# TRIBOLOGICAL STUDY OF ADDITIVE MANUFACTURED ALUMINIUM ALLOY ER5356 FOR POTENTIAL PART REPAIR

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**UNIVERSITI SAINS MALAYSIA**

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## DECLARATION

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

Signed………..……… ……………… (Siti Syairah binti Mohd Noor Ariffin)

Date: 24/7/2022

STATEMENT 1 This thesis is the result of my own investigations, except where otherwise stated. Other sources are acknowledged by giving explicit references. Bibliography/references are appended.

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## LIST OF SYMBOLS

| | |
|---|---|
| $^{o}C$ | Temperature |
| kg | Mass |
| $mm^3$ | Wear volume loss |
| $mm^3/Nm$ | Wear rate |
| MPa | Pressure |
| N | Force |

# LIST OF ABBREVIATIONS

| | |
|---|---|
| AA | Aluminium Alloy |
| AFM | Atomic Force Microscopy |
| AM | Additive Manufacturing |
| ASTM | American Society for Testing and Materials |
| COF | Coefficient of Friction |
| DED | Detailed Engineering Design |
| DF | Degree of Freedom |
| DOE | Design of Experiment |
| EDS | Energy Dispersive X-Ray Spectroscopy |
| ER | Electrode Rod |
| GMAW | Gas Metal Arc Welding |
| GTAW | Gas Tungsten Arc Welding |
| HAZ | Heat Affected Zone |
| MIG | Metal Inert Gas |
| OA | Orthogonal Array |
| PAW | Plasma Arc Welding |
| SEM | Scanning Electron Microscopy |
| S/N | Signal-to-Noise |
| SS | Sum of Squares |
| TIG | Tungsten Inert Gas |
| UTS | Ultimate Tensile Strength |
| USM | Universiti Sains Malaysia |
| WAAM | Wire Arc Additive Manufacturing |

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## ABSTRAK

Aluminium digunakan secara meluas dalam pelbagai bahagian automotif kerana nisbah kekuatan kepada beratnya yang tinggi. Malangnya, rintangan untuk hausnya agak rendah, mengakibatkan sebahagian hayatnya pendek apabila digunakan kerana sentuhan gelongsor. Sebagai alternatif bahagian yang tidak dipasang kerana haus teruk yang kini dihantar ke tapak pelupusan, mempunyai peluang kedua untuk diservis melalui pembinaan semula kawasan haus menggunakan kaedah pembuatan bahan tambahan logam. Walau bagaimanapun, sifat bahan termendap perlu dikaji sebelum ia sesuai untuk digunakan semula. Kajian ini bertujuan untuk menyiasat prestasi aloi aluminium perkilangan aditif pada sifat tribologi seperti kadar haus dan pekali geseran. Percubaan ini menganggap spesimen penempaan sejuk dan tidak tempa ER5356 menggunakan susunan bola atas rata salingan dengan kelajuan 30RPM, 50RPM dan 70RPM dengan beban berbeza 1KG, 3KG dan 5KG. Hasilnya mendapati spesimen tempaan sejuk yang dikimpal menunjukkan nilai pekali geseran (COF) dan kadar haus yang lebih rendah. Untuk kekerasan sampel penempaan sejuk menunjukkan nilai yang paling tinggi berbanding keadaan yang lain. Keputusan eksperimen dibandingkan dan ia telah diperhatikan persetujuan yang baik. Berdasarkan penemuan awal, bahan perkilangan aditif menghasilkan kadar haus yang lebih rendah berbanding bahan yang tidak dikimpal, tetapi bagi pekali geseran adalah hampir sama.

# ABSTRACT

Aluminum alloys are widely used in a range of automotive parts due to their high strength-to-weight ratio. Unfortunately, it's resistance to wear is relatively low, result in short part life upon application due to sliding contact. As an alternative unfitted part due to severe worn which is currently send to landfill, has second chance to service via reconstruction of the worn area using metal additive manufacturing method. However, the properties of deposited material need to be studied before it fit to be reused. The study intent to investigate the performance of additive manufactured aluminium alloy on tribology properties like wear rate ($mm^3/Nm$) and coefficient of friction. This experiment considers cold forging and unforging specimen ER5356 utilising a reciprocating ball-on-flat arrangement with a speed of 30RPM, 50RPM and 70RPM with different load of 1KG, 3KG and 5KG. The result found that the welded specimen of cold forging indicated lower value of coefficient of friction (COF) and wear rate ($mm^3/Nm$). For the hardness of cold forging samples shows that the highest value compared to others condition. The results of the experiment are compared and it has been observed good agreement. Based on the initial findings, the additive manufactured material result in less wear rate ($mm^3/Nm$) compared to material that non-weld, but for the coefficient of friction is almost same.

# CHAPTER 1

# INTRODUCTION

## 1.1 Overview

Wear has been a topic of practical concern for at least a thousand years, although it has received little theoretical consideration. The prevalent belief is that it is easier to replace the part as it wears rather than to ensure appropriate life in design. This may have been true in the past, but in today's economic context, it is an extremely expensive practise for the following reasons:

- Maintenance is costly. It is not only the expense of the item and its replacement, but also the fact that maintenance workers must be present at all times, ready to perform maintenance tasks.
- Materials and parts are in short supply. As a result, equipment is out of service for longer periods of time, or greater stocks must be kept.
- Worn parts contribute to secondary issues such as increased vibration (which causes fatigue), stress loading, misalignment, and accelerated wear.
- Downtime for part replacement due to wear results in a loss of production and personnel.

Because of more effective cost accounting, the industry has just begun to recognise the need of wear management, and new information is being sought to allow proper wear designs. The use of hardness as a material quality to determine wear resistance is well established, and this relationship was strengthened with the wear rate ($mm^3$/Nm) models. Surface roughness is a critical issue throughout the manufacturing process and has a significant impact on product quality. The roughness that is inherent in the friction process is one of the components that impact the age of surfaces. To comprehend the roughness as well as the coefficient of wear, it is necessary to understand how sliding impacts the surface roughness through interactions between surfaces and causes deformation, which causes economic damage (Al-Samarai et al., 2012).

