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RESEARCH ARTICLE

The influence of steel powders on the microstructure and mechanical properties of Al/Cu alloy

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Abstract

Aluminum is one of the most important materials with various usages. It has important features such as lightness, corrosion resistance, the compatibility with heat treatment, formability and affordable price. Conversely, Al-Cu alloys are extensively employed in the aerospace industry because of their exceptional combination of high specific strength and excellent machining characteristics. In this alloy, copper increases the strength of the material as it forms intermetallic compounds with alloying elements. Moreover, precipitation hardening is possible by dissolving copper in aluminum in the solid phase. This study examines the microstructure and mechanical properties of composites with matrix of Al-Cu alloys. To accomplish this, the initial step involved melting the Al-Cu alloy at a temperature of 800 °C, followed by the addition of 0.3% and 0.5% steel powder by weight into the molten mixture. The Al-Cu melt mixed at 300 rpm for 10 minutes, was controlled with Aluflux and degassing tablets and the resulting mixture was cast into a steel mold. The Al-Cu alloys of the heat treatment were fulfilled at 500 degrees for 2 h and then cooled in water. The aging process of T6 was carried out by keeping it in an annealing furnace at 150 and 200 degrees for 1 and 3 h. Following the manufacturing procedures, the samples were polished and etched to facilitate microstructural studies. The obtained Vickers hardness values were analyzed with the Taguchi method and the results were evaluated. The maximum hardness value recorded in this study was 263.86 HV. The Al-Cu casting alloy exhibited a relatively higher density, indicating lower porosity, when a synergistic combination of 0.3% steel powder additive and a 1-hour aging time was applied.

1. Introduction

Aluminum which stands out with its high ductility and low-density properties is an indispensable material especially in aviation applications and the automotive industry. Furthermore, the metal industry recognizes the significance of aluminum due to its exceptional attributes, including the ability to manipulate its mechanical properties through heat treatment and its suitability for alloy formation. These characteristics have solidified aluminum's crucial position within the metal industry. Besides all these, following iron-based materials, aluminum alloys rank among the extensively used materials in tribological applications [1-4].

Aluminum and its alloys have been used in many industries owing to their extraordinary properties. One of the areas, for example, where aluminum is most widely used is the food industry. Aluminum cans account for approximately 80% of the total global usage in the beverage can industry. This is because they are light, easy to open, impact resistant, robust, the fast cooling and recyclable. Aluminum plays a paramount role in the manufacturing of transportation, establishing itself as one of the most vital materials in the industry. Approximately 25% of aluminum use belongs to the production of transportation. This situation has great benefits in terms of both reducing the carbon emissions of vehicles into the atmosphere in terms of environmental health and the economy it will provide for the fuel costs of the drivers. Apart from its lightweight nature, aluminum has made an immense contribution to the advancement of aircraft and consequently the aviation sector. After the duralumin (aluminum-copper) alloy, composite materials such as aluminum-lithium alloys will be among the important materials used in aircraft construction. With the progression of industry and technology, the use of aluminum is witnessing a steady rise. Aluminum is favored for its ability to create lighter, stronger, more efficient, durable, and ultimately cost-effective products. It has become an indispensable material in various engineering applications, including aircraft (including spacecraft), superior infrastructure such as buildings and bridges, power transmission lines, and many other fields [5-7].

By varying the alloying element and adjusting the heat treatment conditions, it is feasible to generate aluminum alloys with distinct properties. The properties of aluminum alloys can vary based on the specific type of alloying element employed. Studies in the literature generally focus on increasing the mechanical characteristics of aluminum without reducing its elongation ability or corrosion resistance by alloying it [8]. Among aluminum alloys, aluminum-copper (Al-Cu) alloy gains importance especially for automotive applications because it exhibits high strength and toughness. Through the incorporation of copper (Cu), the precipitation hardening capability of aluminum alloy is enhanced through a suitable heat treatment regimen. For instance, when subjected to heat treatment

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processes such as solution heat treatment and artificial over-aging, the Al-Cu alloy showcases remarkable mechanical properties akin to those observed in ductile iron [9-11]. Based on the equilibrium diagram of the Al-Cu system, the Al-Cu alloy dissolves 0.5% Cu in aluminum at room temperature, while this value increases to 5.65% at eutectic temperature (548°C). This phenomenon enables effective precipitation hardening [12]. Conversely, both grain size and heat treatment play a vital role in influencing the mechanical properties of the material. It is possible to explain this situation with the Hall-Petch equation famous in material science. Research has indicated that incorporating grain-refining elements into an aluminum alloy is a successful approach for enhancing its mechanical properties [13]. It is declared that Al-Cu-Mg composite composites reinforced with TiB_2 and solution-treated showed a remarkable balance between strength and ductility [14]. Significant enhancements in the mechanical properties of Al-Cu-Si-Mg alloys were observed through T5 and T6 heat treatments [15]. Furthermore, the introduction of nano-MgO particles and SiC resulted in notable improvements in the mechanical properties of Al matrix composites [16-24].

