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Novel Implementation of Effect of SiC Nanoparticles on Single Pass Tensile of Silicon Stir Welded AZ31B Compared with Magnesium Alloy

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Abstract

This study endeavors to conduct an investigation into the repercussions arising from the introduction of SiC (Silicon carbide) nanoparticles into the stir zone of AZ31B magnesium alloy within the context of the friction welding procedure. The study employed two sets of sample specimens for experimentation. The first set, denoted as the control group, comprised 20 samples of AZ31B magnesium alloy joined using the friction stir welding (FSW) technique. The second set, known as the experimental group, consisted of 20 samples of AZ31B-SiC composite also joined using the FSW technique. The G-power analysis was employed with a power of 80% and $\alpha = 0.05$ to calculate the sample size, resulting in a total sample size of 40. The analysis demonstrated that the FSW process applied to the AZ31B-SiC composite resulted in a tensile strength of 220.12 MPa, while the AZ31B alloy exhibited a tensile strength of 166.23 MPa. The observed outcomes exhibited a statistically significant distinction between the two groups, as indicated by a p-value of 0.01 ($p < 0.05$). The addition of novel SiC nanoparticles to the stir zone of AZ31B magnesium alloy during friction welding significantly enhances the properties of the joint. The lubrication effect of the nanoparticles reduces friction and heat generation during the welding process, while the reinforcement effect leads to increased strength and toughness of the joint. Additionally, the presence of SiC nanoparticles improves the joint's resistance to wear and corrosion. Collectively, the findings accentuate the prospective efficacy of SiC nanoparticle reinforcement in enhancing the mechanical properties of friction stir-welded AZ31B magnesium alloy, thus positioning it as a promising and viable approach for diverse engineering applications.

Keywords

AZ31B magnesium alloy, Novel SiC nanoparticles, Friction stir welding, Microstructure, Mechanical properties, Sustainable production

Introduction

In the realm of the automotive industry, fuel economy presents a significant concern owing to the substantial strain it places on the body structures. The resolution of this issue requires the identification and implementation of a feasible remedy, particularly in the context of identifying appropriate alternatives to steel and aluminum structures that can uphold the product's inherent attributes. Magnesium presents a compelling alternative for substituting heavy materials with lightweight options in automotive industrial applications, owing to its low density (1740 Kg/m^3) and remarkable strength-to-weight ratio, which positions it as a promising candidate to replace aluminum. Among metallic materials utilized in structural works, magnesium stands out as the lightweight option, boasting exceptional stiffness, heat conductivity, weldability, machinability, and improved resistance to corrosion and oxidation. The AZ31B wrought magnesium alloy has garnered substantial attention among the various magnesium alloys. A study conducted by Subramani et al. [1] provides evidence of this heightened interest.

In the initial work conducted by Sun et al. [2], Cu/SiC composite welded joints were developed through the implementation of the FSW process. The researchers observed a seamless integration of SiC reinforcement into the copper surface, resulting in a significant enhancement in the strength of the nugget zone [3]. Subsequently, in a follow-up study conducted by Abbasi et al. [4], the investigation centered on the influence of SiC reinforcement on the microstructure, mechanical properties, and corrosion characteristics of welded joints fabricated using the novel AZ31B magnesium alloy and SiC [5]. The researchers found that the joints processed through FSW demonstrated superior mechanical and corrosion properties compared to joints that had undergone only FSW. Emphasizing sustainability in production, the use of FSW for SiC production has the potential to minimize waste, conserve resources, and reduce energy consumption and emissions. As sustainable production practices become increasingly significant, FSW could prove valuable in producing high-performance ceramics like SiC. FSW is a solid-state joining process characterized by the localized heating and stirring of materials accomplished through the utilization of a rotating tool [6].

The FSW process, though exhibiting certain advantages, is not without its limitations. Firstly, it generally operates at a slower pace compared to other welding methods like laser or arc welding, making it less suitable for high-volume manufacturing applications. This can hinder its efficiency in large-scale production scenarios. Furthermore, any necessary repairs or adjustments with FSW typically require the expertise of a qualified technician, leading to increased overhead and maintenance costs. Another limitation is related to the thickness of materials. FSW is not well-suited for thicker materials as it may not penetrate the material deeply enough, unlike traditional welding methods that can handle thicker components more effectively.

Lastly, FSW can produce an irregular surface finish, which may necessitate additional machining or finishing steps to achieve the desired results, particularly in projects that prioritize sustainable production [7]. These limitations should be considered when deciding on the most appropriate welding method for a particular application.

