

Effect of Surface Conditions and Tool to Interface Spacing in Refill Friction Stir Spot Welding of Aluminum to Titanium

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Abstract. Optimizing the performance and reliability of welding techniques for dissimilar aluminum (Al) to titanium (Ti) is a promising way to establish new applications in aerospace industry. Due to structural weight reduction, lightweight materials can help to minimize fuel consumption and save emissions. Solid-state welding technologies allow short joining cycles and metallurgical changes, residual stresses and severe intermetallic compound formation can be reduced by limited thermal exposure. Besides temperature and plastic deformation, intimate contact plays an important role for diffusion. In this work, AlMgSi alloys with systematic variations of Mg and Si alloying elements, were welded to Ti6Al4V (Ti64) by refill Friction Stir Spot Welding. The focus lays on the effect of Ti64 sheet surface roughness, varied by different surface preparations. Additionally, the influence of the plunge depth, the distance between the tool and the Ti64 sheet surface is analyzed. It was found that a reduced tool to interface spacing has a beneficial influence on joint integrity. Grinding trenches allowed better bonding compared to the pit-like surface structure generated by sandblasting, which led to an increase in mechanical lap-shear properties. Knurling the grinded surfaces resulted in high standard deviation, as most likely not the whole interface area was bonded. However, the partially outstanding properties showed that a beneficial effect can be expected due to mechanical interlocking mechanisms, when sufficient diffusion is ensured.

Introduction

Lightweight materials such as aluminum (Al) and Titanium (Ti) are widely used in the aerospace industry. While Ti is characterized by outstanding high temperature resistance and strength, Al is cost effective. To balance the structural and economic demands, Al / Ti hybrid structures are of great interest [1]. However, techniques for joining them efficiently are still under investigation, as conventional fusion welding techniques are associated with issues based on the huge material property discrepancies of Al and Ti [2].

Solid-state welding, such as friction stir welding and refill Friction Stir Spot Welding (refill FSSW), represents excellent solutions and has been proven to be suitable for several alloy combinations [3]. A crucial factor for obtaining sound joints is the plunge depth (PD). It was found for refill FSSW of AA5754 to galvanized DP600 that a higher PD up to close to the interface allowed for a strong increase in mechanical joint properties [4]. In terms of welding dissimilar Al / Ti, challenges occur as the formation of brittle Al₃Ti [5] and the introduction of residual stresses due to the substantial differences in physical and chemical properties of Al and Ti [1]. These difficulties can lead to interfacial fractures, often occurring well below the strength of the Al, for instance in a friction stir welded ADC12 Al/Ti joint [6], failing at 62 % of the base material.

To improve joint strength, surface pre-treatments may be a suitable approach to maximize the effect of mechanical interlocking mechanisms at the interface to support the diffusion-based bonding. Additionally, it was shown during the solid-state deposition process Friction Surfacing, that

increasing topography depth led to a decreased average grain size [7]. This could potentially support diffusion mechanisms due to higher grain boundary density [8] and therefore accelerate the bond formation, which could allow to reduce the process duration and correlated thermal exposure. Enhancements in the mechanical properties were shown for other dissimilar material combinations, such as AA5052 resistance spot welded to galvanized steel [9] and AA5182 laser welded to PA66 [10]. Particularly the increased surface roughness and correlated with that the increased interfacial area for diffusion, has shown positive effects on the weld strength [9,11]. For ultrasonic spot welding of AA1100 to stainless steel [12], it was found that cleaned stainless steel surfaces exhibited better mechanical properties compared to electrolytically polished surfaces, indicating the relevance of surface roughness. Nonetheless, surface roughness can also have a negative influence, as e.g. within grinding trenches small voids and unbounded regions can occur which then act as crack initiation sites [13,14]. In this context, He et al. [15] showed that ordered patterns enable superior improvements compared to simple grooves. Perpendicular and 45 ° diagonal textures provided better strength under multiaxial loading due to improved mechanical interlocking and microstructural pinning effects [15]. In this study, the effect of surface roughness and topography of Ti64 as well as PD is investigated during dissimilar Al/Ti welding using refill FSSW, to vary micro-mechanical interlocking and diffusion bonding mechanisms. Two different PD levels and four different Ti64 sheet surface pre-treatments were tested to allow for a better understanding of the influence on joint integrity including mechanical properties and failure mode.