Additive manufacturing (AM) is a promising process that enables for the layer-by-layer fabrication of large, complicated geometric, and completely dense metal structures. AM has a considerable advantage over traditional manufacturing and has the potential to alter a variety of industrial applications (Attaran, 2017). The traditional production approach frequently needed a significant amount of machining and cannot fulfil the ever-increasing demands. The desire to automate machine movement, decrease waste material, reduce energy consumption, and increase material efficiency drives the use of additive manufacturing (Muller et al., 2019). Aside from that, AM's potential to generate three-dimensional and free form components layer by layer is a primary driving force for breakthroughs (Rodrigues et al., 2019). Both academics and industry are now interested in the potential of WAAM due to its ability to minimise costs and material waste while also reducing lead times. WAAM generates energy from an electric arc and feedstock from solid wire. It uses gas metal arc welding (GMAW), gas tungsten arc welding (GTAW), or plasma arc welding (PAW). The benefit comes from its capacity to construct neat-net shapes and much greater deposition rates. The automotive and aerospace industries are two of the driving forces behind the usage of WAAM in lightweight construction with titanium or aluminium alloy as a filler material (Gu et al., 2014).

## 1.2 Recycle, remanufacture and repair approach.

AM may be used to not only produce new high-value customised end-use items in small quantities (Despeisse et al., 2017), but also to improve their durability through redesign, and/or (ii) upgrade or repair and remanufacture damaged products, either in-situ or through the creation of replacement parts on demand (Sauerwein et al., 2019). Remanufacturing, refurbishing, and re-pairing are restorative techniques that restore damaged parts into usable ones in order to increase a product's quality (Leino et al., 2016). Because these products, components, and materials are targeted at preserving a product's usability and value over its entire lifecycle, they play a significant role in the implementation of the circular economy in the industrial environment.

The main advantages of WAAM include the ability to create massive components, up to a few metres, at a very fast deposition rate, which may exceed 10 kg per hour when employing materials such as steel, aluminium, titanium, and others (Williams et al., 2016). The fundamental disadvantage of WAAM is that the produced surfaces have a significant degree of waviness, requiring machining procedures following the deposition process to attain the requisite surface finish. For repair operations, this is not an issue because machining is always necessary to restore worn functional surfaces. WAAM also makes it possible for such a technology to be quickly integrated with current processes and machines, resulting in a hybrid additive-subtractive process that has the potential to significantly improve the productivity of a repair operation due to reduced change-over times and the ability to repair complex parts in a streamlined way (Pragana et al., 2021). Furthermore, a new repair technique that takes advantage of both processes (additive and subtractive) and overcomes their limitations, such as the poor surface finishing associated with AM or the inability to implement high complexity features in conventional machining procedures, is being developed (Bennett et al., 2019).

Various types of grooves, such as circular truncated cones (Liu et al., 2014), V-shaped grooves (Branza et al., 2009), and U-shaped grooves, have been studied in metal component restoration research projects (Graf et al., 2012). There is presently no agreement in the literature on the optimum type of concave groove due to the potential geometric variety of components to be repaired and the complexity of possible defects (e.g., shape, geometry). For the purpose of simplicity, the study in this article is based on the following assumptions. To begin, a rectangular foundation form is appropriate for setting down weld beads. The machining procedures can also shape the groove into a pyramidal frustum with two rectangular bases. Three statements can be derived from these assumptions. On a smooth surface of a part, morphological defects should develop. The groove's two bases should ideally be parallel. After then, each layer sliced from the groove can have the same thickness. It's important to note that the offered assumptions are based on a technical simplification in order to investigate the fundamentals, rather than a theoretical or methodological limitation. Technical solutions based on these assumptions are transferrable and can be used as a foundation for more sophisticated applications.

## 1.3 Problem Statement

WAAM, one of the AM techniques, which is one of the advantages are to rebuild a 3D profile with high flexibility in terms of shapes complexity. However, due to heat during welding, properties of the material like wear resistance and hardness may be affected. Cold deformation is one of the methods to improve those properties via mechanical compression. Therefore, study is needed to investigate the effect.

## 1.4 Objectives

This experiment aims:

- To study the wear rate ($mm^3$/Nm) of the additive manufactured aluminium using ball on flat wear test.
- To investigate the effect of cold forging on tribology properties like wear rate ($mm^3$/Nm) and coefficient of friction.
- To optimize of the tribological parameters (sliding speed, load and condition of specimen) using Taguchi method.

## 1.5 Scope of Work

This study is based on ASTM-G133-05 linearly reciprocating ball-on-flat sliding wear, this experiment method covers laboratory procedures for evaluating the sliding wear of materials. Moreover, the wear study is focus on aluminium material only as the material is commonly applied in the automotive industries due to its properties and advantages. Rockwell hardness testing machine used to investigate the hardness number of different composition of ER 5356 and aluminium 5083-H112 alloy and dry sliding wear tests have been carried out using different loads and at different sliding speed. Moreover, the welding wire was 0.8 mm and the shielding gas was 99.9% argon were running at same filler speed of 7 and travel speed of 70.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Overview on wire arc additive manufacturing