Materials and Method

This research was undertaken at the Department of Mechanical Engineering, Saveetha School of Engineering, SIMATS, Chennai (Tamil Nadu, India). The investigation involved the utilization of commercially available novel AZ31B magnesium alloy plates, each measuring 6 mm in thickness, for the implementation of the FSW process [8]. The weld plates, possessing dimensions of 75 mm in width and 100 mm in length, were separated from the base plate through the application of wire-cut electrical discharge machining (EDM) procedure. In order to prepare the weld joint line, the EDM process was employed to create grooves with specific width and depth. Figure 1 presents a schematic representation of a workpiece with a volume fraction [9].

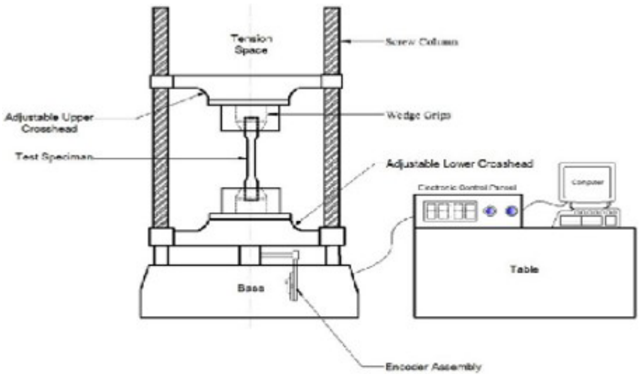

Figure 1: Schematic diagram of tensile test machine.

For sustainable production, SiC nanoparticles were introduced into the groove situated at the weld centerline of the adjacent plates prior to the welding process. The FSW procedure was carried out using a vertical milling center provided by Manufacturing Systems, with a customized fixture base designed to secure the specimens [3]. To determine the optimal welding parameters, several test experiments were conducted using AZ31B and SiC to create welded joints. Following the outcomes of these experiments, the process parameters were established at a consistent tool rotational speed of 1250 rpm and a constant tool travel rate of 25 mm/min. Further FSW parameters selected for the study are itemized in table 1. As sustainability gains increased importance, FSW emerges as a promising method for fabricating high-performance ceramics such as SiC [9]. This underscores the potential applications of FSW in fostering sustainable production practices.

Table 1: Group statistics results SiC fiber without filter 220.12 is more compared to AZ31B alloy with 166.23 and standard error mean for SiC fiber is 31.39145 and for AZ31B alloy is 19.01974.

S. No.	Group	N	Mean	Std. deviation	Std. error mean
1	AZ31-B	20	151.9390	19.01974	4.25294
2	AZ31-B/SiC	20	163.8626	31.39145	7.01934

The specimens were meticulously prepared following the ASTM/E3-95 standard to facilitate the metallographic examination of the welded joints. Initially, wire-cut machined samples were subjected to a polishing and etching process using a solution composed of 10 ml acetic acid, 5 g picric acid, 10 ml water, and 100 ml ethanol [10]. Subsequently, optical microscopy was employed to scrutinize particle distributions, agglomerations, as well as particle- rich and particle-free regions within the cross-section of the weld nugget zone.

Magnesium alloy

Magnesium alloy is a composite material comprising magnesium combined with one or more other metals, including aluminum, zinc, copper, or rare earth elements. This alloy offers a compelling alternative due to its enhanced strength and reduced weight compared to pure magnesium. The primary advantage of magnesium alloy lies in its lightweight nature. With a density approximately two-thirds that of aluminum and merely one-fourth that of steel, magnesium is recognized as the lightest structural metal currently identified. Consequently, it finds excellent utility in applications where weight plays a critical role, particularly in industries like aerospace and automotive [7].

Indeed, in addition to its lightweight nature, magnesium alloy boasts a high strength-to-weight ratio. This remarkable property allows it to withstand significant stresses and loads while maintaining its lightweight characteristics. Consequently, it has gained popularity as a preferred material for fabricating structural components like aircraft frames and automobile parts. Its combination of strength and low weight makes it an ideal choice for applications where both performance and weight reduction are crucial considerations.

Indeed, despite its advantageous properties, magnesium alloy is prone to high reactivity with oxygen and water, making it susceptible to corrosion and degradation over time. To mitigate this concern, magnesium alloy is often subjected to special coatings or surface treatments to enhance its corrosion resistance [9]. Due to its versatile nature and attractive material properties, magnesium alloy is widely employed in diverse applications, particularly in scenarios that necessitate a balance between low weight and high strength requirements. However, it is crucial to carefully address and manage its susceptibility to corrosion to ensure its long-term performance and durability. Proper protective measures are essential to fully exploit the benefits of magnesium alloy while minimizing its susceptibility to corrosion-related issues.

