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Thermal Mechanism to Improve Properties of Zrsio4 Reinforcement of ZA-27 Aluminum Alloy

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This study aims to assess the impact of ZrSiO4 grain sizes ranging from 45 to 100 µm and weight % of 0.5, 1, 2, and 3% on the enhancement of characteristics in ASTM ZA-27 aluminum alloy. The Aluminum Composite Material (AMC) was created using stir casting and Gravity Die Casting (GDC processes). Research indicates that the inclusion of zircon in a material leads to enhanced mechanical characteristics, with the optimal tensile strength being achieved at a concentration of 1%. The percentage of additive utilized in the process is employed to fabricate the AMC through a novel casting technique called New Rheocasting (NRC). AMC's mechanical properties were improved to the NRC process utilized in its production. The AMC produced by the two processes underwent solution treatment for 3 hours at 320 °C. Afterwards, it was heated to 150 °C for 2 hours to simulate natural aging. This is a new thermal mechanism process that aims to enhance the properties of AMC casting.

Keywords: ZA-27 aluminum alloy, stir casting, Gravity Die Casting, New Rheocasting, wear resistance

1. Introduction

Due to the special advantages of Aluminum, such as its softness, lightness, ductility, and ease of recycling, competition to improve its properties continues. In the manufacture of AMC, Aluminum alloys are frequently employed as matrix material. Zinc alloys with a higher aluminum content possess distinct advantages compared to regular zinc alloys, such as increased strength, enhanced wear resistance, and superior resistance to deformation under constant stress. However, when wear resistance is required, ZA-27 has shown exceptional performance. Researchers have sought to enhance the desirable characteristics of the ZA-27 alloy by using various reinforcements, including Alumina, Graphite, and Titanium Carbide. [1]– [3]. The incorporation of graphite and SiC into the alloy has led to improved mechanical and wear characteristics [4]. Under actual casting conditions, ZA alloys have the characteristic denderitic structure, the size of which is determined by the specific casting method employed. The rate at which the cooling occurs in the mould has a substantial influence on the level of detail in the structure. The dendritic structure has ramifications, most notably in the decreased ductility of the cast alloy and the comparatively high homogeneity of mechanical characteristics. The second significant issue involves dimensional instability in high aluminum zinc alloys, which is brought on by the presence of a metastable phase [5]. K. H. W. Seah et al examined the mechanical properties of ZA-27 alloy reinforced with graphite particle composites. The findings demonstrated that augmenting the graphite content led to substantial enhancements in ductility, ultimate tensile strength, and compressive strength, while drastically reducing hardness [6]. D. R. Somashekar et al. used 1-5% zircon particles. The study found that adding 5% ZrSiO4 improved ultimate tensile strength and yield strength by 28% and 18%, respectively [7].

2. Methods and Methodology:

Table 1 shows the chemical composition of the Matrix material employed in this study, which was ZA-27.

Table 1. Chemical Analyses for ASTM Za-27

Element (wt %)	Al%	Cu%	Mg%	Fe%	Cd%	Pb%	Zn%
ZA-27 Aluminum	27.16	2.35	0.013	0.087	0.0013	0.0011	Rem

