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Wear Properties of Wire and Arc Additive Manufacturing Components: A review on recent developments on Processes, Materials and Parameters

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ABSTRACT:
This paper presents a critical review of the characterization and tribology of 304L stainless steel manufactured by Wire Arc Additive Manufacturing (WAAM). This paper begins with an introduction to additive manufacturing (AM), detailing various AM processes with a focus on WAAM followed by the introduction of tribology and about its importance. WAAM, which uses an electric arc as a power source and wire as a feedstock, offers high deposition rates and cost efficiency compared to other AM processes. The tribological performance of 304L stainless steel, material used in WAAM, is evaluated under various conditions. 304L is the grade of austenite stainless steel that is used in various industries like nuclear, chemical, etc. things examine include significant improvements in wear resistance and friction reduction when employing impact texturing with Sic particles and nano-scale surface peening. The study also reviews the superior performance of 316L stainless steel over 304L in terms of wear and corrosion resistance due to its higher molybdenum and chromium content [1]. Additionally, the effect of ambient temperature on the wear performance of AISI 304L stainless steel is examined [2], showing variable friction coefficients and wear rates influenced by temperature changes. This comprehensive review underscores the potential of WAAM-produced 304L stainless steel in diverse applications, emphasizing the importance of proper surface treatments to enhance performance.

1. INTRODUCTION

2. 1.1 Additive manufacturing

Additive manufacturing, commonly referred to as 3D printing, is an evolution of the concept of rapid prototyping. It operates by depositing material in successive layers to create the desired object. This technology is based on the principle that a digital model, initially created using 3D computer-aided design (CAD) software, can be manufactured directly without requiring detailed process planning. Each layer of material corresponds to a thin cross-section of the part, which is generated from the CAD data [3]

Unlike traditional manufacturing methods such as subtractive manufacturing, where material is removed from a solid workpiece to achieve the desired shape, additive manufacturing builds the product layer by layer. In casting, the material is first melted, poured into a mold with the desired shape, and then subjected to compressive forces to form the final product. These traditional techniques differ significantly from additive manufacturing, where material is added rather than removed or molded. [4].

Additive manufacturing (AM), as a layered production approach, enables exceptional design flexibility and the potential to construct complicated geometrical forms, hybrid structures, and functionally graded materials with great precision, which are not achievable through traditional manufacturing procedures [4] AM technology is widely used in industries such as nuclear, biomedical, aerospace, marine, and construction due to its numerous advantages. Research indicates that using additive manufacturing (AM) technology in construction can minimize labour costs, material waste, and enable customized, complicated designs. Geometries are challenging to create using standard building techniques [5].

3. **1.2 Types of Additive Manufacturing**

Currently, various additive manufacturing (AM) techniques are continually advancing. However, the American Society for Testing and Materials (ASTM) has classified AM processes into seven primary categories.
that are shown in Figure 1.1.

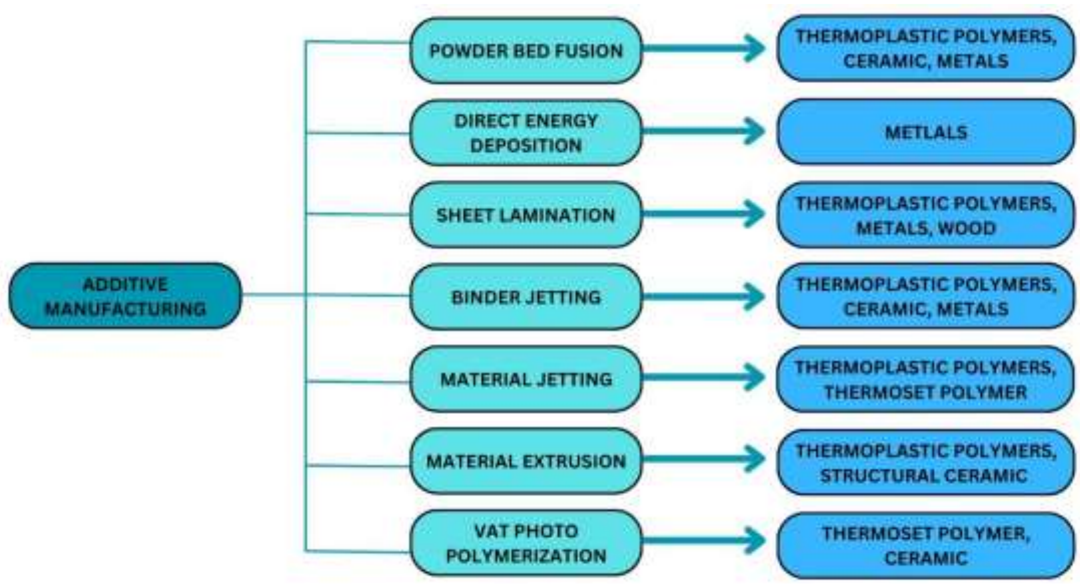
AM technology has evolved greatly from its early prototype application to its present use in modling, tooling, and productionInitially, this technology was applied to materials such as polymers, paper laminates, and waxes. Plastics were among the earliest raw materials used in additive manufacturing and continue to be widely utilized in various applications. Over time, advancements have led to the introduction of metals, ceramics, and composites into the process. However, the area of metal additive manufacturing is still in its early stages [6]. Metal additive manufacturing (MAM) primarily developed through processes such as direct energy deposition, powder bed fusion, welding, sheet lamination, and binder jetting [7] . Powder Bed Fusion (PBF) uses lasers or electron beams to fuse and bond powdered materials. Directed Energy Deposition (DED), on the other hand, utilizes a nozzle capable of moving in multiple directions. Similar to material extrusion in additive manufacturing, DED relies on a power source-such as a laser, plasma arc, or electron beam and uses feedstock that can either be in powder or wire form [8–10].