Materials and Methods

Joints of Ti64 (100 x 25.4 x 2.0 mm³ sheets) with five different Al alloys (100 x 25.4 x 1.8 mm³ sheets), based on AA6013 with systematic varied Mg and Si content, were welded via refill FSSW. The Al alloys were gravity die casted at 700 °C, water quenched and afterwards the billets were extruded at 450 °C. Optical emission spectroscopy was used to determine the chemical composition of the alloys, see Table 1.

Table 1. Chemical composition of the five Al alloys determined by optical emission spectroscopy, based on AA6013 (Al1Mg1Si). For the other alloys, the amount of Mg and Si was systematically varied. All values in wt.%.

Alloy	Si	Mg	Cu	Fe	Mn	Zn	Cr	Ti	Al
Al1Mg1Si	0.98	1.10							Res.
Al1Mg0Si	0.01	1.06	0.6 –	Max	0.2 –	Max.	Max.	Max.	Res.
Al1Mg1.5Si	1.52	1.03	1.1	.0.5	0.8	0.25	0.1	0.1	Res.
Al3Mg1Si	1.10	3.13							Res.
Al5Mg1Si	0.78	5.30							Res.

Refill FSSW, developed by Helmholtz-Zentrum Hereon [16], is a solid-state spot welding technique that allows short welding cycles and the production of energy efficient joints. The process is schematically presented in Figure 1 and works with a tool consisting of three components. The outer clamping ring (CR) is stationary and applies a constant force to the sheets below to keep these in position. The inner components are the probe in the center and the shoulder in between the probe and the CR. Both rotate, typically at the same rotational speed and direction, whereby the shoulder plunges into the workpiece and the probe retracts in the opposite direction. Due to the friction between the tool and workpiece, the upper Al sheet heats up and plasticizes. The plasticized Al deforms and flows into the cavity which is created by the probe during the first process stage. Then an optional dwell time can be used to extend the process without any translational, but still rotational tool movement. Afterwards shoulder and probe retract to the original positions and the process finished with lifting all 3 components from the workpiece. Each joint was welded in overlap configuration with the Al sheet being placed above the Ti64 sheet, with an overlapping area of 25.4 x 25.4 mm². The PD of the shoulder into the Al sheet varied between 1.2 and 1.5 mm, meaning between 0.6 and 0.3 mm distance of the shoulder to the Ti64 surface. Except for the PD, all other process parameters

were kept constant in this study and were selected as: dwell time (DT) of 5 s, rotational speed (RS) of 2200 rpm, clamping force (CF) of 8 kN and plunge time of 1 s.

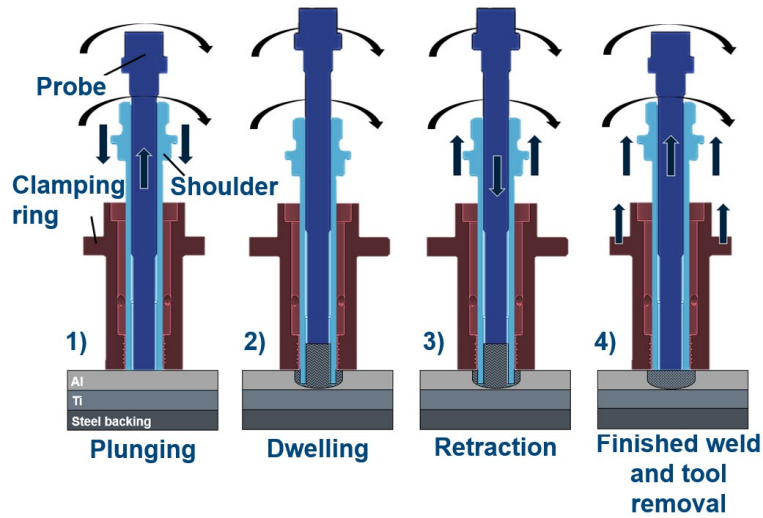


Fig. 1. Schematic illustration of the refill FSSW process, showing the tool components, sheet orientation and process stages: 1) Plunging phase, 2) Dwelling phase, 3) Retraction phase, 4) Tool removal.

