decrease in UTS and microhardness. This decrease can be attributed to potential grain coarsening during solidification at higher temperatures.

Coarse grains, formed under elevated melting conditions, tend to exhibit reduced strength and hardness compared to their finer counterparts. Additionally, the reduction in solubility of alloying elements and reinforcements at higher temperatures may diminish the effectiveness of solid solution strengthening, resulting in less efficient strengthening mechanisms and inferior mechanical characteristics. Excessive temperatures can also lead to poor wetting of Si_3N_4/ZrO_2 particles by molten metal, causing agglomeration or uneven distribution of reinforcing phases. This poor dispersion adversely impacts the reinforcement's ability to contribute effectively to the material's mechanical properties.

3.2.2. Effect of wt.% of reinforcements on UTS and micro hardness

The presence of $Si_3N_4 + ZrO_2$ reinforcements in the AA8011 matrix material leads to an enhancement in ultimate tensile strength (UTS) and microhardness. Augmenting the weight percentage of $Si_3N_4 + ZrO_2$ reinforcements not only strengthens the bond between the matrix and reinforcements but also imparts higher resistance to abrasion and deformation. The heightened load-carrying capacity of the reinforcements contributes to improved hardness and UTS. Noteworthy ceramic materials renowned for their exceptional hardness, wear resistance, and thermal stability include silicon nitride (Si_3N_4) and zirconia (ZrO_2). When incorporated as reinforcements in a metal matrix, these ceramics can enhance the mechanical and thermal properties of the composite material. Ultimate tensile strength (UTS) represents the maximum stress a material can endure while being stretched or pulled before necking, which occurs when the specimen's cross-section undergoes significant reduction. An increase in UTS is generally advantageous, indicating enhanced material strength and durability. Microhardness, a microscopic-scale measure of a material's hardness, can be significantly influenced by the addition of robust ceramic reinforcements like Si_3N_4 and ZrO_2. This results in increased resistance to deformation and wear. The ceramic reinforcements, specifically Si_3N_4 (silicon nitride) and ZrO_2 (zirconia), act as hard particles embedded in the matrix. These particles effectively impede the movement of dislocations within the matrix material and making deformation more challenging [42]. This dispersion strengthening effect contributes to the increased to the UTS and microhardness.

3.2.3. Effect of stirring speed on UTS and micro hardness

Enhancing the stirring speed in the squeeze casting process parameter has a positive impact on microhardness and ultimate tensile strength (UTS). An increase in stirring speed facilitates the even distribution of Si_3N_4 and ZrO_2 reinforcements within the AA8011 matrix material. Conversely, lower stirring speeds can lead to the accumulation of these reinforcements in the matrix material. The uniform dispersion of reinforcements plays a crucial role in improving UTS and microhardness by resisting the dislocation of particles. Increasing stirring speed during squeeze casting enhances alloy melt mixing and homogeneity, allowing for a more equitable dispersion of alloying elements and minimizing the risk of localized composition changes. A homogeneous composition throughout the material contributes to improved microhardness and UTS. Higher speed for stirring can also result in finer grain structures in the cast material, a trait frequently linked with elevated strength and hardness. The intensified agitation during stirring aids in dividing larger grains into smaller, more refined structures, potentially enhancing the material's strength [43]. Increasing stirring speed is effective in removing or breaking down inclusions and impurities in the molten metal, preventing the formation of weak areas or faults in the material that could compromise its mechanical properties. Cleaner, defect-free materials are known to exhibit better microhardness and UTS. Moreover, the reduction of porosity in the cast material, achieved by increasing stirring speed, is beneficial as porosity is often detrimental to mechanical characteristics. This reduction increases the likelihood of the material demonstrating higher microhardness and UTS. Higher stirring speeds induce agitation that can influence the alignment and strength of grain boundaries. The resulting stronger grain boundaries contribute to enhanced resistance to deformation, ultimately leading to higher microhardness and UTS.

3.3. Optimization of Squeeze casting parameters by GRA

The effect of squeeze casting process parameters of AA8011 HMMCs on UTS and micro hardness is obtained by utilizing GRA technique. TABLE 13 displays the results for GRA optimization. GRA helps to compute the best combinations of squeeze casting input parameters.

TABLE 13

GRA results for UTS and Micro Hardness (MH) under NaCl environment

Normalized Data		Evaluation Sequence		Grey Relation Coefficient		GRG	Rank
UTS	MH	UTS	MH	UTS	MH		
0.000	0.000	1.000	1.000	0.333	0.333	0.3333333	9
0.508	0.500	0.492	0.500	0.504	0.500	0.5019242	6
1.000	1.000	0.000	0.000	1.000	1.000	1.0000000	1
0.472	0.417	0.528	0.583	0.487	0.462	0.4740511	7
0.967	0.917	0.033	0.083	0.937	0.857	0.8971838	2
0.590	0.958	0.410	0.042	0.550	0.923	0.7364093	4
0.647	0.458	0.353	0.542	0.586	0.480	0.5330441	5
0.263	0.500	0.737	0.500	0.404	0.500	0.4520418	8
0.761	0.958	0.239	0.042	0.676	0.923	0.7996394	3

The normalizing of the UTS and micro hardness followed by determination of deviation sequence is obtained by utilizing GRA equations. The GRC of UTS and micro hardness is computed by utilizing deviation sequence. The GRG for both UTS and micro hardness is computed based on GRC. The higher GRG values represent the better combination of squeeze casting input parameters. From the TABLE 14, L_3 combination of squeeze casting input parameters has higher GRG value and hence this combination of parameters for input produces higher UTS and micro hardness than other orthogonal array combination of input parameters.

