Silicon Carbide Nanoparticle-Enabled Strengthening of Aluminum and Copper Resistance Spot Welds

Vinayagamurthi PONNUSAMY [1] *, Ravikumar MUTHAIYAN [2], Suresh SUBRAMANIAN [3], Rajamurugan GOVINDASAMY [4]

[1] *Department of Mechanical Engineering, Jayalakshmi Institute of Technology, Thoppur, Tamil Nadu, India*
[2] *Department of Mechanical Engineering, Bannari Amman Institute of Technology, Sathyamangalam, Tamil Nadu, India*
[3] *Department of Mechanical Engineering, Erode Sengunthar Engineering College, Erode, Tamil Nadu, India*
[4] *Department of Mechanical Engineering, Vellore Institute of Technology, Vellore, Tamil Nadu, India*

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Resistance spot welding (RSW) is a widely employed technique for joining aluminum and copper alloys, valued for its efficiency and effectiveness. However, the mechanical properties of the resulting welds, particularly their tensile strength and resistance to deformation, often fall short of industrial demands. This study explores the incorporation of Silicon Carbide nanoparticles (SiC NPs) as a method to enhance the mechanical performance of RSW joints in aluminum and copper alloys. Experimental results demonstrate that the addition of SiC NPs significantly improves tensile strength, with gains primarily attributed to grain refinement and the formation of dispersion-strengthening mechanisms. Advanced characterization techniques, including Field Emission Scanning Electron Microscopy (FESEM) and EDS analysis, provide detailed insights into the morphological and structural transformations within the weld zones. These findings underscore the potential of SiC NPs to not only enhance the strength and durability of RSW joints but also to advance the overall quality and reliability of welding processes in aluminum and copper alloys. This research opens new avenues for the application of nanoparticle reinforcement in industrial welding, offering a pathway to achieve superior joint performance.
Keywords: resistance spot welding, aluminium alloys, copper, dissimilar spot-joint.

1. INTRODUCTION

Resistance spot welding (RSW) is a prevalent technique for joining aluminum and copper alloys in various industrial applications, including automotive, aerospace, and electronics manufacturing [1, 2]. This approach utilizes the contact resistance between the base materials and the electrodes. As the temperature increases from the electrical resistance of the materials, melting at the interface creates a weld nugget. Joule's law can be used to calculate the heat generated during RSW [3]. Despite its widespread use in industry, resistance spot welding (RSW) can sometimes produce joints with lower mechanical properties in dissimilar material welds, such as aluminum to copper, due to the significant differences in material properties and heat input during welding. The grain coarsening that may occur in the weld zone is often attributed to higher heat input and slower cooling rates. However, this effect is highly dependent on the specific process parameters and materials involved [4]. To tackle these challenges, researchers have explored various strategies to enhance the mechanical properties of RSW joints, including alloying additions, post-weld heat treatments, and surface modifications [5]. In contrast, laser welding offers higher cooling rates due to its concentrated heat source, which can result in a finer microstructure and improved mechanical properties.

Previous studies in joining Al/Cu dissimilar joints by RSW reported the cause of various input process factors on mechanical, electrical, and metallurgical behaviors of the dissimilar weld. Fujii et al. [6] extensively analyzed the interfacial microstructure of Cu/Al joints employing ultrasonic welding, revealing that ultrasonic energy significantly hastened the growth of $CuAl_2$ through the augmented diffusion of Cu atoms. Jafari and Senkara [7] typically analyzed the Effect of Multi-Pulsed Current AA-2219 Sheets through RSW and demonstrated logical optimization of joint strength according to the mechanical properties.

Recent advancements in nanotechnology offer a promising avenue for improving the performance of welded joints through the incorporation of nanoparticles [8 – 11]. Diverging from conventional methods, Zhou et al. [12] employed Zn-15 %Al filler metal to repress the arrangement of Cu-Al intermetallic compounds (IMCs) in laser-brazed joints of 5052 Al alloy and brass, noting the presence of brittle IMCs like CuZn, Cu-Al-Zn, and Cu_9Al_4 in the reaction layers, which led to susceptibility to cracking. In previous studies, zinc has been employed as an intermediate layer between Mg–Al joints to improve the weld strength [13]. Using a gold-coated nickel interlayer during the RSW of dissimilar Al and Mg alloys effectively inhibited the formation of Al-Mg intermetallic compounds, resulting in robust Al/Mg welds with enhanced strength [14].

