FRICTION STIR WELDING WITH DIFFERENT TOOL PROFILES ON STRUCTURE AND HARDNESS OF DISSIMILAR ALUMINIUM ALLOY AA5083 AND AA6061-T6

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DEDICATION

To my beloved Father and Mother, Mr Hasnol Bin Suleiman & Mrs Maisarah Binti Mohd Nor And my dear family Abdurrahman Fikri, Abdullah Fahim, Siti Khadijah, Ahmad Ibrahim and Siti Fatimah, thank you for all the sacrifices, encouragements and support provided. Thank you also for the words of motivation and concern to encourage the spirit to continue this struggle.

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ABSTRACT

Underwater dissimilar friction stir welding (FSW) of an aluminium alloy AA5083 and AA6061-T6 in butt joint configuration was studied. Underwater FSW is the solid-state joining operation that utilises the non-consumable tool to connect two facing workpieces without melting the workpiece substance in the underwater environment. Defect has been proven to have negative impact on overall welding engagement. It is becoming an area of increasing concern in any type of manufacturing, including welding. The present study continually looked for ways to manufacture the best underwater FSW tool pin profile for specific applications while minimising the different welding defects. The experimental method was to choose 1 sample among underwater FSW and normal FSW fabricated according to the welding process parameter and met the research criteria based on comparable studies. In addition, optical microscopy was employed to observe the microstructures and welding defects of the joints. The effects of the different tools at three profiles of straight, threaded, and tapered cylindrical tools on the structure and hardness of the joint dissimilar aluminium alloy were investigated. The presence of water is an excellent alternative to enhance durability and reduce the various types of welding defects during the welding process changes occurring in underwater FSW and normal FSW. These results have been used to understand the variation in the welding strength and the microhardness obtained in underwater FSW and normal FSW at both different tool pin profiles and values of welding speed. Results have revealed the presence of various types of defects such as groove and tunnel defects in the weld region. Metallurgical macrostructure observation on the underwater FSW and normal FSW samples revealed the presence of welding defects which were groove and tunnel in the stir zone. The tapered cylinder pin profile and 60mm/min welding speed remarkably affected welding textures resulting in a higher hardness value than the other samples. Furthermore, the optimal combination of rotational speed and welding speed can significantly improve the hardness strength of the welded joint. The study indicates that underwater FSW was achieve 77.56 HV, which is supported by the result obtained. This number was 18% greater than the hardness value achievable with the normal FSW, 63.30 HV. For underwater FSW, higher rotational speed and welding speed were suggested to establish sound welded dissimilar joints and achieve better microstructures which could collectively improve the welding strength.

ABSTRAK

Kimpalan kacau geseran dalam air (KKG) bagi aloi aluminium AA5083 dan AA6061-T6 dalam konfigurasi sambungan hujung telah dikaji. KKG dalam air merupakan operasi penyambungan keadaan pepejal yang menggunakan mata alat tidak boleh haus untuk menyambung dua bahan kerja tanpa mencairkan bahan kerja dalam persekitaran dalam air. Kecacatan telah terbukti mempunyai kesan negatif terhadap keseluruhan penglibatan kimpalan. Ia menjadi bidang yang semakin membimbangkan dalam mana-mana jenis pembuatan, termasuk kimpalan. Kajian ini secara berterusan mencari cara untuk menghasilkan profil pin alat KKG bawah air terbaik untuk aplikasi tertentu sambil meminimumkan kecacatan kimpalan yang berbeza. Kaedah eksperimen adalah untuk memilih 1 sampel di antara KKG bawah air dan KKG biasa yang difabrikasi mengikut parameter proses kimpalan dan memenuhi kriteria penyelidikan berdasarkan kajian bandingan. Di samping itu, mikroskop optik digunakan untuk memerhatikan struktur mikro dan kecacatan kimpalan pada sambungan. Kesan alatan berbeza terhadap tiga mata alat iaitu profil silinder lurus, berulir dan tirus pada struktur dan kekerasan aloi aluminium tidak serupa sambungan telah disiasat. Kehadiran air adalah alternatif yang sangat baik untuk meningkatkan ketahanan dan mengurangkan pelbagai jenis kecacatan kimpalan semasa perubahan proses kimpalan yang berlaku dalam KKG dalam air dan KKG biasa. Keputusan ini telah digunakan untuk memahami variasi dalam kekuatan kimpalan dan kekerasan mikro yang diperolehi oleh KKG dalam air dan KKG biasa pada kedua-dua profil pin mata alat dan nilai kelajuan kimpalan yang berbeza. Hasil keputusan telah mendedahkan kehadiran pelbagai jenis kecacatan seperti kecacatan alur dan terowong di kawasan kimpalan. Pemerhatian struktur makro metalurgi pada KKG dalam air dan sampel KKG biasa mendedahkan kehadiran kecacatan kimpalan iaitu alur dan terowong dalam zon kacau. Profil pin silinder tirus dan kelajuan kimpalan 60mm/min sangat mempengaruhi tekstur kimpalan yang menghasilkan nilai kekerasan yang lebih tinggi daripada sampel lain. Selanjutnya, gabungan optimum kelajuan putaran dan kelajuan kimpalan boleh meningkatkan kekuatan kekerasan sambungan yang dikimpal dengan ketara. Kajian menunjukkan bahawa KKG dalam air mencapai 77.56 HV, yang disokong oleh keputusan yang diperolehi. Nombor ini adalah 18% lebih besar daripada nilai kekerasan yang boleh dicapai dengan KKG biasa, 63.30 HV. Untuk KKG dalam air, kelajuan putaran dan kelajuan kimpalan yang lebih tinggi dicadangkan untuk mewujudkan sambungan tidak serupa yang dikimpal dalam keadaan baik dan mencapai struktur mikro yang lebih baik yang secara kolektif boleh meningkatkan kekuatan kimpalan.

