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Experimental Investigation on Hardness of AA4032 Reinforced Nano Si_3N_4 Using Novel Encapsulate Technique

Hemachandran Bharath Ram[1], Lakshmaiya Natrayan[1*] and Anbalagan Saravanan[2]

[1]Department of Mechanical Engineering, Saveetha School of Engineering, Saveetha Institute of Medical and Technical Sciences, Chennai, Tamil Nadu, India

[2]Department of Sustainable Engineering, Saveetha School of Engineering, Saveetha Institute of Medical and Technical Sciences, Chennai, Tamil Nadu, India

***Correspondence to:**
Lakshmaiya Natrayan
Department of Mechanical Engineering,
Saveetha School of Engineering,
Saveetha Institute of Medical and
Technical Sciences,
Chennai, Tamil Nadu, India.
E-mail: natrayanl.sse@saveetha.com

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Abstract

This study compared the hardness of composites reinforced with 10% nano Si_3N_4 and produced using a novel encapsulation technique to as-cast AA4032. The samples for both groups were produced using the stir-casting method and a new encapsulating approach. For group 1, the combination of nano Si_3N_4 (10%) and AA4032 was used as a composite, while for group 2, AA4032 as-cast was used. The samples were created following ASTM E92 criteria, and their hardness was assessed using a Vickers hardness machine. In each group, there were 20 samples. G-power of 80% = 0.05 per set and a total sample size of 40 were used to calculate the sample size. The 10% nano Si_3N_4 filled material was the most challenging material, which was 35% tougher than the as-cast AA4032. According to the t-test statistical analysis, the mean-variance of hardness between group 1 and group 2 differs by $p = 0.00$ ($p < 0.05$). Within the constraints of this work, it is clear that the inclusion of 10% nano Si_3N_4 reinforcement dramatically increases the hardness of the AA4032 composite.

Keywords

AA4032, Silicon nitride, Stir casting, Innovation, Composite, Energy, Novel encapsulation, Hardness, Sustainability

Introduction

The development of ultra-high strength, lightweight, stiffer, and wear-resistant engineered materials for exceptional performance has been the subject of extensive scientific research in recent years [1]. To get qualities superior to those of the constituent phases and fulfill the intended goals, metal matrix composite is considered suitable material. For aircraft industries, marine, and transportation applications, materials with uncommon combinations of properties such as low densities, strength, stiffness, and impact resistance are required. Metals, typical metallic alloys, ceramics, and polymeric materials cannot fulfill these requirements [2]. Aluminum and its alloys are the primary ingredients in the vast majority of metal matrix composites in research and development and industrial applications [3]. This is because aluminum is lightweight, a fundamental requirement for most metal matrix composite applications [4]. In addition, it is less expensive than other light metals like copper, titanium, and magnesium [5]. The machinability of aluminum alloy 4032 is considered to be acceptable to good. Pistons are frequently made of aluminum 4032 alloys [6].

Various publications about the metal aluminum 4032's properties and hardness have recently been published [7]. The AA4032 and its hardness properties have been the subject of 9275 publications in Science Direct and 25698 articles in Google Scholar. Due to its excellent weldability, aluminum alloy is widely employed to join structural components [8]. The finest publication that described the innovative encapsulating process in depth is thought to be the work on the hybrid composites created using this technology [9]. This research exhibits the fusion of the mechanical and computer science domains by optimizing the composite well with more than one reinforcement and adding to this; they also applied the artificial neural network approach with a novel encapsulation feeding technique for casting [10].

We discovered that there had been comparatively few investigations on creating composites using innovative encapsulating techniques. This work aimed to create a brand-new encapsulating stir-casting technique to create the AA4032/10% nano Si_3N_4 composite. The study aimed to evaluate the as-cast material's and the composite material's hardness characteristics.

