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Evaluation of thermo-mechanical response of components by rotary friction welding technique

Abstract. Rotary friction welding (RFW) is one of the most important processes for bonding metal together, either alike or unlike. RFW has gained acceptance among many manufacturing sectors because it reduces thermal distortion, produces fewer heat affected zone areas, provides for increased production rates, and eliminates the need for filler metals. The focus of this investigation was the mechanical properties of welds with an emphasis placed upon the relationship of spindle speed with the quality of the welds for three different types of materials that are bonded; i.e., aluminium-aluminium, steel-aluminium, and steel-steel. These welds were fabricated utilising the rotary friction welding technique at a lathe. Tensile tests were performed to measure how well the welds would perform under stress. Ultrasonic inspections were completed to find any cracks or holes inside the welds. Micro measurements were taken to assess the weld zone. Hardness tests were performed to determine the amount of resistance the material could withstand. Finally, metallographic analysis was conducted to examine the micro structural characteristics of the welds. The tests revealed that as the spindle speed increased so did the loss of elastic resistance of the welds. It was determined that this loss of elastic resistance resulted from the high temperatures produced by the high spindle speeds causing micro-structure softening. At 1,250 RPM, the optimal (mechanical) performance was found as well as the highest level of mechanical properties such as strength and hardness. Furthermore, through ultrasonic testing, it was confirmed that all weld seams produced by RFW were completely free of defects. Therefore, these results clearly demonstrate that RFW can produce weld seams with high mechanical properties and no defects if optimum process conditions exist, especially if the spindle speed is adjusted to match the respective materials

Keywords: solid-state joining; thermo-mechanical analysis; heat-affected zone; metallographic characterisation; dissimilar metal welding

INTRODUCTION

Rotary friction welding (RFW), a process that does not melt the original material of two metal parts which are joined together through friction heat generated by a rotating spindle is capable of producing high-strength welds between very different types of metals. A significant advantage of RFW over other processes is that it produces minimal heat input thereby creating little or no thermal distortion and/or a heat-affected zone, therefore RFW eliminates the need for filler materials or shielding gases. However, although there are many advantages to using RFW, the process has some limitations, specifically, it requires the proper selection of the metal to be welded and proper operating conditions including spindle speed and pressure to produce a high-quality weld. The applications of drill pipe, truck axle and hydraulic cylinder rod are examples of the versatility and efficiency of the RFW process.

Researchers H. Ghari *et al.* (2024) conducted a detailed literature review on rotary friction welding (RFW) as it relates to aluminium steel weldments; however, they focused their discussion primarily on the metallurgical transformations occurring during the RFW process at the weld interface, specifically those associated with the development and management of brittle intermetallic compounds (IMCs). They also used artificial neural networks to develop relationships between RFW process variables and mechanical properties. N. Gangil *et al.* (2025) have reviewed linear