To eliminate grease and contaminants from the cutting process, ZA-27 aluminum was cut into small pieces and then cleaned with dilute ethanol. To remove moisture content, heat the matrix material, reinforcement, and mould to 150 °C. Aluminum is melted in an electric furnace at 750 °C. The ZA-27 molten matrix alloy was reinforced with ZrSiO4 particles ranging in size from 45 to 100 µm and with contents from 0% to 3% by weight, with four castings for each ZrSiO4 ratio, one casting. String at 600 rpm at 10 min. molten metal was poured into a steel mould for gravity die casting when the temperature approached 570ºC. The melting technique for NRC was like that of GDC, except that the pouring temperature was 532ºC and the stainless steel (AISI 304) mould temperature was suddenly water cooled when it reached 410 ºC [8]. The casting procedures were conducted utilizing a mold with dimensions of 12x6x6 cm. The mold was inclined at a 75-degree angle to optimize the contact area between the molten metal and the mold wall. This angle promotes the creation of crystals on the wall and increases the distance that the metal flows. These factors boost the likelihood of separating the frozen crystals from the mold wall [9]. At around 532 °C, the molten material was placed onto the inclined mould wall; the mould was quenched with water until the semi-solid temperature reached 410 °C. After artificially aging the specimens for two hours at 150°C using water quenching, they were air-cooled. [10]. An optical microscope was used to determine the volume fraction of the current phases, as well as the Al particle size and dendritic arm space. The grain size was calculated using the lineal intercept method. The Scion Image software was utilized to determine the proportion of white (α-Al phase) and black (eutectoid) sections in the digital image through the volume fraction program. Heat treatment (age hardening) was used to investigate three tensile test specimens for matrix alloys with all percentages of addition.

The Brinell hardness test was conducted using a 2.5mm diameter ball with a weight of 31.25 kgf.

3. Result and Discussion:

The microstructure of the GDC specimen exhibited complete dendritic formation over its entire cross-section, from the wall to the center. The as cast ZA-27 alloy has a structure composed of four phases: α, β, ϵ, and η, as determined by X-ray diffraction analysis. Figure 1 illustrates that the central part of the dendrite consists of the initial cemented phase rich in aluminum, while the surrounding area is composed of the dissolving phase rich in zinc.

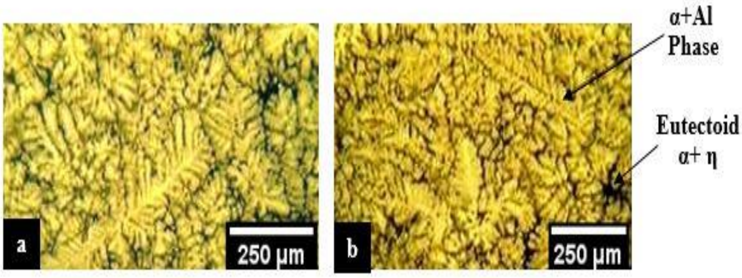

Figure 1. The microstructure of the GDC ZA-27 alloy: Distances from wall (a) 2 mm and (b) 30 mm.

Within the interdendritic region, there exist eutectoid phases of η and α, as well as the metastable epsilon phase CuZn5. The measurement of Dendritic Arm Spacing (DAS) from the wall to the center of the casting showed minimal variation. The mean size of the primary α-Al phase was 20 µm. The average volume fraction of this phase varied from 0.58 near the wall to 0.67 in the center of the casting, with a mean value of 0.64, as depicted in Figures 2 and 3.

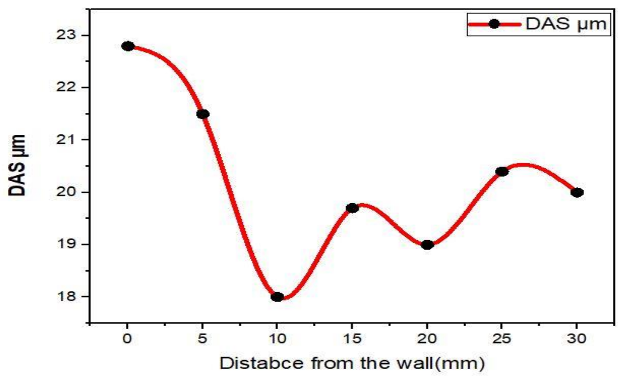

Figure 2. Variation in DAS

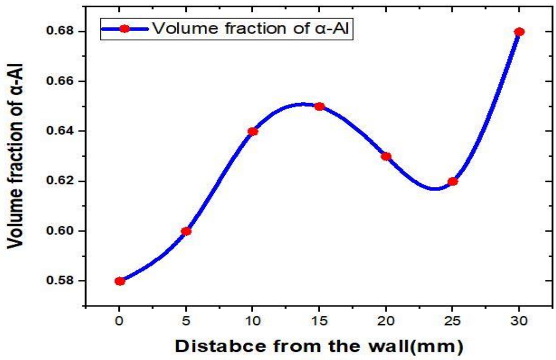

Figure 3. Varying the volume percentage of α-Al.