Materials and Method

The comprehensive study was orchestrated across at Saveetha Industries, Saveetha School of Engineering, and Saveetha Institute of Medical and Technical Sciences, Chennai (Tamil Nadu, India). Central to this study is examining hardness attributes in two distinct material groups: the as-cast material and its composite counterpart. Each group comprised 40 samples, further divided into sets of 20 sizes. These divisions were ascertained based on a G-power calculation pegged at 80% [11].

For the preparation of the first set of 20 samples, the material in its as-cast state, designated as group 1, was utilized. A 20 mm AA4032 rod underwent lathe operations to ensure impeccable surface finishing, eliminating potential blemishes or excess material. The post-machining weight of the alloy was a consistent 1 kg within a crucible of the same capacity [12]. Upon positioning the crucible inside a furnace, the alloy melts as temperatures soar to 700 °C. Following liquefaction, the alloy is channeled into a mold by leveraging gravity to solidify, after which superfluous material is shed, rendering it ready for extraction [13]. The final step entails segmenting the casting metal into 8 - 10 mm chunks for subsequent hardness evaluation.

Group 2, the composite material set, underwent a slightly modified process. A 20 mm diameter AA4032 rod was expertly lathed to ensure a smooth and burr-free surface [14]. The rod was then punctuated with an array of holes, culminating with a 15 mm thick cup, crafted via lathe operations, which snugly covered the rod once it was laden with 10% nano Si_3N_4 (Figure 1). Post this filling operation, the rod undergoes a melting phase in a furnace (Figure 2), subsequently leading to a blend of molten AA4032 alloy and nano Si_3N_4 using a stir-casting technique (Figure 3). After molding and cooling, any excess material is sheared off, and the composite is segmented into 8 - 10 mm sections for hardness assessment.

To ascertain the hardness of both these groups, a Vickers hardness tester [15] was employed. In compliance with ASTM E92 standards, every sample from the total 40 was meticulously diced into 10 x 10 mm sections (Figure 4). During testing, the sample is precisely positioned, and an indentation is made using a diamond-tipped tool, under a force of 0.5 kgf for 15 s. The indentation's depth, gauged at three distinct points, is then measured under microscopic scrutiny to compute the hardness, which is subsequently displayed on the machine. It's worth noting that this procedure, encompassing all the aforementioned steps, was reiterated thrice for each 20-sample batch. To provide a visual reference for the hardness values, results for the as-cast samples are elucidated in figure 1, while the composite samples are detailed in figure 2.

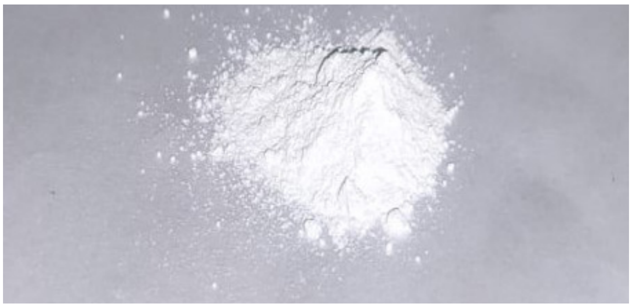

Figure 1: Nano Si_3N_4 (10% reinforcement).

Figure 2: Feeding nano Si_3N_4 to novel encapsulated AA4032.

Figure 3: Stir casting.

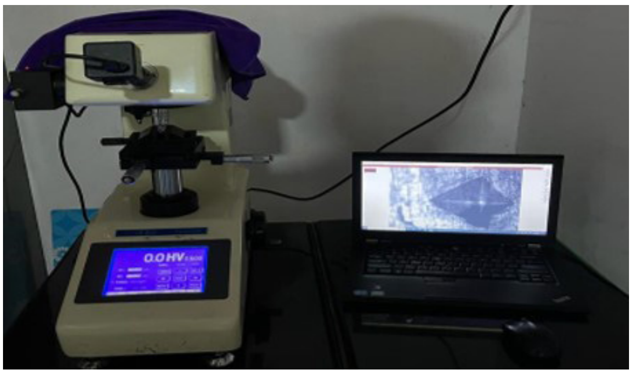

Figure 4: Hardness test.

