THE INVESTIGATION OF BFSW VIBRATION SIGNAL IN UNSUCCESSFUL WELD AND TOOL FAILURE BY FAST FOURER TRANSFROM

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BACHELOR OF MECHANICAL ENGINEERING TECHNOLOGY WITH HONOURS

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DEDICATION

I dedicate this report to all my loving family members, who have encouraged and supported me throughout my studies, to my parents who have given me motivation, belief, prayers and support through all the stages of my studies. To my fellow colleagues and friends who have helped me directly and indirectly. My supervisor Ts Dr. Mohammad Kamil Bin Sued for giving me the opportunity to venture into this study and providing guidance and knowledge throughout and to the completion of this study. My never ending thanks to everyone who has helped me through this study and to the success of this research.

ABSTRACT

Bobbin friction stir welding is an advanced form of solid-state welding, derived from conventional friction stir welding. It incorporates a modified tool configuration comprising an upper and lower shoulder connected by a penetrating pin, eliminating the need for a backing plate commonly used in traditional friction stir welding. During bobbin friction stir welding, the tool's two shoulders rotate in synchronization, spinning along the upper and lower surfaces of the workpiece in the same direction and at the same speed. This synchronized rotation ensures a uniform distribution of frictional heat throughout the welding process, positively affecting the weld material by enhancing its plastic deformation characteristics and eliminating common defects associated with conventional friction stir welding. In this study, the variation of tool rotational speeds and tool travel speeds is explored as a means to study the generated vibration in the weld material during the welding process. The resulting vibration has subsequent effects on weld quality and mechanical characteristics. Vibrational data is collected using accelerometers, while the heat generated during welding is also measured. The primary objective of this research is to investigate the impact of vibration on the weld material, providing valuable insights into the behaviour and performance of bobbin friction-stir-welding.

ABSTRAK

Bobbin friction stir welding adalah satu bentuk canggih pengelasan keadaan padat, yang dihasilkan daripada pengelapan friksi padat konvensional. Ia menggabungkan konfigurasi alat yang diubahsuai yang terdiri daripada bahu atas dan bawah yang disambungkan oleh pin penetrasi, menghilangkan keperluan untuk plat sokongan yang biasa digunakan dalam pengelasan friksi tradisional. Semasa bobbin friction stir welding, kedua-dua bahu alat berputar dalam sinkronisasi, berputar di sepanjang permukaan atas dan bawah bahagian kerja dalam arah yang sama dan pada kelajuan yang sama. Rotasi yang disegerakkan ini memastikan pengedaran haba geseran yang seragam sepanjang proses pengelasan, memberi kesan positif kepada bahan pengelapan dengan meningkatkan ciri-ciri deformasi plastik dan menghilangkan cacat biasa yang berkaitan dengan pengelaian mesh geseran konvensional. Dalam kajian ini, variasi kelajuan rotasi alat dan kelajuan perjalanan alat dipelajari sebagai cara untuk mengkaji getaran yang dihasilkan dalam bahan salutan semasa proses pengelasan. Vibrasi yang dihasilkan mempunyai kesan seterusnya pada kualiti dan ciri-ciri mekanikal pengelasan. Data getaran dikumpulkan menggunakan akselerometer. Matlamat utama penyelidikan ini ialah untuk menyiasat kesan getaran pada bahan pengelasan, memberikan wawasan yang berharga dalam tingkah laku dan prestasi bobbin friction-stir-welding.

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LIST OF SYMBOLS AND ABBREVIATIONS

FSW	-	Friction Stir Welding
BFSW	-	Bobbin Friction Stir Welding
CNC	-	Computer Numerical Control
°C	-	Degree Celsius
Mm	-	Millimetre
RPM	-	Rotations Per Minute

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

Background

Friction stir welding (FSW) is a versatile solid-phase metal joining technique that operates with low energy consumption and eliminates the need for filler materials or shielding gas. It finds extensive application in industries like automotive and aerospace, enabling efficient joining of non-ferrous metal alloys such as aluminum, magnesium, titanium, and copper alloys. FSW offers several advantages, including energy efficiency, cost-effectiveness, and reduced thermal distortion. By utilizing frictional heat and a rotating tool, FSW softens the metals, ensuring a strong bond while minimizing environmental impact. The solid-state nature of FSW eliminates solidification defects and produces clean welds with superior mechanical properties. Automotive manufacturers benefit from lightweight vehicles, improving fuel efficiency, while aerospace industries rely on FSW for secure aircraft structures. With its broad industrial use and ability to join diverse metal alloys, FSW continues to drive advancements in metal joining technology. (Fouladi et al., 2017). The conventional friction stir welding (C-FSW) offers benefits for joining aluminum alloys, but if the welding parameters are not set properly, it can result in bottom defects like lack of penetration and kissing-bond. Furthermore, achieving high-quality welding of complex-shaped hollow extrusions is challenging with C-FSW due to limitations in shape and the need for a significant axial forging load during the process. In response to these challenges, the bobbin tool friction stir welding (BT-FSW) technique has been developed to address these limitations and drawbacks (Yang et al., 2022).

The utilization of the bobbin tool in bobbin friction stir welding distinguishes it from standard friction stir welding (FSW). The bobbin tool incorporates an additional shoulder, known as the lower shoulder, at the tip of the probe. This enhancement in the tool design allows bobbin friction stir welding to effectively eliminate root flaws like lack of penetration (LOP), which are occasionally encountered in standard FSW. Moreover, the presence of shoulders in the bobbin tool eliminates the requirement for a fixed backing plate, as it restricts the vertical process loads within the tool. This innovative design eliminates the need for plunge loads, resulting in a simplified and cost-effective fixture design. The integration of the lower shoulder and the modified fixture design in bobbin friction stir welding to contribute to an improved weld quality and enhanced efficiency in the welding process.(G. H. Li et al., 2020).

However, it is frequently observed that insufficient weld quality is often linked to identifiable vibrational interactions. These interactions play a critical role in determining the success or failure of the welding process, and their presence or absence significantly affects the overall integrity and strength of the weld joint. The occurrence of these distinct vibrational interactions during welding can result in detrimental effects such as incomplete fusion, inadequate penetration, or the formation of undesirable defects like cracks or porosity. Therefore, it is crucial to monitor and control these vibrational interactions to ensure optimal welding outcomes and the production of high-quality welds (Sued & Pons, 2016). The clamping system's effectiveness in reducing welding forces and vibrations caused by the rotating tool's movement is directly linked to its rigidity. Rigidity refers to the system's capacity to resist and counteract these forces and vibrations, preventing their spread and minimizing their negative impact on welding. A rigid clamping system securely holds the workpiece, limiting excessive movement and maintaining alignment to prevent distortion or deformation. This robust clamping capability is vital for ensuring weld joint integrity and accuracy, enhancing welding quality, and producing reliable welds (Sued, M., 2015).

Problem statement

Bobbin friction stir welding, a variation of conventional friction stir welding, is renowned for its capability to overcome common weld defects by eliminating the need for backing plates or anvils to support the substrate. Vibration can play a role in the characteristics and quality of the welded joint, as friction welding process require constant contact between the substrate, when vibration is generated, this may disrupt the constant contact and can cause inefficient bonding of materials due to irregular heat generation. In general, heat generation plays a crucial role in friction stir welding, and vibrations can impact the symmetrical heat distribution exhibited by the bobbin friction tool, thereby influencing the quality of the welded joint. Despite its significance, limited research has been conducted to thoroughly investigate and validate these aspects. Therefore, there is a need for comprehensive research to substantiate and further enhance the efficacy of bobbin friction stir welding.

Research Objectives

The objectives of this study are:

1. To characterize the defect formation on unsuccessful bobbin friction stir welding by visual inspection.

2. To distinguish vibrational magnitudes generated during the bobbin friction stir welding process using fast Fourier transform.

Scope of Research

This study aims to investigate the influence of vibrations towards the properties of the welded substrate during bobbin friction stir welding. Specifically, we examine how variations in the weld rotational speeds and tool travel speeds on the substrate can result in different vibration frequencies that affects the quality and mechanical characteristics of the welded joints. To achieve this, accelerometers are used to measure and analyse the vibrations generated on the workpieces throughout the welding process. Vibrations generated during the welding process on the welding material are dependent on the welding rotational speeds which leads to welding defects and impacts the characteristics of welding.

Organization

This report is organized as follows. The first chapter includes the description of the background, problem statement, study objectives and scope of the project. Whereas the second chapter provides a review of related literature covering the research conducted within the scope of this study and from the basis for further discussions in subsequent chapters. The third chapter will be the methodology, where all the procedures in obtaining the data and results will be discussed. The fourth chapter will discuss the results and the analysis of the data obtained from the experimentation. The fifth and final chapter will discuss the conclusions on the research findings and the recommendations that can be implemented to improve the results for future research.

CHAPTER 2

LITERATURE RIVIEW

2.1 Introduction

This chapter provides an overview and examination of research carried out by utilizing various reference writing sources, which include articles, journals, past academic studies and reference books. This chapter will delve into the concept of Friction stir welding, an overview of bobbin friction stir welding, Rigidity factor in bobbin friction stir welding, weld defects in bobbin friction stir welding, Aluminum alloy 6xxx series, Metallurgical properties and mechanical properties of bobbin friction stir welding.

2.2 Concept of Friction stir welding

In today's modern era, the demand of light weight structures in the transportation industry has increased significantly as it is a major factor that directly links with fuel efficiency. The common types of light weight metal materials are Al-Mg-Zn alloys, these combination of alloying metals have exceptional weight to strength ratio and low density but may be difficult to join (Singh et al., 2020). Fusion welding of aluminum alloys is accompanied with complications such as porosity formation as well as substantial distortion of welded joints and bulk melting. Additionally, the mechanical properties of the joint can also be greatly reduced. To solve these issues, friction stir welding is a technique used to join aluminum alloys without melting it (Shao et al., 2022). Friction stir welding is a revolutionary welding technique that involves the use of a rotating non-consumable tool. This tool consists of a pin and a shoulder, which are inserted between the butting edges of the workpieces to be joined. During the welding process, the tool rotates and moves along the line of the butting edges, resulting in frictional heat generation through the rubbing action. This localized heat causes the metal to undergo plastic deformation. As the rotating tool continues its journey through the joint, it exerts pressure on the material, pushing it from the front to the back of the tool. The remarkable aspect of friction stir welding is that it achieves a joint without melting the material. Instead, the process operates in a "solid-state" manner, where the metal undergoes plastic deformation and forms a strong bond as it cools. The combination of the rotating tool, frictional heat, and plastic deformation allows friction stir welding to create robust joints in a wide range of materials. This innovative technique offers numerous advantages over traditional fusion welding methods, including the preservation of material properties, increased strength and fatigue resistance, and minimal distortion and defects. Friction stir welding has revolutionized the welding industry by enabling the production of high-quality, solid-state joints with exceptional mechanical properties. (Mishra & Ma, 2005) .

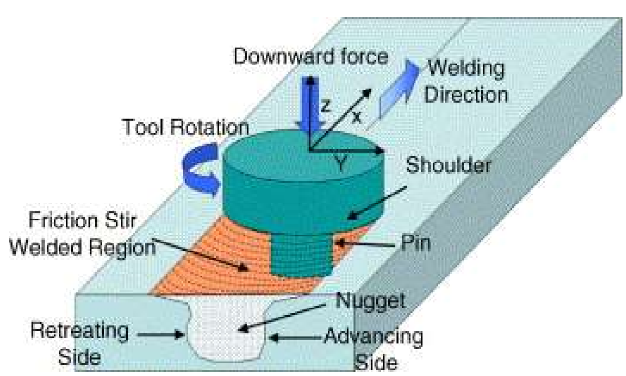

Figure 0.1Schematic drawing of friction stir welding

Friction stir welding (FSW) stands out as a highly effective welding technique for joining dissimilar metals and non-ferrous metal alloys. It offers outstanding mechanical properties in the as-welded state, while preserving the inherent characteristics of the base materials. In comparison to fusion welding methods, FSW excels in maintaining the original properties of the materials being welded. (Mohammad Kazem Besharati and Parviz Asadi, 2014). Friction stir welding method is known to be versatile, energy efficient and environmentally friendly. It consumes very less energy and during the welding process, the absence of filler metal eliminates the concerns for composition compatibility. Additionally, friction stir welding method offers the advantage of easily joining dissimilar aluminum alloys and composites, the process also does not require any shielding gas making it a more cost-effective welding method. There are numerous advantages of friction stir welding method, in terms of metallurgical benefits, friction stir welding has minimal deformation on the workpiece, excellent consistency and reliability in terms of dimensions, no depletion of alloying elements, the joint area exhibits excellent metallurgical properties, smooth microstructure and no occurrence of cracking. Whereas, in terms of environmental benefits, it eliminates the use of solvents and production of grinding wastes, surface cleaning is eliminated and saves on consumable materials. All these factors prove why Friction stir welding method is regarded a noteworthy advancement in metal joining and is recognized as a green technology (Mishra & Ma, 2005; Mohammad Kazem Besharati and Parviz Asadi, 2014).