In a simultaneous study, Ni et al. [15] performed RSW on Cu/Cu joints using copper nanoparticles added as an interlayer. They observed that the presence of hard Cu NPs

*Corresponding author: V. Ponnusamy
E-mail: *vinayagamurthi.mech@jit.net.in*

significantly boosted the generation of frictional heat and initiated surface activation of the base metal, thereby promoting the formation of more efficient welded regions.

Among these nanoparticles, Silicon Carbide (SiC) nanoparticles have garnered significant attention due to their excellent thermal stability, high strength, and compatibility with aluminum and copper alloys [16]. By dispersing SiC nanoparticles within the weld zone, it is possible to refine the microstructure, inhibit grain growth, and enhance the mechanical properties of the welds [17, 18]. However, the precise mechanisms governing the strengthening effects of SiC nanoparticles in RSW joints remain to be fully elucidated, warranting further investigation.

This work's innovation is in examining the combined effects of SiC nanoparticles and RSW processes, especially for joining aluminum and copper alloys. This research seeks to address this gap by thoroughly examining the impact of SiC NP reinforcement on the microstructure and mechanical properties of Al/Cu dissimilar RSW joints, offering valuable insights into the viability and efficacy of this method.

2. EXPERIMENTAL PROCEDURE

The RSW trials were performed with sheets of 6061 aluminum alloy and commercially pure copper, both measuring 1.5 mm in thickness. Before welding, surface preparation involved cleaning the sheets with acetone to remove any surface contaminants. Silicon Carbide nanoparticles (SiC NPs), averaging 50 nm in size, were used as reinforcement particles. Fig. 1 represents the TEM micrograph of the as-received SiC NPs.

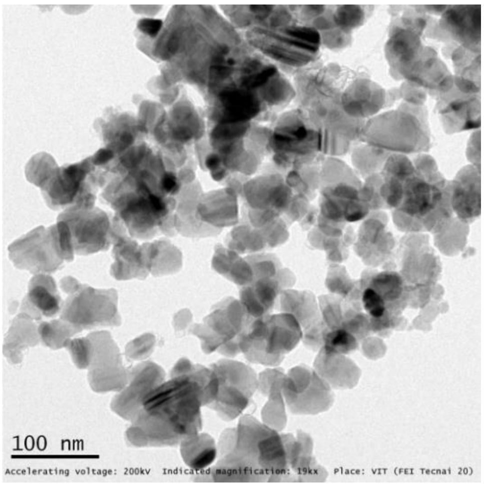


Fig. 1. TEM image of SiC nanoparticles

High-purity SiC NPs were mixed with ethanol and applied to the aluminum-overlapped surface. This mixture was allowed to evaporate, and any remaining traces of ethanol were eliminated by drying the surface in an oven. Following this, a copper piece was placed on top of the aluminum sheet, as illustrated in Fig. 2.

Aluminum-copper (Al/Cu) dissimilar spot joining was conducted utilizing a programmable logic controller (PLC)-controlled, 100 kVA RSW machine. In a systematic approach, the welding current was incrementally augmented from 18 to 22 kA with an increased value of 1 kVA. It was observed that values below 18 kA and above 22 kA resulted in defects during trial runs, highlighting the critical range for optimal welding performance. Key welding parameters, including welding time, electrode holding time squeeze time, and electrode force, were meticulously maintained at 0.8 s, 0.2 s, 0.6 s, and 1.5 KvN. The welding parameters were optimized based on preliminary trials to ensure adequate weld formation without excessive spattering or expulsion.