TABLE 14

Response Table for Means for GRG of UTS and Micro Hardness

Level	Melting temperature (ºC)	Wt.% of $Si_3N_4 + ZrO_2$	Stirring speed (rpm)
1	0.6118	0.4468	0.5073
2	**0.7025**	0.6170	0.5919
3	0.5949	**0.8453**	**0.8101**
Delta	0.1076	0.3985	0.3028
Rank	3	1	2

The values obtained from GRG are optimized by Taguchi approach by utilizing Minitab 19 software. TABLE 14 displays the response table for Means of GRG. The higher level of wt.% of $Si_3N_4 + ZrO_2$ reinforcements, higher level of stirring speed and medium level of melting temperature combination exhibits higher UTS and micro hardness. The influencing sequence for squeeze casting process parameters is wt.% of $Si_3N_4 + ZrO_2$ reinforcements, stirring speed and melting temperature.

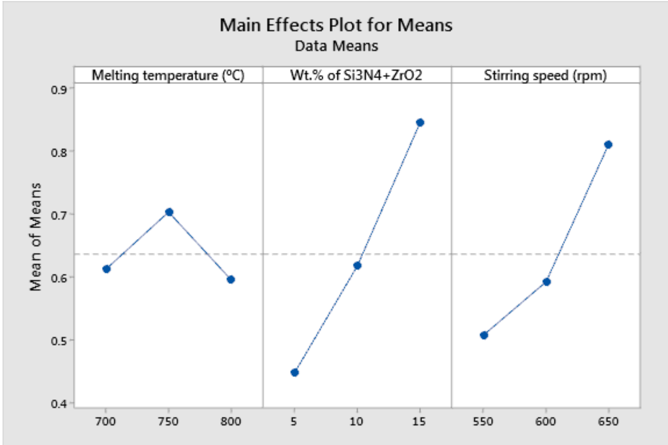

Fig. 6. Main effect plot for GRG of UTS and Micro Hardness

The Fig. 6 displays the trend obtained for squeeze casting input parameters impact on UTS and micro hardness. The increasing of melting temperature from 700 to 750°C enhance the UTS & micro hardness and further enhancement of 750 to 800°C decrease the UTS & microhardness. The enhancement of wt.% of $Si_3N_4 + ZrO_2$ reinforcements improves the GRG value from 5 to 15 wt.%. The increasing of stirring speed from 550 rpm to 750 rpm increases the GRG value [44]. The optimized better combination of input parameters of squeeze casting for fabricating AA8011 HMMCs is medium level of melting temperature 750°C, higher level of stirring speed 750 rpm and higher level of wt.% of $Si_3N_4 + ZrO_2$ reinforcements for combined responses UTS and micro hardness.

Increasing the melting temperature, such as to 750°C, promotes the uniform dispersion of reinforcements, reduces viscosity, enhances wettability, prevents segregation, and ensures uniform solidification. This measure helps to maintain the consistent presence of reinforcements in the manufactured composites, ultimately yielding high-quality composite materials. Raising the stirring speed facilitates the uniform distribution of reinforcements within the molten alloy. For instance, a stirring speed of 750 rpm ensures consistent presence of reinforcements by evenly dispersing them throughout the mixture.

At 750°C, the molten alloy attains sufficient fluidity for uniform distribution of reinforcements without becoming overly viscous, ensuring effective mixing. This temperature facilitates the incorporation of reinforcements to enhance microhardness by striking a balance between promoting flowability and preventing premature solidification. Adding a higher weight percentage (15 wt.%) of Si_3N_4 and ZrO_2 reinforcements increases the density of reinforcing particles within the alloy matrix, resulting in a greater volume fraction of reinforcements. This augmentation introduces additional strengthening phases and hinders dislocation movement, thereby contributing to improved microhardness.

Thorough mixing and dispersion of reinforcements occur within the molten alloy at a higher stirring speed of 750 rpm. This promotes homogeneity and uniform distribution of reinforcing particles, critical for ensuring consistent microhardness properties in the composite material. The combination of increased weight percentage of reinforcements, medium melting temperature, and faster stirring speed collectively optimize conditions for enhanced microhardness. The medium melting temperature ensures appropriate alloy fluidity, the higher weight percentage of reinforcements augments the reinforcing phase content, and the faster stirring speed facilitates uniform dispersion, all contributing to improved microhardness properties.