2.3 Bobbin Friction Stir Welding

The weld tool holds paramount importance in friction stir welding, as it acts as a critical component. Its precise configuration plays a vital role in governing various aspects of the welding process, including heat generation and material flow. Moreover, the tool configuration directly influences the operational speed at which friction stir welding can be conducted. This, in turn, has a profound effect on the resultant strength and quality of the joint. Therefore, careful consideration and optimization of the weld tool's design and setup are crucial for achieving desirable outcomes in terms of joint integrity, mechanical properties, and overall welding performance. By meticulously adjusting the tool's parameters, such as its geometry, traverse speeds, and rotational speed, it becomes possible to fine-tune the heat input, control the material displacement, and optimize the welding process for superior joint characteristics. (Mishra & Ma, 2005). Bobbin friction stir welding is a variant of the modification of conventional friction stir welding, where it is an advancement of solid-state welding technology by optimizing a combined tool that consists of an upper and lower shoulder connected by a penetrating pin as shown in 2.2.

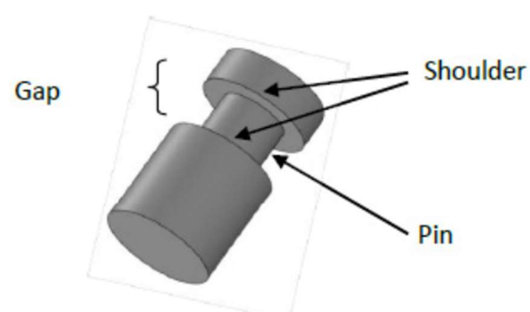

Figure 2.2 General feature of Bobbin tool (Kamble & Soman, 2019)

Both conventional friction stir welding and bobbin friction stir welding operate on similar fundamental principles, harnessing frictional heat to facilitate plastic deformation.

However, they differ primarily in terms of plunge load and heat distribution. In bobbin friction stir welding, a notable distinction arises from the rotational motion of the tool's two shoulders, which move in unison, spinning in the same direction and at the same speed along both the upper and lower surfaces of the workpiece. This synchronized rotation engenders a uniform distribution of frictional heat throughout the welding process, effectively contributing to the material being welded and influencing its propensity for plastic deformation. Consequently, this consistent and even distribution of frictional heat fosters extensive plastic deformation across the entire thickness of the weld. By capitalizing on the shoulders of the tool, the need for a fixed backing plate is rendered obsolete since the vertical process loads are confined within the tool itself. Consequently, the necessity for plunge loads is eliminated, thereby streamlining the fixture design and yielding a more cost-effective approach to welding. (G. H. Li et al., 2020). Figure 2.3 shows a configuration of bobbin friction stir welding.

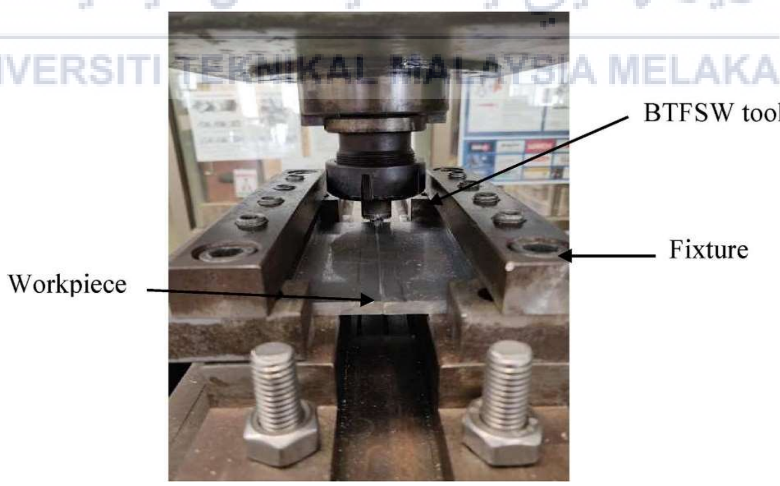

Figure 2.3 Configuration of Bobbin friction welding (Fuse & Badheka, 2020)

Furthermore, the utilization of bobbin friction stir welding offers numerous advantages in comparison to traditional friction stir welding. Firstly, it facilitates a consistent distribution of temperature across the workpiece by eliminating the presence of a backing plate. This elimination prevents the transfer of cooling paths from the workpiece to the backing plate, resulting in a more even and higher temperature gradient that is uniformly distributed throughout the workpiece. Consequently, bobbin friction stir welding generates a weld region with a finer and more consistent grain structure when compared to conventional friction stir welding. Additionally, by achieving complete consolidation, it is possible to refine the grain near the bottom surface of the plate, thus reducing the risk of root defects commonly associated with conventional friction stir welding caused by incorrect plunge depth or pin size (Khalid et al., 2022).

2.4 Advantages of Bobbin Friction Stir Welding

Bobbin friction stir welding, stemming from conventional friction stir welding, offers a multitude of benefits in terms of weld quality and operational efficiency. This advanced technique significantly enhances the overall quality of welds and streamlines the welding process, leading to improved performance and operational ease.

(a) Eliminates root defects in welded joints.

Tunnel void defects are a frequently encountered issue in conventional friction stir welding, primarily attributed to irregular and inconsistent heat generation. However, the implementation of bobbin friction stir welding offers a solution to this problem. By employing a controlled traverse speed of the rotating bobbin tool, the process ensures that there is no excessive heat input and facilitates a symmetrical heat distribution. As a result, the occurrence of tunnel void defects can be completely eliminated, leading to the formation of defect-free joints. This improvement in the welding process guarantees a higher level of quality and reliability in the resulting welds. By addressing the heat generation inconsistencies that contribute to tunnel void defects, bobbin friction stir welding provides a more robust and efficient approach to achieving defect-free joints. (LI et al., 2021).

(b) Efficient bonding of material

According to Khalid et al. (2022), the bobbin friction stir welding process offers several advantages that contribute to the production of efficient bonds and the elimination of bonding defects. One key factor is the symmetrical heat generation on both the upper and lower sides of the material during welding. This balanced heat distribution results in a more uniform temperature profile and promotes the formation of a finer grain structure within the weld zone. The finer grain structure enhances the bond strength welded joint. Moreover, the unique material flow conditions observed in bobbin friction stir welding create a characteristic compressed hourglass-shaped stir zone, as illustrated in Figure 2.4. This shape arises due to the pressure exerted by the upper and lower shoulders of the bobbin tool during the welding process. The compressive forces facilitate the fusion of materials and contribute to the consolidation of the weld. The resulting weld exhibits improved integrity and eliminates common bonding defects such as insufficient bonding and kissing bond (F. F. Wang et al., 2015).

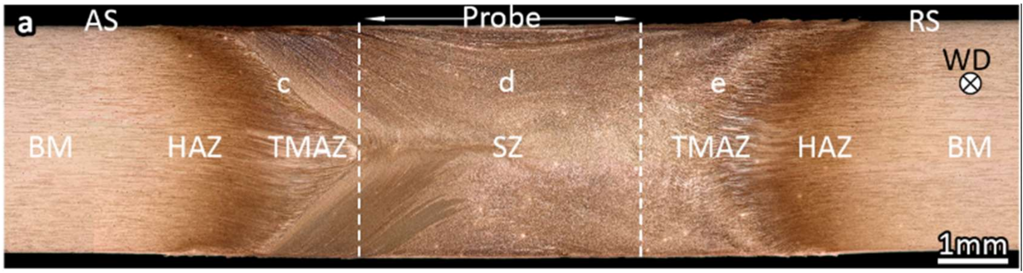

Figure 2.4 Macrograph of Bobbin friction stir welded joint displaying the hourglass shape (F. F. Wang et al., 2015a).

(c) Enhanced process stability

Bobbin friction stir welding (BFSW) distinguishes itself by offering enhanced process stability, making it an attractive option for various welding applications. One of the key factors contributing to this stability is the unique configuration of the bobbin tool, featuring two rotating shoulders. This design provides a larger contact area between the tool and the workpiece, facilitating improved material flow during the welding process. The increased contact area afforded by the bobbin tool promotes a more efficient distribution of heat and forces, resulting in a more consistent and controlled welding process (G. Li et al., 2020). The enhanced material flow leads to better mixing of the parent materials, ensuring a metallurgically sound bond with reduced defects such as voids or inclusions. This improved material flow also contributes to a reduction in process variation, enhancing the overall quality and reliability of the welds produced. By minimizing process variation and achieving greater weld consistency, BFSW offers advantages in terms of both quality and productivity.

Moreover, the stability provided by BFSW extends beyond the welding process itself. The reduced process variation and enhanced material flow contribute to improved dimensional control and surface finish, minimizing the need for extensive post-welding processing such as grinding or polishing (Meng et al., 2021).

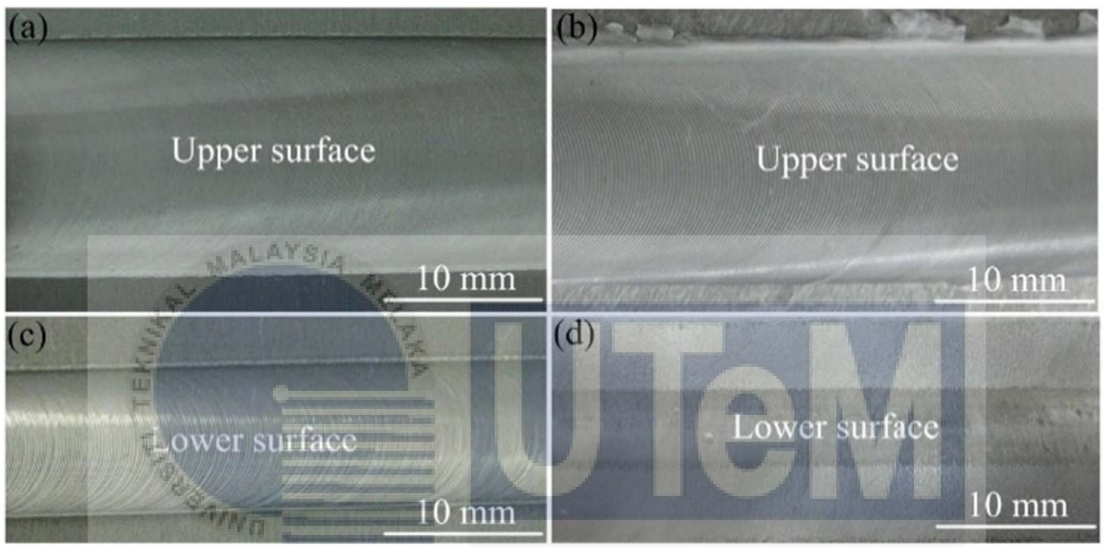

Figure 2.5 Surface finish of friction stir welded joints.

2.5 Rigidity Factor of Bobbin Friction Stir Welding

The quality of the weld is directly influenced by various process settings, including the utilization of clamps, the arrangement of supports, the size of the shoulder gap, and the direction in which the welding is conducted. These process settings play a significant role in generating compression forces, inducing vibrations, and distributing heat throughout the welding process, thereby impacting the overall quality of the weld (Sued et al., 2014a). In the realm of friction stir welding, it is commonly observed that inadequate weld quality is frequently associated with specific and discernible vibrational interactions. These vibrational interactions play a crucial role in determining the success or failure of the welding process, and their presence or absence can greatly impact the overall integrity and strength of the weld joint. When these distinctive vibrational interactions occur during welding, they can give rise to various detrimental effects such as incomplete fusion, inadequate penetration, or the formation of undesirable defects like cracks or porosity. Therefore, it is imperative to monitor and manage these vibrational interactions to ensure the achievement of optimal welding results and the production of high-quality welds (Sued & Pons, 2016).

The effectiveness of the clamping system in mitigating the impact of welding forces and vibrations caused by the rotation of the tool as it travels through the plate is directly related to the rigidity of the system. The rigidity of the clamping system refers to its ability to resist and counteract these forces and vibrations, preventing their propagation and minimizing their negative effects on the welding process. By providing a stable and secure hold on the workpiece, a rigid clamping system restricts excessive movement and displacement, maintaining the desired alignment and preventing distortion or deformation during welding. This robust clamping capability is crucial for ensuring the integrity and accuracy of the weld joint, enhancing the overall quality of the welding operation, and ultimately contributing to the production of structurally sound and reliable welds (Sued. M, 2015).

2.6 Defects in Bobbin Friction Stir Welding

The attainment of flawlessly welded joints with superior quality in friction stir welding is contingent upon several interrelated factors. These factors encompass the careful selection of process parameters, meticulous configuration of the welding tool, and effective clamping of the substrate. Each of these elements plays a pivotal role in regulating the quantity of heat generated throughout the welding process. Undoubtedly, the amount of heat generated constitutes a critical determinant that profoundly influences the outcome and success of all types of friction stir welding. Therefore, by meticulously optimizing the process parameters, ensuring an optimal tool configuration, and implementing robust clamping techniques, it becomes possible to achieve defect-free joints with exceptional quality and strength. A comprehensive understanding of the intricate interplay among these factors empowers welders to exercise precise control over the heat input, thereby enhancing the overall integrity and performance of the friction stir welding process. (Fuse & Badheka, 2020).