Many researchers like Ford, (2016) and Thompson et al., (2016), have indicated that additive manufacturing (AM) will play significant role in the future manufacturing industry. AM is gaining popularity due to its multiple advantages, which include the ability to handle a wide range of materials, including metals, polymers, and ceramics, as well as the ability to make innovative, complex, and near net form parts without the need for further tooling or re-fixturing. The wire arc additive manufacturing (WAAM) approach, which is considered a derivation of the AM process, incorporates some of the most prominent properties of arc welding to implement additive manufacturing (AM) and outperforms conventional joining procedures. WAAM constructs a flat surface by depositing weld beads, creating in a metallic wall with a minimum width of 1–2 mm (Ding et al., 2011). Similar to cladding, the wire feedstock is deposited in layers over a substrate, which may be part of the finished structure or removed during the machining process. MIG, TIG, or plasma arc welding are the welding technologies that may be used in WAAM, as shown in Figure 2.1 researched by Rios et al., (2019) and Zhang et al., (2018). The WAAM process is automated and consists of a series of processes for acquiring the appropriate construction characteristics. High deposition rates, the ability to fabricate larger geometries, compatibility with various arc heat sources, and weld torch motions and alignments are all characteristics of WAAM (Bekker et al., 2016) and (Michel et al., 2019). Nonetheless, residual stress and deformation are seen in WAAM samples, which are similar to those produced during additive manufacturing (AM) or welding. WAAM research might contribute to the development of new design methodologies aimed at extending the functional material grading process feasibility and component manufacture with integrated elements to give accurate control and automation, controlled mechanisms, parametric optimization with in-situ monitoring, and non-destructive testing can all be utilized. Ti and Al alloys are used as filler materials in lightweight construction, whereas steel is used as the base material for pipe couplings and flanges, nodal joints, and beam reinforcements are just a few of the design possibilities that may be studied and applied using WAAM.

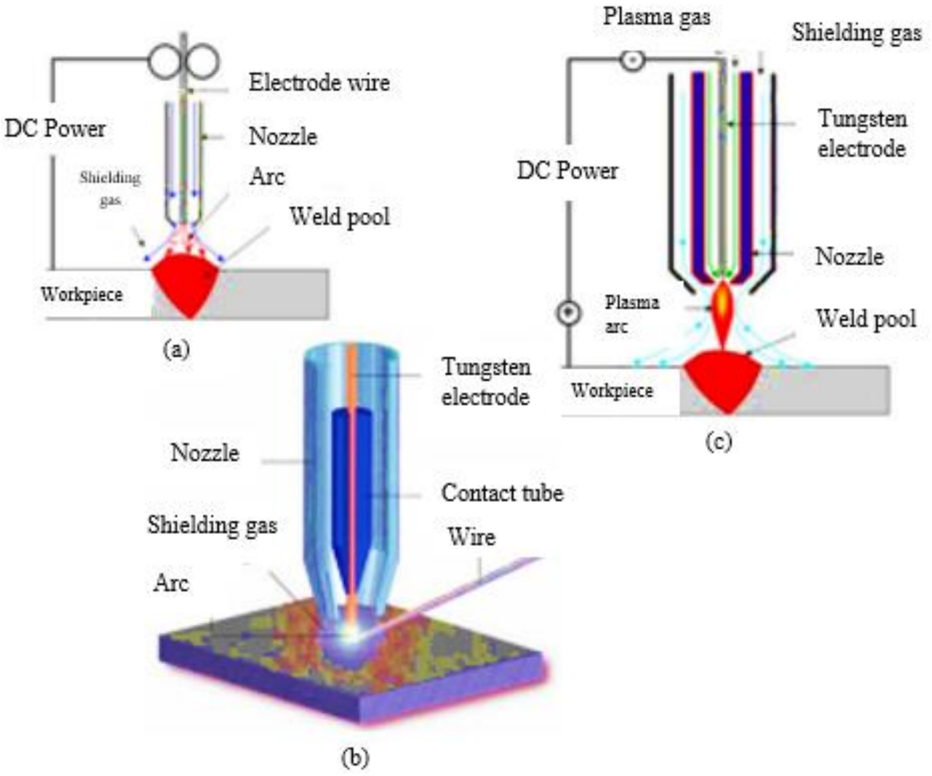


Figure 2.1: Wire Arc Additive Manufacturing. Principle of WAAM with: (a) MIG; (b) TIG; (c) Plasma Arc Welding.

WAAM is also recommended since it requires the fewest resources and energy. All of these favourable characteristics contribute to WAAM's suitability for use in the aerospace, aviation, car, and medical sectors. In addition, the fast deposition rate results in reduced resolution and a wavy surface finish. Working with WAAM requires caution and preparation due to the high heat input, which limits the materials available. Material characterisation and testing, using suitable inquiry methodologies (Zhang et al., 2013). To improve the efficiency of the process and the quality of the components fabricated by WAAM, make it easier to choose the best parameter range. Furthermore, residual stresses and deformation in the structures must be reduced by a well-designed monitoring and control system. Preheating, lowering the heat input, and raising the welding speed all help to reduce residual stresses (Cunningham et al., 2018). Thick substrates are thought to cause more stress at the substrate-deposit contact.

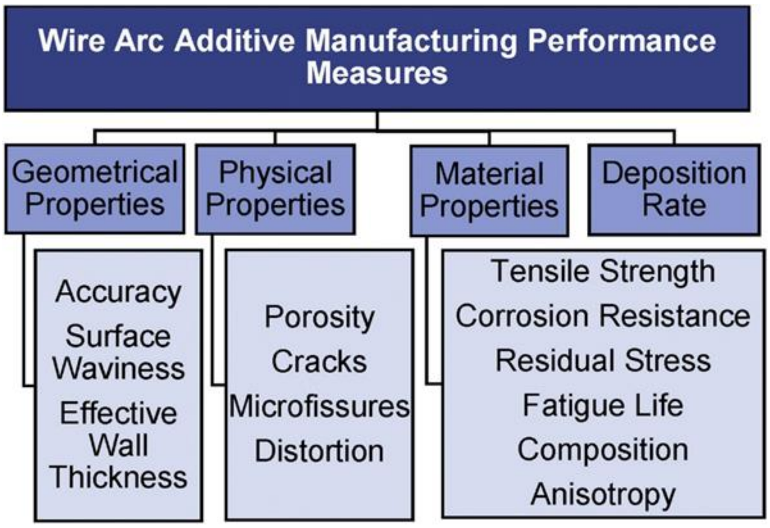


Figure 2.2: Performance measures in WAAM.