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LIST OF ABBREVIATIONS

AA	-	Aluminium Alloy
ANOVA	-	Analysis of Variance
AISI	-	American Iron and Steel Institute
ASTM	-	American Society for Testing and Materials
BM	-	Base Material
CS	-	Cylindrical Straight
CT	-	Cylindrical Threaded
EDM	-	Electrical Discharge Machining
FSW	-	Friction Stir Welding
HAZ	-	Heat Affected Zone
HV	-	Vickers Hardness
RPM	-	Revolutions Per Minute
SEM	-	Scanning Electron Microscopy
SZ	-	Stir Zone
TC	-	Tapered Cylinder
TMAZ	-	Thermo Mechanically Affected Zone
TWI	-	The Welding Institute
UFSW	-	Underwater Friction Stir Welding
UTM	-	Universiti Teknologi Malaysia
UTS	-	Ultimate Tensile Strength

LIST OF SYMBOLS

mm	-	Millimetre
N	-	Newton
Si	-	Silicon
Fe	-	Iron
Mn	-	Manganese
Mg	-	Magnesium
Zn	-	Zinc
Ti	-	Titanium
%	-	Per cent
min	-	Minute
g	-	Gram

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CHAPTER 1

INTRODUCTION

1.1 Project Background

Friction stir welding (FSW) is a solid-state joining operation that utilizes a non-consumable way to connect two facing workpieces without melting the workpiece substance. FSW methods are versatile enough to be used for welding joints configured with either similar or dissimilar materials. The friction between the rotating tool and the workpiece generates energy, contributing to the soft area near the FSW way. Sengupta et al. (2021) illustrated that using FSW techniques on dissimilar materials to those used for the base materials could improve joint efficiency. This would allow for better macrostructure observation and hardness testing. Additionally, using the FSW method will facilitate the joining process of the two parent materials.

This study investigates the optimal welding settings for manufacturing a high-quality aluminium AA5083 and AA6061-T6 plate butt-weld FSW technique. According to Thomas et al. (1991), The Welding Institute (TWI) developed a novel method of combining materials using a solid-state welding process called friction stir welding (FSW). Generally, FSW is controlled by several process parameters that are taken into consideration when performing the welding. Picot et al. (2018) stated that numerous studies were carried out on the influence of these variables on the properties of the FSW and Feng et al. (2022) discovered underwater FWS joints of dissimilar aluminium. According to Wan and Huang (2018), FSW could combine metal alloys, copper alloys, soft steel, and stainless steel. It has recently been used to successfully weld polymers. Furthermore, FSW has achieved the joining of different metals, such as metal to magnesium alloys, as reviewed by Singh et al. (2020).

The tool profile, which includes the geometry of the FSW tool shoulder and tool pin profile, also influences weld strength. As a result, studying the FSW process entails investigating the characteristics of the tool pin profile. Systematically investigating the effect of the tool pin profile on the FSW welded joint requires knowledge of material-specific fundamental tool features. Following that, the effects of various tool pin profiles on the hardness of a commercially available aluminium alloy welded joint were investigated.