While Bobbin friction stir welding stands out as an exceptional form of friction stir welding, it is not exempt from encountering specific weld defects inherent to this welding variation. Given the high levels of strain, successive thermal exposures, and the limitations imposed by the bobbin tool on process loads, the occurrence of defects becomes more likely. (Liu et al., 2022) . These defects influence the metallurgical properties of the welded material. There are several weld defects in bobbin friction stir welding, they are listed as follows:

2.6.1 Flashing

In bobbin friction stir welding, it is common to observe the formation of flash on the retreating side of the upper surface of the welded material. This phenomenon can be attributed to the transfer of heated plasticized material from the advancing side to the retreating side. As the tool advances, it meets colder material, and the friction between the tool and the material generates heat, leading to its heating. The circular movement of the tool causes the material on the advancing side to heat up first as it is carried along by the tool and subsequently deposited on the retreating side. Consequently, a portion of the deposited material forms the flash on the retreating side (Fuse & Badheka, 2020). The excessive occurrence of flashes during welding can result in the weld becoming thinner, thereby impacting the overall performance and functionality of the welded joint (Sun et al., 2023). According to a study conducted by Fuse & Badheka, 2020 on the effects of shoulder diameter of bobbin friction welding of AA 6061-T6 alloy, a 24 mm tool shoulder diameter deposited a higher flash height, while a 20mm tool shoulder diameter deposited smaller flash height. This indicates that a 16.67% increment of shoulder size increases the occurrence of flashing on the weld material. The weld appearance at the bottom and top surface of the welded joint can be shown in figure 2.7,

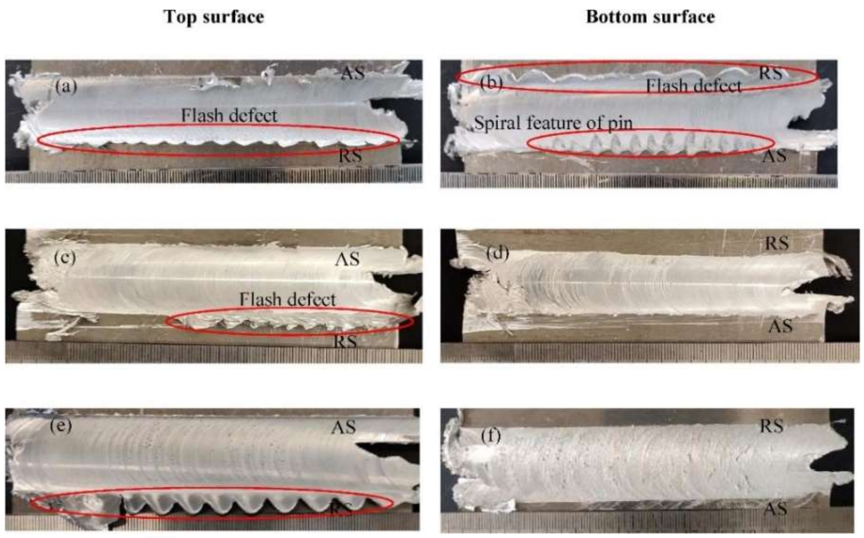

Fig. 2.6 Weld appearance at top and bottom surface with different shoulder diameter (a, b) 20 mm (c, d) 22 mm (e, f) 24 mm (Fuse & Badheka, 2020).

2.6.2 Void Defects

During the welding process, material flows from the front side, also known as the advancing side of the pin to the back of the pin, known as the retreating side. As the bobbin tool travels through the joining section of the material, the material fills the gap and causes the material to fuse with one another. Micro-void defects occur when there is a deficient material flow driven by the pin of the bobbin tool, forming a void. This is commonly due to excessive tool traverse speeds (Liu et al., 2022).

Figure 2.7 Void defect formed under 400rpm and tool traverse speed of 120 mm/min.

(Liu et al., 2022)

2.7 Factors Causing Weld Defects in Bobbin Friction Stir Welding

The emergence of defects within the realm of Friction Stir Welding (FSW) can be ascribed to the intricate and interconnected dynamics that transpire during the flow of the constituent materials. These defects arise due to the intricate interplay, interweaving, and interdependence between the flowing materials engaged in the FSW process, leading to imperfections or irregularities in the final weld (Z. L. Wang et al., 2022). In the realm of bobbin friction stir welding, defects often arise due to the presence of sub-optimal process parameters (Wu et al., 2021). These parameters play a crucial role in determining the quality of the weld, and several common factors have been identified. The key parameters that are frequently associated with these defects include the following:

2.7.1 Traverse Welding Speeds

The tool travel speed plays a crucial role in bobbin friction stir welding and significantly contributes to the quality of the weld. This speed corresponds to the rotation of the tool as it traverses the welding joint. The traverse welding speed has a substantial impact on the material's thermal exposure, which, in turn, affects its flow characteristics. In bobbin friction stir welding, it is possible to identify different weld zones, each of which is influenced by both thermal exposure and strain rate. Figure 2.8 provides a visual representation of these zones, where the stirred zone on the ascending side exhibits the finest grain structure. This can be attributed to the highest levels of thermal exposure and strain rate experienced in that zone, in contrast to the bimodal grain structure of the parent metal. The occurrence of various defects in these zones is influenced by the grain structure consolidation, which, in turn, is affected by the traverse speeds used during the welding process. (LI et al., 2021).

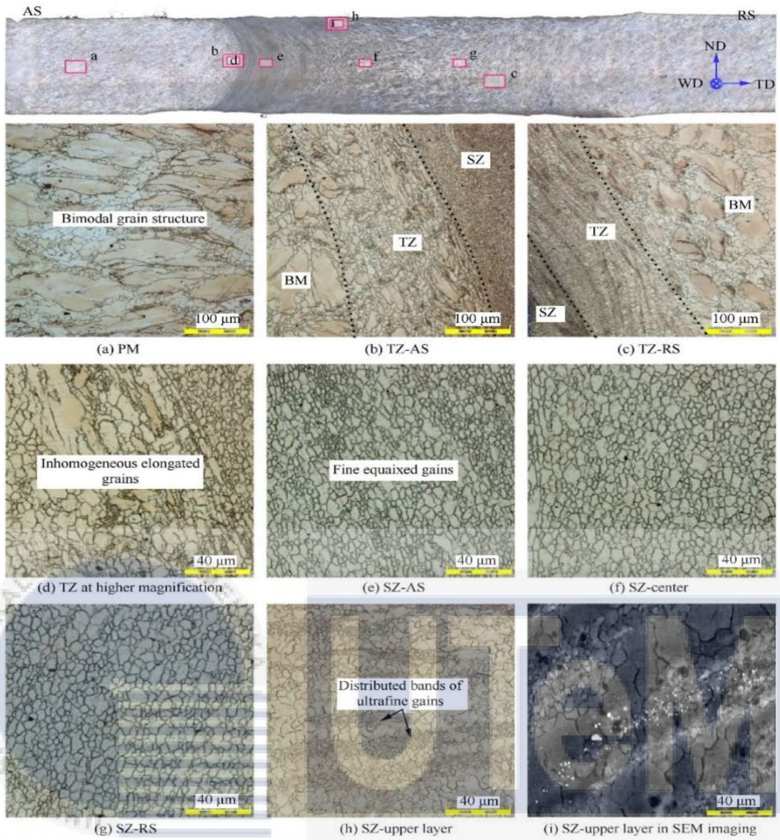

Figure 2.8 Grain structure in various regions of a BTFSW joint.(LI et al., 2021)

In a recent study conducted by LI et al. (2021), the effects of bobbin friction welding on ZK60 Mg alloy were investigated. It was observed that when a lower traverse speed of 150 mm/min was employed, the macrograph analysis of the welded joints revealed the presence of numerous tiny cavities or micro-voids within the stir zone, as depicted in Figure 2.9. This phenomenon was primarily attributed to the excessive heat input resulting from the low travel speed, which caused an imbalance in mass flux and ultimately led to the formation of tunnel defects. On the other hand, when a higher tool travel speed was utilized, specifically at 400 mm/min, an elongated fracture pattern was observed in the welded material within the stir zone. This fracture was attributed to the insufficient heat input, preventing the metal from undergoing a plasticized state. Consequently, a lack of bonding occurred at the initial butt interface. Similar findings were also reported by Wang et al. in 2022, where they found that lower traverse speeds of the welding tool promoted the formation of micro-voids within the stir zone. According to the authors, the researchers noted that if too much heat is applied at a slow traverse speed, it could cause an imbalance in the flow of material, resulting in defects in the tunnel. However, by increasing the traverse speed, it is possible to improve the reverse flow of softened metal into the area where tunnel defects commonly appear. As a result, at higher traverse speeds, it becomes achievable to obtain BFSW joints without any defects.

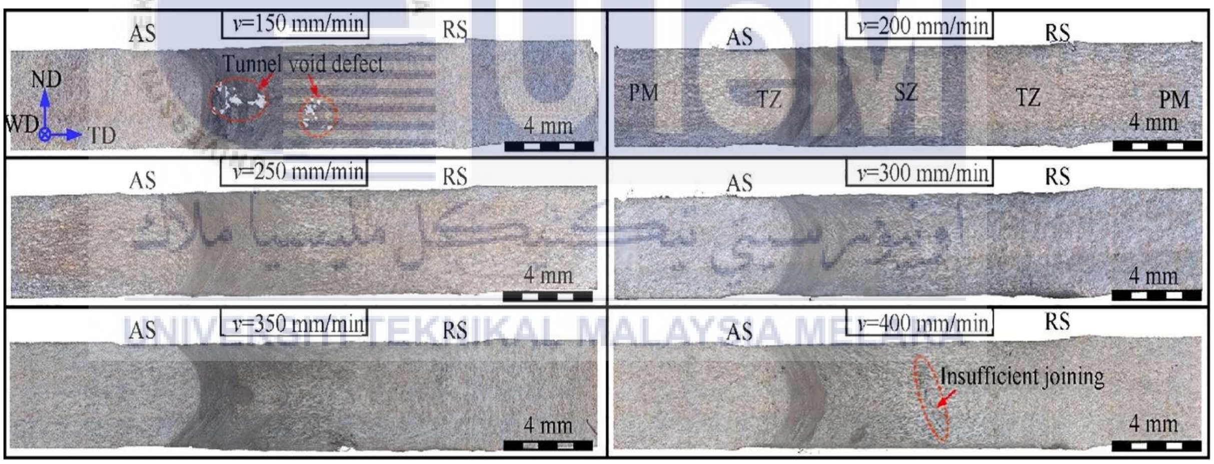

Figure 2.9 Cross-sectional macrostructures for Bobbin Friction stir welding obtained at different traverse speeds.

2.8.2 Shoulder diameter of Bobbin tool

The diameter of the shoulder in bobbin friction stir welding significantly influences the quality of the welded joints, because the shoulder is the primary source of heat generation. In this context, the direct interaction between the shoulder and the substrate assumes utmost importance, as the material beneath the shoulder undergoes a motion resembling the process of forging, while the material surrounding the pin experiences a movement akin to extrusion. Consequently, understanding and controlling the precise contact between the shoulder and substrate is of utmost importance to ensure optimal material flow and minimize the likelihood of defects during the welding process (Fuse & Badheka, 2020). A common defect caused by the shoulder diameter is flashing. According to a study conducted by Fuse & Badheka, 2020 on the effects of shoulder diameter of bobbin friction welding of AA 6061-T6 alloy, a 24 mm tool shoulder diameter deposited a higher flash height and a higher heat input of 345°C was generated, while a 20mm tool shoulder diameter deposited smaller flash height and lower heat input at 295°C. Furthermore, when utilizing a smaller shoulder diameter of 20mm, there is insufficient heat input, resulting in improper intermixing of the materials. This inadequate intermixing leads to the formation of void defects within the weld, as depicted in Figure 2.11. Conversely, defect-free joints are achieved when employing larger shoulder diameter, which consolidates the higher heat input. As discussed earlier, reducing the shoulder diameter of the bobbin tool increases the probability of defect occurrence. The temperature profile of respective shoulder diameters during the welding process is shown in figure 2.12.