Wire feeding and powder feeding methods produce comparable material properties and microstructures; however, the powder-based approach often leads to slightly higher porosity. In the binder jetting process, layers of powder are bound together using an adhesive, with both materials being deposited alternately. Sheet lamination encompasses methods like laminated object manufacturing (LOM) and ultrasonic additive manufacturing (UAM)[11–13]. UAM use ultrasonic frequencies to join the material.

Based on the material used, Metal Additive Manufacturing (MAM) can either be wire-based or powder-based [3]. Powder-based AM techniques primarily use lasers or electron beams as power sources to melt the feedstock powder, while wire-based AM can use lasers, electron beams, or electric arcs as power sources. Figure 1.2 presents a general classification of MAM techniques based on the form of the material used.

Wire Arc Additive Manufacturing (WAAM) is a cutting-edge metal additive manufacturing technique that falls under Directed Energy Deposition (DED). This process employs an electric arc as its power source and uses wire as feedstock, allowing for material to be deposited layer by layer. WAAM offers a notably higher deposition rate than other additive manufacturing methods, and the raw materials used are generally more economical than those found in powder-based additive manufacturing. This cost-effectiveness makes WAAM ideal for both large and small construction projects [14–16]. WAAM has various benefits, including compatibility for a wide range of metallic materials and a greater deposition rate than laser-based AM approaches. As a result, WAAM may achieve better deposition rates at reduced costs, making it a leading alternative to conventional hybrid MAM systems [17].

This study presents a critical review of the characterization and tribology of 304L stainless steel manufactured by WAAM. The review begins with an introduction to additive manufacturing (AM), followed by a discussion of various AM types. It briefly explores WAAM and introduces 304L stainless steel, emphasizing the importance of tribology. Subsequently, other characterizations of 304L will be discussed here.



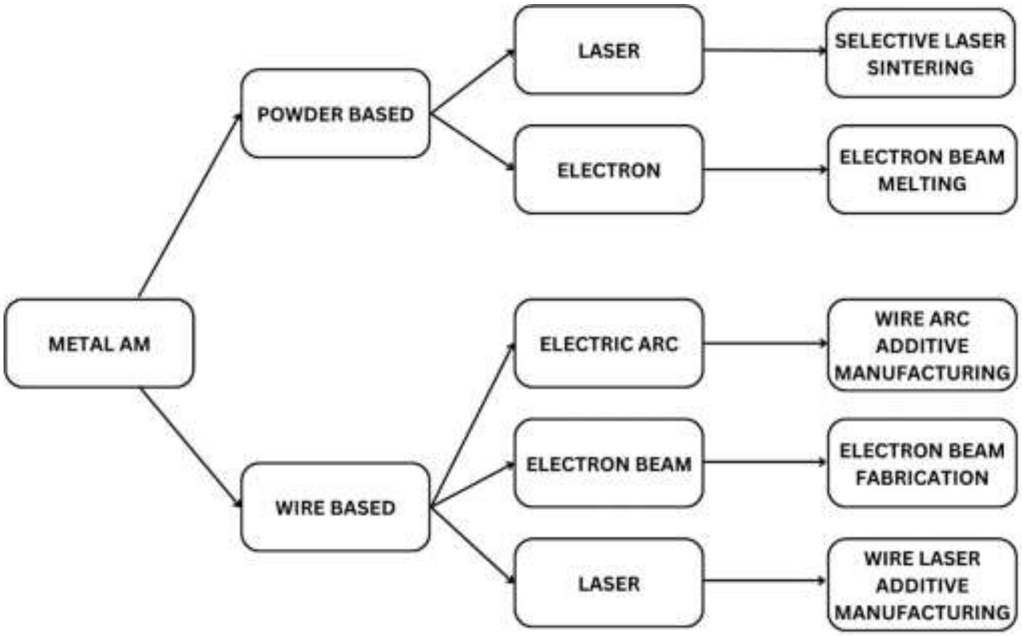
4. Figure 1.1 types of additive manufacturing

5.

6. **1.3 Welding technologies in Additive Manufacturing**

Figure 1.3 It illustrates various welding techniques used in additive manufacturing, including laser-based, electron beam-based, and arc-based methods, all of which are classified as welding-based AM. Welding technology significantly influences additive manufacturing due to its distinct advantages over other methods, such as material efficiency, high deposition rates, time savings, and the absence of build volume limitations [18]. SLM and SLS are examples of laser-based AM methods. In SLS, the laser source sinters the powder material, forming the structure [19] The key limitation, of SLM is that it is only suitable to metals, whereas SLS can operate with a wide range of materials.

7.