Gite et al. (2019) stated that the process parameters are essential in tool geometry, joint design and welding parameters. As seen in Figure 1.1, the FSW technique uses a non-consumable rotating tool as a shoulder, pin, or probe. The lower part of the tool, referred to as the tool pin, is completely inserted between the material surfaces. This continues until the higher part of the tool, referred to as the shoulder, contacts the base plate material near the bottom of the welded joint. During FSW, friction between the shoulder surface, the parent material and localised plastic deformation are primary contributors to heat generation. Verma et al. (2021) evaluated the effect of the combined action of the rotating tool and shearing of the shoulder on plasticizing the material through traversed motion to produce a butt-welded joint. The FSW is the friction process that occurs between the tool surface and workpiece, resulting in plastic deformation at high-speed rotation along the plunging force exerted by the tool. Most applications for welding aluminium and alloys, such as FSW, have many benefits in the manufacturing process—for instance, the shipbuilding, space shuttle, and transportation industries.

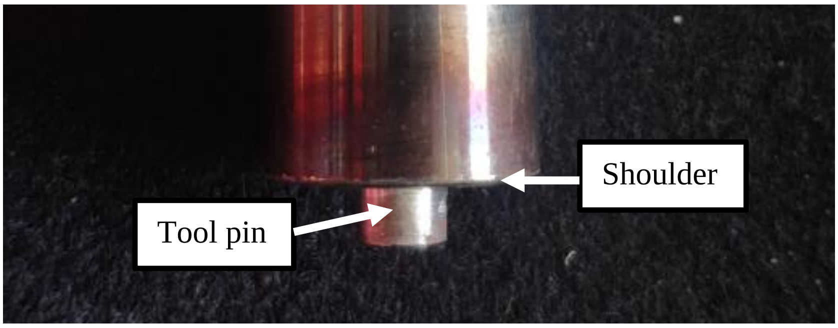

Figure 1.1 FSW welding tool

In most cases, friction stir welding (FSW) is managed by considering several process parameters when manufacturing the welding joining. Muhayat et al. (2018) found that the FSW tool shoulder and tool pin profile geometry is crucial in determining the weld strength stirring effect even in the welded zone. According to Sucharitha et al. (2020), the surface of the metal becomes plasticized during the FSW process, allowing bonding to happen. When the tool shoulder rubs against itself during the FSW process, frictional heat is generated, causing the parent metal to deform. Yuqing et al. (2017 discovered that the combined action of two forces (plunge force and forward motion) causes the plasticized material to develop around the pin inside the stir zone when performing FSW on AA7075-T6. As shown in Figure 1.2, there are three different zones that can be found in most FSW joints which are the stir zone (SZ), the thermo-mechanically affected zone (TMAZ), and the heat-affected zone (HAZ).

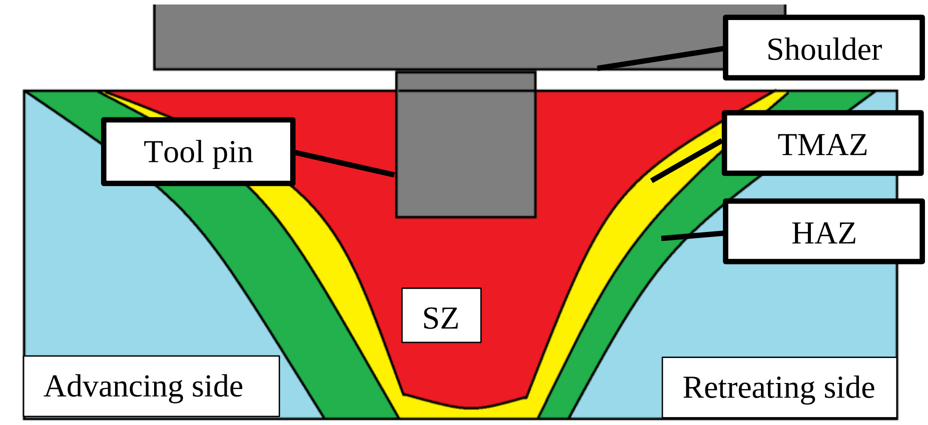

Figure 1.2 Cross-section showing the different regions of weldment

Emamikhah et al. (2014) studied the effect of tool pin profiles that penetrated the surface plate as well as dwelled time at the weld line. They stated that the dwell time is the pre-heat time before the tool pin penetrates the workpiece. The rotational pin raises the temperature of the surface due to frictional heating, making it easily accessible through the welding line. Podrzaj et al. (2015) stated that the main parameters of FSW that engage the joint, the welding parameter, are rotational speed, welding speed, plunge force, and tool design. Figure 1.3 shows a schematic diagram of the fundamental of the FSW process.