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friction welding (LFW) and focused specifically on how LFW is used to join different types of materials (both similar and dissimilar). The study provided a detailed overview of the LFW process, characteristics of the welds formed, microstructural changes that occur during LFW and the impact of various parameters on the quality of the welds formed. It identified potential applications of LFW in aerospace and transportation industries and outlines the major areas of research that will be important in the future for the development of LFW. J. Wang *et al.* (2021) were able to analyse the formation of joints between Fe-Al and the mechanism of evolution for IMCs using Laser Weld/Braze processes as opposed to Friction Welding, which provided an additional understanding of the mechanisms involved in solid-state and fusion-assisted joining. Researchers M. Farbakhti *et al.* (2025) studied the joining of both the same materials (e.g., steel) and different materials (e.g., steel-aluminium, aluminium-copper) through RFW. The study examined how the various process parameters used during RFW can impact the microstructural evolution; grain size reduction; carbide dissolution; and redistribution of inclusions, while at the same time relating these changes to the mechanical characteristics of the weld and addressing problems associated with the welds, such as residual stresses and the development of brittle phase(s). Overall, these studies demonstrates that processing conditions have a significant effect on the interfacial microstructure and mechanical characteristics of welds formed using RFW and other similar processes, with the primary constraint on dissimilar joints (i.e., steel/aluminium and aluminium/copper) being due to the brittleness induced by IMCs, requiring either optimisation of parameters; use of interlayers; or application of post weld heat treatment. There have been studies into advancements in rotary and inertia friction welding (RFW/IFW) processes for like and unlike metals. These are looking into how the process parameters can influence the microstructure and mechanical behaviour. X. Xu *et al.* (2020) studied inertia friction welding of 1045 carbon steel and 30CrMnSiNi2A high strength low alloy (HSLA) Steel, with results indicating that the optimal mechanical properties were achieved at a speed of 2,200 rpm, with 713 MPa ultimate tensile strength and 97% joint efficiency, due to refinement of martensitic and bainitic microstructures. EN1A mild steel joints welded in both dry and wet conditions were examined by V.V. Kulkarni & P.C. Kulkarni (2021). The authors indicated the advantages of the process; particularly the EN1A mild steel joints had superior joint strength when compared to dry joints and there was no distortion as a result of the process. Samples of stainless steel types code (SS316-SS304-SS202) were illustrated for performance by J.S. Chatha *et al.* (2021). The results showed that SS316-SS304 performed better than all of their other test samples. They reported that the SS316-SS304 samples had a tensile strength of 3,920 kgf and a hardness of 278 HV. L.F. Malau *et al.* (2025) studied AA6061 aluminium alloy joints and found that an increase in welding time resulted in increased strength, with the greatest strength being observed after 10 seconds (223.2 MPa). With further increases in welding time, excessive flash developed. The importance of compression test in forming good metallurgical bonds in Al-Cu dissimilar joints was emphasised by R. Ariyansah *et al.* (2025); they demonstrated that the application of 20 kg/cm^2 resulted in the most optimal metallurgical bonding with high strength and low levels of intermetallic compounds (IMCs). Ultimately, N. Gotawala & A. Shrivastava (2021) investigated Al6061-mild steel joints; they found that the highest tensile strength (136 MPa), was achieved when using an intermediate welding rate (20 mm/min). This increased tensile strength was obtained as a result of reduced intermetallic compound (IMC) layer thicknesses and enhanced dynamic recrystallisation. In general, all the above mentioned studies demonstrated that optimising the welding process through varying speed, time and/or pressure are key factors in producing high-quality solid-state welds without defects from various materials. The purpose of this study was to investigate the stiffness and mechanical properties of cylindrical joints manufactured using rotary friction welding on a parallel lathe machine.

MATERIALS AND METHODS

The basis materials were 15 mm diameter cylindrical bars. Their chemical compositions were assessed using a Thermo Fisher Scientific analyser (USA) in compliance with ASTM E18 guidelines (ASTM International, 2025). and are summarised in Tables 1 and 2. Material 1 corresponds to steel grade A60, predominantly composed of iron (approximately 97.972 wt%) with minor alloying elements such as Mn, Cu, Ni, Cr, Mo, Co, and Sn. Material 2 is aluminium alloy AA 6063, consisting mainly of aluminium (approximately 99.25 wt%) with small quantities of Fe, Cr, Ti, V, Sn, Pb, and Zn. The mechanical behavior of both materials was evaluated through tensile testing. For this purpose, five specimens were machined to a diameter of 12 mm as shown in Figure 1.

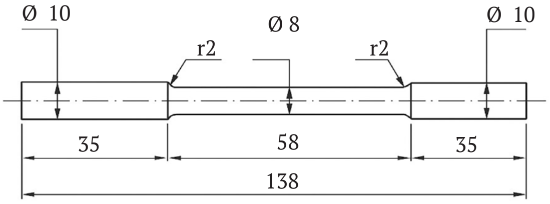

Figure 1. The dimensions of the specimen used for RFW

Source: developed by the author

Table 1. Chemical composition of material 1 (Steel)