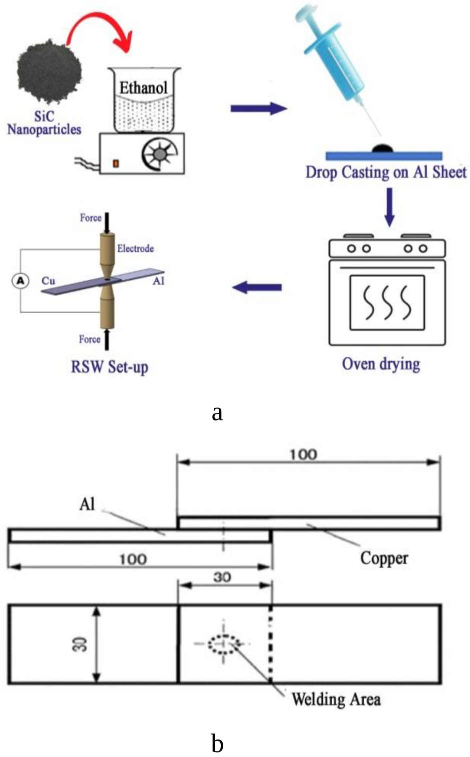


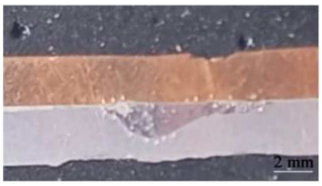
Fig. 2. a – experimental procedure to add SiC NPs in base materials; b – weld pate dimensions

Following welding, the samples underwent meticulous preparation for microstructural analysis. They were carefully sectioned, polished to a mirror-like finish, and subsequently etched in a solution comprising 5 g of $FeCl_2$, 50 ml of HCl, and 100 ml of H_2O. This etching process exposed the microstructural texture of the welds, enabling a detailed examination of their morphology and composition. Microstructural observations were conducted using advanced imaging techniques, including GX51 Olympus optical microscopy (OM) and TESCAN MIRA3 FESEM. The optical microscopy provided high-resolution kV to ensure optimal imaging conditions. The tensile-shear test was employed as the primary method to establish the mechanical behavior of the joints. For this test, samples with dimensions of 100 × 30 mm were prepared to ensure standardized testing conditions. Images of the overall microstructure, while the FESEM allowed for detailed examination at higher magnifications. Both instruments work at an accelerating voltage of 15 kV to ensure optimal imaging conditions.

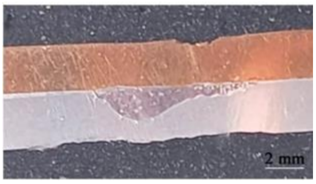
3. RESULTS AND DISCUSSION

Fig. 3 shows the cross-sectional macrostructures of the Al/Cu RSWed joints at various welding currents. Fig. 3 reveals that the nugget area is changing according to the welding current. It is observed that all the samples are free from defects. It is also worth indicating that the area of the nugget zone varies concerning the welding current. Both sheets exhibited electrode indentations, with the Cu sheet protruding into the Al side.

The nugget area expanded with increasing welding current. At 20 kVA, the nugget area matched that of the intermediate joint. The nugget area increased as the current was raised from 18 to 20 kVA. The slight decrease in nugget area at 21 kVA could be due to heat loss from expulsion, resulting in the base metal reaching a lower peak temperature compared to the joint welded at 20 kVA.



a



b

c

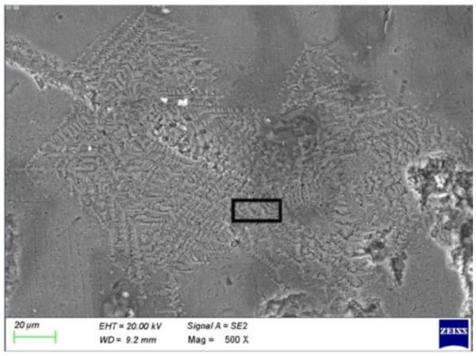
d

e

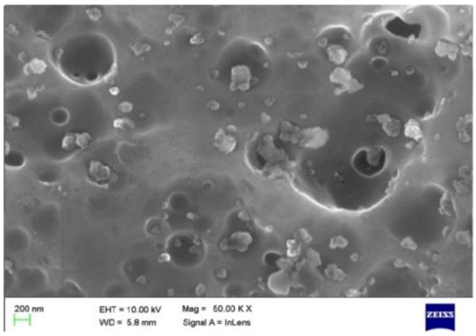
Fig. 3. Appearance of the cross-section of welded joint made with a welding current of: a – 18 kVA; b – 19 kVA; c – 20 kVA; d – 21 kVA; e – 22 kVA

Fig. 4 presents the FESEM image of a typical Cu/Al spot joint incorporating SiC NPs, captured at the nugget center of the sample welded at 20 kVA. The microstructure of the weld nugget, as depicted in Fig. 4, exhibits micro-cracks along with fine equiaxed grain boundaries, which are surrounded by SiC NPs [18, 19]. Notably, as shown in Fig. 4 b, the SiC NPs are located at the centers of numerous grains. These nanoparticles act as grain-refining agents, contributing to the enhanced lap shear strength of the joint [20]. Fig. 5 represents the EDS study of the Al/Cu spot weld at the center of the weld nugget.