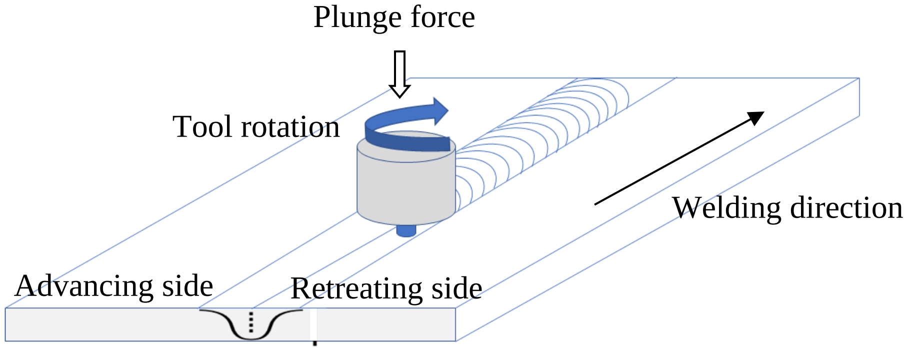

Figure 1.3 Fundamental of the FSW process for butt joints

Singh et al., (2018) stated that butt and lap joint configuration is the most convenient joint design welding for FSW. Fathi et al. (2019) analyzed the experimental method for FSW butt welding of AA6061-T6 to improve hardness under different process parameters such as rotational speed and welding speed. They discovered that using a water-cooling environment improved the hardness compared to normal FSW. Gungor et al. (2014) investigated the microstructure and mechanical characteristics of the FSW on AA5083-H111 and AA6082-T651. They determined that the welded joint might achieve better fatigue life and appropriate strength by using FSW at moderate welding speeds. Tang et al. (2019) stated that microstructure and aluminium matrix composite properties contributed to the critical factors during FSW processing.

The factorial technique was utilised in the parametric design of the experiments to analyse the relationship between the rotational speeds and welding speeds affecting the hardness at the welded joint. In order to maximise the numerous quality features of friction stir welded AA5083 and AA6061-T6 dissimilar aluminium alloys, Taguchi orthogonal array L9 was used. Optimization targets included hardness values at various rotational speeds and welding speeds. This research focuses on the impact of these two variables on hardness in the stirred zone (SZ) of friction stir welds. The study employed analysis of variance (ANOVA) to determine the most critical factor in welding parameters as well as the relative importance of each process variable. Variations in process parameters within a given range were used to fabricate FSW butt-welds between dissimilar materials, and conclusions about the best settings were be illustrated and discussed.

In this study, an AA5083 and AA6061-T6 aluminium alloy available on the market was chosen as the experimental parent material. Besides that, according to Das et al. (2019), AA5083 are non-heat-treatable aluminium alloys with good weldability and better strength properties (250-350Mpa). Li et al. (2017) discussed the use of AA5083 aluminium alloy hardness after fire exposure. They found that the 5083 aluminium alloy used in cryogenic pressure vessels is safe when realizing the thermal condition on the mechanical performance. Furthermore, FSW is the ideal method for the joining process for aluminium alloys to get sound welded joints, as stated by Vasu et al. (2019). For comparison, alloy AA5083, AA6061-T6 is a treatable heat alloy with extremely high strength, excellent welding characteristics and good mechanical performance, but these materials are prone to stress corrosion cracking due to welding.

Due to its favourable strength, aluminium alloy is a feasible option to replace steel in obtaining an effective weld. In addition, welding quality and aluminium types have improved to some extent in terms of the hardness of the joints produced. The traditional method of fusion welding is inferior to the more modern method of FSW, which has many advantages. Many fusion welding methods can be categorised according to the heat source, such as electric arc welding, gas welding, electrical resistance welding, and high-energy welding. In addition, compared to fusion welding, FSW methods are significantly more versatile, eco-friendly, and efficient in energy use. Tamjidy et al. (2017) investigated various aluminium alloy joints that are frequently used in various applications. Some of these applications include marine structures, pipelines, and storage tanks.