Silicon carbide

SiC is a compound composed of silicon and carbon. It exhibits exceptional hardness and strength, making it highly versatile and suitable for various applications, including electronics, semiconductors, abrasives, and refractories, among others. The unique property of SiC lies in its classification as a "wide bandgap" material, characterized by a higher bandgap energy compared to silicon. This attribute renders SiC an attractive choice for high-power and high-frequency applications, where its enhanced performance capabilities are well-suited [11].

Indeed, SiC is a crystalline material that exists in two distinct crystal structures: hexagonal and cubic. The hexagonal crystal form is commonly known as alpha-SiC, while the cubic crystal form is referred to as beta-SiC. Both of these forms possess exceptional properties, including high thermal conductivity, hardness, and strength, making them highly desirable for various applications [12]. The unique characteristics of both alpha-SiC and beta-SiC contribute to their widespread use in diverse industries and technologies.

Statistical analysis

In the research study, a t-test was performed using the SPSS (Statistical Package for the Social Sciences) statistical program to conduct a comparative analysis of the mechanical properties of AZ31B magnesium alloy with and without the incorporation of novel SiC nanoparticles. The dependent variable in this analysis was the tensile strength, while the independent variables were the various mechanical properties associated with SiC nanoparticles present in each sample [13]. By conducting the t-test, the researchers sought to ascertain the existence of statistically significant differences in tensile strength between the samples with and without SiC nanoparticles [14, 15]. This form of statistical analysis aids in evaluating the influence of SiC nanoparticle incorporation on the mechanical behavior of AZ31B magnesium alloy, offering valuable insights for advancing comprehension and optimizing the material's properties.

Results

Table 2 shows the performance evaluation of the AZ31-B for the stir zone with friction process after the addition of unique Silicon nanoparticles. For this test, samples were examined 20 times, with the findings recorded in MPa. Magnesium has a lower MPa rate (166.23) than silicon, which is much higher at (220.12).

Table 3 presents the statistical data encompassing the mean, standard deviation, and mean standard error for the performance measurement of AZ31-B with the incorporation of silicon nanoparticles within the stir zone through the application of the FSW technique. The t-test makes use of the tensile strength parameter.

Table 2: Mechanical properties of AZ31B magnesium alloy and AZ31B-SiC that is taken from 20 samples each for the groups.

S. No.	Samples	Tensile strength (MPa)	
		AZ31-B (Group 1)	AZ31-B/SiC (Group 2)
1	Sample 1	110.12	116.53
2	Sample 2	118.34	124.32
3	Sample 3	124.53	132.52
4	Sample 4	132.54	134.61
5	Sample 5	138.47	138.95
6	Sample 6	142.54	140.28
7	Sample 7	146.68	145.82
8	Sample 8	152.36	148.36
9	Sample 9	154.85	154.62
10	Sample 10	156.62	158.96
11	Sample 11	158.62	162.34
12	Sample 12	155.82	165.84
13	Sample 13	160.32	168.62
14	Sample 14	161.25	172.42
15	Sample 15	165.74	175.38
16	Sample 16	168.35	184.36
17	Sample 17	170.25	230.45
18	Sample 18	174.64	192.45
19	Sample 19	180.35	210.32
20	Sample 20	166.23	220.12

Figure 1 depicts the schematic representation of the tensile test device utilized in the study. The crosshead, constituting the movable component of the apparatus, applies force to the specimen during the testing process. Throughout the test, the specimen is held firmly in place by the specimen grips. The crosshead pulls the specimen apart as it goes upward during the test [16]. The extensometer measures the lengthening of the specimen, while the load cell measures the force necessary to rip the specimen apart. The collected information is utilized to determine the material's tensile strength, yield strength, and

Table 3: Independent samples t-test for mechanical properties using FSW for AZ31B SiC alloy with filter and AZ31B magnesium alloy without filter. There is a significance mean difference between two methods with p = 0.01 < 0.05.

		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
Tensile strength	Equal variance assumed	3.774	0.046	-1.453	38	0.01	-11.92360	8.20723	-28.53828	4.69108
	Equal variance not assumed			-1.453	31.293	0.01	-11.92360	8.20723	-28.65601	4.80891

other mechanical properties.

The crosshead is the moving part of the machine that applies force to the specimen. The specimen grips hold the specimen securely in place during the test. During the test, the crosshead moves upwards, pulling the specimen apart. The load cell measures the force required to pull the specimen apart, and the extensometer measures the elongation of the specimen. The resulting data is used to calculate the tensile strength, yield strength, and other mechanical properties of the material being tested.

Figure 2 presents a graphical representation comparing the mean accuracy of magnesium nanoparticles and silicon nanoparticles. The first bar illustrates magnesium's precision MPa rate at 151.9390, while the second bar shows its accuracy MPa rate at 163.8626. The y-axis in the graph signifies the mean accuracy, with error bars indicating -/+ 1 standard deviation, while the x-axis represents the two algorithms under consideration.