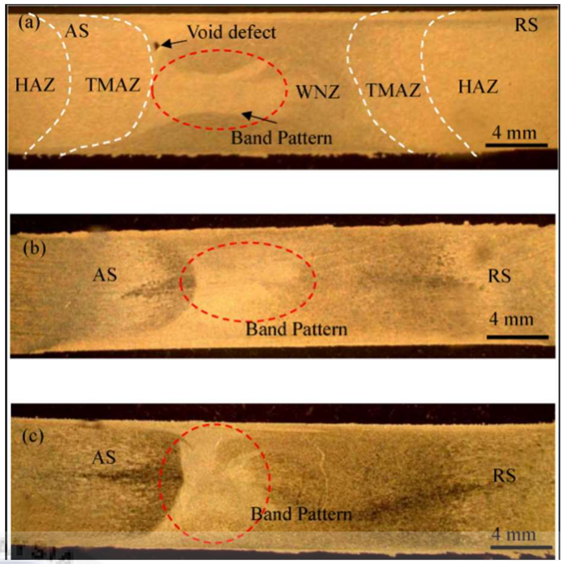

Figure 2.10 An optical macrograph of the cross-section of BTFSW sample welded with shoulder diameter (a) 20 mm (b) 22 mm (c) 24 mm (Fuse & Badheka, 2020).

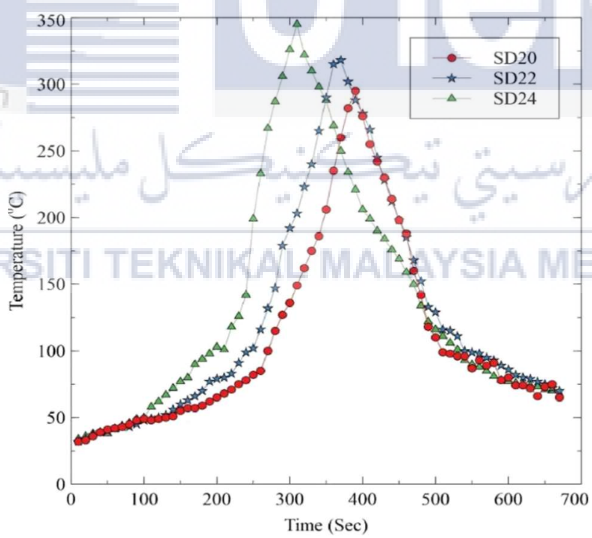

Fig. 2.11 Temperature profile generated with different shoulder diameter.(Fuse & Badheka, 2020).

2.8.3 Tool Rotational Speeds

The inappropriate combination of rotating and advancing velocities in bobbin friction stir welding can give rise to various types of defects. Deficiencies in the choice of these velocities can result in insufficient or excessive heat input, as well as abnormal stirring. Specifically, defects such as wormholes and tunnel defects tend to manifest on the advancing side of the weld due to inadequate heat input and improper material flow. Kissing bond and joint line remnant defects, on the other hand, occur when there are low rotating speeds and high advancing speeds. Incomplete stirring action and inadequate heat input cause the oxide layer to fracture, impeding the flow of plasticized material and resulting in the formation of joint line remnant defects (Dialami et al., 2020).

The rotational speed is a critical parameter in welding that significantly affects the material flow and heat generation, ultimately influencing the microstructures and mechanical properties of the joint. Based on a study conducted by F. F. Wang et al., 2015, It was observed that as the rotational speed increases, the heat input also increases, resulting in reduced material flow stress, torque, and gap force between the rotating tool and the workpieces. Conversely, at lower tool rotational speeds, the heat input decreases, therefore, exhibiting more material flow stress, increasing the torque and gap force during the welding process, the data of the study is presented in figure 2.13 (F. F. Wang et al., 2015b). At lower tool rotational speeds, tunnel defects as shown in figure 2.14 may manifest due to the reduced heat input, which results in inadequate material flow and mixing within the weld. As a consequence of this insufficient heat input, the material does not reach the required temperature for proper plastic deformation and intermixing, leading to the formation of tunnels or voids within the weld structure. These tunnels represent regions where the material did not flow and bond effectively, compromising the integrity and strength of the welded joint (W. Y. Li et al., 2014).

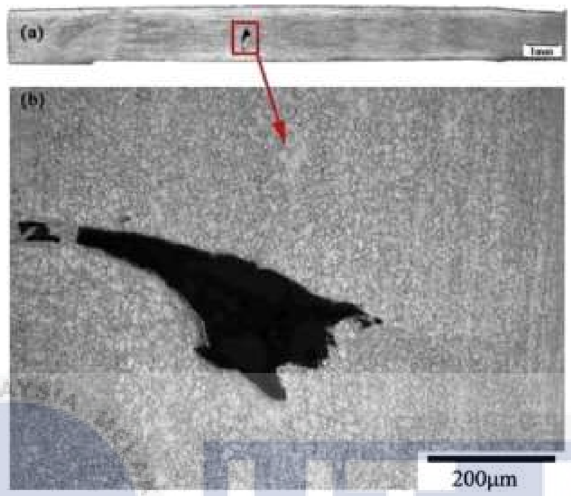

Figure 2.12 Tunnel defect in stir zone (W. Y. Li et al., 2014).

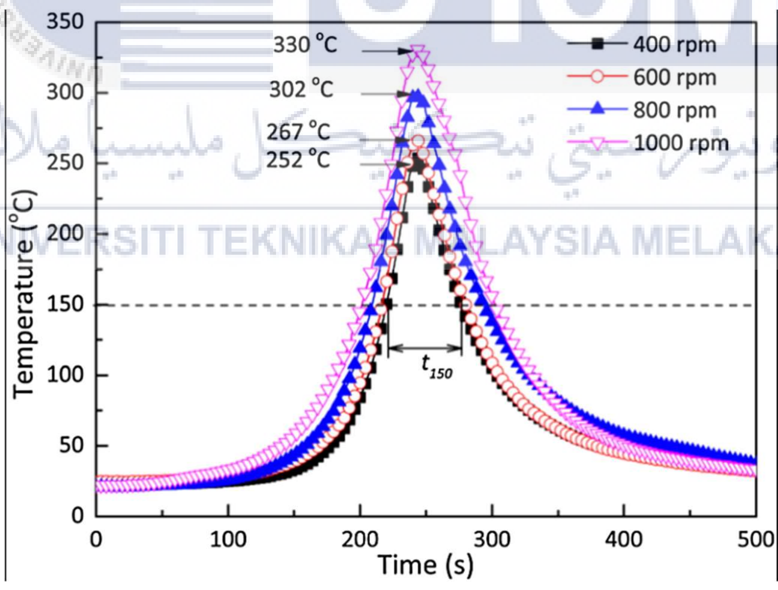

Figure 2.13 The welding thermal cycles of the joints produced with different rotational speeds (F. F. Wang et al., 2015) .

2.9 Aluminum Alloy 6 xxx series and 1xxx series

Aluminum is a one of the most highly abundant metal on earth hance it is the cheapest and most cost-effective type of metal used in most industries, unfortunately the base properties of aluminum is that it is highly ductile and soft, making it unsuitable for load bearing and structural applications. A method of overcoming this disadvantage of aluminum, is by alloying the base metal with a variety of alloying elements to achieve a desirable mechanical, chemical and physical properties, such as increased strain resistance, toughness, corrosion resistance (Kuruveri et al., 2022). Consequently, the excellent characteristics of aluminum alloys stimulated their development and research, due to their density to strength ratio, formability, corrosion resistance, impact resistance, toughness index, lightweight and impact resistance. As stated by Ebrahimi et al. (2023), aluminum alloys have achieved a weight reduction of 38% while exhibiting excellent specific strengths, therefore, integrating aluminum alloys into the transportation industry can enhance fuel efficiency and promote environmentally friendly modes of transportation. The incorporation of lightweight alloys in various vehicle applications, such as high-speed trains, automobiles, and airplanes, has emerged as an enduring and sustainable trend. This aligns with the increasing global awareness of environmental protection and the reduction of carbon dioxide emissions (G. Li et al., 2023).

Aluminum alloys combine various elements like Magnesium, Silicon, Copper, Iron, and Chromium to yield diverse properties. These alloys are classified into series, ranging from 1xxx to 8xxx, based on their compositions and unique characteristics. Series categorization helps organize aluminum alloys and determine their suitability for different applications. Each series exhibits specific traits like corrosion resistance, strength, formability, heat resistance, and electrical conductivity. This versatility makes aluminum alloys suitable for a wide range of industries. For example, the 1xxx series with pure aluminum excels in corrosion resistance and electrical conductivity, making it ideal for electrical transmission lines and packaging. The 6xxx series, containing Magnesium and Silicon, offers a balance of strength, formability, and weldability, making it popular in automotive, aerospace, and construction structural applications. Understanding the composition and series classification is vital for selecting the right aluminum alloy for specific needs. (Dubey et al., 2023; Kuruveri et al., 2022).

Additionally, mechanical, thermal, or thermo-mechanical treatments can be utilized to enhance the mechanical properties of aluminum alloys, resulting in improved characteristics compared to their base properties. In particular, the 6xxx series of aluminum alloys is often employed in either the T4 or T6 temper conditions. When in the T4 state, the alloy undergoes a solution treatment and naturally ages to attain a stable state without requiring cold work. On the other hand, the T6 state involves solution heat treatment followed by artificial aging, without any cold work, to achieve precipitation hardening. Through these specific heat treatments, the mechanical properties of aluminum alloys can be effectively modified. The T4 condition allows for the gradual precipitation of strengthening elements, leading to increased stability. Meanwhile, the T6 condition promotes the formation of strengthening phases through artificial aging, resulting in notable improvements in hardness, strength, and resistance to deformation. These tailored treatments offer significant advantages in various industries, including automotive and aerospace, where a balance between strength and formability is crucial. The 6xxx series alloys, commonly used in the T4 and T6 temper conditions, undergo specific heat treatments to achieve improved characteristics, ensuring their suitability for diverse applications and offering valuable benefits in terms of performance and reliability (Kuruveri et al., 2022). Table 2.2 shows the chemical composition and basic mechanical properties of the important 6xxx series aluminum alloys:

Table 2.2: Chemical composition and basic mechanical properties of important 6xxx series Al alloys. YS, UTS, and Elongation in 50 mm gauge.(Kuruveri et al., 2022)

Alloy type and temper	Composition (wt%)	Mechanical Properties
6005A – T6	Si: 0.6–0.9, Fe: 0.3–0.6, Cu: ≤ 0.1, Mn: ≤ 0.1, Mg: 0.4–0.6, Cr: ≤ 0.01, Zn ≤ 0.1, Ti ≤ 0.1 Al: balance	YS: 200 MPa, UTS: 250 MPa, Elong: 8%
6061 – T6	Si: 0.4–0.8, Fe: ≤ 0.7, Cu: 0.15–0.4, Mn: ≤ 0.15, Mg: 0.8–1.2, Cr: 0.04–0.35, Zn ≤ 0.25, Ti ≤ 0.15 Al: balance	YS: 276 MPa, UTS:310MPa, Elong: 12%
6063-T6	Si: 0.2–0.6, Fe: ≤ 0.35, Cu: ≤ 0.1, Mn: ≤ 0.1, Mg: 0.45–0.9, Cr: ≤ 0.10, Zn ≤ 0.15, Ti ≤ 0.1 Al: balance	YS: 214 MPa, UTS: 241 MPa, Elong: 12%
6082-T6	Si: 0.7–1.3, Fe: ≤ 0.5, Cu: ≤ 0.1, Mn: ≤ 0.4–1.0, Mg: 0.6–1.2, Cr: ≤ 0.25, Zn ≤ 0.2, Ti ≤ 0.1 Al: balance	YS: 260 MPa, UTS: 310 MPa, Elong: 10%

The options for joining some aluminum alloys are often restricted due to certain limitations. Fusion welding, for instance, is hindered by the unique properties of aluminum, such as low molten viscosity and the formation of an oxide layer, which result in cracking and inefficient fusion. Therefore, friction stir welding is considered the ideal method for joining aluminum alloys, as it effectively prevents excessive heat input and avoid the undesirable increase in hardness within the weld zone (Singh et al., 2020).

2.9.1 Aluminum Alloy 6061

The 6061 alloy is well-known for its capability to undergo precipitation hardening, which is achieved through the presence of intermetallic compounds like $CuAl_2$, Mg_2Si, and $MgZn_2$. This process enhances the durability, hardness, and strength of the alloy. Moreover, the 6061 alloy demonstrates favorable corrosion resistance properties, making it a reliable choice for structural applications. It finds widespread use in various industries, including vessels, aircraft components (such as fuselage and wings), bicycle frames, motorcycles, and more. By employing different processing methods or tempering techniques, it is possible to modify the mechanical properties of the alloy, including yield strength (YS), ultimate tensile strength (UTS), shear strength, and fatigue strength. The 6061 alloys are typically utilized in the T6 condition, which involves a process of solutionizing followed by precipitation hardening, further enhancing their mechanical properties**.** (Kuruveri et al., 2022)

2.9.2 Aluminum Alloy 1xxx

The aluminum alloy 1XXX series and are composed of commercially pure aluminum, boasting a minimum aluminum content of 99%. These alloy compositions are renowned for their remarkable feature of having incredibly low concentrations of additional elements. While predominantly composed of aluminum, any trace amounts of other elements found in these alloys are considered minor. One notable characteristic of the 1XXX series compositions is their relatively low strength, even when subjected to straining or hardening. However, they possess exceptional ductility and formability, enabling them to be easily worked or shaped. Moreover, the 1XXX alloys exhibit exceptionally high electrical conductivity and demonstrate remarkable resistance against various corrosive environments. As a result, they can be effectively joined together using a variety of commercially available processes (J. Gilbert Kaufman, 2000).