Element	Sn	Mo	Ni	Co	Fe	Mn	Cr	Cu
Wt%	0.010	0.052	0.432	0.146	97.968	0.810	0.165	0.414
Error	±0.004	±0.002	±0.034	±0.062	±0.085	±0.031	±0.012	±0.026

Source: developed by the author

Table 2. Chemical composition of material 2 (AA 6063)

Element	Sn	Pb	Zn	Al	Fe	Ti	Cr	V
Wt%	0.011	0.004	0.011	99.237	0.326	0.025	0.072	0.030
Error	±0.005	±0.001	±0.002	±0.021	±0.013	±0.003	±0.005	±0.006

Source: developed by the author

To minimise machining effects, the gauge sections were ground parallel to the specimen axis using abrasive papers. Rotary friction welding was performed on a parallel lathe equipped with a universal carriage and threading system (model E3N-01), which provided all necessary tooling for specimen preparation as shown in Figure 2.

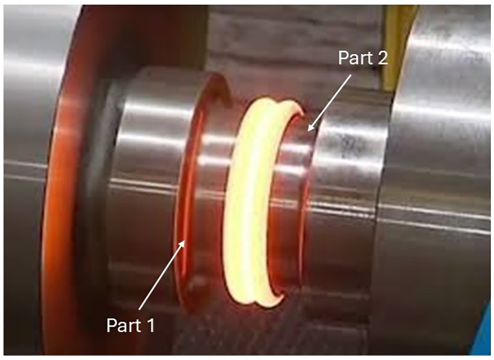

Figure 2. Test tube specimen prior to sectioning after soldering

Source: photo by the author

Tensile tests were conducted using a WP310 GUNT HAMBURG hydraulic testing machine (Gerätebau GmbH, Germany) with a 50 kN load cell and a displacement speed ranging from 0 to 425 mm/min. Ultrasonic inspection was carried out based on the transmission, reflection, and absorption of ultrasonic waves within the material. The emitted pulse was reflected from the specimen boundaries or internal discontinuities and returned to the transducer, serving as both transmitter and receiver. A D10+ ultrasonic device (United Kingdom) operating at 3 MHz was used for surface examination as shown in Figure 3.

Figure 3. D10+ ultrasonic detector

Source: photo by the author

Microhardness tests were carried out on a 24i hardness tester (Germany) that was modified to allow the microhardness to be tested on welds; an example is shown in Figure 4. The composition of the two materials used in this investigation are detailed in Tables 1 and 2. Steel grade A60 material 1 contained approximately 97.972wt% iron and trace amounts of other alloying elements, manganese, copper, nickel, chromium, molybdenum, cobalt, tin, as indicated by the relative measurement uncertainties. Aluminium alloy AA 6063, material 2, had a major constituent of aluminium at approximately 99.25wt%, with lesser amounts of iron, chromium, titanium, vanadium, lead, tin and zinc. The mechanical properties of both materials were evaluated through tensile testing, and were summarised in Tables 3 and 4.

Table 3. Characteristics of test tube in steel

Variance	R_e(N/mm²)	R_m(N/mm²)	A%	Hardness
A 60	336	590-710	14.5	HV = 171-204

Source: developed by the author

Table 4. Characteristics of test tube in AA 6063

Variance	R_e(N/mm²)	R_m(N/mm²)	A%	Hardness
AA 6063	24	50	48	HV = 15

Source: developed by the author

Steel A60 exhibited a yield strength of 336 N/mm², a tensile strength between 590-710 N/mm², elongation of 14.5%, and hardness in the range of HV171-204, indicating high strength and moderate ductility. The AA 6063 alloy, on the other hand, has significantly less strength than does steel, with a yield strength of 24 N/mm² and tensile strength of 50 N/mm², but very much greater elongation (48%), and very much lower hardness (HV15), which suggests that it is softer and more ductile than steel.