The rise in the percentage of volume from the wall to the centre is attributed to the existence of alloying elements with a low melting point in the most recently solidified liquid. This causes them to act as nuclei for the α-Al phase, resulting in the observed increase in volume fraction. Furthermore, The quick cooling near the wall leads to an augmentation in the volume % of the eutectoid phase [11]. Table 2 displays the ultimate tensile strength, yield strength, elongation, and hardness measurements from the wall to the center of the casting.

Table 2. Mechanical Characteristics of Zrsio4 / GDC Za-27 Composites

Properties / Materials	Tensile strength (MPa)	Yield stress. (MPa)	Elongation (%)
ZA- 27	320	295	2.8
0.5% $ZrSiO_4$ / ZA- 27	335	315	1.8
1% $ZrSiO_4$	370	355	1.6
2% $ZrSiO_4$ / ZA- 27	360	343	1.5
3% $ZrSiO_4$	340	310	1.3

Tensile strength improves by 50 MPa to 370 MPa, representing a 15.6% increase, whereas elongation decreases by 42.8%. The agglomeration of ZrSiO4 particles produces a significant loss in tensile and yield strengths when the fraction of reinforcement particles is increased to 3%. The hardness was enhanced by 3% to 135HB at 2mm from the wall and 109HB at the center, with an average of 123HB. The hardness measured 109HB at the wall and 90HB at the center, indicating a 1% decrease in hardness from the wall to the center. The average hardness was found to be 106HB. The mean values for the 2% inclusion are 116HB, while the mean values for the 0.5% inclusion are 102HB. The addition of 3% resulted in a 28% increase in hardness, while the addition of 1% resulted in a 10.5% increase in hardness compared to the ZA-27 alloy.

3.1 Solution Treatment and Age Hardening of GDC ZA-27

The GDC ZA-27 alloy had a solution treatment at a temperature of 320°C for a duration of 3 hours in order to achieve homogeneity. This treatment was conducted to investigate the influence of precipitation hardening on the alloy's characteristics and to determine the optimal aging period for achieving optimal wetting between ZrSiO4 and the matrix alloy. Subsequently, the metal was quenched using water, subjected to artificial aging at a temperature of 150 °C for a duration of 1-4 hours, and finally cooled using ambient air. The study showed that the optimal duration for ageing a substance is 2 hours, at which point it achieves a maximum hardness of 121HB. This value of time was then used for all aging processes. After age, a combination of much coarser particles partially replaced the minute zinc and aluminium lamella that had formed in the previous beta area around the alpha cores. This phase called epsilon was gone, and a lot of the steady τ- phase, which is made up of AlCuZn, had copper in it. The aging of ZA-27 alloy is a result of the gradual transformation of the epsilon metastable phase $CuZn_5$ to a stable copper-rich intermetallic τ-phase, which is closer to equilibrium. The τ-phase comprises 53.98 wt% Cu, 15.89 wt% Zn, and 30.13 wt% Al; it is isomorphous and has a deformed structure based on an ordered body centered cubic lattice, which enhances mechanical properties. A f.c.c solid solution has been produced by the heat treatment effect on the structure, which, upon quenching and aging, breaks down into a mixture of zinc (η) and aluminum (α) grain [6].