As illustrated in Figure 2.2, the materials processing issues in WAAM relate to the accomplishment of performance criteria linked to geometric, physical, and material qualities, with numerous instances of possible needs offered. The method's deposition rate is critical to WAAM's commercial adoption as a high-deposition-rate DED technology. As a result, this is the last performance measure against which the aforementioned performance measures must be maintained. Despite the fact that the mechanical qualities of WAAM-fabricated components are often equal to those of their conventionally processed counterparts, there are several AM processing flaws that must be addressed for important applications. Components that are usually exposed in extreme environment must avoid porosity, cracking and excessive residual stress level. This can contribute to failure modes such as temperature fatigue. Poor programming approach, unstable weld pool dynamics due to poor parameter setup, thermal deformation associated with heat deposition researched by Wu et al., (2017), external impact (such as gas pollution), and other machine failures can all cause defects in WAAM.

## 2.2 Effect of cold forging to material properties

Forging is a manufacturing method that involves shaping metal using concentrated compressive stresses to produce high-quality, robust products under temperature-controlled circumstances. It is classified as hot, warm, or cold according on the temperature at which the forging process is carried out. Cold forging, which takes place at room temperature, provides a number of advantages, including superior forged component mechanical qualities, little material waste, and the ability to forge net shape or near net shape products, among others. Cold forging tools, on the other hand, are subjected to abrasive wear and extremely high mechanical stresses, resulting in surface pressures of up to 3000 MPa due to high flow stress in billet material at room temperature (Geiger et al., 2008) and (Ku et al., 2014). Wear and fatigue restrict the life of tools used in the cold forging process (Geiger et al., 2001). Mechanical fatigue is thought to be responsible for about 80% of all service failures, whether due to cyclic plasticity, sliding or physical contact (fretting and rolling contact fatigue), environmental deterioration (corrosion fatigue), or high temperature (creep fatigue) (Ritchie, 1999). Because tool expenses account for a significant amount of overall production costs in cold forging, it is critical to extend tool life using a variety of methods, including design, material, surface treatment, and so on. Fatigue is defined as a gradual, localised, permanent structural change in materials subjected to fluctuating loads and strains, which can lead to fractures or fracture after a significant number of variations. The combined action of cyclic stress, tensile tension, and plastic strain causes fatigue fractures. Fatigue cracking will not begin or propagate if any of these three factors are missing. Certain parameters, such as surface topography and residual stress, have been found to be crucial in influencing fatigue behaviour. The stresses that persist within a body in the absence of external loading or temperature gradients are known as residual stress. The beginning and growth phases of the fatigue process are known to be accelerated by near-surface tensile residual stresses, whereas compressive residual stress near a surface increases fatigue life (Casavola et al., 2012). Furthermore, surface roughness is the most affecting element in the short life regime, and fatigue life decreases as roughness increases (Alang et al., 2011).

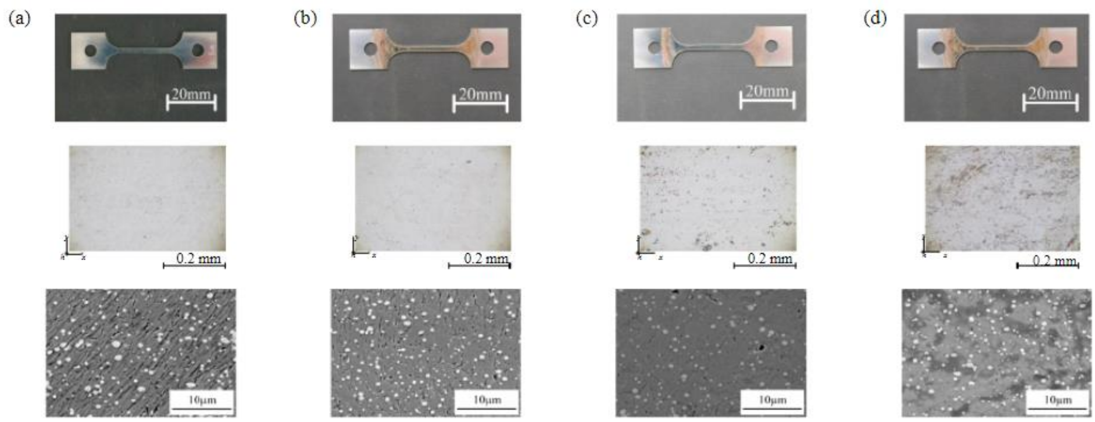


Figure 2.3: Full image, optical microscope image (x20) and SEM image of specimens (x3000); (a) unforged; (b) forged-150kN (contact pressure: 750 MPa); (c) forged-300 kN (contact pressure: 1500 MPa); (d) forged-450kN (contact pressure: 2250 MPa) (Nuwan et al., 2018).

The peaks of the surface were plastically deformed and the peak height was lowered as a result of the applied pressure, resulting in a flat surface. This is why, when the contact pressure was increased, the surface roughness of the specimen surface reduced. The carbide content of the material may be seen as white spots. The oxide layer is identified by the light ash colour in the SEM picture of a specimen as shown in Figure 2.3 exposed to 2250 MPa contact pressure. Due to forging, the thickness decreased while the parallel route width rose. The contact pressure applied to the specimen surface has a positive relationship with the average change in thickness and parallel path width (Nuwan et al., 2018). The breadth direction provides the most degree of freedom for material movement due to the form of the specimen and the forging set up arrangement. As a result, the change in parallel path width outpaced the change in thickness as the contact pressure increased.