Fig. 6 presents the EDS analysis of the weld nugget-interface region, clearly demonstrating the presence of alloying elements from the base metal. The predominant elements identified were Al, Cu, Si, C, and oxides, all located at the joint interfaces. Notably, there is a pronounced peak of Si and C at both sides of the weld nugget, confirming the distribution of SiC within the weld area. The EDX results in the current study provide a broad elemental analysis of the Al/Cu weld region, indicating the presence of key elements such as Mg, Si, and Cu. These elements are known to form precipitates in aluminum alloys, such as Mg_2Si and $CuAl_2$, which contribute to the material's mechanical strength [21].



a



b

Fig. 4. a – FESEM micrograph at nugget zone made with 20 kVA, b – magnified image of the portion mentioned in a)

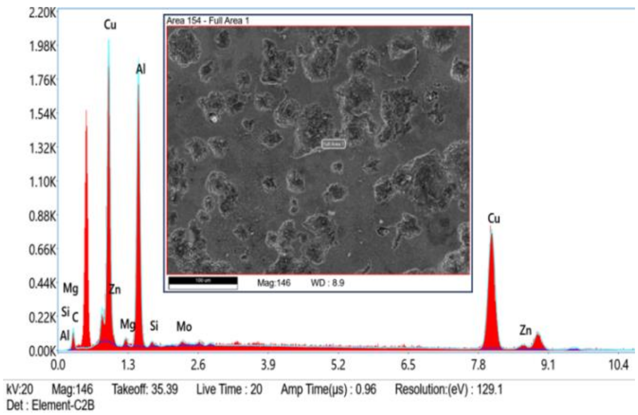


Fig. 5. EDS analysis at the nugget zone

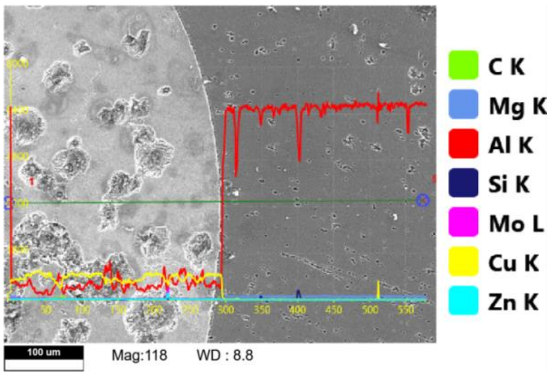


Fig. 6. EDS analysis at the weld-interface region

The presence of SiC NPs along the Al/Cu interface is expected to markedly decrease the formation of Al/Cu intermetallics [22]. However, it is important to acknowledge the limitations of this technique, particularly when detecting nano-sized particles like the Silicon Carbide nanoparticles (SiC NPs) used in this study, which have an average size of 50 nm. The beam size used during EDX analysis is larger than these nanoparticles, and the detection area can extend beyond the nanoparticles themselves, potentially including contributions from the surrounding matrix.

A standard lap shear tensile test was conducted to examine the influence of SiC nanoparticles on the lap shear strength of the weld at various welding currents. The highest lap shear load measured is displayed in Fig. 7. The inclusion of SiC NPs in the interface of the Al/Cu dissimilar weld significantly enhanced joint strength, showing a 14.8 % improvement in the highest joint strength value compared to joints without SiC NPs. The maximum lap shear load reached 1896 N with SiC nanoparticles and 1436 N without them. This demonstrates that at the optimal welding current of 20 kVA, the highest strength is achieved.

This suggests that the heat input is adequate for mixing the dissimilar materials and properly dispersing the SiC nanoparticles. Notably, the strength of the joint is significantly higher compared to the weld strength obtained in ultrasonic spot welded Al–Cu joints reported by Satpathy et al., [23] highlighting the superior performance of this method. The thickness of Al/Cu plates affects tensile strength by influencing heat input, material flow, and nugget formation during welding. Thicker plates typically require more heat, altering the joint's microstructure and strength. In this study, a uniform plate thickness of 1.5 mm was used to minimize this variable and focus on the effects of welding current and nanoparticle reinforcement.