After heat treatment, the microstructure analysis of the GDC ZA-27 alloy showed a significant increase in the spacing between dendritic arms (DAS), from 20 µm to 49 µm. Furthermore, following the heat treatment, the average volume percentage of the α-Al phase rose to 0.85, up from its prior value of 0.64. Figures 4 and 5 illustrate the impact of heat treatment on the dendrite arm spacing (DAS) and the volume percentage of the α-Al phase.

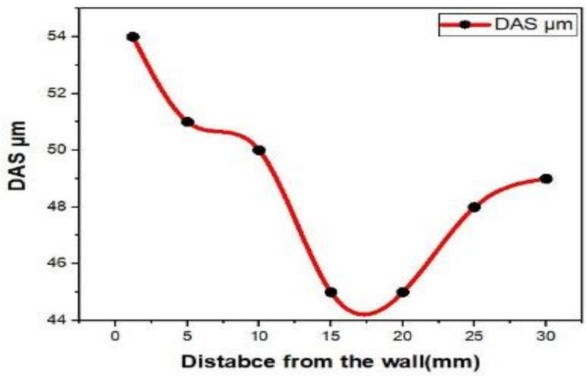

Figure 4. Variation of DAS with the distance.

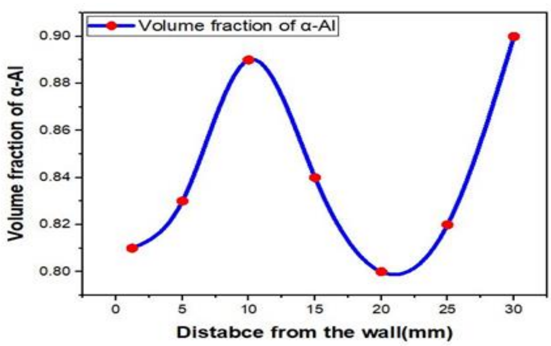

Figure 5. Variation of volume fraction of α-Al with the distance.

It has been found that these alterations significantly impact the mechanical characteristics. An increase in the proportion of the α-Al phase leads to a decrease in mechanical properties. However, the appearance of a new phase (τ-AlCuZn) during the aging process impedes the movement of dislocations and results in a notable enhancement of properties [6]. Thermal processing The cross-section hardness was enhanced to 104 HB from 96 HB after heat treatment. Additionally, the yield strength and tensile strength increased by 85 MPa and 70 MPa, respectively, resulting in a percentage rise of 28.8% and 21.8%. However, there was almost no change in the elongation percentage.

3.2 Solution Treatment and Age Hardening of GDC ZA- 27/ ZrSiO4

After undergoing heat treatment, the behavior of the α-phase volume fraction and DAS (Dendrite Arm Spacing) in AMCs (Aluminum Matrix Composites) remained unchanged when compared to ZA-27. The α-phase volume fraction and DAS values were found to be 0.82 and 54µm respectively at 1% ZrSiO4. Even a small quantity of ZrSiO4 increases the toughness of GDC ZA-27. The hardness of the material increases to an average of 132HB with a 3% addition, while it equals 121HB with a 1% addition, achieves an average value of 127HB with a 2% addition, and reaches an average value of 111HB with a 0.5% addition. When a 3% addition is applied, the hardness of the composite rises by 7.3%, and a 1% addition raises the hardness by 14% relative to the composite before heat treatment. The results of the tensile test indicate that both the yield strength and ultimate tensile strength are enhanced after undergoing heat treatment, as shown in table 3.2. After heat treatment, the ultimate tensile strength of GDC ZA-27 with 1% ZrSiO4 increases to 425 MPa, compared to its strength before heat treatment. After heat treatment, the yield strength of GDC ZA-27 /1% ZrSiO4 increased to 400 MPa, compared to its initial value of 355 MPa with a 1.4% elongation. The X-ray diffraction analysis revealed the existence of the τ-AlCuZn phase after the heat treatment, along with the previously identified phases of α-Al, β-Zn, η-Zn, and ε-CuZn5.The presence of the τ-AlCuZn phase could perhaps account for the observed enhancement in mechanical properties after undergoing heat treatment.