This study aimed to enhance the mechanical properties of Al-Cu alloy by refining its grain structure through the addition of steel powder. To achieve this, 0.3% and 0.5% steel powder by weight were meticulously incorporated into the molten Al-Cu alloy, followed by thorough mechanical mixing. Subsequently, the mixture was casted into samples, which underwent various heat treatment processes. The resulting samples were then evaluated for their density, hardness, and microstructure. This study aimed to provide valuable insights into the effects of grain refinement through the addition of steel powder and subsequent heat treatment on the mechanical properties of Al-Cu alloy. By investigating the density, hardness, and microstructure, a comprehensive understanding of the alloys behavior and potential performance improvements could be gained.

2. Experimental methods and materials

2.1. Materials

In this study, Al-Cu alloy and steel powders were used as matrix and reinforcement materials. The chemical composition of matrix material is provided in Table 1, offering a comprehensive overview of its elemental constituents. Additionally, Figure 1 displays a scanning electron microscope (SEM) image, revealing the steel powders with an average dimension of 20 μm. The choice of Al-Cu alloy as matrix material stems from its desirable properties, such as high specific strength and excellent machining characteristics. The alloy composition, as outlined in Table 1, plays a significant role in determining its mechanical and chemical attributes, influencing the resulting composites performance. To further enhance the properties of Al-Cu alloy, steel powders (low Carbon steel) were incorporated as reinforcement material. These powders showcased in Figure 1, exhibit an average dimension of 20 μm, highlighting their finely divided nature. The use of steel powders as reinforcement offers the potential for improved strength, stiffness, and other desired mechanical properties within the composite material. By combining Al-Cu alloy as the matrix and steel powders as the reinforcement, this study aimed to create a composite material with enhanced overall performance.

2.2. Casting and heat treatments

The Al-Cu alloy was subjected to a melting process at a temperature of 800 °C, using an electrical furnace. To ensure the removal of slag from the molten alloy, the Aluflux method was employed. Additionally, degassing process was conducted to eliminate any unwanted gases in the alloy. During the melting stage, steel powders with concentrations of 0.3 wt.% and 0.5 wt.% were carefully introduced into the molten alloy. To achieve thorough mixing, the melt was stirred at a speed of 300 rpm. Subsequently, the resulting slurry was poured into a steel mold to shape the castings. To mitigate the formation of gas porosity within castings, argon gas was employed during casting process. This helped to minimize the presence of gas voids and ensure more compact and defect-free structure in the final samples. Following the casting and solidification process, the samples were brought to desired size through appropriate machining techniques. Subsequently, a heat treatment procedure was implemented, beginning with a homogenization step at a temperature of 500 °C for duration of 2 h. After completing the homogenization process, the samples were rapidly cooled by immersing them in water. The aging process was carried out at temperatures of 150 °C and 200 °C, with varying durations of 1 and 3 h. This step aims to promote the precipitation of strengthening phases within the alloy, leading to improved mechanical characteristics. By following this comprehensive manufacturing and heat treatment approach, the studies analyzed the resulting microstructure and evaluate the mechanical properties of Al-Cu alloy samples.

Table 1. Chemical composition of Al-Cu matrix (wt.%)

Fe	Si	Cu	Cr	Mn	Mg	Zn	Ti	Al
0.25	0.073	1.83	0.005	0.06	0.01	0.019	0.019	Rem.