2.10 Mechanical Properties

The mechanical properties of bobbin friction stir welded joints are significantly influenced by the variation in microstructure. The unique characteristics and behaviour of the microstructure directly impact the strength, durability, and overall performance of these joints. This variation introduces different grain sizes, crystal orientations, and phases within the joint, which in turn affect its mechanical response under various loading conditions. It is crucial to understand and control the microstructural variation to achieve desirable mechanical properties and ensure the reliability of bobbin friction stir welded joints (G. H. Li et al., 2021).

During the friction stir welding process, the weld region can be divided into three distinct zones: the heat-affected zone, thermos-mechanically affected zone, and weld nugget zone. Each of these zones possesses unique properties compared to the parent metal. The microstructure and characteristics of these zones are highly dependent on dynamic recrystallization, which is closely associated with heat generation (Sued, 2015). The temperature field plays a crucial role in friction stir welding (FSW) as it not only governs the flow characteristics of the base material (BM), but also influences the changes in the microstructure across various weld regions. Moreover, these temperature variations have a direct impact on the mechanical properties exhibited by the joints formed during the welding process. Therefore, the temperature field in FSW holds significance not only in shaping the flow behaviour of the base material, but also in shaping the resulting microstructural properties and overall mechanical performance of the weld joints.

Bobbin friction stir welding generates higher heat compared to conventional friction stir welding, resulting in the formation of a much finer grain microstructure. (Khalid et al. 2022) conducted a study on a bobbin friction stirred magnesium welded alloy and found that higher tool rotational speeds (1600 RPM to 2000 RPM) exhibiting higher heat input, led to a finer grain microstructure in the welded regions. However, in terms of mechanical properties, the ultimate strength and yield strength of the welded regions were lower compared to the parent metal. Similar results were reported by G. Li et al. (2020), where the yield strength, ultimate strength, and elongation of bobbin friction stir welded joints were inferior to the parent metal, despite the presence of a finer grain microstructure in the welded regions.

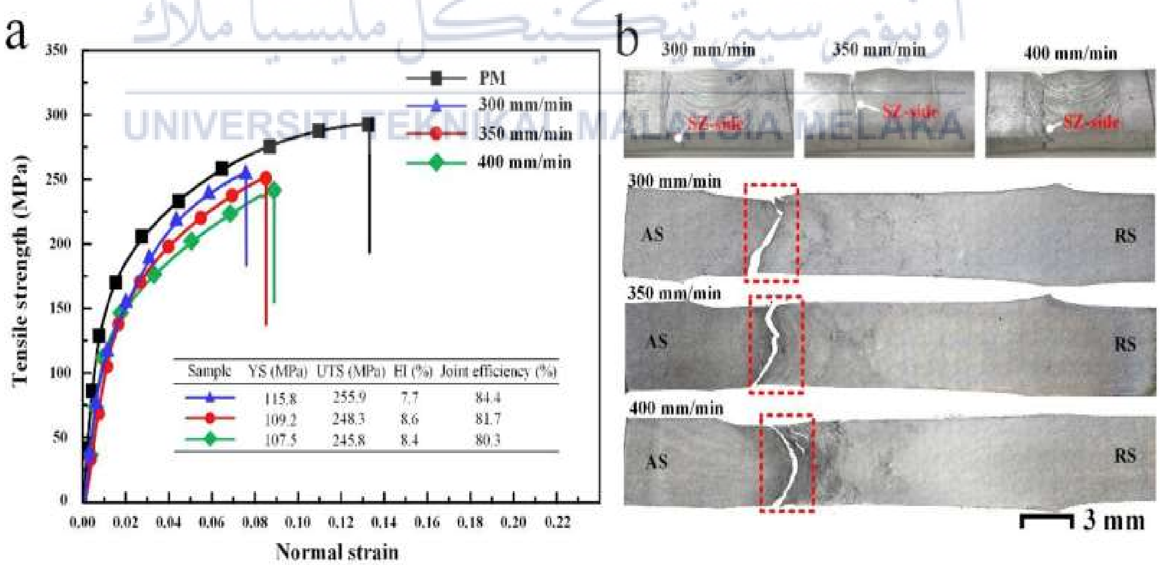

Figure 2.14 (a) Stress-strain curves along with (b) fracture locations of the BTFSW joints(G. Li et al., 2020).

Overall, the microstructural variation in bobbin friction stir welded joints plays a critical role in determining their mechanical properties. While a finer grain microstructure is often observed in these joints, it can result in a decrease in strength compared to the parent metal. Therefore, careful control and optimization of the welding parameters are necessary to achieve the desired mechanical properties and ensure the reliability of bobbin friction stir welded joints.(Khalid et al., 2022; G. Li et al., 2020)

2.12 Summary

This comprehensive study extensively investigates various aspects of Bobbin friction stir welding, including its fundamental principles, process parameters, tool design, and material considerations. By thoroughly examining these different elements, the aim of this research is to deepen our understanding of Bobbin friction stir welding and explore its potential applications.

The study specifically focuses on addressing the limitations associated with Bobbin friction stir welding, with an emphasis on the impact of camping rigidity during the friction welding process and its effects on the welded joint. By thoroughly investigating these limitations, the study provides valuable insights into ongoing research efforts and offers strategies for overcoming and improving this factor. This, in turn, enhances the understanding and applicability of Bobbin friction stir welding.

Moreover, this literature review not only contributes to the existing knowledge on Bobbin friction stir welding but also helps to bridge the research gaps in this field. It serves as a valuable resource for researchers and practitioners who are interested in exploring the potential of Bobbin friction stir welding, providing guidance and direction for current and future studies. The findings of this study are expected to lay a solid foundation for further advancements and developments in the field of bobbin friction stir welding, ultimately fostering progress in this area of research and application.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter will comprehensively address the methodology and procedures employed for conducting bobbin friction stir welding operations, as well as the subsequent vibrational testing, tensile testing, and metallography testing. The development of these methods and procedures is rooted in an extensive review of existing literature in the field. Moreover, the selection of controllable process parameters for this study is informed by the hypothesis formulated in the preceding chapter, ensuring a logical and coherent research approach.

3.2 Process Flow Chart

Figure 3.1 presents a comprehensive flow chart illustrating the sequential progression of the research study, offering a clear overview of the entire process leading to the accomplishment of the defined objectives. This visual representation serves to provide a visual roadmap, delineating the step-by-step progression and highlighting the key stages and activities involved in the successful completion of the research study.

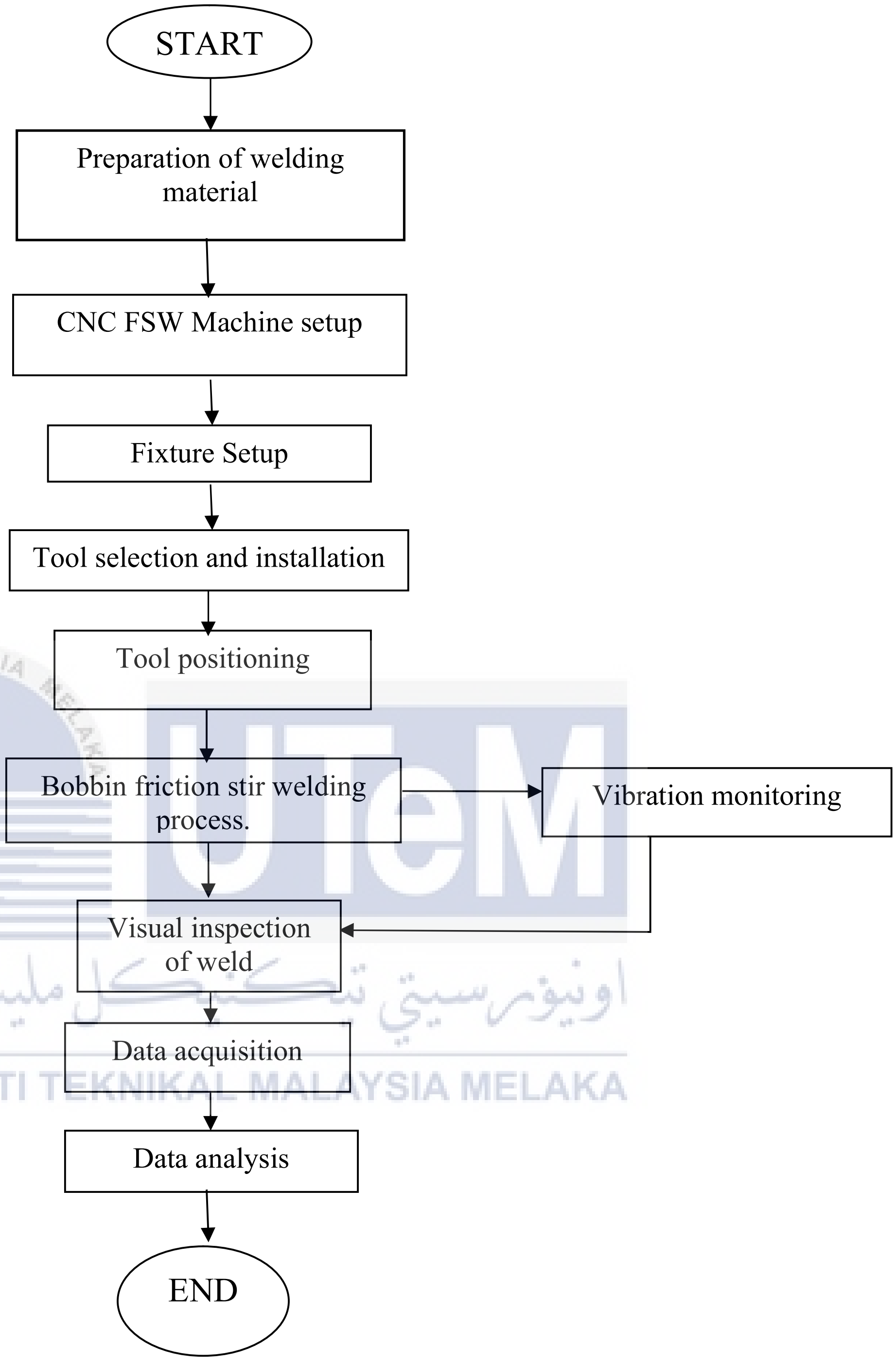

Figure 3.1 Process Flow chart

3.2 Material Preparation and Tool Selection

The material used for the bobbin friction stir welding process will be the aluminium alloy 6061 series. The surface of the aluminium must be cleaned off from impurities such as grease, dirt, dust or any forms of oxidation. The dimensions for each of the aluminium will be 200mm x 100mm x 6mm. Whereas, for the tool, 8mm diameter pin bobbin tool with 22mm shoulders will be selected for this experiment, in relation to a study conducted by Fuse & Badheka, 2020,Where the welding process was conducted on the same type of aluminium alloy, the AA 6061 series. Both the upper and lower shoulders have identical diameters. The shoulders are equipped with four spiral features on their surfaces. These spiral features facilitate the movement of plasticized material from the outer periphery of the tool towards the centre, where the pin is located. This arrangement helps prevent the formation of voids in the stir zone. The rotation speed and feed rate, along with other process parameters, remained constant throughout the experiment.

3.3 CNC Friction stir welding machine and bobbin tool setup.

The Computer Numerical Control Friction Stir welding machine manufactured by Ningbo Jinfeng Welding and Cutting Machinery Manufacture Co. ltd. The machine is the HMC1007-2D model, capable of welding aluminium or copper material with thickness ranging from 2mm to 6mm. The power supply voltage is 415V, 50 Hz frequency. After the tool selection for the welding process has been done, the tool will be installed and secured into the spindle chuck of the machine. Later, the machine will require to be calibrated, and the process parameters of the welding process will be keyed into the computer numerical control, where the tool positioning will be specified, welding speed will be set at 600 RPM and 800 RPM, the tool travel speeds will be varied at 100,150 and 250 mm/min and the tool path and rotation direction will be set. Once the parameters have been set, the welding process can be executed.

Figure 3.2 CNC Friction stir welding machine.

3.4 Vibration Analysis

Accelerometers measures the changes in velocity and converts them into electronic signals. The natural frequency of induced by the welding process of the aluminium alloy at differed clamping distances will be measured by fixing the accelerometer sensors at the welding material, the aluminium alloy. The electronic signals will be received by the Analog-to-digital converter (ACDs) to be recorded and analysed. Figure 3.4 shows the cDAQ-9171-NI used to obtain the signal and will be connected to the piezoelectric accelerometer, which will be placed on the weld material with a mild steel plate placed between the clamp and the material and at a minimum of 15mm from the weld path as the vibration is induced mainly on the welded material. The digital representation of the vibration signal will be captured using the graphical program, National Instruments Data

Acquisition (NI Daq). The data obtained from the NIDaq software will be in the form of time domain, also known as the acceleration time graph.