Statistical analysis

IBM created the statistical software program SPSS (Statistical Package for the Social Sciences) for data administration, analysis, mathematical modeling, etc. The t-test is performed on the hardness measurements produced for the research samples using the statistical program SPSS. The statistical program SPSS is used to run the descriptive table and the Bonferroni analyses. In this study, the dependent variable is hardness, and the independent variables are stirred speed and the % of reinforcement weight.

Results

The research documentation distinctly lays out a systematic comparison of the hardness of AA4032 in its as-cast state, with and without the inclusion of nano Si_3N_4 as a reinforcing agent. Table 1 offers a direct comparison of these two conditions. For a more granular analysis, table 2 delves into group statistics, presenting detailed data on the hardness of the as-cast AA4032, both in its reinforced and non-reinforced forms. Moving further, table 3 focuses on the independent samples test, specifically spotlighting the hardness. This table provides insights into the variance and consistency of the hardness measures across the samples. Lastly, table 4 delivers descriptive statistics on the hardness of both as-cast materials, namely AA4032 in its unaltered state and its counterpart that's reinforced with Si_3N_4. In sum, this comprehensive tabulation meticulously chronicles the hardness data for the two groups, ensuring clarity and facilitating informed comparisons.

Discussion

The study underscores the significant influence of nano Si_3N_4 reinforcement on the hardness of AA4032 aluminum alloy. When assessed against its as-cast counterpart without any reinforcement, AA4032 enhanced with nano Si_3N_4 displayed notable hardness improvements. Descriptive tables were provided to facilitate a thorough and clearer understanding of these observations, capturing metrics such as mean, standard deviation, and mean standard error. This inclusion aids in simplifying the analysis process, making it straightforward to gauge the hardness differences between the reinforced and non-reinforced materials.

Table 1: Hardness of as-cast AA4032 without reinforcement and AA4032 with reinforcement Si_3N_4.

Sample number	As-cast AA4032	AA5059/Si_3N_4
1	138.98	159.392
2	138.83	159.242
3	137.92	158.332
4	138.89	159.302
5	136.69	157.102
6	135.89	156.302
7	136.55	156.962
8	134.77	155.182
9	136.12	156.532
10	137.22	157.632
11	135.78	156.192
12	135.13	155.542
13	133.81	154.222
14	133.43	153.842
15	131.67	154.822
16	133.03	185.632
17	134.83	155.242
18	135.83	156.242
19	137.43	157.842
20	137.82	158.232

Table 2: Group statistics of tensile strength in as-cast AA4032 without reinforcement and AA4032 with reinforcement nano Si_3N_4.

Group statistics		N	Mean	Std. deviation	Std. error mean
Hardness	As-cast AA4032	20	136.0310	2.04227	0.45666
	AA4032/Si_3N_4	20	158.1895	6.66824	1.49106

Placing these findings in the broader context of previous research, hardness values show a clear contrast. For instance, a past study highlighted that the hardness of AA4032 aluminum alloy gas tungsten arc welded joints was reduced by 38% compared to the base material. Another investigation, focusing on friction stir-welded AA4032 aluminum alloy joints,

Table 3: Independent samples test of the hardness in as-cast AA4032 without reinforcement and AA4032 with reinforcement Si_3N_4.

Hardness	Levene's test for equality of variances		T-test for equality of means						
	F	Sig.	t	df	Sig. (2-tailed)	Mean difference	Std. error difference	95% CI of the difference	
								Lower	Upper
Equal variances assumed	1.233	0.274	-14.209	38	0.000	-22.1585	1.55943	-25.3153	-19.0016
Equal variances not assumed			-14.209	22.533	0.000	-22.15850	1.55943	-25.38812	-18.92888

Table 4: Descriptive of the hardness of as-cast AA4032 without reinforcement and AA4032 with reinforcement Si_3N_4.