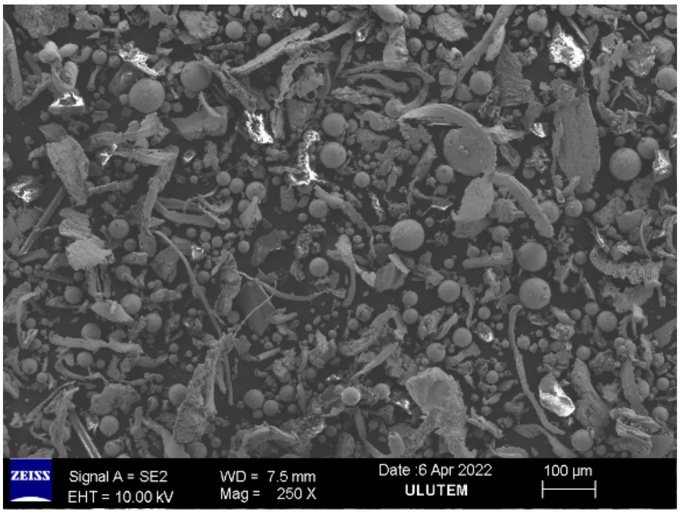

Figure 1. The SEM image of steel powders

2.3. Characterizations

The primary focus of this study involved the investigation of both microstructure and mechanical properties of the samples. To prepare the samples for analysis, a series of steps were followed. Initially, the samples underwent sanding and polishing procedures to ensure smooth and uniform surface. For microstructural analysis, the samples were subjected to etching using Keller's reagent. The etching process involved immersing the samples in a solution prepared by combining 2 ml of HF (hydrofluoric acid), 3 ml of HCl (hydrochloric acid), 5 ml of HNO_3 (nitric acid), and 190 ml of water. The etching time was carefully controlled, typically ranging from 40 to 50 seconds.

Optical microscopy and scanning electron microscopy techniques were employed to examine and analyze the resulting microstructure of samples. In addition to microstructural analysis, the mechanical properties of the samples were assessed using Vickers hardness test. This test involved applying an indenter with a specific load on the sample surface and measuring the resulting indentation. The hardness values obtained from the Vickers hardness test provided insights into the materials resistance to indentation and served as an indicator of its mechanical strength. To determine the density of the composites, Archimedes principle and mixing rule were used. By employing Eq 1, which involves a combination of the Archimedes principle and the mixing rules, the density of the composites could be accurately calculated. Furthermore, the porosity content of the samples was estimated by comparing the experimental and theoretical densities using Eq 2. This allowed for quantification of any voids or porosity within the composite material, providing valuable information regarding its structural integrity and potential defects.

$$d_c = d_m \text{ x } V_m + d_{r1} \text{ x } V_{r1} + d_{r2} \text{ x } V_{r2} \qquad (1)$$

$$\text{Porosity (\%)} = ((dt/dm) - 1)100 \qquad (2)$$

To determine the density of the composite material, several parameters were considered. These included the densities of the composite itself (d_c), the matrix material (d_m), and the two types of reinforcement materials (d_{r1} and d_{r2}). Additionally, the mass fractions of matrix (V_m), reinforcement 1 (V_{r1}), and reinforcement 2 (V_{r2}) were considered. The density of the composite material (d_c) was calculated using the equation.

In this equation, the mass fractions (V_m, V_{r1}, V_{r2}) are multiplied by their corresponding densities (d_m, d_{r1}, d_{r2}) and then summed together to obtain the overall density of the composite material. Using this equation, it becomes possible to accurately estimate the density of the composite material, considering the contributions of the matrix and the two types of reinforcement materials. This information is essential for understanding the overall mass and volume characteristics of the composite and further analysis of its properties and performance. Eq 1 provides a useful tool for determining the density of the composite material by considering the mass fractions and densities of the matrix and reinforcement materials. By accurately quantifying the density, researchers can gain valuable insights into the structural and physical attributes of the composite, which are vital for evaluating its suitability for various applications.

Porosity is an important factor to consider when evaluating the quality and integrity of composites. It quantifies the presence of voids or empty spaces within the material. In this study, the porosity content of the composites was estimated using Eq 2, which involves the comparison between the theoretical density (dt) and the measured density (dm) of the composites. In this equation, the theoretical density (dt) represents the density expected in an ideal scenario with no porosity or voids. On the other hand, the measured density (dm) is the actual density obtained through experimental measurements. By subtracting one from the ratio of dt/dm and multiplying the result by 100, Eq 2 provides the percentage of porosity within the composites. Higher porosity percentage indicates greater presence of voids or gaps, which can compromise the mechanical strength, structural integrity, and overall performance of the composites. The estimation of porosity content using Eq 2 allows researchers to assess the porosity and understand its potential impact on the composites' properties and applications. It serves as a valuable metric for quality control and enables adjustments in manufacturing processes to minimize porosity and enhance the overall integrity of the composite material.