Once the vibration signal is obtained and recorded on the NIDaq software, the data will then be converted to a spreadsheet which will then be imported to MATLAB software for further analysis. Once the data, is imported, a Fast Fourier Transform (FFT) is then applied to the data to obtain the frequency domain representation. The FFT is employed to obtain the dominant frequency and its magnitude during the welding process.

Figure 3.3 cDAQ-9171-NI Analog-to-digital converter (ACDs).

Figure 3.4 Model 352C33 Piezoelectric Accelerometer.

3.3 Expected Results

This chapter outlined the processes to study the impacts of rigidity factor on Bobbin friction stir welding. By employing the welding process with varied tool rotational speeds and tool travel speeds with the utilization of the accelerometer to quantify and analyze the vibrational magnitudes of each test, the second objective can be achieved which was to measure the value of vibrational magnitude generated by different fixturing or clamping distances of weld material. Furthermore, this study delves deeper into the impact of vibration by considering both vibrational and temperature data. These data are essential for analyzing the characteristics of the grain microstructure of the welded material, which can be examined through metallurgical microscopy. Additionally, the mechanical properties of the welded joints, obtained through tensile testing, are also considered. By integrating vibrational and temperature data with the microstructural analysis and mechanical testing results, this study offers valuable insights into the intricate relationship between vibration, process parameters, and the resulting mechanical characteristics. The findings will contribute to the success of analyzing the effects of vibration towards the mechanical strength and hardness of the joint highlighted as the third objective of this study. By adopting these holistic approaches, which encompasses the analysis of vibrational and temperature data, along with metallurgical microscopy and mechanical testing, this study ensures a thorough exploration of the relationship between vibration, process parameters, and the resulting mechanical characteristic and achieves all the objectives of the research study.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Introduction

In this chapter will cover in detail the processes in analysing the vibrational signals obtained from the experiment and weld quality conditions based on the research study in Chapter 2. The data and analysis obtained from the experimentation will provide a guide to achieve the objectives of this research study. Additionally, this chapter will address the challenges encountered during the welding process, specifically the inability to achieve the fusion of the aluminium alloy. The factors contributing to this failure will be thoroughly discussed.

4.2 Welding parameters and Vibrational analysis

Vibration is considered the most crucial factor affecting the quality of the weld. During the experimentation process, the vibrational signals were acquired using the National Instruments Data Acquisition (DAQ) device. The piezoelectric accelerometer (PCB Model 352C33,20g, 100mVg sensitivity) was attached to the workpiece between two clamps to obtain the optimal vibration of the welding process shown in figure 4.1. The data acquisition (DAQ) module transforms analog signals received from the sensor into digital signals, enabling their utilization in decision-making processes. The capture of vibration was performed using the graphical program NI LabVIEW. The welding parameters were set at 400 RPM, 600 RPM and 800RPM with tool travel speeds at 200mm/min represented in table 4.1 welding parameters. The vibrational data that was collected will then be analyzed using MATLAB R2023A software to perform a Fast Fourier Transform analysis and obtain the acceleration time, velocity-time and frequency domain graphs.

Figure 4.1 experimental setup for data acquisition.

Table 4.1: Welding parameters

Tool Rotational speeds (RPM)	Tool Travel speeds (mm/min)	Aluminum Dimensions (mm)
600	100	120mm x 240mm x 6mm
800	150	120mm x 240mm x 6mm
800	250	120mm x 240mm x 6mm

4.2.1 Vibrational analysis and Fast Fourier Transform Results at 600 RPM

Figure 4.2 visually depicts the acceleration graphs derived from welding parameters of tool rotational speeds at 600 RPM and tool travel speeds of 150 mm/min. Employing MATLAB software, the obtained acceleration data underwent Fast Fourier Transform, facilitating the generation of an acceleration time graph and frequency domain representations for comprehensive insights, this is depicted in Figure 4.2 to Figure 4.3. Based on the acceleration time graph obtained , the maximum acceleration obtained was 10.487 m/s2 at 3.32 seconds , at the first 5 seconds of the welding process, it was observeed that an intense fluctuation was obtained , depicting the entry of the tool at the begining of the welding process . Susequently, as the tool travels further , at the 15 second mark, the amplitude of the graph starts to decrease, this indicates that the welding process starts to stablize.

For the frequency domain representation , the maximum frequency measured after conducting the fast fourier transform was at 79.87 Hz , the amplitude represents the strength of the signal , the most dominant signal from the graph was measured at 0.01 Hz , this represents the noise levels that are unwanted , the high amplitude depicts that the signal was most dominant. As for the 19.96 Hz signal , this depicts the moment a single tool rotation occured as the tool grips onto the material during the welding process.

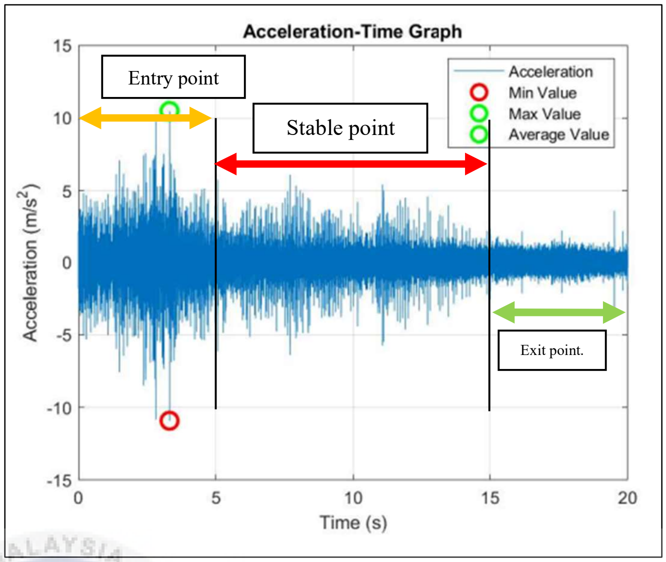

Figure 4.2 Acceleration time graph of 600 RPM and 150 mm/min welding parameter.

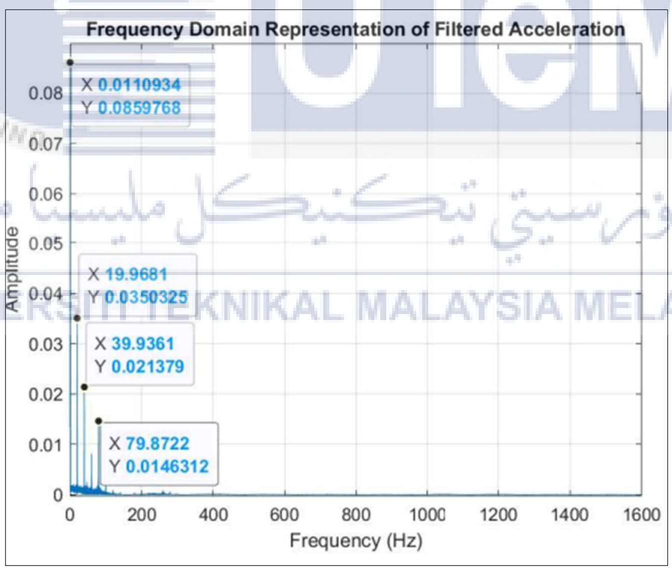

Figure 4.3 Frequency domain representation after the FFT of the 600 RPM and 150 mm/min welding parameter.

4.2.2 Vibrational analysis and Fast Fourier Transform at 800 RPM

For friction stir welding process at 800 RPM tool rotational speeds and 250 mm/min , a notable reduction in frequency magnitude and change of displacement was obtained. Figure 4.5 depicts the acceleration time graph of the welding process prior to the fast fourier transfrom analysis. The maximum acceleration recorded from the graph was 2.844 m/s^2 with the minimum acceleration of -3.334 m/s^2, a less intense vibration is recorded. As observed from the acceleration time graph, the characteristics of the acceleration time graph depicts that an increase in vibration occured at the 20th second point , during this period, the tool has travelled near the end of the workpeice approcahing the tool exit point.

Concerning the graph's frequency domain representation as shown in figure 4.5 Frequency domain representation after the FFT of the 800 RPM and 150 mm/min welding process. , it was observed that a frequency of 10 Hz predominates, indicating unwanted noise originating from the surroundings. Additionally, a frequency of 40 Hz was recorded as the highest within the frequency spectrum, exhibiting the maximum signal strength during the friction stir welding process. The highest frequency with with relevant magnitude recorded was at 129 Hz. Due to the higher rotational speeds of the welding process at 800rpm, the decrease in the rate of change of displacement, also known as the acceleration depicted in figure 4.4 is linked to the high temperature generation. With a higher temperature generation, the mateial will be more maleable, hence, lesser resistance occured during the welding process, thus, reulsting in a slight reduction observed in the acceleration time graph as compared to the vibration at 600rpm.

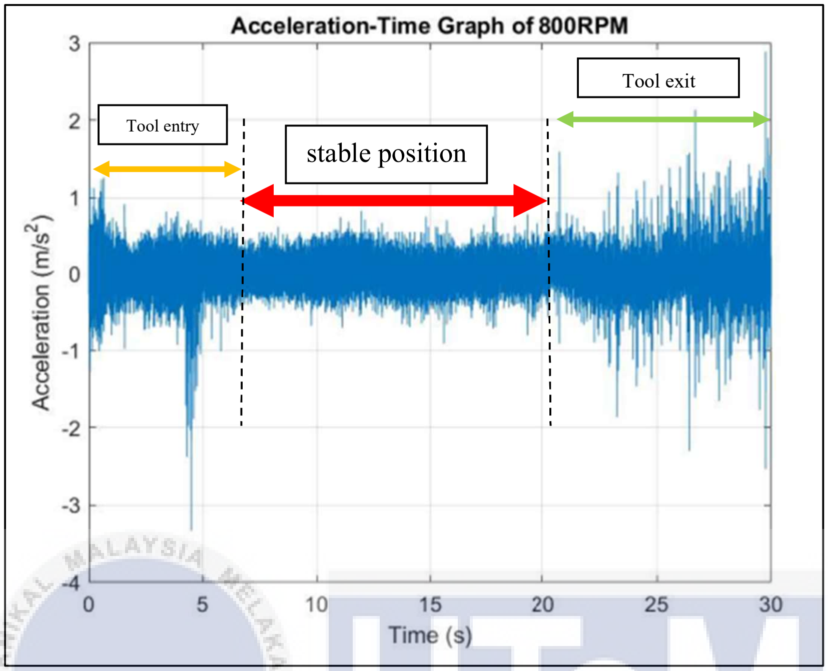

Figure 4.4 Acceleration time graph of the welding process at 800 RPM

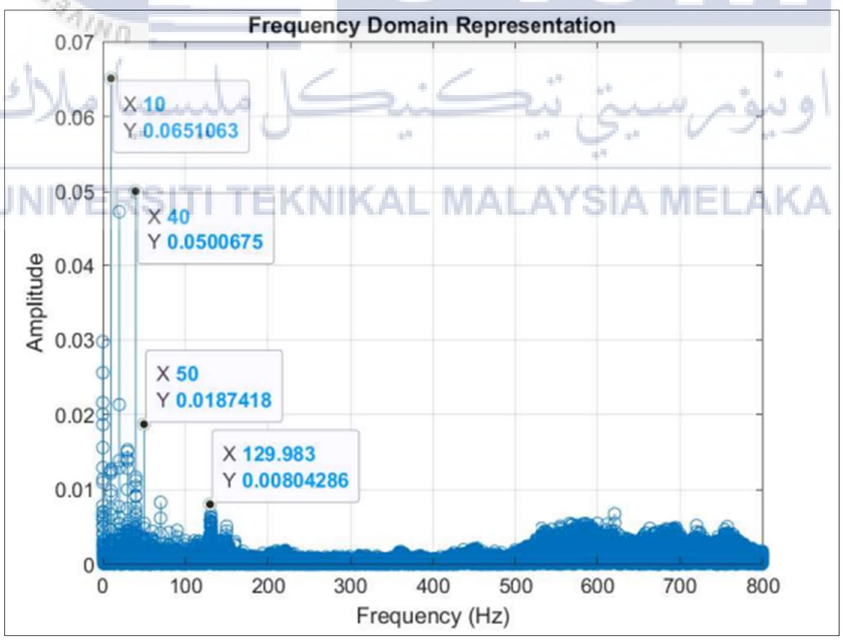

Figure 4.5 Frequency domain representation after the FFT of the 800 RPM and 150 mm/min welding process.

4.2.3 Vibration analysis of Tool Failure

During the experimentation, the too rotational speed was set at 800 RPM, this deliberate choice aimed to establish a standardized condition to ensure sufficient heat production, hence, metal fusion, ensuring a consistent foundation for the welding process. The total time taken for the welding process was at 51.5 seconds, during the at the peak of the tool stabilization, the tool failure occurred, where the base of the tool fractured and detached from the body of the bobbin tool.