8. Figure 1.2 classification MAM

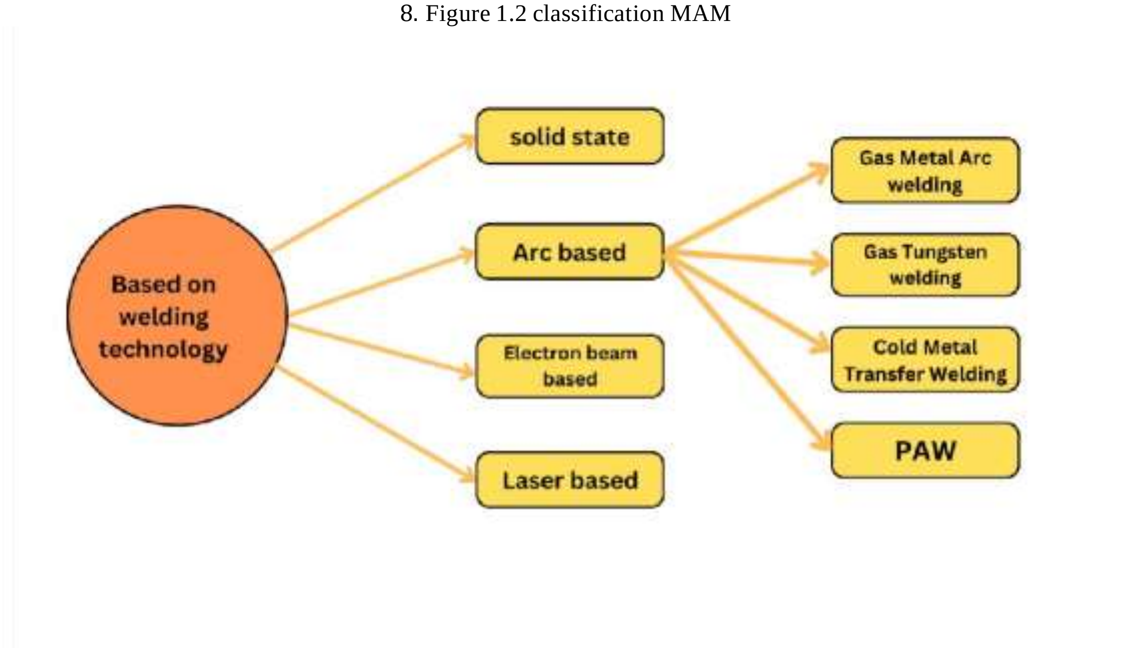


Figure 1.3 welding technology in AM

Similarly, EBM generates heat by employing an electron beam to fuse raw materials under vacuum environments, The raw material can be in the form of either wire or powder [20,21] Ultrasonic Welding (USW) uses high-frequency ultrasonic vibrations under pressure to fuse objects and generate thermal energy at the interface. The generated heat is substantially lower than the melting point, preventing unwanted changes in the material's properties. It is also well-suited for combining materials with different properties.[22]. Arc-based welding methods consist of Gas Metal Arc Welding (GMAW), Gas Tungsten Arc Welding (GTAW), Cold Metal Transfer (CMT), and Plasma Arc Welding (PAW).

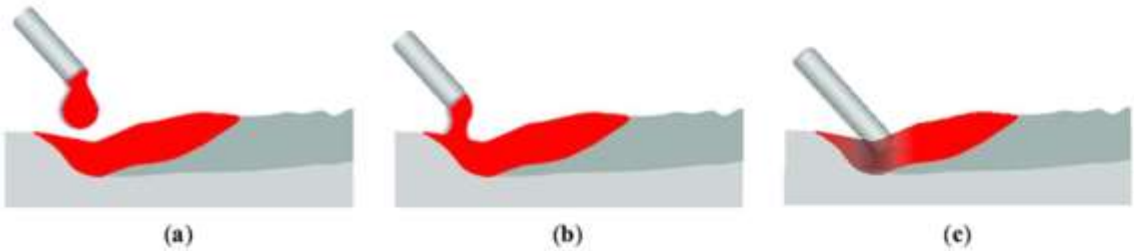


Figure 1.4 droplet mechanism of WAAM by arc [23]

9.

10. **1.4 Wire Arc Additive Manufacturing (WAAM)**

WAAM is an emerging technology that produces heat through the use of an electric arc. It creates a 3D structure by melting wire from a wire feeding system using an electric arc power source. naming diagram of WAAM is shown in figure 1.5 The procedure can be digitized to allow for more regulated metal deposition. A line diagram of WAAM is shown in figure 1.6. Ralph Baker's patent for the wire arc additive manufacturing was filled in 1920 and was accepted in 1925 [24] However, the usage of WAAM as an AM technology has grown significantly in a variety of industrial areas, particularly in the last two decades [25]. This experiment focuses on direct energy deposition, utilizing an electric arc as the heat or power source, with metal wire serving as the material feedstock deposited layer by layer. When wire is employed as the material feedstock and electric current serves as the heat source, this process is collectively referred to as wire arc additive manufacturing. rate of deposition of material is high rather than any other AM. Using metal wire as the feedstock, this procedure was used to perform local repairs on damaged and to manufactured round component and ornaments. For feedstock deposited material metal wire or powder of material like alloy of titanium, aluminum, nickel, steel are used [26]. Laser, Electron Beam, Plasma, and Arc welding (TIG/MIG) can all be used for heating purposes, albeit the first two are considerably more expensive due to the high system costs and additional environmental requirements for creating laser and electron beams. protective shielding in a laser beam and a vacuum chamber in an electron beam is required. The two main components need for WAAM employing welding as a heating medium are welding equipment which includes welding transformer, wire feeder, torch and shielding gas and another one is the robotic system or the CNC machine for the movement of the welding equipment. TIG and MIG welding source is preferred in WAAM for the welding equipment. MIG (CMT) welding system is shown in the figure. WAAM has various distinct advantages, including the capacity to make complex-shaped parts at bigger sizes, cost-effectiveness, ease of configuration, and high efficiency. Furthermore, it has a high deposition rate, ranging between 15 and 130 grams per minute [27].