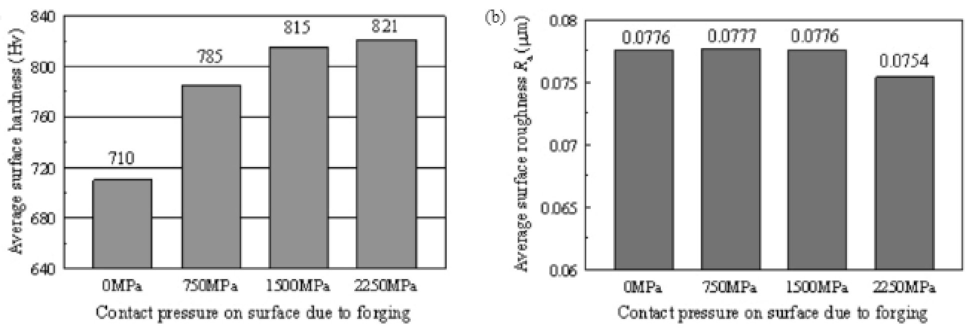


Figure 2.4: (a) Average surface hardness vs. contact pressure; (b) average surface roughness vs. contact pressure 0 MPa before forging (Nuwan et al., 2018).

To investigate the hardness change in the material owing to forging, three specimens were forged with 150, 300, and 450 kN. Figure 2.4 depicts the change in hardness as a function of contact pressure (a). The results show that forging increases the hardness of the specimen surface. The work hardening of the specimen surface as a result of plastic deformation during forging causes it. The surface of the material gets brittle as the hardness increases. This brittleness is caused by the material's inability to tolerate incremental loading as a result of the jamming process. Figure 2.4 illustrates the influence of forging on the surface roughness of the specimen (b). Surface roughness of specimens forged at 750 and 1500 MPa contact pressures did not differ much from initial roughness. Surface roughness was decreased marginally in specimens forged with a higher contact pressure (2250 MPa) (Nuwan et al., 2018).

The contact pressure is related to dimensional change, surface hardness, and surface compressive residual stress. Surface roughness and contact pressure did not have a significant connection. Furthermore, as compared to unforged specimens, tensile strength increased in specimens forged at low and medium contact pressures, but the tensile strength of specimens forged with greater contact pressure decreased (Nuwan et al., 2018). The axial fatigue test revealed that when the specimen was forged with lower and medium contact pressures, fatigue life improved. The fatigue life of the specimens forged with high contact pressure, on the other hand, reduced.

## 2.3 Wear test

A method called wear testing measures the erosion or sideways displacement of a material from its "derivative" and initial position on a solid surface under the influence of another surface. This test is frequently employed as a quick indicator of a material's suitability for usage. It may be necessary to conduct mechanical experiments that mimic the conditions the material would encounter in real-world use since various materials respond differently in the presence of friction. A crucial factor for assessing the quality of these materials is the results of wear testing on the chosen alloy. These materials experience compressive loads and strains when in use, and how well they are able to withstand them without breaking is a measure of how reliable they are. The first step to efficient quality control and good production practises is the availability of a wear testing equipment for materials. To ensure compliance with applicable standards and maintain product quality that will continue to fulfil the demands of the uninformed users, manufacturers must create quality control facilities for continuous assessment of product quality (Amal et al., 2011).

### 2.3.1 Ball-on-flat linear reciprocating test

Despite the importance of quantifying wear volume in tribological testing, present approaches for volume computation in tribo elements have major limitations, as Blau, (1996) detailed. Gravimetric methods cannot be used to determine minor wear quantities, 2D approaches can only be used to characterise the wear track on flat specimens and 3D profilometry can be time-consuming by Sharma et al., (2013) and Kucharski et al., (2011), particularly when calculating the wear volume of extensive testing campaigns (Chattopadhyay et al., 2012). Simple and quick procedures are desired, yet the durability and quality of measured data are critical for meaningful tribological research. A recent study looked at the repeatability and validity of tribology research, and found that the experimental designs were, on the whole, rather inadequate. Similarly, Blau, (2019) evaluated parts of wear research article quality and content, arguing that “progress in wear science and engineering depends on good communication, and archive tribology journals and conferences assist to service those communication demands”.

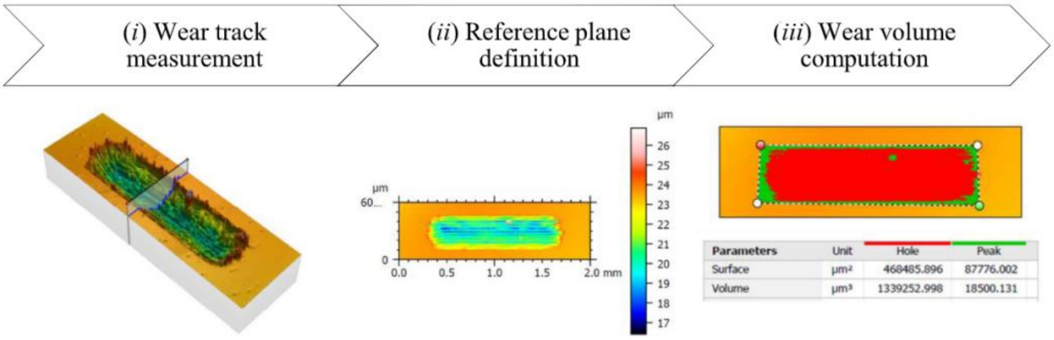


Figure 2.5: Representative diagram of the steps that constitute the wear volume calculation of a wear track on the flat specimen using 3D profilometry (Blau, 2019).