The vibration characteristics illustrating the welding process, with tool rotational speeds set at 800 rpm and the occurrence of tool failure, are presented in the graphs below.

Figure 4.7 shows the acceleration time graph of the complete welding process. The minor peaks observed throughout the graphs are attributed to noise, which may be generated by the moving parts of the friction welding machine, external environmental factors inducing vibration, or minor external vibrations detected by the piezoelectric accelerometer. By applying a low pass filter to the graph with MATLAB software, to remove the unwanted noise, allowing a clearer representation of the underlying vibration patterns related to the welding process. A Fast Fourier Transform was then applied to convert the acceleration time graph, to velocity time graph and finally the frequency domain representation.

Figure 4.6 illustrates the acceleration-time graph during the initial 20 seconds of the welding process, corresponding to the tool entry phase. Notably, fluctuations are discernible in the graph before the stabilization process takes place. This period signifies the commencement of the tool's engagement with the aluminium, initiating the process of gripping and generating heat for the welding process. At this period, the highest magnitude measured was at 1.25 m/s^2 at 0.65 second and the lowest magnitude at -3.33 m/s^2 at 4.50

seconds. Passing the 5 second period, the graph starts to stabilize, where the tool starts to travel further to the middle section of the workpiece.

In the acceleration time graph of the complete welding process, prior to the tool failure, an increase in the magnitude of the acceleration is observed, this indicates that the tool is undergoing major stress as the tool starts to become more unstable, inducing high vibration. The highest peak recorded represents the moment the tool failed and snapped during the welding process. The maximum acceleration recorded was 28.57 m/s2 and minimum values of the acceleration recorded was -51.02 m/s2.

In contrast, illustrated in figure 4.8 of the velocity time graph, the highest recorded velocity reached 4.96 m/s, while its lowest point dipped to -0.005 m/s. The graphical representation of these velocity measurements vividly demonstrates a discernible escalation in imbalances throughout the welding process. Specifically, at the precise moment of tool failure, there was a remarkable surge in the magnitude of velocity where the maximum magnitude was recorded. This indicates a pivotal juncture in the welding operation, where the dynamics experienced a significant and abrupt change, as evidenced by the rapid and substantial increase in velocity magnitude.

Moreover, following the implementation of the Fast Fourier Transform on both the acceleration and velocity data, the vibrational data's frequency domain is revealed, as depicted in Figure 4.9. The maximum magnitude observed was 139 Hz, while the minimum frequency registered at 0.0055 Hz. The noteworthy occurrence of the recorded frequency, was at 40 Hz, signifies the prevalence and significance of this frequency signal within the dataset. This signal can be linked to every rotation the tool has completed.

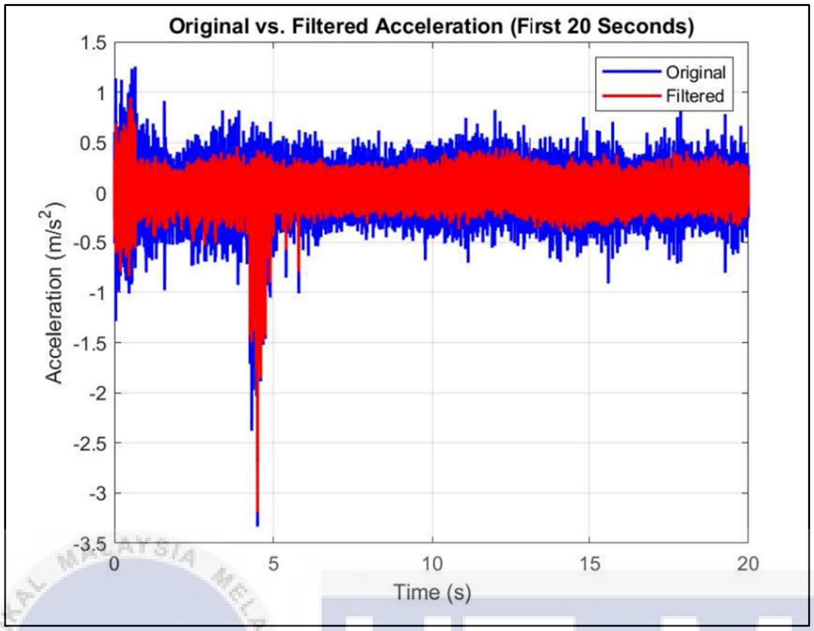

Figure 4.6: Filtered acceleration – time graph for the 20 seconds welding period.

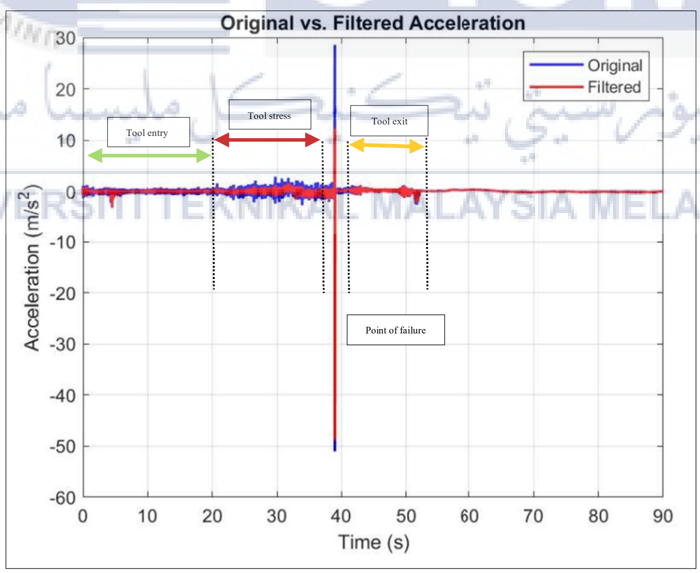

Figure 4.7: Maximum and minimum values of acceleration

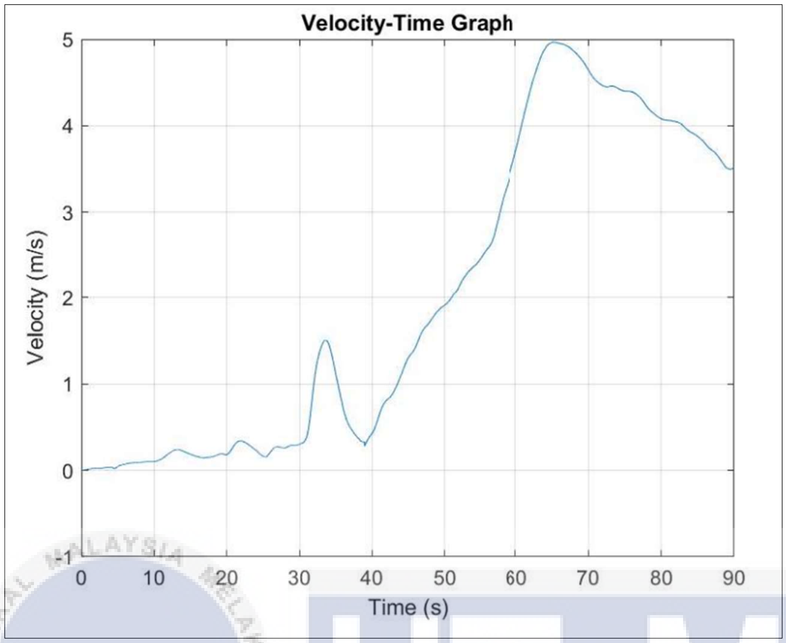

Figure 4.8: Velocity time graph

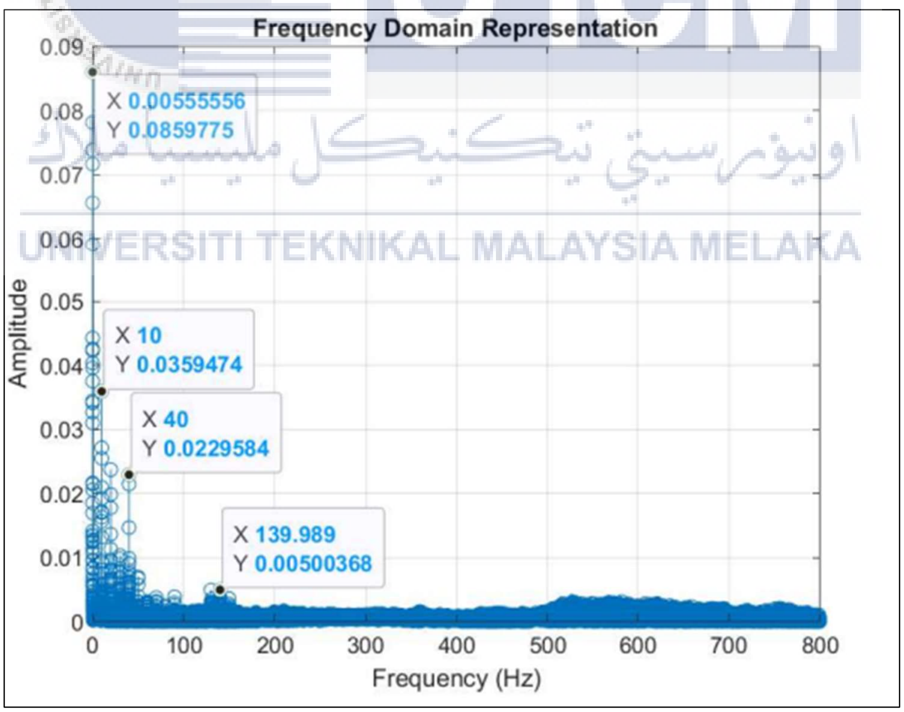

Figure 4.9: Frequency domain representation graph

4.3 Weld Defects

In the examination of the welded aluminum plate through the process of Friction Stir Welding, discernible defects emerge prominently, encompassing notable issues such as intense flashing and chipping that extend consistently along the entirety of the weld line. The crucial absence of fusion between the two plates becomes evident, primarily as a consequence of the pronounced intensity of vibration coupled with tool travel speeds set excessively high. This heightened vibrational force and rapid tool travel not only impede the seamless amalgamation of the plates but also result in a deficiency of the settlement of the material to fom a weld nugget, which is pivotal for the effective formation of weld nugget joints within the material.

4.3.1 Weld Defects at 600RPM

Figure 4.10 shows the defect of weld under the parameters of 600 RPM and 150 mm/min tool travel speeds. The developed length of the flash was 17 cm long on the ascending side of the tool, with a height of 0.35 cm. The flash exhibited a developed length of 17 cm along the ascending side of the tool, accompanied by a height of 0.35 cm. Notably, the flashing defect manifested itself 7 cm beyond the tool entry point, marking the initiation of heightened heat generation in the process. With a significant surge in heat generation, the material undergoes plastic deformation, accelerating the rate of material flow , due to the excessive rate of tool travel speeds and tool rotational speeds, outside the weld nugget zone, the material remains relatively cooler due to inefficient heat exposure. This temperature disparity leads to the collision of heated material with cooler sections, causing extrusion of the material from the weld zone. Consequently, plasticized material becomes evident outside the designated weld area forming the flashing defect.

Furthermore, the failure to form the weld nugget can be attributed to the combination of excessively high tool travel speeds, rapid tool rotational speed, and the generated vibrations during the welding process. This unfavorable synergy led to an excessive material flow that hindered the proper formation of the weld nugget. The intense motion and vibration disrupted the condition suitable for the metal fusion, causing a deficiency in the cohesive bonding of the materials and preventing the desired weld nugget from taking shape.

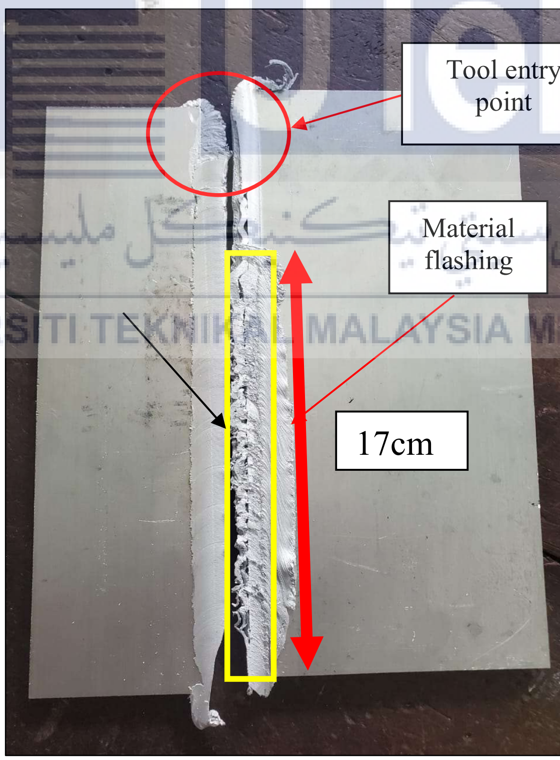

Figure 4.10 Welded aluminium plate at 600 RPM at 150mm/min.