Hardness	N	Mean	Std. deviation	Std. error	95% CI for mean		Minimum	Maximum
					Lower bound	Upper bound		
As-cast AA4032	20	136.0310	2.04227	0.45666	135.0752	136.9868	131.67	138.98
AA4032/Si_3N_4	20	158.1895	6.66824	1.49106	155.0687	161.3103	153.84	185.63
Total	40	147.1103	12.23077	1.93385	143.1987	151.0218	131.67	185.63

recorded a 15% reduction in base metal hardness within the weld zone [16]. Interestingly, a separate study depicted in figure 5, indicated that an aluminum alloy reinforced with a hybrid combination of Al_2O_3 and graphite had a 14% increase in hardness compared to the base material. However, the current research outpaces these findings, revealing a 48% increase in hardness when AA4032 is combined with 10% nano Si_3N_4 compared to its as-cast version.

The method of casting is also noteworthy. The aluminum alloy underwent a casting process using an innovative encapsulation technique, which prior research suggests endows AA4032 with superior hardness compared to other casting methods. The amalgamation of the stir-casting method and this novel encapsulation technique ensures the uniform distribution of reinforcement across the metals during the casting phase [17]. Consequently, the resultant composite, enriched with nano Si_3N_4 via this unique encapsulation approach, exhibited unparalleled hardness levels.

Nevertheless, while the data and findings are promising, certain challenges arose in the study. Specifically, the hardness of the composite metal with the reinforcement saw a peak enhancement of 14% over the as-cast metal. The casting's integrity was also influenced by the stirrer and pouring techniques employed. At times, due to the natural flow of molten metal towards the die driven by gravity, defects such as shrinkage cavities, pinholes, and blow holes emerged in the castings. Recognizing these imperfections as limiting factors in the study, future research aims to harness squeeze casting techniques. The primary objective here is to mitigate the formation of air bubbles, which are the root cause of such casting defects, to achieve even more refined results.

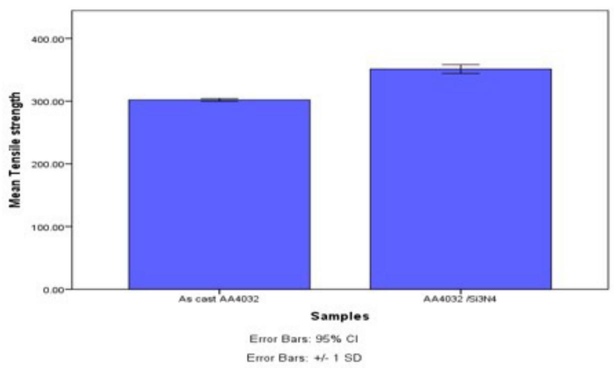

Figure 5: Mean hardness in comparison with and without reinforcement.

Conclusion

The study delves into enhancing the hardness of a specific composite material, which is an amalgamation of AA4032 alloy and 10% Si_3N_4. A composite material is engineered by merging two or more distinct substances to attain properties that aren't inherent in the individual materials alone. In this context, AA4032 represents a type of aluminum alloy. The objective was to see how this alloy's hardness could be improved when combined with Si_3N_4. The hardness of the AA4032 alloy exhibited an increase of approximately 14% upon the addition of the 10% nano Si_3N_4 reinforcement compared to the AA4032 material in its as-cast state. What made this outcome particularly interesting was using a pioneering encapsulation technique paired with stir casting. This method appeared to be instrumental in enhancing the hardness of the composite. The implications of this enhanced hardness are manifold. With its improved properties, the composite material is now a candidate for applications demanding high hardness, such as vehicle armor, which needs to resist specific degrees of impact and strain. In the automotive realm, the reinforced alloy could also find its way into the creation of pistons, parts of a vehicle's chassis, components of racing engines, and other machinery that require superior performance, especially when exposed to elevated temperatures. This opens up new avenues for industries in search of materials that can offer both durability and heat resistance.

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None.

Conflict of Interest

None.

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