3. Results and Discussion

Figure 2 showcases the optical microstructures of samples B, C and the SEM image of sample D. The cast microstructure exhibits eutectic structure and fully equiaxed grain structure, as depicted in Figure 2a and 2b, respectively. Notably, the presence of steel powders can be easily discerned in the microstructure, particularly along the grain boundaries. In case of alloys or composites, the precipitation hardening mechanism serves as the primary method of strengthening. It is widely recognized that the θ phase (Al_2Cu) is the primary precipitate phase in Al-Cu alloys [25]. Incorporation of reinforcement particles contributes significantly to enhancing the overall strength [26].

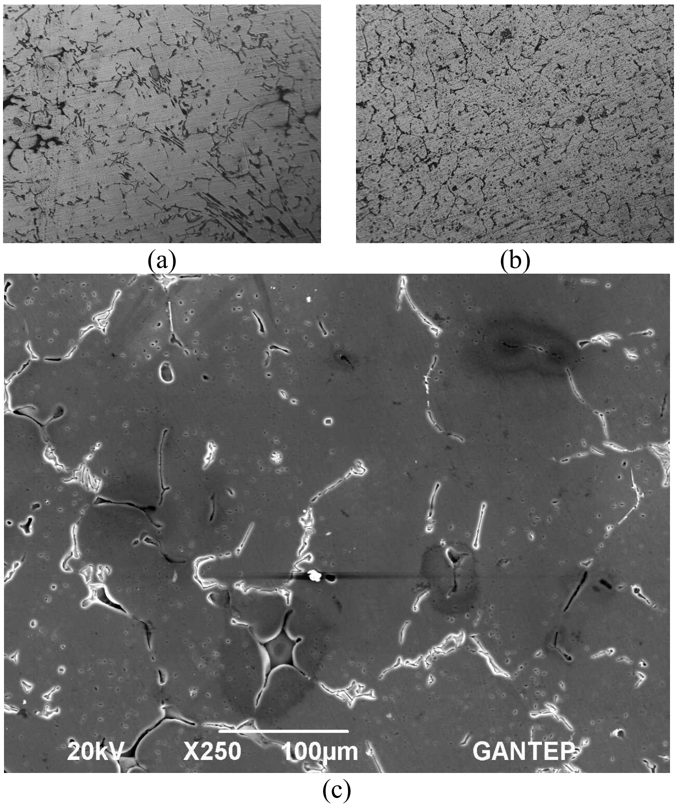

Figure 2. Optical images of a) sample B and b) sample C and SEM images of c) sample D

The density, porosity, and hardness characteristics of the specimens demonstrated diverse trends. The minimum and maximum densities are obtained at samples D and A. While the minimum and maximum porosity contents are observed at samples B and A, respectively. The presented hardness results are not linear. The highest hardness was achieved at sample D as 263.86 HV.

The Taguchi method was employed as an experimental design and analysis technique [27]. The objective was to identify and determine the influential parameters and their corresponding levels in the process of adsorption. To accomplish this, the Taguchi technique was used in conjunction with a specific experimental design. To begin, a set of parameters and their respective levels as outlined in Table 2 were selected. These parameters were considered crucial in understanding and optimizing the adsorption process. To efficiently explore the parameter space, a Taguchi experimental design was constructed using two parameters and three levels. Specifically, an L4 (2^2) orthogonal array was generated using the Minitab program [28]. The performance characteristics of the system were evaluated using the "Larger-the-Better" approach, aiming to maximize the desired outcome. Eq 3 was used to measure and evaluate the performance:

$$\frac{S}{N} = -10\ log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y^2}\right) \qquad (3)$$

Where:
y = Response value
y'= Mean of the response value
s = Standard deviation
n = Number of trails for given experiment

The Taguchi method, combined with the orthogonal array design and the "Larger-the-Better" approach, enabled researchers to efficiently analyze the impact of different parameter levels on the performance of the adsorption process. This approach provided valuable insights into the optimal parameter settings, allowing for the enhancement of adsorption efficiency and effectiveness.