Lap shear testing was performed at room temperature using a Zwick-Roell 1478 universal testing machine. A constant crosshead speed of 1 mm/min was used, and the sample dimensions are presented in Figure 2. The topography micrographs of the surface pre-treatments and after lap-shear testing also the fracture surface micrographs were investigated by using an FEI Quanta 650 scanning electron microscope (SEM). Additionally, the pre-treatment surface roughness was analyzed by a profilometer (Keyence VR 5200) using the average of 10-line measurements.

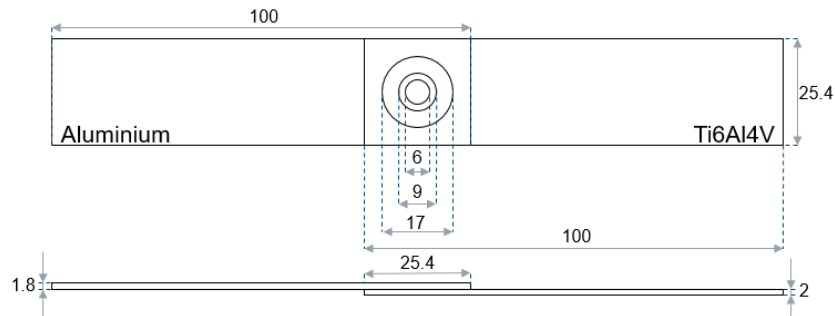


Fig. 2. Schematic of the lap-shear test specimens for determination of the mechanical properties. All dimensions in mm.

The surface pre-treatment of the Al sheet on both surfaces was kept constant using #320SiC paper, while the surface of the Ti64 sheet was pre-treated in different ways, see Table 2. Grinding the sheets was performed immediately prior to welding while sandblasting (SB) as well as knurling (KN) were performed in advance, handling the Ti64 sheets in ethanol afterwards to suppress surface oxidation.

Table 2. Description of the surface preparation methods used on the Ti64 surface.

Method	Designation	Tool / Medium
Grinding (#100)	#100	SiC paper #100
Grinding (#320)	#320	SiC paper #320
Sandblasting	SB	Al ₂ O ₃ , 100-150 μm
Grinding (#320) and Knurling	KN	SiC paper #100; Knurling tool 290196, 20 x 8 / 0.5

SB was used to remove the oxide layer of the Ti64 and to generate a homogenous surface structure that varies clearly from the surface structure after grinding to change the contact conditions of the Al and Ti64 sheets in the interface, Figure 3a,b. As blasting medium Corundum (Al_2O_3 , mesh size 100-150 μm) was selected and the parameters were 60 s of SB, 3 bar of pressure at 300 mm distance in a 30° angle.

For generating indents that may allow macro-mechanical interlocking, knurling was performed using a knurling tool (290196, 20 x 8 / 0.5) with a tooth pitch of 0.5 and knurl type GE 30° (Hoffmann GmbH Qualitaetswerkzeuge, Munich, Germany), Figure 3c. A traverse speed of 2 mm/s and a tilt angle of 0° was used. Prior to knurling, the sheets were carefully ground using #320 SiC paper to remove the oxide layer.

Table 3. Overview of the generated surface topographies, depending on the individual surface pre-treatment.

Method	Rz (Avg.)	Rz (Std. Dev.)	Ra (Avg.)	Ra (Std. Dev.)
Grinding #100	5.99	0.852	0.844	0.105
Grinding #320	4.80	0.882	0.689	0.156
Sandblasting	6.38	2.64	0.803	0.116
Knurling	92.27	18.647	4.766	