Figure 4.11 Oposite side of aluminium plate

4.3.2 Weld Defects at 800RPM

Figure 4.12 illustrates the weld formation under the parameters of 800 RPM and at tool travel speeds of 150 mm/min, flashing defect was also formed on the weld joint, as compared to the aluminum alloy welded at 600RPM tool rotational speeds. A larger and longer flash defect was formed with void defects forming through the weld path. As elucidated by Liu et al. in 2022, void defects arise from insufficient material flow, primarily influenced by the pin of the bobbin tool. The deficient material flow creates voids, and this phenomenon is often linked to excessively high tool traverse speeds. In the observed case, the elevated tool speeds disrupted the equilibrium required for proper fusion between materials, impeding the formation of the crucial weld nugget zone.

The manifested flash in this scenario extended to a length of 21 cm with an average height of 0.9 cm. The enlarged flash formation was a consequence of the heightened heat generated due to the increased tool rotational speeds at 800 RPM. This contrasts with the aluminum alloy welded at 600 RPM, where the heat generated was characterized by non-uniform distribution throughout the weld joint. The irregular heat distribution, in turn, led to the plasticized material extrusion out of the weld zone, a phenomenon consistent with the challenges encountered in the welding process under excessive rotational speed conditions.

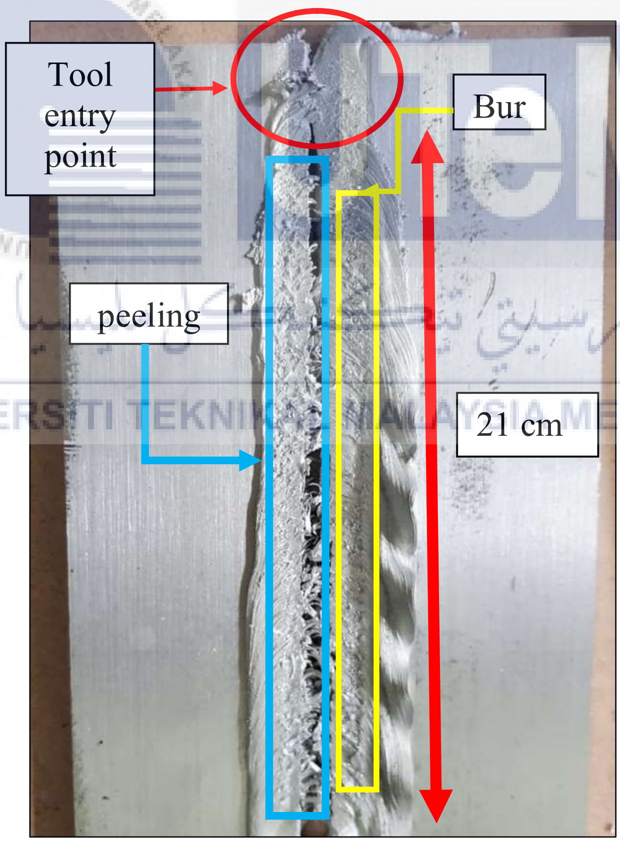

Figure 4.12 Welded aluminium plate at 800 RPM at 150mm/min

4.13 Opposite side of welded aluminium plate

4.3.3 Tool Failure at 800 RPM

In Figure 4.14, we observe an aluminum plate that underwent a noteworthy event of tool failure during the Bobbin Friction Stir Welding process. This specific occurrence of tool failure was induced deliberately, employing the welding parameters of 800 RPM tool rotational speeds and 250 mm/min tool travel speed. The deliberate introduction of these parameters aimed to scrutinize and comprehend the material's response failure and the formation of defects under conditions predisposed to tool under these conditions.

The chosen combination of 800 RPM tool rotational speeds and 250 mm/min tool travel speed serves as a deliberate stress test for the welding tool, pushing it to its limits to gauge the material's reaction and behavior under extreme conditions. As a result, from the welding of the material, the defect formed was also flashing of the material where the plasticized material that was exposed to the heat deposited excessive extrusion outside the weld line. The length of the flash formation as measured at 17.24 cm and the height of the flash was measured at 0.43 cm. Due to the excessive tool travel speeds, the material was exposed to insufficient heat, this caused more resistance towards the tool. Additionally, with the vibration generated, adding more force and stress towards the bobbin tool, causing the tool pin to fracture and detach from the main body of the bobbin tool.

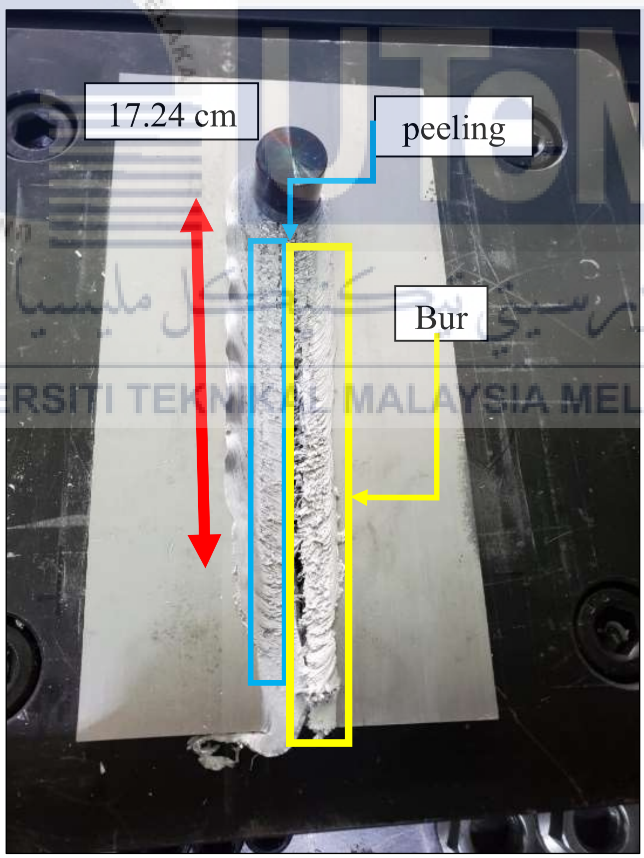

Figure 4.14 Failed fusion of aluminium alloy with tool failure.

4.15 Opposite side of welded aluminium plate.

4.4 Summary

It has been made clear the effects vibration has towards the weld quality in friction stir welding . The elevated rotational speeds were identified as a contributing factor, as they tend to elevate temperatures during the welding process. This, consequently, is associated with the unwarranted formation of flashing at the edge of the welding path. Additionally, the excessive vibrations experienced during the welding process played a pivotal role. These vibrations not only impacted the overall welding dynamics but also resulted in insufficient bonding throughout the weld joint. Recognizing the intricate interplay between rotational speeds, temperatures, vibrations, and bonding is essential for refining the welding process and ensuring a more consistent and reliable outcome.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

In conclusion, this study has provided valuable insights into the impact of vibration induced by varying parameters such as welding speed, tool travel speed, and fixture setups on weld quality and its associated characteristics. The primary objectives of the research have been successfully achieved, particularly in discerning the diverse magnitudes of vibration generated during welding under different parameters. The findings underscore the substantial influence that vibration exerts on the overall outcome of friction stir welding. The significance of the study lies in the identification of weld defects and the establishment of a clear connection between these defects and the vibration generated during the welding process. By systematically examining the interplay between welding parameters and the ensuing vibrations, this research contributes to a nuanced understanding of how these factors collectively shape the quality and integrity of friction stir welds.

The varied magnitudes of vibration observed across different welding conditions emphasize the need for meticulous parameter control to ensure optimal weld outcomes. This study not only advances our understanding of the complex dynamics involved in friction stir welding but also underscores the importance of considering and managing vibration as a critical factor in the pursuit of high-quality welds.

Moving forward, the insights gained from this study can serve as a foundation for refining welding protocols, enhancing process efficiency, and minimizing the occurrence of defects. The comprehensive analysis presented herein provides a valuable resource for researchers, practitioners, and industries seeking to optimize friction stir welding processes and achieve consistently superior results.

5.2 Recomendations

Within the scope of this study, several recommendations have been put forth to guide potential enhancements in the future. These suggestions, which aim to contribute to the continual improvement of the subject under investigation, are presented as valuable insights for further consideration and implementation in subsequent research endeavors:

i. Conduct welding with different clamping distances as a factor of vibration in the welding process.
ii. Monitor the temperature generation during the welding process in the presence of vibration to identify the effects it has towards the temperature generation.
iii. Conduct metallurgical testing , such as tensile testing and metalurgical microsopy to study the effects vibration has towards the strength and characteristics of the weld joint.
iv. Conduct more tests and employ the Taguchi method of optimization to obtain the most optimized welding parameters and factors suitable for a robust bobbin friction stir welding process and product.

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APPENDICES

APPENDIX A List of Chemical composition and basic mechanical properties of important 6xxx series Al alloys. YS, UTS, and Elongation in 50 mm gauge

Alloy type and temper	Composition (wt%)	Mechanical Properties
6005A – T6	Si: 0.6–0.9, Fe: 0.3–0.6, Cu: ≤ 0.1, Mn: ≤ 0.1, Mg: 0.4–0.6, Cr: ≤ 0.01, Zn ≤ 0.1, Ti ≤ 0.1 Al: balance	YS: 200 MPa, UTS: 250 MPa, Elong: 8%
6061 – T6	Si: 0.4–0.8, Fe: ≤ 0.7, Cu: 0.15–0.4, Mn: ≤ 0.15, Mg: 0.8–1.2, Cr: 0.04–0.35, Zn ≤ 0.25, Ti ≤ 0.15 Al: balance	YS: 276 MPa, UTS:310MPa, Elong: 12%
6063-T6	Si: 0.2–0.6, Fe: ≤ 0.35, Cu: ≤ 0.1, Mn: ≤ 0.1, Mg: 0.45–0.9, Cr: ≤ 0.10, Zn ≤ 0.15, Ti ≤ 0.1 Al: balance	YS: 214 MPa, UTS: 241 MPa, Elong: 12%
6082-T6	Si: 0.7–1.3, Fe: ≤ 0.5, Cu: ≤ 0.1, Mn: ≤ 0.4–1.0, Mg: 0.6–1.2, Cr: ≤ 0.25, Zn ≤ 0.2, Ti ≤ 0.1 Al: balance	YS: 260 MPa, UTS: 310 MPa, Elong: 10%

APENDIX B MATLAB Command for Fast Fourier Transform.

```
Command Window
>> % Assuming you have acceleration-time data stored in a vector 'acceleration'
% and a corresponding time vector 'time'

% Plot the acceleration-time graph
figure;
plot(time, acceleration);
title('Acceleration-Time Graph');
xlabel('Time (s)');
ylabel('Acceleration (m/s^2)');
>> grid on
>>
```

```
Command Window
acceleration_range = acceleration(indices);
time_range = time(indices);

% Perform FFT on acceleration data in the specified range
fft_result_range = fft(acceleration_range);
fs = 1600;
frequencies_range = linspace(0, fs/2, length(fft_result_range)/2 + 1);

% Limit frequencies to 800 Hz
capped_frequency_indices = frequencies_range <= 800;
capped_frequencies = frequencies_range(capped_frequency_indices);

% Plot the frequency content using a stem graph for better visualization
figure;
stem(capped_frequencies, 2*abs(fft_result_range(capped_frequency_indices))/length(acceleration_range));
title('Frequency Content of Acceleration Data (0 to 30 seconds)');
xlabel('Frequency (Hz)');
ylabel('Amplitude');

% Calculate maximum, minimum, and average frequencies and magnitudes
[max_magnitude, max_index] = max(2*abs(fft_result_range(capped_frequency_indices))/length(acceleration_range)
min_magnitude = min(2*abs(fft_result_range(capped_frequency_indices))/length(acceleration_range));
average_magnitude = mean(2*abs(fft_result_range(capped_frequency_indices))/length(acceleration_range));
max_frequency = capped_frequencies(max_index);

% Display the calculated values
fprintf('Maximum Frequency: %.2f Hz\n', max_frequency);
fprintf('Maximum Frequency Magnitude: %.4f\n', max_magnitude);
fprintf('Minimum Frequency Magnitude: %.4f\n', min_magnitude);
fprintf('Average Frequency Magnitude: %.4f\n', average_magnitude);
Maximum Frequency: 10.00 Hz
Maximum Frequency Magnitude: 0.0651
Minimum Frequency Magnitude: 0.0000
Average Frequency Magnitude: 0.0009
```

```
>> % Assuming you have acceleration-time data stored in a vector 'acceleration'
% and a corresponding time vector 'time' with a sampling rate of 1600 Hz

% Perform FFT on acceleration data
fft_result = fft(acceleration);

% Calculate corresponding frequencies
fs = 1600;
frequencies = linspace(0, fs/2, length(fft_result)/2 + 1);

% Plot the frequency content using a stem graph for better visualization
figure;
stem(frequencies, 2*abs(fft_result(1:length(frequencies)))/length(acceleration));
title('Frequency Content of Acceleration Data');
xlabel('Frequency (Hz)');
ylabel('Amplitude');

% Limit the plot to 800 Hz
xlim([0 800]);
>> grid on
>>
```