RESULTS AND DISCUSSION

The basis of ultrasonic testing is the behaviour of sound traveling through materials as a result of wave propagation; where in the case of specimens, the specimen receives high frequency acoustic energy which then travels through it and is absorbed and reflected by the interior structure of the specimen. When the returned waveform comes from either the opposite side of the weld or the subsurface defect, the waveform will go back through the same transducer (transmits and receives), thereby enabling the detection and description of possible defects. Analysis of the ultrasonic signals collected from the welded joint found that the joints demonstrated adequate strength; there were no large variations in the ultrasonic pulse that returned, which indicated there were no ultrasonic reflections due to defects and therefore the transmitted waves had not encountered any obstructions. This evidence supports the premise that bonding was uniform over the entire area of contact rather than only at the edges of the weld. Table 5 shows the elastic resistance of the three different types of welds as a function of the spindle speed.

Table 5. Elastic resistance of welded specimens at different spindle rotational speeds

Welded test pieces	Steel-Steel	Aluminium- Aluminium	Steel- Aluminium
900 tr/min	456.72 N/mm²	88.66 N/mm²	187.88 N/mm²
1,250 tr/min	304.88 N/mm²	69.83 N/mm²	159.55 N/mm²
1,800 tr/min	225.34 N/mm²	27.76 N/mm²	146.77 N/mm²

Source: developed by the author

The results clearly show that, regardless of type of joint (aluminium/aluminium, aluminium/steel, or steel/steel), the elastic resistance of the welds decreased as the spindle speed was increased. In terms of actual values: (i) The elastic limit of steel/steel welds decreased from 456.72 N/mm² at a spindle speed of 900 tr/min to an elastic limit of 225.34 N/mm² at a spindle speed of 1,800 tr/min; (ii) For aluminium/aluminium welds, the elastic limit dropped from 88.66 N/mm² to 26.86 N/mm²; and (iii) The elastic limit of aluminium/steel welds decreased from 187.88 N/mm² to 146.77 N/mm² over the same speed interval. These results suggest that an increase in spindle speed during welding will generally lower the elastic resistance of the weld metal, presumably due to the higher temperatures generated during high-speed welding causing some degradation of the microstructure of the weld metal and thus lowering its elastic modulus, and ultimately, its elastic resistance. The variation of Vickers microhardness in the welded joints due to the spindle rotation at 900, 1,250, and 1,800 rpm is shown in Figure 4.

The hardness profiles from this figure will help understand the effect of the rotational speed on the mechanical properties of the welded zones. The peaks of the hardness value (near the weld interface) in Figure 4a, representing the steel-aluminium weld, are higher on the aluminium side. The hardness peak is due to the formation of IMCs, which are harder but also brittle in nature. The highest hardness is observed at 900 rpm due to lower heat input and finer microstructural features, while increasing the speed to 1,250 rpm and 1,800 rpm results in reduced hardness caused by greater heat input and coarser IMC formation. Figure 4b, representing the steel/steel joint, shows relatively uniform hardness on both sides of the weld, with a slight peak at the thermos-mechanically affected zone (TMAZ). Similar to the previous case, the highest hardness occurs at 900 rpm, while higher speeds lead to reduced hardness as a result of increased heat generation and microstructural softening. Hardness values for the aluminium-aluminium joint are, on average, the lowest of all three cases (Fig. 4c). The maximum hardness was also found to occur at a spindle speed of 900 rpm; the hardness decreased with each increase in spindle speed, as a result of increased grain size and the dissolution of strengthening precipitates.