Table 3. Mechanical Properties of ZA- 27 / Zrsio4 Composite after Heat Treatment.

Properties / Materials	Tensile strength (MPa)	Yield stress. (MPa)	Elongation (%)
ZA - 27	390	380	2.5
0.5% ZrSiO4	400	390	1.6
1% ZrSiO4	425	400	1.4
2% ZrSiO4	420	395	1.3
3% ZrSiO4	415	385	1.2

3.3 NRC ZA -27 Alloy

Due to the dendritic structure of the GDC ZA-27 alloy, an alternative casting procedure called NRC is used, which involves an inclined mold with an inclination of 75 degrees. The NRC plans to significantly augment the grain population and alter the morphology of phase dendrites to a semi-globular shape. Analyzing the Microstructure is shown in Figure 6.

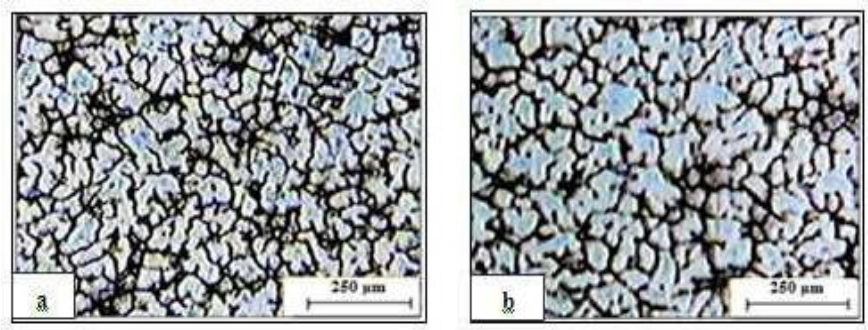

Figure 6. The microstructure of NRC ZA -27 alloy: Distances from wall (a) 2 mm and (b) 30 mm.

Primarily demonstrates the vanishing of the dendrite. The primary phase of aluminum, which is rich in aluminum and has a shape resembling an equiaxed grain, is surrounded by eutectoid. The average grain size near the wall is 36 µm, increasing to 44 µm in the center. Overall, the average grain size is 37 µm with minimal variation across the cross section. This uniformity has a positive impact on the isotropic properties. With volume fraction consistency, which is ascribed to the NRC with consistency along the cross section in Figures 7 and 8, the average volume fraction for the main Al rich α-phase was 0.58, equivalent to 0.64 for GDC ZA-27 alloy.

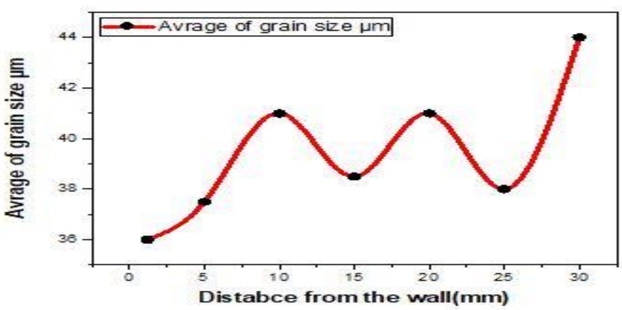

Figure 7. Variation in grain size.

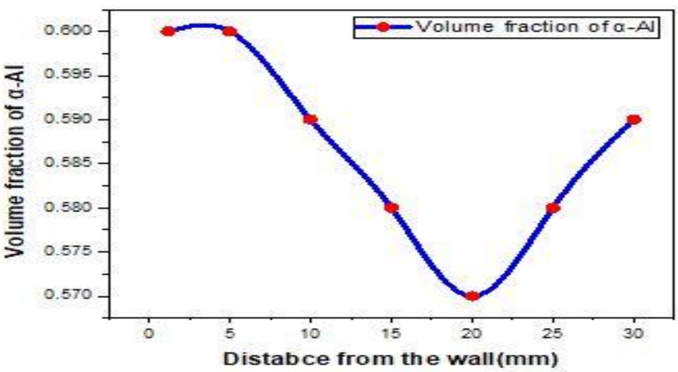

Figure 8. Varying the volume percentage of α-Al.