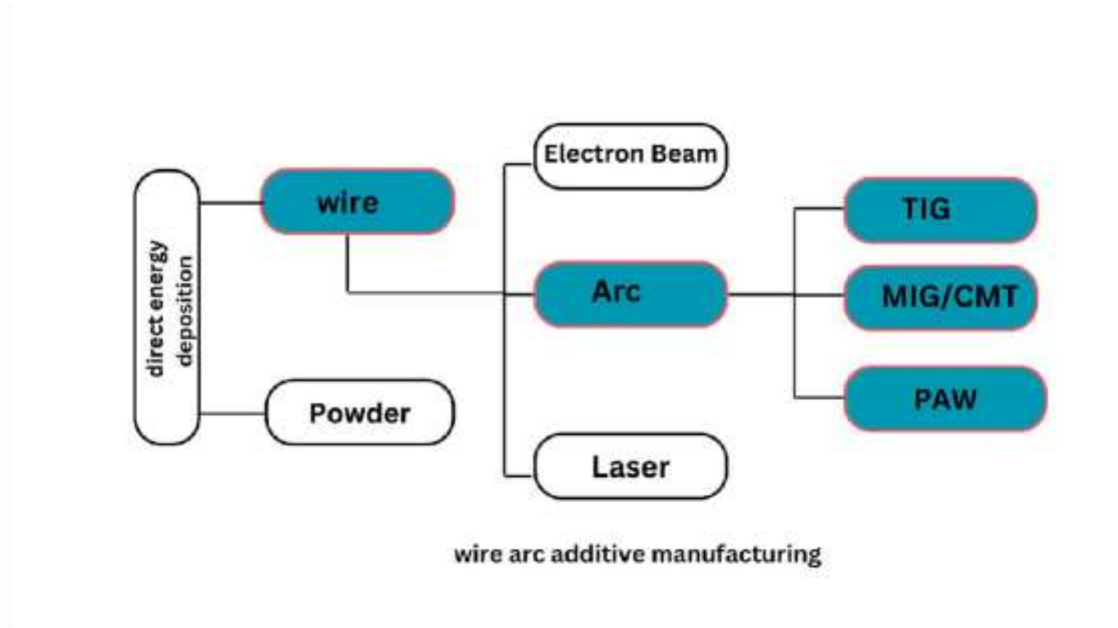


Figure 1.5 Line diagram of WAAM

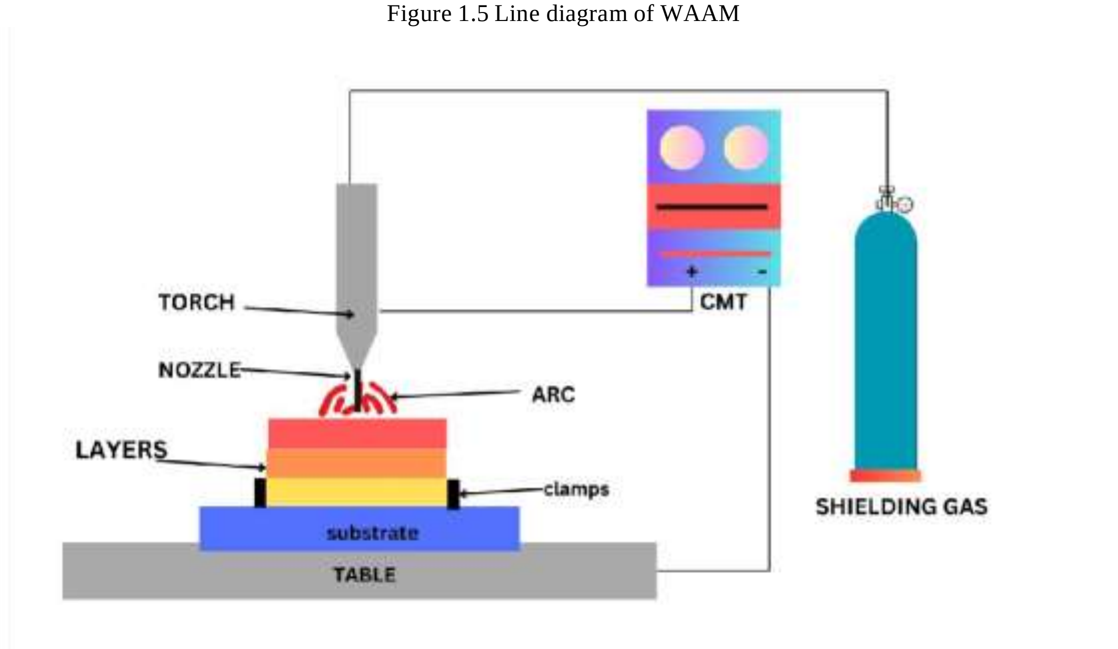


Figure 1.6-line diagram of WAAM

10.1

10.2 **1.4.1 Advantages**

- Deposition rate in WAAM is much higher than other AM process
- Cost of feed stock material is cheaper than powder AM process and other conventional machining
- Parts manufactured by WAAM is much larger than other AM process
- Time and energy efficient

11. **1.5 STEPS IN WAAM**

From the solid modelling of a part in CAD to the final part production, there are several specific steps followed in any additive manufacturing process, as illustrated in Figure 1.7 and briefly discussed below.

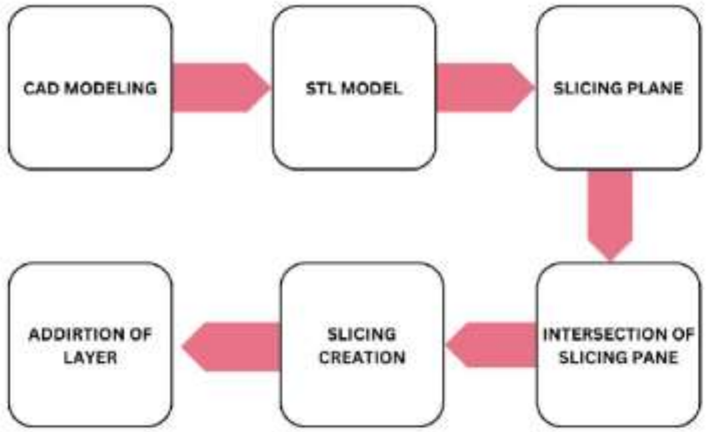


Figure 1.7 steps followed in AM

CAD Modelling: The initial step in additive manufacturing involves creating a CAD model using software such as SolidWorks, PTC Creo, or Autodesk 3ds Max to design a virtual representation of the product. Solid modelling can also be achieved through optical and laser scanning techniques.
STL Conversion: The model is divided into triangular components by converting the virtual solid model into the STL (Standard Triangle Language) format. The slices required for the additive manufacturing process must be calculated using these triangles.
Send STL File to Machine Software: The STL file is sent to the machine software, which modifies the part's alignment and position in accordance with the specifications of the machine. The machine is set up for part manufacture and the solid model is sliced simultaneously.
Part Building: The machine's microcontroller receives the part file as codes (usually G and M codes), and the part is built on the base plate layer by layer in accordance with the instructions.
Part Removal and Post-processing: Following construction, the part is taken out of the base plate and goes through any further machining or finishing work needed to bring it up to code.