At 750°C, the molten alloy attains an optimal viscosity level, delaying premature solidification and allowing thorough mixing and dispersion of reinforcements. This temperature improves the ultimate tensile strength (UTS) fosters by balancing enhanced flowability with sufficient time for uniform dispersion of reinforcements. Increasing the weight percentage (15 wt.%) of Si_3N_4 and ZrO_2 reinforcements within the alloy enhances the density of reinforcing particles in the matrix alloy, leading to a higher volume fraction of reinforcements. This augmentation enhances mechanical properties, including UTS, and strengthens the composite material. A stirring speed of 750 rpm ensures vigorous mixing and dispersion of reinforcements throughout the molten alloy, facilitating effective incorporation into the matrix alloy and uniform distribution of reinforcing particles. This process prevents clustering and contributes to improve UTS.

The optimization of conditions for improved ultimate tensile strength (UTS) is achieved through the synergistic interaction of three parameters: a medium melting temperature, higher weight percentage of reinforcements, and increased stirring speed.

TABLE 15 displays the ANOVA for GRG and it indicates all P values are lesser than 0.05 and it reveals that selected input parameters are significant. The contribution percentage of melting temperature, wt.% of reinforcements and stirring speed are 20.26%, 48.102% and 29.23% respectively.

TABLE 15

Analysis of Variance for GRG of UTS and Micro Hardness

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Contribution %
Melting temperature (ºC)	2	0.1011	0.010057	15.78	0.0360	20.26
Wt.% of Si3N4 + ZrO2	2	0.23994	0.119968	21.23	0.025	48.102
Stirring speed (rpm)	2	0.14647	0.073234	17.96	0.032	29.93
Error	2	0.01130	0.005652	—	—	2.2
Total	8	0.49881	—	—	—	100

The process parameters of stirring speed, weight percentage (wt.%) of reinforcements, and melting temperature exert a significant influence on both microhardness and Ultimate Tensile Strength (UTS). Notably, the weight of reinforcements contributes the most, followed by stirring speed and melting temperature, in terms of percentage contribution to the properties studied. The weight percentage of reinforcements exerts the most significant influence on both microhardness and Ultimate Tensile Strength (UTS). This indicates that variations in the quantity of reinforcement material have a substantial impact on the mechanical properties of the composite. The stirring speed also plays a significant role in influencing both microhardness and Ultimate Tensile Strength (UTS). This indicates that the mechanical properties of the composite are affected by the agitation of the molten material during the fabrication process. While the melting temperature does impact microhardness and UTS, its influence is less pronounced compared to stirring speed and reinforcement content. Nevertheless, it still contributes significantly to the ultimate mechanical characteristics of the composite.

TABLE 16

Model Summary for GRG of UTS and Micro Hardnedss

S	R-sq	R-sq (adj)	R-sq (pred)
0.0751785	97.29%	96.18%	95.22%

The model summary for GRG is displayed in TABLE 16 and it reveals that the conducted experiments are highly accurate because of adj R square value is 96.18. The confirmation test is done for medium melting temperature of 750°C, higher level of wt.% of $Si_3N_4 + ZrO_2$ reinforcements of 15 wt.% and higher level of stirring speed of 750 rpm and it exhibit higher UTS of 179.4 MPa and higher micro hardness of 129 HV.

4. Conclusions

The AA8011 $Si_3N_4 + ZrO_2$ HMMCs was manufactured followed by L9 orthogonal array, and subsequently underwent salt spray corrosion testing. UTS and microhardness values were recorded for the salt spray tested L9 specimens. Confirmation of element presence in AA8011 HMMCs was achieved through EDAX testing. Similarly, SEM testing confirmed the distribution of reinforcements in AA8011. EDAX test results verified that increasing wt.% of silicon nitride and zirconium dioxide reinforcements enhanced the presence of elements such as Si, N, Zr, and O in the manufactured composites. SEM images showed a uniform distribution of reinforcements with increasing stirring speed. An increase in melting temperature from 700 to 750°C confirmed uniform distribution, with accumulation of reinforcements observed at 800°C. Dense reinforcements were uniformly distributed at a combination of higher stirring speed, medium melting temperature, and high wt.% of silicon nitride and zirconium dioxide. Squeeze casting process parameter optimization for AA8011 HMMCs was performed using the Taguchi approach for UTS and microhardness. The optimized combination included a medium melting temperature (750°C), higher wt.% of Si_3N_4 and ZrO_2 reinforcements (15 wt.%), and higher stirring speed (750 rpm). Contribution percentages for UTS, microhardness and GRG for melting temperature, wt.% of reinforcements, and stirring speed. Confirmation testing was conducted for optimized input parameters, resulting in a higher UTS of 179.4 MPa and microhardness of 129 HV. Al8011 /15% SiCp/ composites exhibited UTS of 159 MPa from previous research [45] and the present investigation exhibited UTS of 179.4 MPa without subjected into ageing.

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