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Material Flow-Induced Interfacial Microstructure and Surface Characteristics in Friction Stir Welded 304 Stainless Steel/2024-T3 Al Alloys Tailor-Welded Blanks

Fayaz Ahmad Mir, Noor Zaman Khan, Turali Narayana, Irfan Anjum Badruddin, and Sarfaraz Kamangar*

Tailor-welded blanks (TWBs) of dissimilar alloys offer a promising route to lightweight, high-performance structures, yet their reliability hinges on precise control of interfacial phenomena during joining. This study establishes a direct correlation between friction stir welding (FSW) speed and the resulting microstructure, material flow characteristics, and surface properties in TWBs fabricated from 2024-T3 aluminum (Al) alloy and 304 stainless steel (SS304). Despite earlier investigations into dissimilar FSW, the coupled effect of welding speed on grain refinement, interfacial bonding, and tribomechanical performance remain underexplored. Through systematic variation in welding speed—from 40 to 20 mm min^{-1}, this work demonstrates enhanced thermal input and plastic deformation at lower speeds, reaching peak temperatures of 371.5 °C. Electron backscattered diffraction analysis confirms substantial grain refinement, with an average grain size of 4.2 ± 0.2 µm in stir zone. Tribological assessment reveals improved wear resistance, as wear rate drops from 4.56×10^{-6} mm^3 Nm^{-1} to 3.69×10^{-6} mm^3 Nm^{-1}, accompanied by a reduced wear track depth of 12.087 µm and smoother surface roughness of 0.512 µm. Microhardness peaks at 413 Hv due to the effective dispersion of steel fragments within an aluminum matrix enriched by intermetallic layers of $FeAl_3$ and Fe_2Si.

1. Introduction

Energy and the environment are important issues of sustainable development.[1,2] In alignment with UN Sustainable Development Goal (SDG) 13 (climate action), stringent emission regulations across automotive, marine, and aerospace sectors are driving technological advancements to improve fuel efficiency and environmental performance, with weight reduction emerging as a critical strategy.[3,4] To reduce the component weight, industries have adopted a hybrid structural model based on dissimilar materials.[5] However, joining dissimilar materials remains challenging, especially with conventional fusion welding techniques, which often lead to defects such as porosity, hot cracking, wide heat-affected zone (HAZ), thick and continuous intermetallic compounds (IMCs), and residual stresses.[6] Solid-state welding technique, friction stir welding (FSW), overcomes such challenges using a rotating tool to generate frictional heat, softening materials without melting, refining the microstructure, improving material flow, and producing strong joints through plastic deformation.[7,8] Boeing used FSW for rocket fuel tanks, demonstrating its cost and time savings.[9] Researchers successfully applied FSW to join dissimilar materials (AA2024 and AA7075), achieving high bonding efficiency.[10] Singh et al.[11,12] investigated the role of IMCs on the joint quality of FSWed AA5052 and AZ31 alloys, reporting that the thickness of the IMC layer plays a crucial role in determining joint integrity, mechanical performance, and corrosion behavior. Venugopal et al.[13] examined the influence of process parameters and tool pin profiles on the microstructure and mechanical behavior of FSWed AA5052 and observed that variations in these parameters significantly affect the resulting joint quality. FSW often produces rough weld surfaces, influencing tribology, wear, and microcracks. Surface refinement improves performance and durability. Weld ripples affect roughness, tribology, microhardness, and corrosion resistance.[14,15] Al/SS alloys combine the low density, sufficient strength, and manufacturability of Al with the high strength, corrosion resistance, and toughness of SS. This has led to extensive research on FSW of Al alloys to SS in butt and lap configurations for applications in marine equipment, spacecraft, ship hulls, agricultural, and the automotive industry.[16] Among these,

F. Ahmad Mir, N. Z. Khan
Department of Mechanical Engineering
National Institute of Technology Srinagar
Srinagar, J&K 190006, India
E-mail: Fayaz_07phd19@nitsri.ac.in

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T. Narayana
Department of Mechanical Engineering
Aditya Institute of Technology and Management
Tekkali, AP 532201, India

I. A. Badruddin, S. Kamangar
Mechanical Engineering Department
College of Engineering
King Khalid University
Abha 61421, Saudi Arabia