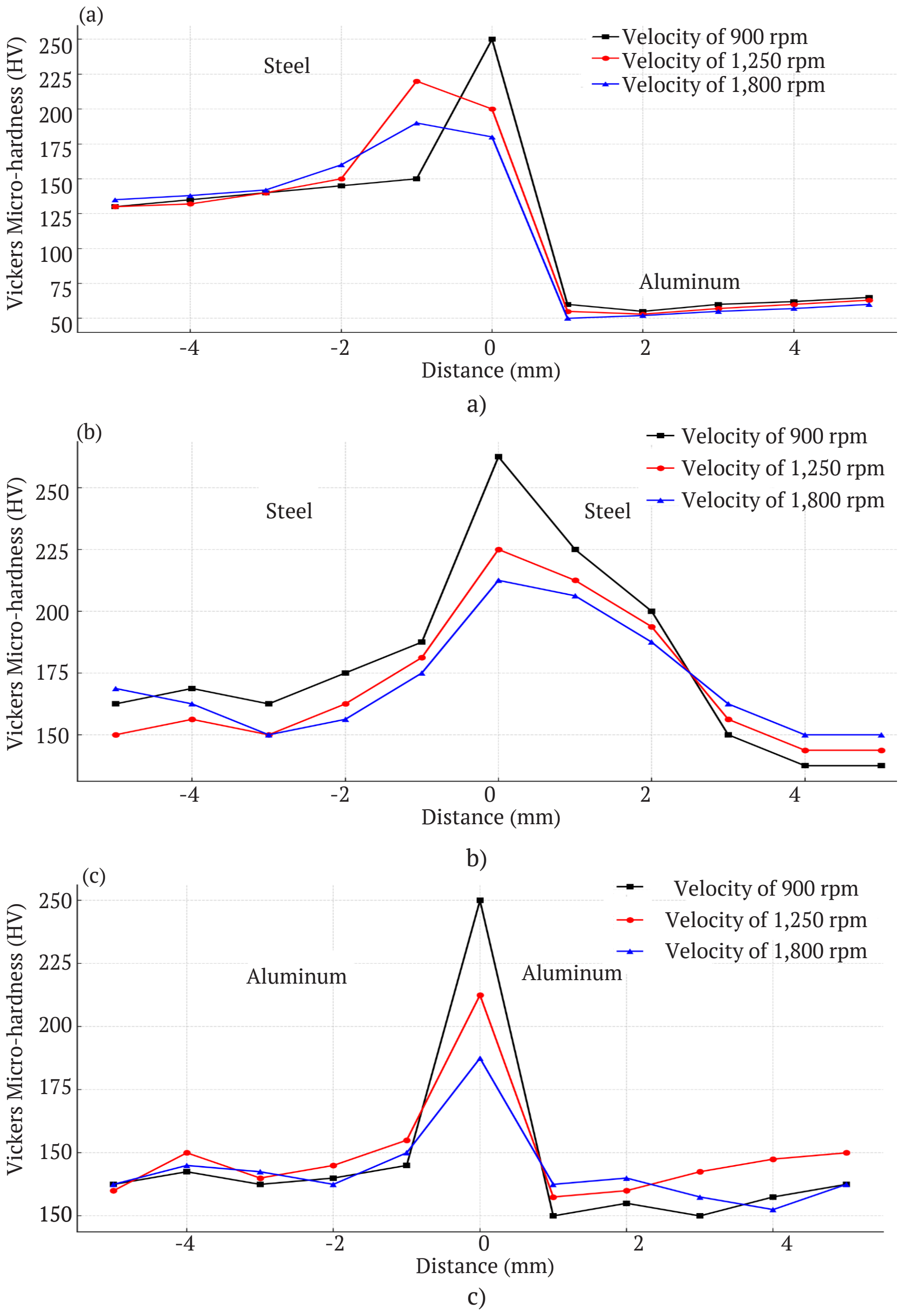

Figure 4. Microhardness test at three rotational speeds for
Note: a – steel-aluminium; b – steel-steel; c – aluminium-aluminium
Source: developed by the author