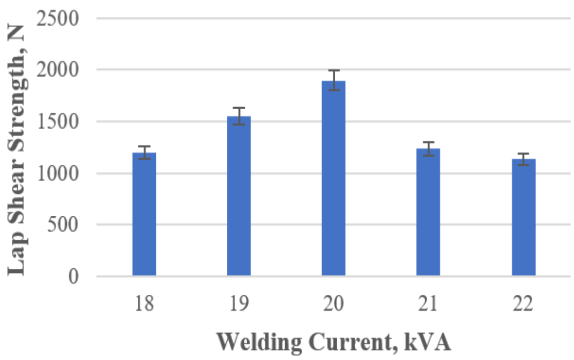


Fig. 7. Lap shear strength of Al/Cu joints with SiC NPs

Conversely, samples with SiC NPs welded at a low welding current exhibited reduced strength. This could be due to insufficient time and heat input for the effective mixing of Al/Cu and SiC NPs. In all conditions except at 18 kVA, increasing the welding current, such as to 22 kVA, results in decreased joint strength. The decreased joint strength at higher currents, like 22 kVA, was expected based on previous studies, where excessive heat led to material softening and overflow, creating microstructural defects [24, 25]. This result is in line with the work published by Zare and Pouranvari [26], where excessive heat input caused material softening and overflow, potentially leading to microstructural defects. When comparing these results to standard spot welds, it is evident that the inclusion of SiC nanoparticles enhanced joint strength. However, the lap shear fracture load is somewhat lower than what might be expected in homogeneous material welds. This discrepancy is due to the inherent challenges of dissimilar material welding, especially between aluminum and copper, which exhibit different thermal and mechanical properties. Nonetheless, the improvement achieved with SiC nanoparticles suggests that further refinement of the welding process could lead to even higher joint strength, bringing it closer to the performance of standard spot welds in homogeneous metals.

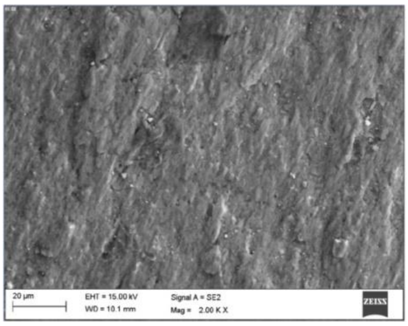


Fig. 8. FESEM images of fracture surface (20 kVA welding current)

Additionally, the temperature rise can lead to the formation of brittle IMCs, which further reduces joint strength. Fig. 8 depicts a characteristic fracture area of a joint that failed during a lap shear tensile test, revealing a semi-cleavage fracture pattern. The FESEM analysis highlighted distinct cleavage planes. Examination of the fracture surface indicates that the crack propagated through the nugget zone [27, 28]. The influence of SiC NPs and welding current on the strength of Al/Cu dissimilar welds is significant. However, the findings indicate that beyond a specific welding current threshold, the joint's strength is not impacted by the inclusion of SiC NPs.

4. CONCLUSION

This study shows that adding Silicon Carbide nanoparticles (SiC NPs) to aluminum and copper resistance spot welds improves their mechanical properties. The key findings are:

1. SiC NPs significantly increased tensile strength, with the highest lap shear load reaching 1896 N at an optimal welding current of 20 kVA, compared to 1448 N for welds without SiC.
2. SiC NPs helped refine the grain structure and created dispersion-strengthening mechanisms, as seen in FESEM images showing clear peaks of Si and C at the weld interface.
3. The best results were achieved at a welding current of 20 kVA, where proper mixing of Al and Cu and effective dispersion of SiC NPs occurred.
4. Fracture surface analysis revealed semi-cleavage characteristics, with SiC NPs and the right welding current being critical for strength.
5. This study not only confirms the existing theory that nanoparticle reinforcement can enhance joint strength

but also provides a nuanced understanding of the importance of welding parameters. The observed decrease in strength at higher welding currents corroborates the theory that excessive heat input can negate the benefits of nanoparticle reinforcement by introducing defects and brittle intermetallic compounds.

6. The incorporation of SiC NPs in RSW presents a significant advancement in welding technology, offering a valuable approach to enhancing weld strength and quality in industrial processes. This research lays the groundwork for future studies to explore and optimize nanoparticle-enhanced welding techniques across various metal systems.

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