12. **1.6 Processes used in WAAM**

In wire-based AM, arcs can be created using GTAW, GMAW, CMT, or PAW. Each has unique features, efficiency, and raw material processing requirements. GMAW simplifies tool path development and programming in comparison to GTAW and PAW, which both rely on an external wire feeding system. GMAW achieves the highest deposition rate, making it well-suited for steel and aluminium. On the other hand, PAW generates a high-density arc, which leads to lower distortion and improved weld quality. Titanium welding requires either GTAW or PAW due to arc wandering caused by GMAW. PAW is constrained to small-sized equipment [28].

Metal inert gas welding/gas metal arc welding (MIG/GMAW)

MIG welding is a widely used technology in the industry. Metal inert gas welding (MIG) occurs when an active gas in the atmosphere, such as O2 or CO2, is combined with an inert gas. In GMAW, an arc forms between the substrate and wire electrode [29,30]. This method is cost-effective, has high deposition rates, works with a variety of metals, and is suitable for medium size component to large-sized component. GMAW-based WAAM methods have higher deposition rates compared to GTAW and PAW, making them suitable for larger parts [31–33]. Welding dissimilar metals using MIG welding is difficult because of the production of poor intermetallic compound (IMC), which results in fatigue buildup. MIG welding is more effective than other welding processes, including oxyacetylene welding, at fusing dissimilar metals. Using a tandem torch for pulse-MIG welding and providing external cooling atmospheres increased deposition rate and stability due to multiple wire feeding [34].

Tungsten inert gas welding/gas tungsten arc welding (TIG/GTAW)

TIG/GTAW welding use non-consumable tungsten electrodes, produces high-quality welds. TIG welding procedure requires forming an arc between the workpiece and tungsten electrode. The method requires inert conditions with argon or helium gas. The inert environment protects the deposited materials against oxidation, rust, and fusion defects [35 36]. The fundamental constraint of this technique is that it has lower deposition rates than PAW or CMT [37,38].

Cold metal transfer welding

Cold Metal Transfer (CMT) is a more refined version of metal inert gas (MIG) welding, differentiated principally by its distinct droplet transition behaviour. This feature considerably minimizes heat input, improving precision and control during welding. CMT, an enhanced variant of MIG welding, is particularly useful in situations that need low heat distortion and high-quality welds. CMT-based wire arc additive manufacturing (WAAM) is gaining popularity in the research community because to its potential to produce lower heat input than traditional gas tungsten arc welding (GTAW). This leads in lower heat stresses, less warping, and better mechanical qualities for the generated products

1.7 WAAM EQUIPMENT

Figure 1.8 illustrates the basic equipment setup for wire arc additive manufacturing (WAAM). A typical WAAM system can include a three-axis robotic arm equipped with a wire feeder, a shielding gas cylinder, and a power source. The setup often integrates manipulation systems and CAD/CAM software for precise control and automation. The choice of power source depends on the specific components and materials being used.

Recent advancements in WAAM technology have led to notable improvements, such as enhanced control software and better thermal management techniques. Additionally, the incorporation of a turntable with unlimited rotation capabilities allows for more complex geometries and greater flexibility in part design. Upgraded power sources have also been developed, enabling extended arc durations and more consistent deposition rates. These advancements contribute to improved process efficiency, part quality, and the ability to manufacture a wider range of components [39]

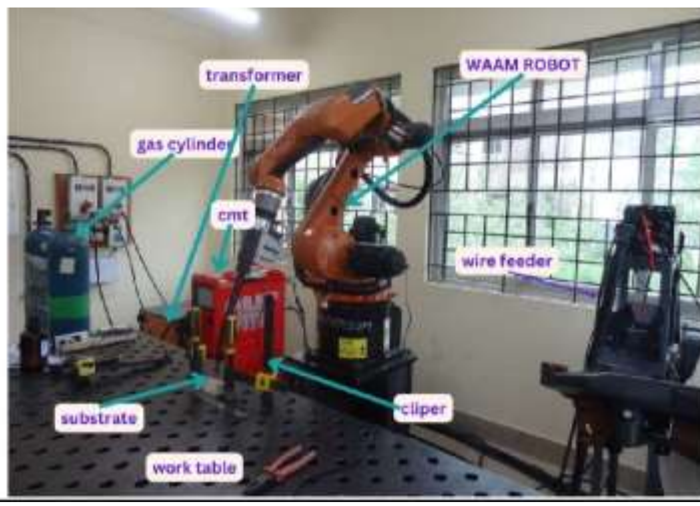


Figure 1.8 typically setup of WAAM

Work on WAAM

Ralph Baker's patent for the wire arc additive manufacturing was filled in 1920 and was accepted in 1925. He used an ordinary welding arc to deposit metal and receptacle or container of ornament and useful shape. He also worked on the controlling the motion of arc using various mechanical means [24]