H. Miao *et al.* (2024) analysed factors influencing fatigue life in linear friction welded (LFW) joints of low-carbon steel, finding that fatigue life is controlled by stress concentration, weld toe geometry, residual stress, and microstructural evolution. They emphasised the importance of post-oscillation pressure in improving mechanical performance H. Miao *et al.* (2023) investigated fatigue strength improvement through pressurisation after oscillation, highlighting its positive effects on joint properties. The two studies are relevant to this study due to their identification of spindle speed as an important variable affecting elastic resistance, hardness and micro-structure. The results from the current study show that higher spindle speeds (i.e., 1,800 RPM) will reduce microstructural hardness and resistance while lower spindle speeds (i.e., 1,250 RPM) produce the most favourable mechanical properties. The studies provide further justification for the need to optimise process parameters to achieve welds with good mechanical properties, durability and surface finish. P. Geng *et al.* (2021) performed computational models to investigate plastic deformation and interfacial self-cleaning of the weld zone in linear friction welding of super alloys. As a result, they were able to develop a greater understanding of the mechanisms involved in producing micro structural changes and the joint strength in terms of the optimisation of processing parameters including weld speed and pressure. They found that plastic deformation and heat generated during the welding process have a great impact on the weld interface quality and therefore a major factor to be considered when optimising process parameters to achieve superior mechanical properties. Similar to the conclusions made by H. Miao *et al.* (2024; 2023), the study showed that the quality of the weld interface was primarily affected by heat input and plastic deformation which is a critical aspect in producing strong and defect free welds. H. Benkherbache *et al.* (2020), investigated the mechanical behaviour properties of a parts joined (similar and dissimilar) through the process of RFW, emphasising the criticality of thermal conditions and welding parameters for the microstructure and weld properties. The authors studied the heat generated during the process and how it affected the inter-metallic compounds (IMC's) in the case of dissimilar joint types such as steel-aluminium; they concluded that an increase in heat input results in a coarse-grained structure, micro-structurally softer, and lower hardness. This is consistent with the current research study, which demonstrated that an increase in heat input will have a negative effect on weld quality. In addition, C. Saib *et al.* (2025) performed a thermal, metallurgical, and mechanical analysis of single pass INC 738 welded parts and emphasised the influence of heat input on the formation of intermetallic phases, which may result in reduced weld strength. The conclusions from their study are consistent with those presented in this paper, and further emphasise the need to optimise the thermal conditions for achieving strong, defect free joints.

E. Maleki *et al.* (2021) illustrated the effects on the fatigue strength of welded steel caused by shot peening, and showed the effect on residual stresses in AISI 1060 Steel. Based upon the results of their study, shot peening was shown to have an impact on the residual stress state of weldments, to increase the fatigue strength, and to lower the probability of crack initiation, which are consistent with the stress relaxation associated with high speed friction welding. The thermal softening that takes place at high rotational speeds will also cause the elastic resistance and hardness to be lowered through stress relaxation mechanisms; as was determined in a study by H. Li *et al.* (2023) who analysed the effects of residual stress relaxation of a EA4T axle steel treated with ultrasonic surface rolling on the corrosion bending fatigue resistance of the steel. The study determined that the effects of residual stress relaxation were beneficial for improving the corrosion and fatigue resistance of the steel, similar to the study currently being discussed, which states that the thermal softening that occurs at high rotational speeds will lower the elastic resistance of the steel. Both of these studies emphasised the importance of controlling the thermal input during the manufacturing process to produce materials with long-term performance. X. Yang *et al.* (2025) have investigated the interrelation between the initial microstructure of GH4169 Superalloy weldments produced by linear friction welding and the mechanical properties and corrosion behaviour of these weldments. They determined that both thermal softening and microstructure modification affect the physical properties of the material, as was shown by the study and the effects of higher rotational speed to cause an excess of heat into the weld causing a loss of hardness due to microstructure softening and elastic resistance. In a study regarding low-temperature friction stir welding of TA5 titanium alloy joint microstructural development and mechanical behaviour, Y. Su *et al.* (2025) examined the effect of different cooling rates. The study demonstrated that the quality of the weld will be affected by the temperature of the weld, as stated by this study's results. A study showed that too much heat into the weld caused microstructural changes to the metal, reducing its strength and hardness. Therefore, thermal softening and stress relaxation occur at high spindle speed to produce the mechanical properties of the weld.