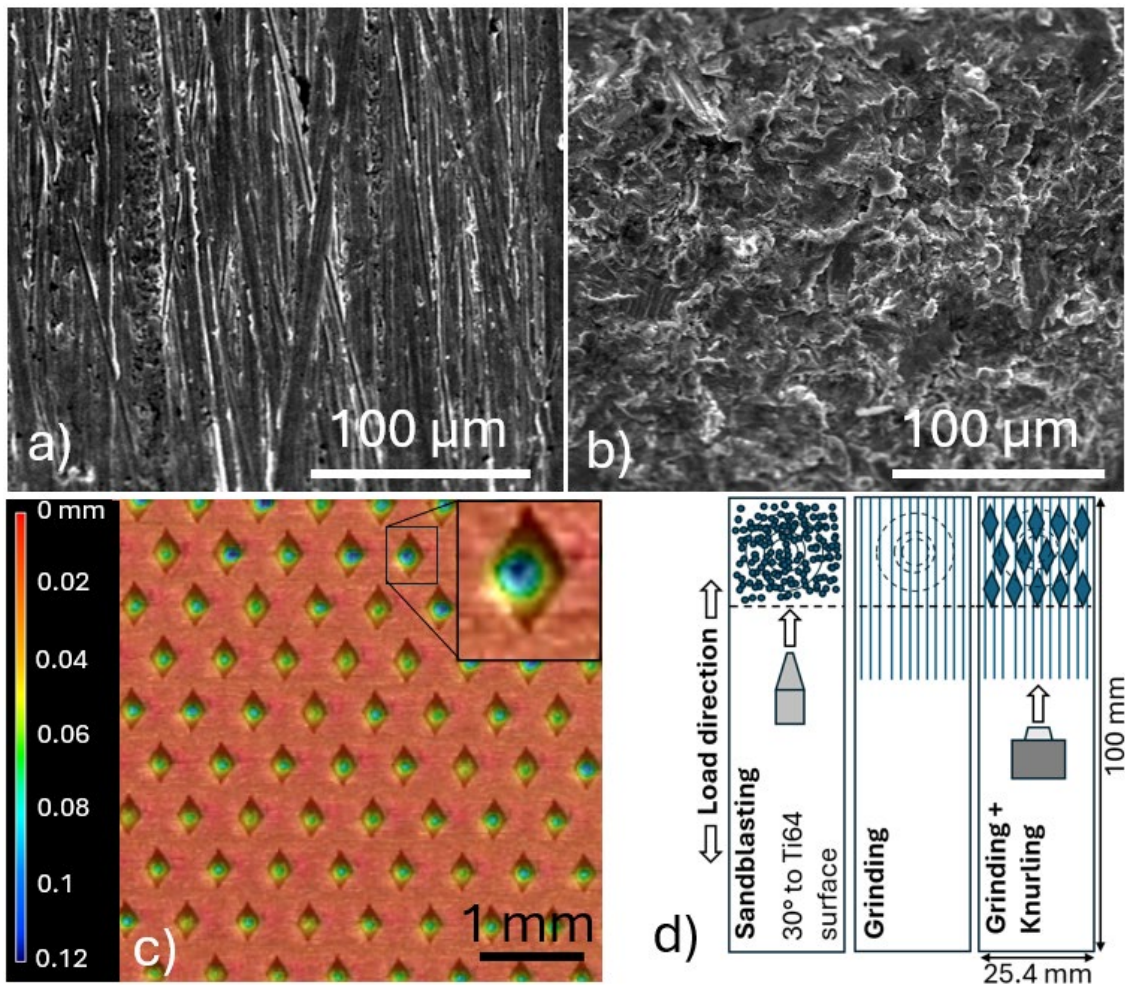


Fig. 3. Ti64 surface appearance after pre-treatment a) SEM micrograph of grinded Ti64 using SiC paper #100, b) SEM micrograph of SB Ti64 surface, c) Topography measurement of the KN pattern, d) sketched orientation of the surface pre-treatments with regard to the lap-shear testing direction.

Results and Discussion

Tool to interface spacing.

All joint combinations and surface pre-treatments performed at 1.5 mm PD resulted in high-quality joints with sound mechanical properties. Figure 4 presents the results, revealing that PD reduction of 0.3 mm, i.e. PD of 1.2 mm, resulted already in a significant decrease in ultimate lap shear force (ULSF). The Al3Mg1Si / Ti64 joints were particularly affected and failed at low ULSF of around 1.25 kN, most likely correlated with the lower process temperature due to the lower solidus temperature of the alloy [17].