Furthermore, there was a transition in the microstructure from dendritic to equiaxed grain, accompanied by an increase in the volume percentage of eutectic. This led to enhanced mechanical properties. The hardness of ZA-27 alloy manufactured by NRC surpasses that of GDC, reaching a value of 107HB. This increase in hardness is attributed to a rise in the eutectic volume fraction and the refinement of the α-Al phase. In addition, the yield strength and tensile strength experience an increase to 340 and 360 MPa, respectively, while the elongation shows a smaller increase of 3% compared to the values shown in GDC Table 4.

Table 4. Mechanical Properties of Za- 27 / Zrsio4 Composite By GDC& NRC

Properties / Materials	Tensile strength (MPa)	Yield stress. (MPa)	Elongation (%)
ZA -27 GCD	320	295	2.8
0.1% ZrSiO4 / ZA -27 GCD	370	355	1.6
NRC ZA- 27	360	340	3.0
1% ZrSiO4 / NRC ZA- 27	390	380	2.8

3.4 DNRC ZA-27/ZrSiO4 Composite

Based on the previous discussion, it has been determined that the optimal percentage of reinforcement particle addition is 1%. Therefore, this proportion is utilized in the production of MMCS utilizing the NRC method, which combines the effects of both equaxid refining and ZrSiO4 addition. Figure 10 illustrates a microstructure that is equiaxed, meaning the grains have a similar size in all directions. The average grain size of this microstructure is 36 μm.

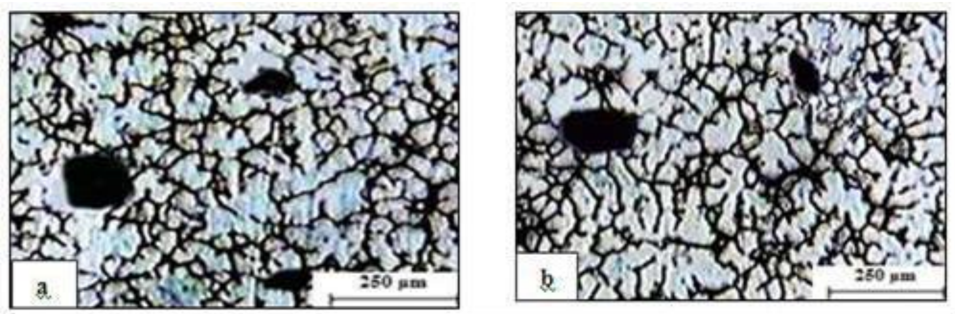

Figure 9. The microstructure of NRC ZA- 27 / ZrSiO4 : Distances from wall (a) 2 mm and (b) 30 mm.

The grain size increases as anticipated towards the center of the casting and remains at values very similar to NRC ZA-27, suggesting that stirring does not impact the resulting microstructure. Additionally, the average volume fraction for the primary - Al phase is 0.56, which closely aligns with NRC ZA-27. The NRC AMCs exhibited a higher level of hardness in comparison to the GDC AMCs, with an average hardness value of 116HB. The results of the tensile test indicate a rise in the yield stress from 355MPa to 380MPa, as well as an increase in the ultimate tensile strength from 370MPa to 390MPa, and an increase in elongation to 2.8%. (Table 4).

When utilizing the NRC process to create a composite with a 1% addition, the tensile strength measured 390 MPa and the yield strength measured 380 MPa. These results were in line with the findings of the compocast method in terms of tensile strength. However, the NRC process resulted in a significant increase in yield strength, with an additional 70 MPa (22.5%).