The 3D structure of the wear track, is illustrated in Figure 2.5, and the surrounding flat surface are measured first. Second (ii), a mathematical reference plane is constructed, which is frequently accomplished by least-squares fitting the plane to the data of the non-affected surface in the worn track's data surroundings. In third (iii), the wear volume is computed by subtracting the wear track topography from the simulated planar surface. Given the three-dimensional and irregular nature of a wear track, 3D analysis may be the most suited method. Because the residual depth – if any – will be considered, the predicted wear value may contain a plastic deformation component in addition to real material loss. Although this impact is generally overlooked, the indentation tests with the same counterpart and force as wear testing can be used to quantify the contribution of plastic deformation (Huang et al., 2015).

### 2.3.2 Pin-on-disc

Materials are frequently characterised for friction and wear (typically wear rates and wear resistance) using several types of tribometers, with the pin on disc test being one of the most used. The method's popularity derives from its relative simplicity and quantity of tribological contacts that may be accurately represented by a simple pin on disc motion: from bolt screw dry connections Takuya et al., (2019) to rail wheels to rail contact Yezhe et al., (2016) and to lubricated biological implant contact typically, the test enables for the testing of many motion modes, such as unidirectional, fretting modes, and, more recently, any other complicated motion patterns. Typically, the tests are carried out in accordance with the following standards: ASTM G99, ASTM G133, and ASTM F732.

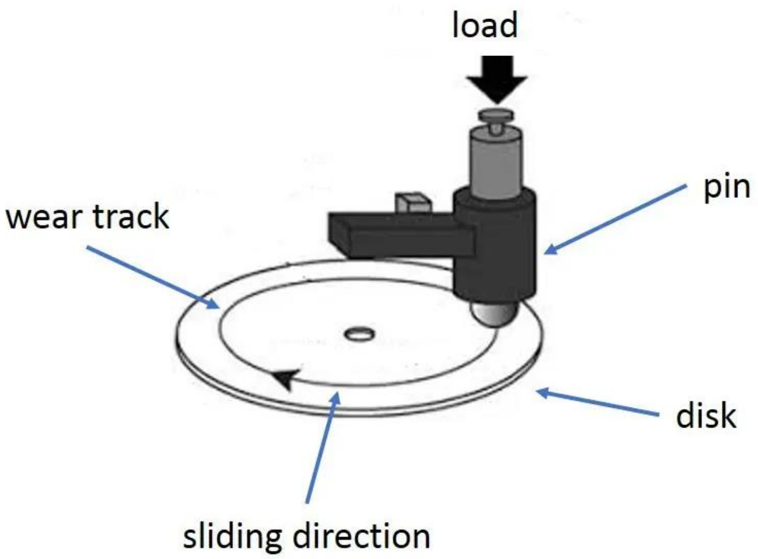


Figure 2.6: Schematic of pin-on-disc wear test system (Takuya et al., 2019).

The pin on disc test is shown schematically in the Figure 2.6. Under the applied stress, the rotating disc is pushed against the stationary pin. The pin can be any shape, although because to its ease of alignment, spherical (ball or lens) and cylindrical forms are the most common. Temperature, wear, and friction force are continually measured during the test (Yezhe et al., 2016).

## 2.4 Tribological study

To assess volumetric wear, noncontact optical approaches such as white light interferometry Leach, (2011), confocal profilometry, and more recently focus variation are utilized (Wang et al., 2015). The measuring capabilities of each approach varies and with magnification Tato et al., (2020), optical resolution and spatial sampling rate change, altering measurement resolution. As a result, all process variables for volume characterisation must be provided. The use of atomic force microscopy (AFM) to the evaluation of macroscopic wear scars created by stitching was investigated by Capella et al., (2015). They determined that, whereas AFM is more accurate than interferometry, the optical method's overall accuracy is adequate. Furthermore, the AFM detection technique is time-consuming and inefficient, which limits its use. Optical profilometry is the most commonly used and best approach for acquiring exact wear-volume data in a reasonable length of time, according to the literature study. However, the findings are dependent on the measuring technology used, the setup chosen, and the volume computation post-processing. As a result, the development of recommendations for measuring wear volume using optical profilometry would be of importance.

### 2.4.1 Wear rate ($mm^3/Nm$)

Wear is a complicated process that happens when two surfaces are slid against one another, gradually removing one or both materials. Wear appears to be irreversible, changing the functioning of mechanical and biological systems and eventually leading to system collapse. Material wear is growing more essential and might easily have the same functional and economic impact as friction. In many industrial applications, for example, components wear out and must be replaced. These replacements may be costly owing to expensive components, labour, and machine downtime while the item is being replaced (Archard et al., 2004).

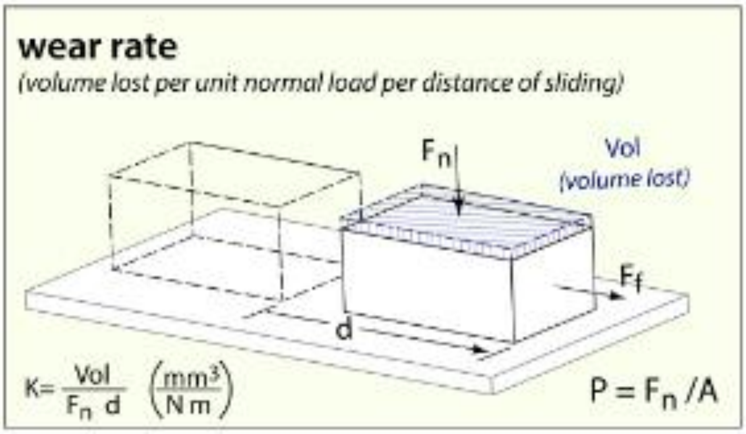


Figure 2.7: Schematic of wear rate ($mm^3$/Nm) (Archard et al., 2004).