Graphs of mean density and S/N ratio showing optimum values of steel powder amount (0.3% and 0.5%) added to Al-Cu alloy and aging time (1 and 3 h) on apparent density are given in Figure 3 (a) and (b), respectively. As can be seen from the graphs in Figure 3 (a), the apparent density value of Al-Cu alloy decreased with the increase of steel powder additive and aging parameters. The S/N ratio graphs in Figure 3 (b) confirm the effect of the parameters on the apparent density since the S/N ratio is small, the better performance characteristic is studied. The low value in this graph indicates that there is a close relationship between the input and output parameters. In fact, although it is expected that the density will increase with the increase in the amount of steel added to the Al-Cu alloy, the opposite situation has happened. This is because Fe disrupts the microstructure and increases the porosity. Mose et al. stated that the added iron to the aluminum alloy negatively affects the cast-ability of the alloy [29].

Table 2. Process parameters and experimental results

Code	Steel powder (%)	Aging time (h)	Density (g/cm^3)	Porosity (%)	Hardness (HV)
A	0.3	1	2.67	3.47	84.26
B	0.3	3	2.65	4.26	86.66
C	0.5	1	2.63	3.77	87.03
D	0.5	3	2.61	4.23	263.86

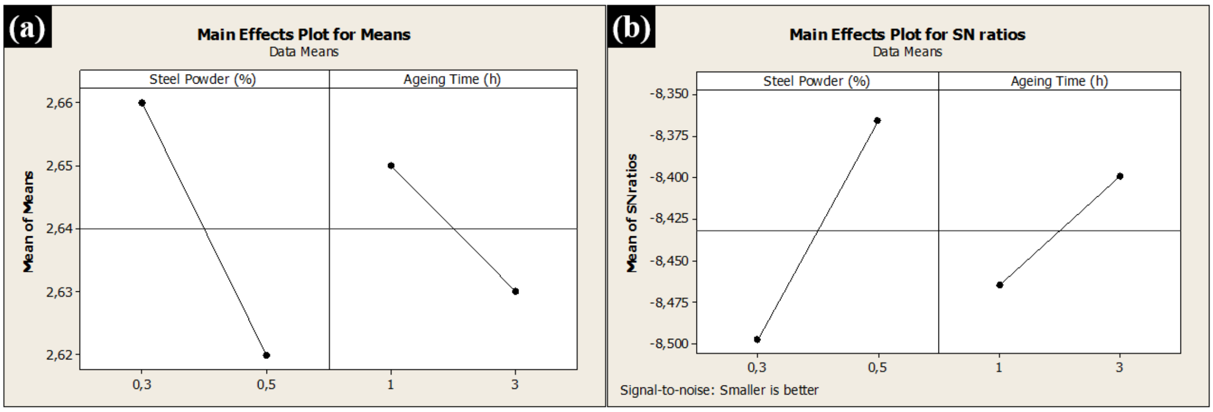

Figure 3. (a) Mean of apparent densities and (b) Mean of SN ratios

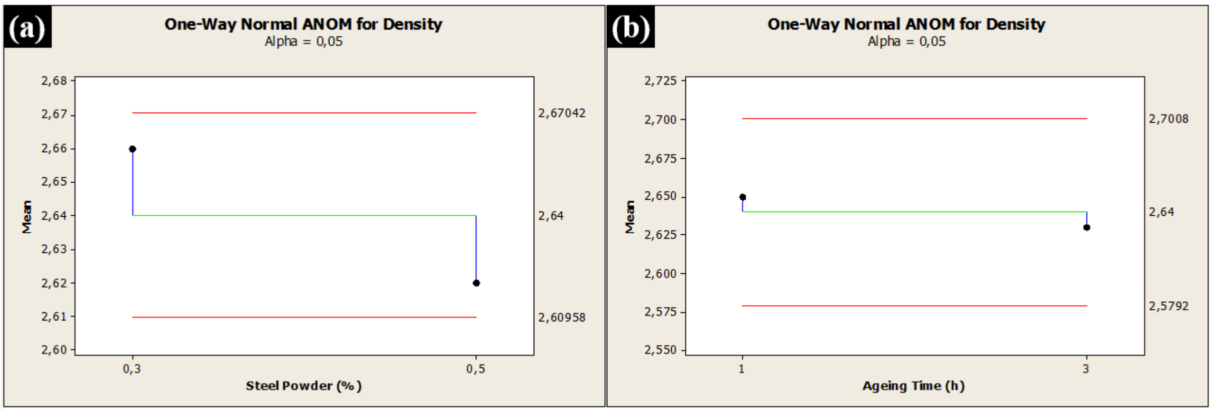

Figure 4. ANOM analysis for apparent density; (a) steel powder addition, (b) aging time