CONCLUSIONS

This research has shown that RFW is a viable and reliable solid state welding method for both similar and dissimilar metals provided that optimal processing conditions have been achieved. NDE tests using ultrasonic techniques confirmed the formation of defect free welds and thus, the structural integrity and metallurgical soundness of the weld regions. Based on this research it can be concluded that the spindle speed is the major control variable for determining the thermal energy transferred into the workpiece during RFW, as well as the resultant microstructures formed and the mechanical behaviour of the weldments. For example, increasing the rotational speed from 900 to 1800 rpm resulted in a decrease in elastic resistance in the weld region that can be attributed to over heating, thermal softening and undesirable microstructural changes. Conversely, the intermediate speed of 1250 rpm produced the best thermo-mechanical balance producing the best weld quality and mechanical performance. In addition, based on the mechanical testing, it was determined that the mechanical behaviour of the welded joints were dependent on the base metal composition. Welded steel to steel specimens had the best mechanical behaviour (i.e., the highest tensile strength and hardness), and this was attributed to the good plastic flow, fine microstructure and strong metallurgical bonding in the weld region. Aluminium to aluminium welded joints had the poorest mechanical performance, primarily due to grain growth and thermal softening in the weld region. Finally, steel to aluminium dissimilar welded joints had mechanical properties between those of the other two sets of specimens and had localised hardness peaks formed at the weld interface as a result of the formation of intermetallic compounds (IMCs). Therefore, the mechanical behaviour of these weldments were the result of the complex interactions between diffusion, heat input and phase transformations.

Overall, the results provide strong evidence that rotary friction welding (RFW) is an efficient and robust industrial weld process that can create high integrity welds in various material configurations; however, the study provides clear evidence that optimising the RFW process; especially the rotational speed will be required to prevent excessive thermal input and produce uniform microstructures as well as superior mechanical properties. Future studies should focus on a quantitative residual stress analysis, detailed characterisation of intermetallic phases present within RFW joints, as well as evaluating fatigue and fracture properties of both similar and dissimilar RFW joints. In addition, integrating numerical thermo-mechanical modelling with experimental validation would enable predictive optimisation of welding parameters for advanced structural and multi-material engineering applications.

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CONFLICT OF INTEREST

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Оцінка термо-механічної реакції компонентів за допомогою техніки ротаційного тертя при зварюванні

Анотація. Ротаційне термове зварювання (RFW) є одним з найважливіших процесів для з'єднання металів, як однакових, так і різних. RFW здобуло популярність серед багатьох виробничих секторів, оскільки зменшує теплові деформації, зменшує площу термічно уражених зон, забезпечує підвищені темпи виробництва та усуває потребу у заповнювальних матеріалах. Основною метою цього дослідження були механічні властивості зварних швів, з акцентом на взаємозв'язок швидкості шпинделя з якістю зварних швів для трьох різних типів матеріалів, що з'єднуються: алюміній-алюміній, сталь-алюміній та сталь-сталь. Ці зварювання були виготовлені за допомогою техніки ротаційного тертя на токарному верстаті. Проведено випробування на розтягування для оцінки того, як зварювання витримує навантаження. Здійснено ультразвукові перевірки для виявлення тріщин або пор в зварних швах. Проведено мікрометричні вимірювання для оцінки зони зварювання. Тести на твердість були проведені для визначення ступеня опору матеріалу. Нарешті, була проведена металографічна оцінка для дослідження мікроструктурних характеристик зварних швів. Тести показали, що з підвищенням швидкості шпинделя знижувався еластичний опір зварних швів. Було встановлено, що ця втрата еластичного опору виникає через високу температуру, яка утворюється при високих швидкостях шпинделя, що призводить до пом'якшення мікроструктури. Оптимальна механічна продуктивність була досягнута при швидкості шпинделя 1 250 об/хв, що забезпечило найвищий рівень механічних властивостей, таких як міцність і твердість. Крім того, через ультразвукові тести було підтверджено, що всі зварні шви, отримані за допомогою RFW, були повністю без дефектів. Отже, ці результати чітко демонструють, що RFW може створювати зварні шви з високими механічними властивостями та без дефектів, якщо існують оптимальні умови процесу, особливо якщо швидкість шпинделя налаштована відповідно до матеріалів

Ключові слова: з'єднання у твердому стані; термо-механічний аналіз; зона термічного впливу; металографічна характеристика; зварювання різнорідних металів