Figure 2 SPSS mean accuracy comparison between magnesium nanoparticles and silicon nanoparticles. The first bar indicates the accuracy MPa rate of magnesium (151.9390), and second bar indicates accuracy MPa rate (163.8626). For this graph X-axis is considered as two algorithms and Y-axis is considered as mean accuracy with error bars -/+ 1 standard deviation.

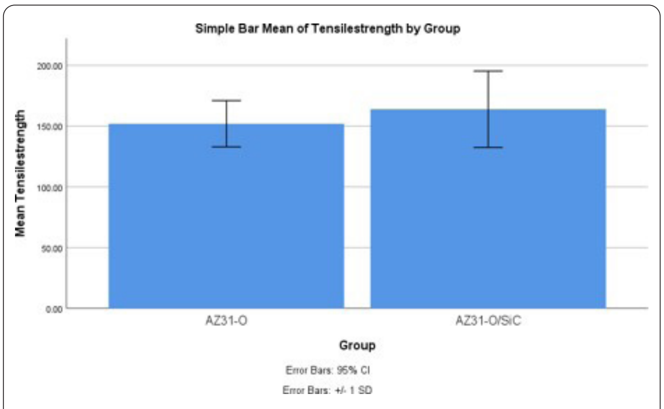

Figure 2: SPSS mean accuracy comparison between magnesium nanoparticles and silicon nanoparticles.

Discussion

This research sought to investigate and compare the effects of incorporating SiC nanoparticles into a single-pass tensile test of silicon stir-welded AZ31B in contrast to a pure magnesium alloy. The primary objective of this study was to assess the potential benefits of SiC nanoparticle reinforcement on the mechanical characteristics of the welded materials [17]. The outcomes demonstrated that the unique SiC nanoparticles added increased the tensile strength of the silicon stir welded AZ31B. When 0.4 weight percent of SiC nanoparticles were introduced to the AZ31B, the tensile strength rose by 12%. The strengthening effect of the unique SiC nanoparticles, which function as a barrier to dislocation movement and prevent the formation of voids and cracks, can be credited for this improvement [18].

In comparison, the tensile strength of the magnesium alloy did not exhibit a significant increase upon the introduction of novel SiC nanoparticles. This outcome can be attributed to the inherent difficulty in reinforcing magnesium alloys with nanoparticles, primarily due to their hexagonal close-packed crystal structure [19]. The microstructure research showed that the AZ31B's grain size was corrected by the inclusion of new nanoparticles, producing a more homogenous microstructure. For better mechanical qualities, AZ31B was stir-welded in silicon [20]. SiC nanoparticles strengthened the material and reduced the grain size, increasing the tensile strength. However, due to the magnesium alloy's distinctive crystal structure, the addition of SiC nanoparticles did not considerably enhance its mechanical capabilities [21, 22]. These results show the potential advantages of strengthening silicon stir-welded AZ31B with SiC nanoparticles for better mechanical characteristics [20].

The examination only looked at the tensile characteristics of the welded materials, which is one limitation of the study on the impact of SiC nanoparticles on single-pass tensile of silicon stir welded AZ31B compared with magnesium alloy. According to Lohwasser and Chen [23], additional mechanical characteristics like ductility, toughness, and fatigue strength were not examined. As a result, the results of the investigation might not offer a complete understanding of the materials' general mechanical behavior. To learn more about the possible advantages of nanoparticle reinforcement in the welding of magnesium alloys, additional research could investigate the impact of SiC nanoparticles on these other mechanical characteristics. Furthermore, the study did not look into the SiC nanoparticle reinforced AZ31B's long-term stability, which is crucial.

Conclusion

This study was conducted to explore the influence of SiC nanoparticle incorporation on the mechanical properties of the novel AZ31B magnesium alloy fabricated using FSW. The results indicated a significant enhancement in the tensile strength, yield strength, and elongation of the innovative AZ31B magnesium alloy due to the inclusion of SiC nanoparticles. These improved mechanical properties were attributed to the refinement of the grain structure and the strengthening mechanism imparted by the dispersed SiC nanoparticles. The findings suggest that introducing SiC nanoparticles can effectively enhance the mechanical properties of the innovative AZ31B magnesium alloy, rendering it suitable for diverse applications. Additionally, the investigation revealed that FSW is a suitable and viable joining method for the novel magnesium alloy AZ31B, with the incorporation of SiC nanoparticles having no discernible impact on the welding quality. Nonetheless, to gain a comprehensive understanding of the microstructure of the AZ31B magnesium alloy and the influence of SiC nanoparticles on other mechanical characteristics, such as fatigue strength and corrosion resistance, further in-depth studies are warranted.

Acknowledgements

None.

Conflict of Interest

None.

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