In the realm of brake drum reclamation, H.K Shockey (1930) made a significant contribution by filling a patent for a novel method that utilizes metal deposition. Shockey's approach aimed to address the issue of brake drum wear by depositing material on the worn-out parts, effectively reviving them. Furthermore, he introduced the concept of cladding, a process where a high wear-resistant material is deposited on the inner wall of the brake drum. This innovative method mot only extends the lifespan of brake drums but also enhance their performance by reducing wear and tear [40]

In his work, Ujiie utilized the technique of wire arc additive manufacturing to construct a pressure vessel with a circular cross-section. This was achieved through the incremental layering of molten metal, which was deposited onto a revolving platform. This method showcases the innovative application of additive manufacturing in the fabrication oof complex structures [41]

In the 2012 study by Panagiotis Kazanas and his team, they explored the concept of positional welding, where the workpiece remains static while the welding torch's angle is adjusted. This method is particularly beneficial for constructing features with limited accessibility. Experiments were conducted on both aluminium and steel, and it was observed that the effective wall thickness increased as the angle between the wall and the plate varied from 0^o to 90^o. Walls were constructed at angles of 0^o, 15^o, 30^o and 45^o. It was found that the top surface exhibited less waviness compared to the bottom one, and this discrepancy increased as the angle increased [42]

In their 2015 research, R.J. Silva and colleagues put forth a unique method for 3D printing of metals, which utilizes plasma as the source of heat. They proposed a machine specifically designed for this purpose. The study also provides an insightful introduction to the steps involved in additive manufacturing. A key innovation in their system is the introduction of a device maned the torch holder, which is capable of moving along three axes. The study further delves into the critical parameters that govern the system design including welding current, voltage frequency, wire feed rate, shielding gas flow rate, type of gas, and torch angle. The authors underscore the importance of process stability and establish a correlation between welding parameters and bead geometry. These factors are represented as critical parameters in the system design, highlighting their importance in the successful operation of this 3D metal printing technique [43]

Based on the paper by Craig Buchanan et al., tension and compression tests were conducted on samples made by powder bed fusion technique. The tensile samples ere made at different angles of cross section with respect to the applied load. It was found that the strength of the build samples was more than that of the wrought material due to the rapid cooling of the thin layer. However, the fracture strength decreased as the angle of cross-section increased. For the compression test, hollow rectangular columns with variable were made [44]

J. Gonzalez et al. (2017) studied the optimal process parameters for wire arc additive manufacturing by analysing the geometrical and topographical features of the deposited wall . The geometrical feature study included the width, height, growth per layer deposition, angle between substrate and wall, and deviation in height along the welding direction [45]

This paper evaluates the environmental and economic consequences of wire arc additive manufacturing (WAAM) using multi-criteria techniques. It assesses elements like material waste, energy usage, and cost-effectiveness in order to contrast WAAM with conventional production techniques. According to research, WAAM has the potential to improve the environment by reducing material waste [46]

13.

14. **1.8 Material used in WAAM**

The multiple heat cycles that an additively built component goes through produce microstructure and material characteristics that differ dramatically from those of traditionally made components. Metals often utilized in WAAM processes include stainless steel, alloys of nickel, titanium, and aluminium [47,48]. WAAM is compatible with almost all welding materials. Using welding wire in the WAAM process saves material costs [25]. shows the common application

Application	Alloys				
	Aluminium alloy	Titanium alloy	Stainless-steel	Nickle	bimetals
Aerospace	49	50	-	51	✓
Automotive	52	-	53	-	✓
marine	49	54,55	53	-	-
High temperature	-	56	-	57	57
Chemical resistance	-	58,59	-	60	61
Tools	-	-	62,63	-	-

Table 1 Alloys is being used in WAAM process

14.1 **1.8.1 NICKLE ALLOY**

14.2 **Nickel-based superalloys are well-known for their high strength at high temperatures, great corrosion resistance, and superior mechanical qualities, making them a popular material in additive manufacturing research. These alloys are widely employed in the nuclear, chemical, and aerospace sectors, and great progress has been made in their use [64].**

Inconel 625, renowned for its outstanding material qualities, is widely used in the petrochemical, marine, and aerospace sectors [65]. Deposited nickel alloys have comparable or slightly lower yield strength, ultimate tensile strength, and elongation than wrought and cast materials.

14.3 **1.8.2 Titanium Alloy**

Ti-6Al-4V alloy's exceptional qualities make it a great option for aeronautical applications. It has good strength-to-weight ratio, low density, and resistance to corrosion, among other important qualities [66]. It is divided in alpha and beta grade category. Based on the its properties, each grade is created for particular uses. In general, it is not efficient to manufacture titanium components using traditional production techniques. Because of its limited ductility at room temperature, it has to operate at a high temperature [67]. However, the tensile strength, elongation, and anisotropy of titanium alloys are high [68]

14.4 1.8.3 Aluminium Alloy

Because of their excellent mechanical qualities, low density, and high strength-to-weight ratios, aluminium alloys have a wide range of applications. The aerospace and aviation sectors employ a lot of parts manufactured of aluminium alloys. Al–Cu alloys have the ability to maintain their mechanical characteristics between − 250 and 300 ◦C [69]. Its electrical, thermal, and corrosion resistance are all strong. But there are certain disadvantages to the WAAM of aluminium alloys as well. The main issues with aluminium alloys' WAAM include solidification fractures, porosity, and oxidation. Aluminium components that have had post-processing heat treatments have a more refined microstructure, which improves their strength and mechanical characteristics. A suitable mix of characteristics, including ideal operating temperatures, optimal process parameter selection, and high-quality wire feedstock, may assist minimize porosity. Heat-treatable aluminium alloys can reach their full strength because of the uniformly distributed secondary phase particles [70,71].