Joint formation - surface topography.

Grinding the Ti64 surface using different SiC grinding papers resulted in almost the same ULSF, while varying the Ti64 surface topography by grinding and SB influenced the joint strength significantly. SB led to a drastically reduced ULSF, especially for alloys having only 1 wt.% Mg. As presented in Table 3, mean Rz and Ra values of the generated surfaces were similar, only the standard deviation was larger for the sand blasted Ti64 surface. However, it is assumed that the effect on the ULSF is correlated rather to the topography than simply roughness characteristics. As compared in Figure 3, in terms of surface structure, the trenches generated by SiC paper grinding differed a lot compared to the peaks and valleys generated by SB. It is likely that within the grinding trenches higher diffusion rates are present. The bonding was enhanced, while the effect of mechanical interlocking is expected to be reduced compared to SB. The effect originated due to the parallel orientation of the grinding trenches to the load direction during tensile testing, see Figure 3d.

The higher diffusion rates may result from Al being continuously plastically deformed within the trenches of the grinded topography, enhancing grain boundary diffusion [8], while the Al being squeezed into the SB structure predominantly staying there for the rest of the welding process.

The samples subjected to grinding and knurling showed large variations, where all material combinations, except for the Al1Mg0Si / Ti64 joints, were characterized by high standard deviations. It can be seen by the upper ULSF range that knurling has high potential, but the lower ULSF range indicates that joints are also sensitive to unbonded regions and therefore local crack initiation sites. The results agree with the findings explained in the introduction, which describe the advantages of micro mechanical interlocking, but also the issues correlated with partially unbonded areas [13,14].

Joint formation - alloy chemical composition.

Based on the content of alloying element, it is shown that the absence of Si, i.e. in Al1Mg0Si/Ti64 joints, limits the ULSF to roughly 4.5 kN. This can be recognized e.g. in the 1.5 mm PD #320 sample and might be caused by missing Si required for formation of the strengthening precipitates. Additional Si up to 1 % (Al1Mg1Si/Ti64) improved the mechanical properties significantly, i.e. the highest ULSF increased to 6.5 kN in PD 1.5 mm #320 sample. However, additional Si more than 1 wt.% barely influenced the mechanical properties, as shown in Al1Mg1.5Si/Ti64 sample in 1.5mm PD #100. Meanwhile, an increase in Mg content, i.e. Al1Mg1Si/Ti64 to Al3Mg1Si/Ti64, led to a lower ULSF in ground samples with 1.5 mm PD in #320 and #120 samples, but resulted in a higher ULSF in for the knurled and SB samples, as shown in Figure 4. These results indicate that a higher Mg content might also play an important role in the mechanical interlocking component of the joint performance.