Wear studies are of basic and application interest. Wear can vary by more than eight orders of magnitude among material systems, according to one remarkable finding. It can change by many orders of magnitude for the same material simply by altering the environment or the identity of the counter-material against which the substance is sliding. Much later than the friction coefficient, an acceptable measure for reporting material wear was devised. The total volume of material lost during sliding (the wear volume), V, is equal to the actual area of contact multiplied by the sliding distance, by a wear factor, K, a unit-less proportionality constant as illustrated in Figure 2.7. This wear factor can be caused by, among other things, the material set, sliding conditions, surface topography, and environment. The wear factor may be modified to produce the more practical and Stachowiak et al., (2005) define k as a physically direct particular wear rate (also known as a dimensional wear rate by William et al., (1994)). The wear volume divided by the normal load multiplied by the sliding distance, d, yields the particular wear rate ($mm^3$/Nm).

### 2.4.2 Coefficient of Friction

The friction coefficient is defined as the ratio of the friction force between two bodies to the normal force imparted on the other when these bodies move relative to one other. A tangential force between two bodies is the friction force. Thus, the friction coefficient is an empirical attribute of the contacting bodies that is affected by a variety of contacting variables such as material property, temperature, surface roughness, sliding speed, and so on (Blau, 2001). Friction may be utilised for energy dissipation since it converts kinetic energy to thermal energy. As a result, friction dampers as shown in Figure 2.8 and Figure 2.9 have been designed into structures to diffuse vibration forces. Friction dampers can be employed in steel structure braces Mualla et al., (2002) as well as beam-to-column moment connections (Yang et al., 1995). Friction dampers may considerably improve the earthquake resistance of structures. Recently, self-centering buildings have received a lot of attention, and friction dampers have also been used to release energy (Kim et al., 2008). Brass is typically employed as the friction material in these friction dampers. The usage of friction materials in seismic design should meet the requirements of a high kinetic friction coefficient as well as reliable energy dissipation.

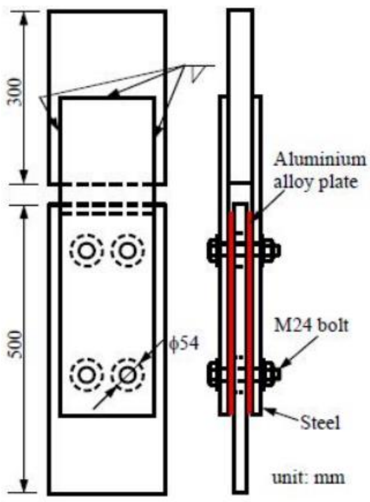


Figure 2.8: Schematic of sliding friction device (Kim et al., 2008).

Figure 2.9: Setup in a hydraulic machine (Kim et al., 2008).

There is relatively little information available on the behaviour and kinetic friction coefficient of aluminium alloy and steel. The kinetic friction coefficient between various aluminium alloys and steel was investigated experimentally in this work. Despite the fact that numerous factors impact frictional behaviour and the friction coefficient, this study concentrated on a constant sliding speed at room temperature (Rojas et al., 2005). The sliding friction device was built and will be utilised in a future steel structural test to investigate seismic behaviour.

## 2.5 Mechanical properties

The composition and mechanical parameters of AA-5083 aluminium alloy is provided in Table 2.1 and Table 2.2, and Table 2.3 shows the chemical composition of ER5356 filler wire. A sheet with dimensions of 150x300x2mm was used for TIG welding. Cleaning chemicals, dirt removers, and other re-agents are used to remove dirt, oil, and other foreign elements from these sheets. Edge preparation is performed where a double V edge is prepared for a $60^{o}$ angle. The aluminium sheets are put on the welding table, where the welding process takes place (Srivatsava et al., 2016).

Table 2.1: Chemical composition of the 5083-aluminium alloy (in Wt %) (Aluminium Alloys, 2005).

| Element | Mg | Mn | Fe | Si | Zn | Cr | Ti | Cu | Al |
|---|---|---|---|---|---|---|---|---|---|
| %wt | 4.5 | 0.7 | 0.4 | 0.4 | 0.25 | 0.15 | 0.15 | 0.1 | 93.0 |

Table 2.2: Mechanical properties of 5083-aluminium alloy (Aluminium Alloys, 2005).

| Material | UTS (MPa) | 0.2% Y.S (MPa) | Elongation (%) |
|---|---|---|---|
| 5083 | 300 | 145 | 15 |

Table 2.3: Chemical composition of ER 5356 filler wire (Srivatsava et al., 2016).

| Element | Si | Fe | Cu | Mn | Mg | Cr | Zn | Ti | Be | Others |
|---|---|---|---|---|---|---|---|---|---|---|
| %wt | 0.25 | 0.4 | 0.1 | 0.05-0.2 | 4.5-5.5 | 0.05-0.2 | 0.1 | 0.06-0.2 | 0.0003 | 0.15 |

### 2.5.1 Hardness

Precipitates interact with moving dislocations in aluminium alloys 5083, which are generated through ingot casting and cold working. At room temperature, this improves strength. When these alloys are welded, however, the precipitates dissolve and/or coarsen, resulting in a considerable reduction in mechanical strength as shown in Table 2.4. This decrease in mechanical characteristics is due grain expansion and precipitate breakdown and/or over ageing, and uncontrolled grain boundary precipitation on cooling The HAZ of 5083 aluminium alloy is completely annealed and recrystallized during welding. When an alloy is subjected to a temperature exceeding 343$^{o}$C for only a few seconds, the impact of any preceding work hardening is lost. As a result, the HAZ shows a decrease in hardness. The amount of heat applied, the welding technique used, the size of the workpiece, and the velocity of cooling all influence the degree of softening. Low heat input levels reduce the amount of softening in the HAZ by shortening the duration at temperature and speeding up the cooling rate.