14.5 1.8.4 Stainless Steel

The fact that stainless steel (SS) has excellent ductility and corrosion resistance is the main reason why researchers are looking into it so much for WAAM manufactured parts. According to studies, stainless steel components made with WAAM methods have good mechanical and microstructural qualities [72,73]. The AISI 316L SS shows strong resistance to corrosion as well as mechanical and thermal stress. Its composition is almost entirely composed of molybdenum, nickel, and chromium, with very little carbon. Because of this, it is best suited for structural productions that must function at temperatures higher than 400 c. Super-duplex SS is an additional alloy with exceptional mechanical and chemical qualities that finds widespread application in the oil and gas, petrochemical, maritime, and other fields [74].

14.6 1.8.5 Other metals

Other metals, including bimetallic steel/nickel, steel/bronze, magnesium alloys, aerospace alloys (like Fe/Al and Al/Ti composites), and automotive materials, have also been studied to evaluate their potential with WAAM technology [75]. Fe–Al intermetallic, is inexpensive and has remarkable resistance to oxidation and corrosion [76] [77].

15. 1.9 Parameters used in WAAM

16. Accurate measurement and monitoring of process parameters is required for efficient dynamic control of the whole process. These factors include current, voltage, welding speed, wire feed rate, welding angle, shielding gas, gas flow rate, and deposition techniques. They have an impact on the quality of WAAM's products, influencing texture, size, form, joint penetration, as well as overall quality, price, and productivity [78].

16.1 1.9.1 Arc current and voltage

In WAAM, the proportion of arc current to weld penetration is linear. However, when current increases, bead roughness reduces. Arc current leads to an increase in bead thickness, wetting angles, and melt depth, while bead height shows minimal variation [39]. As the current increases deposition rate too increases. As the voltage increases, the weld beads flatten, resulting in a greater width-to-depth ratio. To keep the weld shape, lower the voltage as the preheat temperature rises. Controlled voltage, unlike constant voltage, causes the height to expand while the width decreases. This leads to consistent breadth and increased height [79].

16.2 1.9.2 Wire Feed Rate & Angle

Bead height is directly proportional to the wire feed rate (WFR), meaning that a higher WFR results in taller and thinner beads. As the WFR increases, the aspect ratio also rises, while the wetting angle decreases. However, the WFR has a minimal impact on surface roughness and melt-through depth [39]. Figure 1.9 shows the deposition deviation. A high current produces a large bead offset tolerance capacity, which reduces sensitivity to WFR. Higher wire feed angles also increase bead height, but have little influence on melting offset. In one investigation, Wang et al. [80] found that sensitivity rises when the feeding height offset exceeds 2 mm. The wire feed speed was optimized to 190 cm/min with a current of 120 A, a feed angle of 30°, and a feed height of 2 mm.

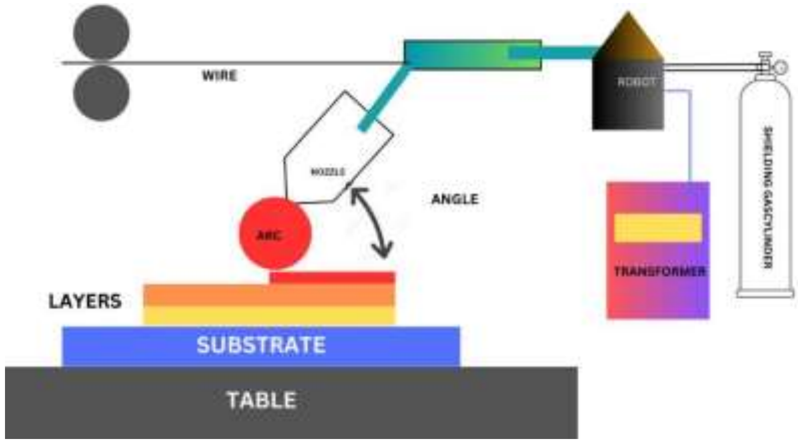


Figure 1.9 deposition deviation

16.3 1.9.3 Travel Speed

The speed at which you travel influences the quality of your joints. The wetting angle, melt-through depth, and bead width decrease with increasing travel speed. Furthermore, bead roughness rises marginally with increasing travel speed [39]. Higher travel speed leads to a little increase in bead roughness.

16.4 1.9.4 Shielding Gas and Gas flow rate

The shielding gas keeps the melt pool safe from airborne gases like O2, N2, and H2. Issues like oxide layer forms and porosity may arise from their reaction. The gas flow rate is vital to the maintenance of regulated surface oxidation. There has been no discernible impact of argon flow rate on the roughness, melt through depth, wetting angle, bead height, or bead breadth [25] but is has been observed the effect of the ions present of carbon gas in the mixture of the shielding gas.

16.5 1.9.5 Heat Input

Overheating during the deposition process might cause layers that have already been formed to remelt, which can damage the bead geometry, microstructure, and mechanical properties. It is advisable to lower heat input as layers are deposited to prevent this. Excessive heat input may result in material burn-off and, in extreme cases, substrate penetration, while insufficient heat input might produce more spatter, uneven deposition, and unfused layers [15].