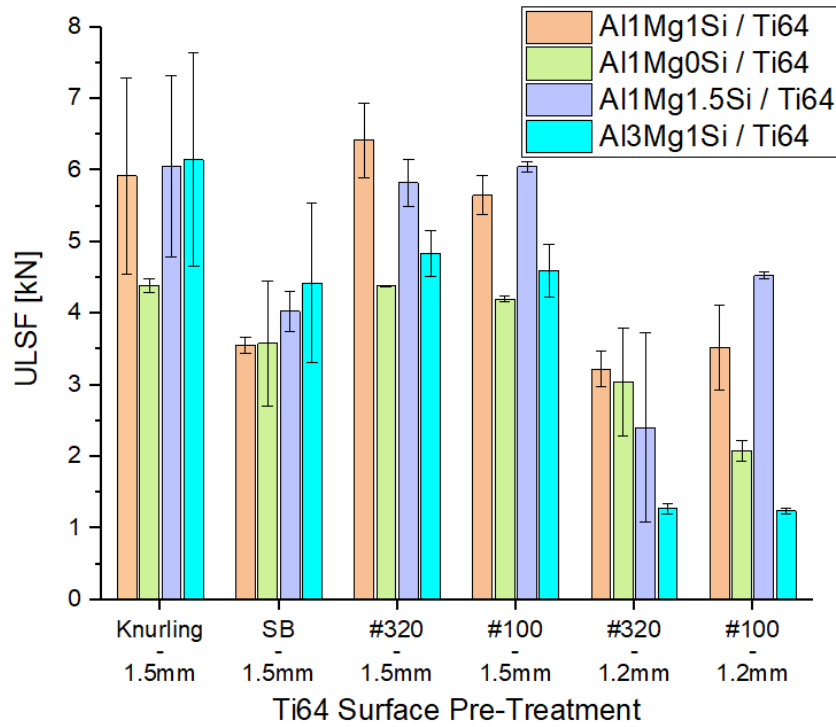


Fig. 4. Ultimate lap-shear forces measured during tensile testing the four Al alloys welded to surface pre-treated Ti64.

Fracture behavior.

Figure 5 presents fracture surfaces of a PD 1.5 mm, #320 Al1Mg1.5Si / Ti64 joint. A clear transition between bonded and unbonded region is presented in Figure 5a. It mainly shows that both interfacial fractures as well as through the Al fractures occur at the interface. The fracture sometimes also alternates several times and a clear behavior for correlating the fracture mode with specific interface areas could not be identified, as shown in the interface presented in Figure 6a. When the fracture propagates through the Al, leaving attached Al on the Ti64 side, this Al is characterized by a clear dimple structure indicating a ductile failure behavior, see Figure 5b.

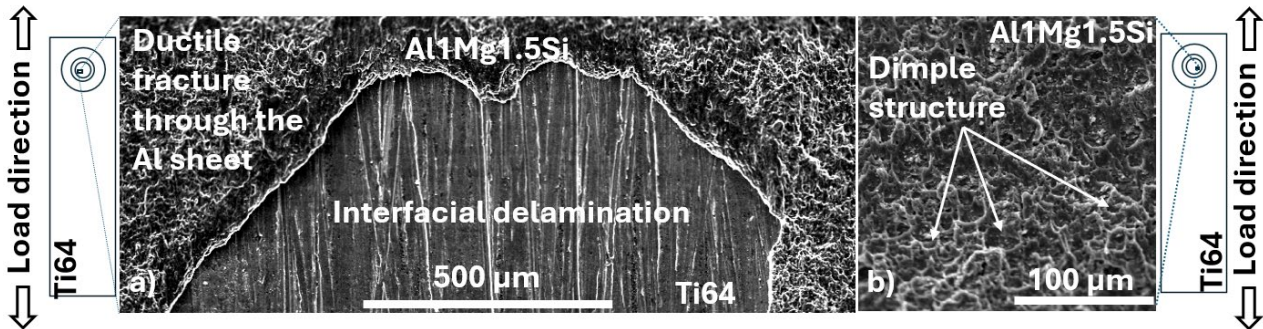


Fig. 5. Fracture surface of a) a PD 1.5 mm, #320 Al1Mg1.5Si / Ti64 joint, highlighting the mixed failure mode of partially interfacial delamination and partial through the Al side with Al being attached to the Ti64 surface, and b) a highlighted area of the PD 1.5 mm, #320 Al1Mg1.5Si / Ti64 joint fracture surface, showing the fracture locally through the Al in a ductile behavior indicated by the observed dimple structure.

Figure 6a presents the fracture surface of a knurled Al1Mg1.5Si/Ti64 joint. It is visible that Al is locally attached inside and between the indents, indicating that fracture propagated through the Al, while the fracture surface without adhering Al shows delamination through the Al/Ti interface. Inside the indents, Al is attached to one side of the indents (upper face), while the Al is mainly detached at lower face, Figure 6 a. Consequently, the fracture runs through the interface on the lower side of the indent and then further propagates through the Al. This is based on the differing interlocking

conditions with regard to load direction, as the Al is pulled towards the upper indent face while the Al is pulled away from the lower face. This phenomenon was observed at different locations of the spot weld, including where the rotation direction and loading direction during the tensile test were in the same and opposite direction, respectively. Therefore, the effect is not mainly related to improved bonding conditions on one side of the indent, influenced by the rotation direction of the tool, but mainly due to the load and secondary bending effects during tensile testing. Figure 6b shows a single indent at higher magnification. Although no Al was visible to be attached to the lower indentation face from the macroscale, a small amount of Al was found to be adhered at the microscale. This implies that such surface pre-treatment needs to be handled with care. Individual parameter optimization needs to be performed to enable sufficient diffusion even in the most unsuitable areas for diffusion of the generated surface structure.