Talebizadehsardari et al. (2021) reported that there are few publications comparing experimental methods on dissimilar materials in underwater FSW investigations to the standard FSW technique. Hence, this study was carried out to evaluate the macrostructure observation and hardness of FSW technique of rotational speed, welding speed and tool pin profile for butt weld configuration on AA5083 and AA6061-T6 aluminium alloy. The experimental study attempts to employ underwater and normal FSW on dissimilar AA5083 and AA6061-T6 grades according to the chemical composition of the material, as shown in Table 1.1.

Table 1.1 The chemical composition of experimental dissimilar aluminium alloy, reproduced from (Hasan et al., 2013 and Fathi et al., 2019)

Weight (%)	**Si**	**Fe**	**Cu**	**Mn**	**Mg**	**Zn**	**Ti**
AA6061-T6	0.6	0.34	0.26	0.07	0.8	0.01	0.01
AA5083	0.40	0.40	0.1	0.2	0.4	0.1	0.15

There are significant hardness value differences between the two dissimilar materials due to the selection of process parameters during the FSW technique. Furthermore, the excellent material flow contributes to the optimal hardness value that may be impacted after a single pass of FSW. Therefore, the present study accomplished dissimilar joining in both underwater FSW and normal FSW between the aluminium alloys AA5083 and AA6061-T6, which have numerous important industrial uses. Besides that, the effect of the tool pin profile on the welding process for a dissimilar aluminium alloy is also determined. Wang et al. (2017) experimented with enhancing the hardness of the FSW 5083Al-H19 joint using water as a cooling medium.

Creating a process requires knowing how to apply the FSW technique correctly. Continuous research is being conducted to investigate how process parameters, welding effects, and monitoring can affect joint quality. Despite the extensive research that has been conducted, there is still a significant amount of research that needs to be conducted in order to fully gather and combine the understanding of the macrostructure and hardness testing process. This topic emerged as a result of a review of previously published research on various FSW methodologies and experiments. This thesis was carried out with the goals of mapping several features that occur during the process of normal FSW and underwater FSW, linking these factors, and highlighting both continuity and gaps in this field of study. This publication also includes the previous study for researchers who are interested in the extra area of the FSW approach, which is used to link materials that are comparable to or different from one another. The following part will discuss the effect of FSW parameters on the material, as the researchers reported it.

1.2 Problem Statement

Friction stir welding provides superior joint characteristics for limited processing times. It allows non-ferrous alloys such as aluminium alloy to be attached. Swaminathan and Sathiyamurthy (2020) stated that the outstanding contribution of a welded friction stir joint is dependent on controlling the welding process variable. Until today, researchers are still finding ways to produce the optimum design for the underwater FSW tool for specific applications and minimize the variety of welding defects like porosity, tunnel defect, cracking, etc. According to Derazkola and Khodabakhshi (2020), voids, flashes, and defects on the surface and welded joint are a major concern. Furthermore, understanding heat generation at various stages is critical for resolving operational issues at the unstable stage following the welding process. According to Mahto et al. (2019), deeper pin penetration results in defects. Thube (2014) also stated that high rotational speed results in a higher generation of grain equiaxed structure. However, Bayazida et al. (2015) pointed out that improper flow metal consolidation in the FSW region could result in cracking. Bergmann et al. (2013) suggested that solid-state welding could solve the problem related to dissimilar alloy of the welded joint in which welding techniques such as friction stir welding might benefit.

FSW joining processes produce reasonably sound welds for a variety of incompatible aluminium alloy combinations. When two metals or alloys in butt joint configuration undergo FSW, they are joined through plastic deformation caused by frictional heat. Rajak et al. (2020) reported that the emergence of numerous defects negatively impacts the quality of the welded joint due to differences in the characteristics of the two materials. This has led to the development of some methods for achieving reliable welds. Kumar at el. (2020) reported that the increase in hardness resulted from the effect of process parameters of two dissimilar metals during FSW.