Table 2.4: Mechanical properties of butt joints in aluminium 5083 welded using ER5183 and ER 5356 filler metal (Olson et al., 2007).

| Base alloy | Filler Metal | Ultimate Tensile Strength, MPa | Minimum Yield Stress, MPa | Tensile Elongation, % | Free Bending Elongation |
|---|---|---|---|---|---|
| 5083 | 5356 | 262-241 | 117 | 17 | 38 |
| 5083 | 5183 | 276-296 | 165 | 16 | 34 |

In the as-supplied state, the average hardness value of 5083-H111 alloy is 91.81 HV (standard deviation of 13.20 HV). Microhardness experiments found that second-phase intermetallic particles have greater hardness values (a maximum of about 794 HV).

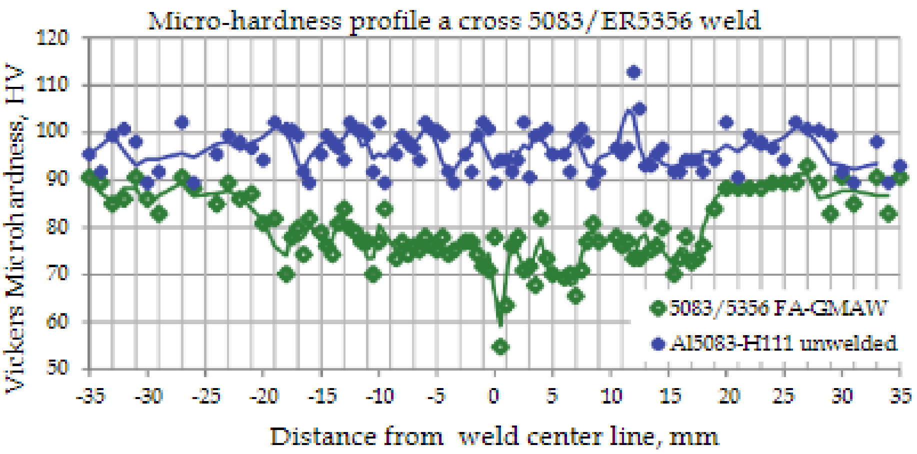


Figure 2.10: Micro-hardness profile across a pulsed SA-GMAW joint welded with ER5356 filler wire (Olson et al., 2007).

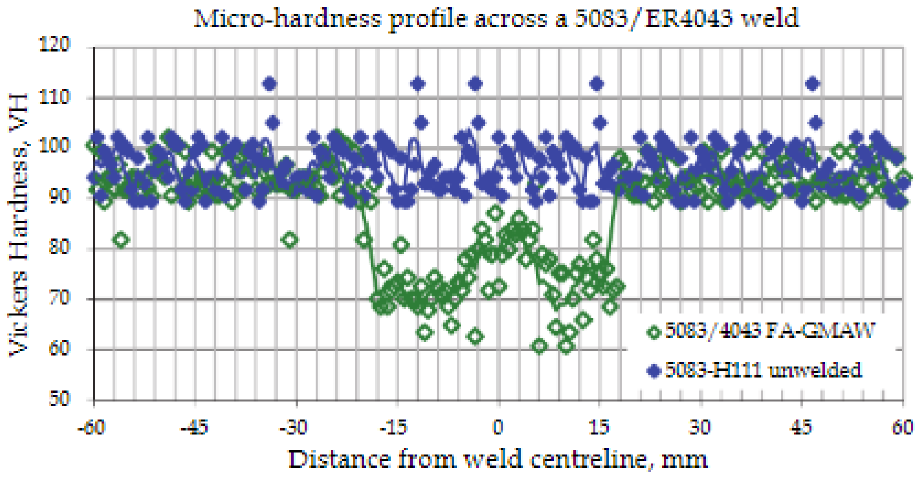


Figure 2.11: Micro-hardness profile across a pulsed SA-GMAW joint welded with ER4043 filler wire (Olson et al., 2007).

Figures 2.10 and 2.11 illustrate that the hardness is typically consistent throughout welds, with a little decline in hardness in the weld metal. This decrease in hardness caused failure in this site during tensile testing. Any weld metal discontinuities, such as gas porosity or lack-of-fusion faults, will impact the tensile parameters measured. The ultimate tensile strength (UTS) of FA-GMAW dressed welds using ER5356 filler wire was equivalent to the base metal, however ER5183 and ER4043 filler wires commonly delivered lower strength values due to their fundamentally lower strength levels.

### 2.5.2 Scanning Electron Microscopy (SEM)

Scanning electron microscopy (SEM), often known as SEM analysis or SEM method, is widely utilised in a variety of fields across the world. It is an excellent approach for analysing organic and inorganic materials on a nanoscale to micrometre (m) scale. SEM operates at a high magnification of up to 300,000x and even 1000000 (in some recent models) to generate very accurate images of a variety of materials SEM and Energy Dispersive X-ray Spectroscopy (EDS) collaborate to provide qualitative and semi-quantitative data. findings (Thermo Fisher Scientific Inc, 2018).

Figure 2.12: SEM Quanta device (Thermo Fisher Scientific Inc., 2018).

As illustrated in Figure 2.12 the analysis is carried out using SEM equipment, which is a highly developed SEM Quanta device for materials research Thermo Fisher Scientific Inc (2018). The machine is made out of a variable pressure system that can handle any sample (even wet or samples with minimum preparation). The equipment can analyse materials with a diameter of up to 200 mm and a height of up to 80 mm. The magnification of the instrument goes from 5x to 300,000x. SEM Laboratory Testing Inc., (2018) accepts organic and solid inorganic materials, including metals and polymers.

# CHAPTER 3

# METHODOLOGY

## 3.1 Introduction

To conduct the experiment of the reciprocating test on ball-on-flat specimen with grade AA 5083-H112 welded with filler wire of ER 5356 aluminium alloy either forged or unforged of the specimens, a framework has been created in accordance with the research objectives. Figure 3.1 shown a flow chart that consists of four phases; Planning, Machining, Testing and lastly Analysis data. Each phase comprises of several steps. The detailed of each step will further explained in this chapter.