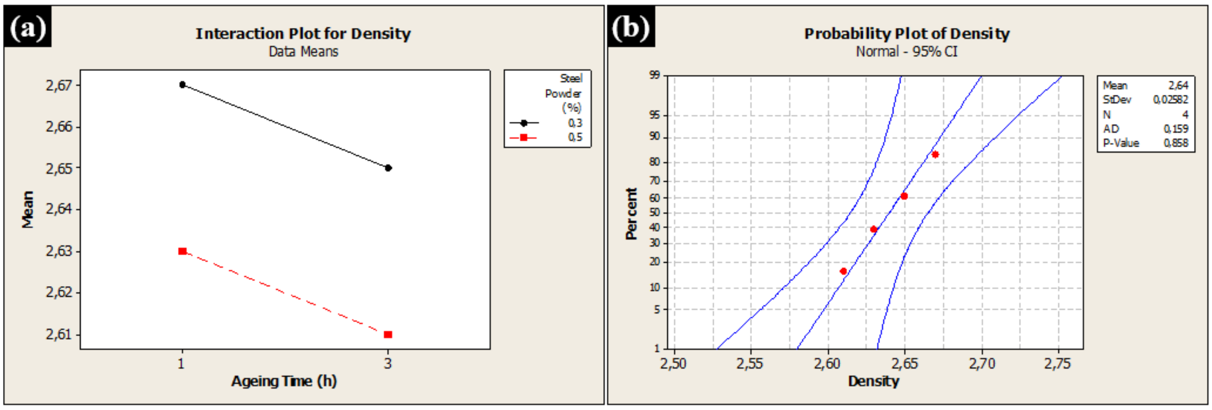

Figure 5. (a) Interaction graph of input parameters, (b) Probability plot of input parameters

As a result, it was determined that the steel powder additive should be 0.3% and the aging time should be 1 h to obtain a relatively higher density or in other words less porosity in the Al-Cu casting alloy. Furthermore, the validity of this finding was corroborated by the analysis of means (ANOM), as depicted in Figure 4 (a) and (b).

When the delta value of the steel powder addition (0.04) is compared with the delta value of the aging time (0.02), it can be said that the amount of steel powder has a greater effect on the density of the alloy. Because, the higher delta value indicates which variable is more effective on the density of the alloy [30]. As can be seen from the interaction graph in Figure 5(a), it can be said that there is no relationship between the parameters, since the lines do not intersect but are parallel. The graph in Figure 5(b) shows the fit of the input parameters to the modeled data. In general, the compatibility changes are not similar.

4. Conclusion

In this research, a stir casting technique was used to produce Al-Cu matrix composites incorporating steel powders. The primary objective of the study was to investigate the microstructures and hardness properties of these composites through utilization of optical microscopy, scanning electron microscopy (SEM), and Vickers hardness tests. Additionally, the Taguchi method was employed to examine the hardness, density, and porosity values systematically. The maximum hardness value recorded in this study was 263.86 HV. Consequently, it was concluded that an optimal combination of 0.3% steel powder additive and a 1-hour aging time resulted in a relatively higher density, or conversely, lower porosity, in the Al-Cu casting alloy. The following significant findings and conclusions were drawn from the study:

1. Analysis of the cast samples revealed eutectic and fully equiaxed grain structures, which provide insights into the solidification behavior of the composites.
2. Notably, the density and porosity content exhibited distinct trends, indicating variations in material composition and processing conditions.
3. The increase in steel powder content and aging time resulted in a decreasing trend in the mean effect plot value, suggesting that these factors have an inverse relationship with the desired properties.
4. The implementation of the Taguchi design demonstrated a minimum standard deviation value, indicating the effectiveness of the experimental approach in reducing variability.
5. A strong correlation was observed between the steel powder content, aging time, and interaction plot of density, suggesting that these parameters play a significant role in determining the composites density characteristics.

This comprehensive study provides valuable insights into the manufacturing and characterization of Al-Cu matrix composites reinforced with steel powders. The observed microstructures, hardness properties, and the analysis of density and porosity contribute to a better understanding of the composite's performance and guide future optimization efforts in composite material design and processing.

Author contributions

Halil Ibrahim Kurt provided valuable guidance and supervision throughout the research process, particularly in the discussion and interpretation of results. Material characterization, under the guidance of Mustafa Guven Gok, was conducted. The experimental investigation, data collection and analysis was carried out by Okan Sert. Engin Ergul was responsible for the writing, control, and editing of the manuscript, ensuring coherence and accuracy.

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