It is important to mention that the compocast method increases expenditures by 1% due to the addition of a higher proportion. When comparing the two methods at the same addition percentage, it is evident that the NRC process resulted in a higher tensile strength of 390MPa, compared to 350MPa for the compocasting process. Additionally, the NRC process led to an increase in yield strength to 380MPa, while the compocasting process only achieved a yield strength of 270MPa.

3.5 Solution Treatment and Age Hardening of NRC ZA-27

The process of solution heat treatment and age hardening of NRC ZA-27 alloy leads to an enlargement of the grain size of the primary α-Al phase over the casting's cross section, increasing it from 37 µm to 63 µm, as depicted in Figure 10.

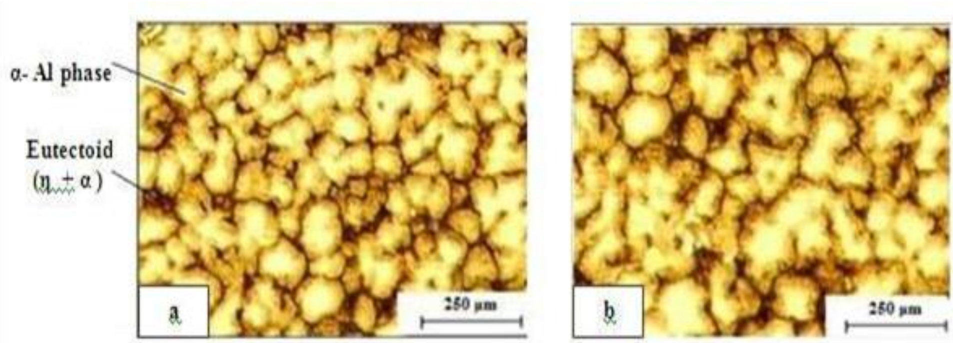

Figure 10. The microstructure of NRC ZA- 27 / after heat treatment: Distances from wall (a) 2 mm and (b) 30 mm.

The volume percentage of the primary α-Al phase varied from 0.72 (2mm away from the wall) to 0.79 at the center, with an average value of 0.79. The increase is a result of a reduction in the proportion of the eutectoid phase, as depicted in Figures 11 and 12.

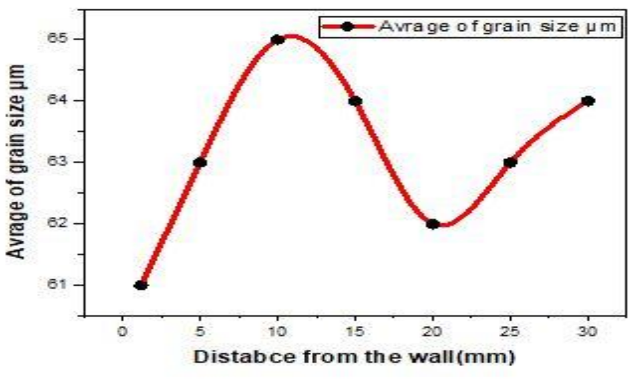

Figure 11. Variation in grain size after heat treatment

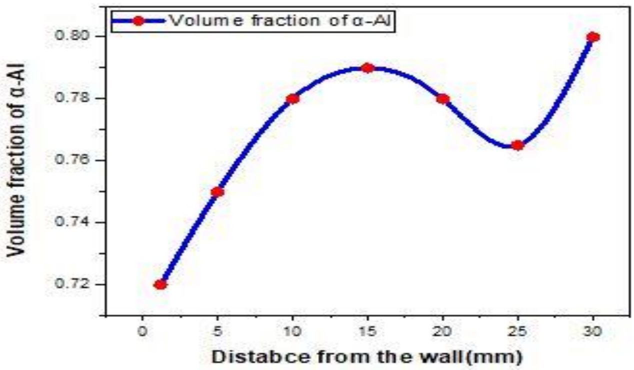

Figure 12. Varying the volume percentage of α-Al.