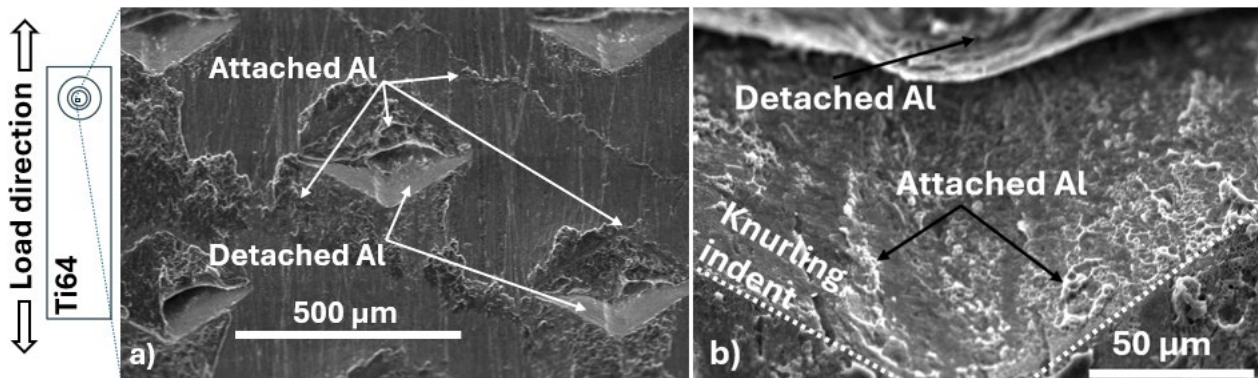


Fig. 6. SEM micrograph of a knurled Al1Mg1.5Si/Ti64 joint fracture surface, showing a) detached Al on one side of the knurling indents. Al is attached on the other side and partially on the Ti64 surface between the indents. Lines of attached Al are visible, indicating discontinuous delamination of the interface, b) Low amount of attached Al fragments within a knurling indent on the mainly detached side.

Conclusion

Refill Friction Stir Spot Welding of AlMgSi with different Mg and Si contents to Ti6Al4V is investigated for two plunge depth (PD) conditions and various Ti sheet surface pre-treatments. The Mg and Si content was systematically varied, and the influence on the mechanical properties of the obtained spot welds was investigated. The following conclusions are drawn:

- 1) The PD plays a significant role in welding dissimilar Al / Ti and a low tool to interface spacing is necessary to obtain sound joints.
- 2) Surface pre-treatments have a strong influence on the mechanical properties of the joints. Randomly distributed peaks and valleys generated by sandblasting led to lower mechanical properties compared to grinding trenches with similar roughness values.
- 3) Knurling the Ti64 surface to enable additional micro-mechanical interlocking is promising as shown by partially outstanding mechanical properties, but also prone to unbonded regions as can be seen by the high variations of properties.
- 4) The fracture surfaces show an alternating crack propagation that led to locally interfacial delamination and fractures through the Al. Attached Al on the Ti64 sheet shows a dimple structure, indicating ductile fracture characteristics.