According to Singh et al. (2021), the tool pin profile is the most influential factor in forming a joint that produces sound welding and is free of any defects, including voids and tunnel defects. Dehghani et al. (2013) investigated parameters for FSW and their effect on tunnel formation. They discovered that the pin profile could be altered, but the tunnel defect could not be easily eliminated, which generates a nugget zone. Furthermore, they noted that because there was no bonding between the two materials, the joint strength between the aluminium plate and tool steel was weak at a lower pin depth. Meng et al. (2021) mentioned that during fabrication work, the shape of the cavity is determined by the rotating pin when the tool pin is plunged into the welding workpieces. Zhang et al. (2019) noted that the tool pin and shoulder and the boundary between the stir zone are the primary locations for material mixed flow. Therefore, a tool pin profile should be designed to generate minimal flashes, as stated by Gupta (2020). In welding, the temperature at the workpiece is closely related to the rotational speed at which frictional heat is created. According to Raturi et al. (2019), when using proper tool pin profiles, the rotational speed and welding speed were determined to be the most relevant parameters. In the FSW technique, tool geometry and welding process parameters create frictional heat and material flow which affect the formation properties of the welded joint. When the joint is complete, the tool is retracted from the workpiece, leaving a keyhole at the weld's end that can easily compromise its surface texture. In addition, Ahmed et al. (2020) reported that poor process parameters conditions can lead to other welding defects that harm mechanical performance, such as grooves and tunnel defects.

Therefore, this work aimed to determine the relationship between the hardness of underwater FSW dissimilar joints made from aluminium alloys AA5083 and AA6061-T6 at varying degrees of tool pin profile, rotational speed, and welding speed. Friction stir welding is used to join the various aluminium alloys together. The study used a Taguchi L9 orthogonal design of experiment to determine the best settings for the fabrication of FSW. The Taguchi method is utilized to determine the required number of experiments when analysing input and output responses, and an ANOVA (analysis of variance) table is employed for statistical analysis. This method can be used to determine the best FSW process parameters and the optimal hardness value predicted for dissimilar joints.

1.3 Research Question

a) How does the tool pin profile affect the macrostructure and hardness properties of underwater FSW?

b) How can DOE be used to optimise the macrostructure observation and hardness testing result for AA5083 and AA6061-T6 underwater FSW?

1.4 Research Objectives

The objective of the research covers:

(a) To determine the effect of tool pin profile with cylindrical straight, cylindrical threaded and tapered cylinder on the macrostructure and hardness of underwater FSW between AA5083 and AA6061-T6.

(b) To optimise the hardness of welded dissimilar Al alloys at various rotational speeds and welding speeds using the Taguchi approach.

1.5 Scope of Research

The scope of this study were as follows:

(a) The study covers the material that uses AA5083 and AA6061-T6 aluminium alloy on joints during underwater FSW and normal FSW.

(b) Experimental method was conducted using a milling machine located in E01, UTM JB.

(c) A fabricated water container rig was used as a platform for the experimental method.

(d) The study covers the material tools ultra-high strength tool steel alloy, H13 grade with high toughness and resistance to thermal fatigue.

(e) The study investigates the selection of welding process parameters, such as rotational speeds and welding speeds.

(f) The experimental method used the designed shape of pin tools profile: cylindrical straight, cylindrical threaded and tapered cylinder.

(g) The study consists of the response that considers all macrostructure observations and hardness testing.

1.6 Significances of Research

(a) For this study, using cooling medium water at room temperature contributed to the cooling rate and enhanced grain refinement after the experimental method.

(b) The critical study optimised process parameters that contribute to the tool pin profile for stirring action. It also plays an important role in the material flow response between the heat input and the stirred zone, which helps to control the defects along the welded joints.

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1. **Hasnol, M. Z**., Ahmad Zaharuddin, M. F., Wan Ali, W. F. F., Sharif, S.& Rhee, S. (2023). Assessment Of Friction Stir Welding: An Overview. *Jurnal Mekanikal*, 45(2), pp. 23–38. https://jurnalmekanikal.utm.my/index.php/jurnalmekanikal/article/view/456
2. **Hasnol, M.Z**., Zaharuddin, M.F.A., Sharif, S.& Rhee, S. (2022). Taguchi Optimisation On Effect Of Water Environment In Joining Dissimilar Al5083 And Al6061-T6 Aluminium Alloy Using Friction Stir Welding. *Jurnal Mekanikal*, 45. pp. 39-52. https://jurnalmekanikal.utm.my/index.php/jurnalmekanikal/article/view/451. **(Indexed by Mycite)**
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4. **Hasnol, M.Z**., Zaharuddin, M.F.A., Sharif, S. & Rhee, S. (2022). Effect of Tool Pin Profile of Underwater Friction Stir Welding of Dissimilar Materials Aa5083 and Aa6061-T6. *International Journal of Innovation Engineering and Science Research*, 6(1) pp. 11-18. https://www.ijiesr.com/liebrary/e34/932424834.pdf (Accessed: 12 July 2022).