The aging of ZA-27 alloy has been proven to occur due to the gradual transformation of the metastable ε-$CuZn5$ phase into the stable copper-rich intermetallic τ-phase AlCuZn [6]. After undergoing heat treatment, the hardness experienced a minor increase to 114HB. Additionally, the yield strength and tensile strength improved to 410 MPa and 425 MPa, respectively. There was also a slight improvement in elongation, as seen in Table 5.

Table 5. Mechanical Properties of ZA- 27 / Zrsio4 Composite After Heat Treatment

Properties / Materials	Tensile strength (MPa)	Yield stress. (MPa)	Elongation (%)
ZA -27 GCD	390	380	2.5
0.1% ZrSiO4 / ZA -27 GCD	425	400	1.4
NRC ZA- 27	425	410	2.6
1% ZrSiO4 / NRC ZA- 27	425	420	2.4

3.6 Treatment and Hardening of NRC ZA-27/ZrSiO4 Composite

Thermal processing of NRC ZA-27 alloy with 1% ZrSiO4 reinforcement resulted in an increase in average grain size to 60 µm from 36 µm prior to heat treatment (Figure 13), as well as an increase in average volume fraction for α - Al phase to 0.79 from 0.56 prior to heat treatment.

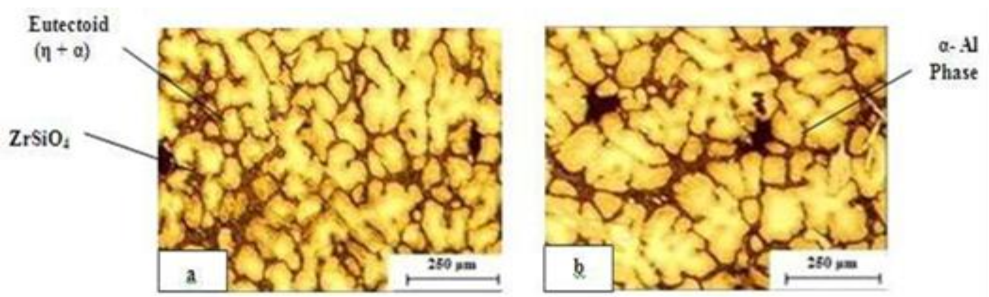

Figure 13. The microstructure of NRC ZA- 27 /1% ZrSiO4 after heat treatment: Distances from wall (a) 2 mm and (b) 30 mm.

The hardness of the material increased from 121HB to 131HB across the entire cross section. After undergoing heat treatment, the tensile strength of GDC ZA-27/1% ZrSiO4 increased from 425 MPa to 445 MPa, and the yield strength improved from 400 MPa to 420 MPa. Additionally, the elongation reached 2.4%. The information is included in table 5. Upon undergoing heat treatment, X-ray diffraction analysis revealed the presence of the stable intermetallic copper-rich phase τ-AlCuZn in all investigated specimens. This finding suggests that the aforementioned phase is one of the factors contributing to the observed improvement in mechanical qualities.

4. Conclusion:

- Apart from the GDC process, NRC can generate AMCs of ZA-27 strengthened using ZrSiO4 particles.
- The NRC manufactures equiaxed grains with an average size of 37 µm, in contrast to GDC's dendritic microstructure.
- The NRC increases the eutectoid volume fraction by 16.6% and decreases the Al volume fraction by 9.3%.
- The NRC approach enhances the mechanical properties of ZA-27 alloy by 12.5%, 15.2%, and 11.5% for tensile strength, yield strength, and hardness, respectively, in comparison to the GDC method.
- The appearance of the τ- AlCuZn phase is responsible for the increased mechanical properties after heat treatment.
- A greater hardness of 121HB is achieved by aging ZA-27/1% ZrSiO4 for 2 hours.

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