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References

- [1] Nan, X., Zhou, L., Sun, T., Yu, M., Song, X.: ‘Strengthening mechanism of Al/Ti friction stir butt welded joints via ultrasonic-induced fast diffusion effects’, *Journal of Materials Processing Technology*, 2025, **338**, (2), p. 118754.
- [2] Gadakh, V.S., Badheka, V.J., Mulay, A.S.: ‘Solid-state joining of aluminum to titanium: A review’, *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications*, 2021, **235**, (8), pp. 1757–1799.
- [3] Grassel, F., Malaske, L., Hoffmann, M., Klusemann, B.: ‘(Semi-)Solid-state joining of aluminium and titanium alloys – A critical review’, *Journal of Materials Research and Technology*, 2025, **39**, pp. 3270–3291.
- [4] Ghirdelli, G.L., Roman, J.S., Plaine, A.H., Suhuddin, U.F.H., Alcantara, N.G.: ‘Process Parameter Optimization in Refill Friction Stir Spot Welding of Dissimilar AA5754 and Electro Galvanized DP600 Joints’, *Mat. Res.*, 2024, **27**, (3), p. 476.
- [5] Janusz-Skuza, M., Bigos, A., Kwiecień, I., Wierzbicka-Miernik, A., Szulc, Z., Wojewoda-Budka, J.: ‘Mechanism and growth kinetics of Al₃Ti phase in fifteen-layered Ti Gr.1/A1050 clads produced with the explosive welding technique’, *Arch. Civ. Mech. Eng.*, 2024, **24**, (3), p. 73.
- [6] Chen, Y.C., Nakata, K.: ‘Microstructural characterization and mechanical properties in friction stir welding of aluminum and titanium dissimilar alloys’, *Materials & Design*, 2009, **30**, (3), pp. 469–474.
- [7] Roos, A., Metternich, F., Kallien, Z., et al.: ‘Friction surfacing of aluminum to steel: Influence of different substrate surface topographies’, *Materials & Design*, 2023, **235**, (2), p. 112390.
- [8] Thiyaneshwaran, N., Sivaprasad, K., Ravisankar, B.: ‘Nucleation and growth of TiAl₃ intermetallic phase in diffusion bonded Ti/Al Metal Intermetallic Laminate’, *Scientific reports*, 2018, **8**, (1), p. 16797.
- [9] Noor Ahmad, F., Sapparman, M.S., Shaari, N.S., Ebenezer Abioye, T.: ‘Effects of Surface Treatment on Strength And Hardness of Aluminum Alloy/ Galvanised Steel Resistant Spot Weld-Zn Coated Single Lap Joint’, *jkukm*, 2025, **37**, (5), pp. 2091–2102.
- [10] Zhang, G., Zhu, Q., Yang, H., Yang, C., Liu, Y., Wang, C.: ‘Effect of surface treatments on the laser welding performance of dissimilar materials’, *Journal of Manufacturing Processes*, 2022, **74**, pp. 465–473.
- [11] Ariyanto, A., Sukardin, M.S., Renreng, I., Arsyad, H., Syahid, M., Alwi, M.: ‘Optimization of resistance spot welding with surface roughness dissimilar mild steel with stainless steel’, *EEJET*, 2023, **5**, (12 (125)), pp. 63–71.
- [12] Das, S., Chandra Routara, B., Kumar Nanda, B., Bikash Mishra, S., Kumar Nayak, S., Prasad Satpathy, M.: ‘Weldability assessment of Al-SS dissimilar joints produced by ultrasonic spot welding route’, *Materials Today: Proceedings*, 2023, **11**, (5), p. 1195.
- [13] Ma, H., Qin, G., Dang, Z., Geng, P.: ‘Interfacial microstructure and property of 6061 aluminium alloy/stainless steel hybrid inertia friction welded joint with different steel surface roughness’, *Materials Characterization*, 2021, **179**, p. 111347.
- [14] Xu, R., Zhu, Y., Li, B., Yang, H., Zhang, C.: ‘Effect of surface roughness on interface characteristics and mechanical properties of dissimilar diffusion bonded 45 steel/additive manufactured 316L steel joints’, *Int J Adv Manuf Technol*, 2024, **134**, (9-10), pp. 4117–4126.

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- [15] He, X., Shi, H., Zhang, P., et al.: 'Laser surface texturing for enhancing wettability and mechanical properties in dissimilar material welding: A review', *Journal of Manufacturing Processes*, 2025, **150**, (1), pp. 357–377.
- [16] Schilling, C., Santos, J.d.: 'Method and device for joining at least two adjoining work pieces by friction welding, Patent No. US6722556B2'.
- [17] Malaske, L., Chen, T., Neves, A.M., et al.: 'Interface evolution during refill Friction Stir Spot Welding and post-weld heat treatment of AA6013/Ti6Al4V with varying Mg and Si content' (2025).