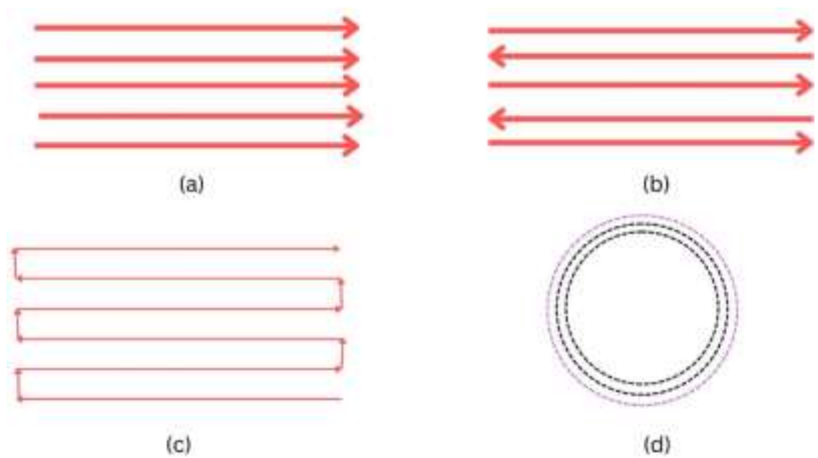
16.6 1.9.6 Deposition Technique

When considering deposition rate, material consumption, and large-scale component development, WAAM outperforms alternative fusion-based MAM approaches. The arc welding procedures that form the foundation of WAAM technology are comparatively well-established and standardized. It has been noted that a low point forms at the start of the weld path and a high point form at the end when all layers are deposited in the same direction. By employing different deposition directions between layers, this effect is mitigated. The deposition technique affects the temperature distribution in the deposited layers. Temperature distribution has an impact on dimensional precision and deposition quality. [81]. Different techniques are shown in figure 1.10.

17. 1.10 Properties of WAAM component

The mechanical property of a substance refers to its physical qualities and behaviour under external forces. WAAM-fabricated components often have equivalent mechanical characteristics to conventionally produced counterparts. Studying mechanical characteristics and defects in WAAM components is crucial since they will face real-world stresses. WAAM components undergo many tastings and characterizations to ensure their safety and quality. Typical tests include hardness, tensile and compressive testing, impact load testing, creep testing etc. Defects in WAAM can arise owing to inadequate programming, unstable weld pool dynamics, and thermal deformation caused by heat accumulation [82]. The properties of WAAM components vary depending on the process parameters and base materials used. The mechanical characteristics of WAAM-deposited Ti-6Al-4V were found to vary owing to varying interphase temperatures [83]. Fluctuations in temperature gradient and cooling rate lead to differences in mechanical properties along the vertical axis of the wall [84]. setup is shown in the figure 1.11.

Figure 1.10 (a). liner method, (b) liner alternate, (c) zig-zag, (d) continuous



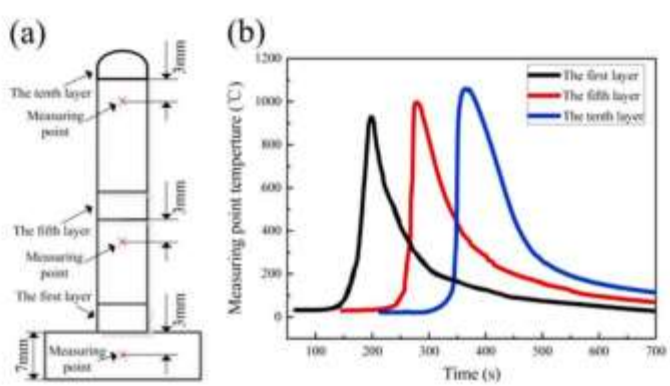


Figure 1.11 Variations in temperature gradient and cooling rate cause mechanical difference along the vertical direction of the wall [84]

18. **1.11 Application**

Additive manufacturing is becoming increasingly popular within the manufacturing industry because to changing consumer demands and market competitiveness because Additive manufacturing allows for mass customisation, in a short period of time. It is used to produce a wide range of products, from small piece to crucial spacecraft components. Recently sky root has developed a rocket with the help of additive manufacturing. Compared to standard machining, this approach involves fewer steps, saving time, money, and labour. Some common applications of additive manufacturing include the following

- Production of prototypes

- Manufacturing high complex geometry product
- Manufacturing of toy
- Being used in medical industries
- In nuclear industries
- In aerospace and automotive industries

1.12 Microstructure properties

Microstructure of metallic components determines their physical and mechanical properties. Metals' mechanical characteristics are affected by their grain size and shape. Fine-grained microstructures often have greater mechanical characteristics than metallic components [85]. Due to the repeated melting and solidification cycles, along with heat gradients in WAAM, controlling microstructure evolution is challenging, making both microstructural and thermal factors crucial in the WAAM process. Controlling the temperature gradient and solidification rate ratio can alter grain structures, A higher cooling rate results in a finer structure [86]. In WAAM, controlling heat input is essential. Insufficient heat input can lead to splashing, uneven deposition, and unmixed layers, while excessive heat input may soften the weld metal [87].

1.13 Limitations of WAAM fabricated component

Defects significantly impact the characteristics of produced components. Programming errors, inappropriate welding settings, heat accumulation resulting in thermal deformation, Porosity, high residual stress levels, and cracking, and other challenges might occur during WAAM [25]

1.13.1 Residual stress

The WAAM process generates residual stress that cannot be fully eliminated. This stress can lead to part deformation, reduced geometric accuracy, layer delamination during deposition, and decreased fatigue and fracture resistance in additively manufactured components. Research is focused on controlling and minimizing deformation and residual stress [88].

Components produced by WAAM experience various forms of deformation, including longitudinal and transverse shrinkage, bending distortion, angular distortion, and rotational distortion [88]. The three primary causes of these stresses are heat fluctuations, phase transitions, and mechanical working conditions. WAAM-produced components display a range of deformations, such as longitudinal and transverse shrinkage, bending distortion, angular distortion, and rotational distortion [89]. Thin-walled structures experience greater longitudinal stress at the base. However, as the number of layers increases, the distortion decreases [90].

1.13.2 Porosity

Porosity is another typical flaw found during WAAM. The molten pool absorbs hydrogen, oxygen, and nitrogen impurities as gas, leading to porosity defects. This gas gets trapped in the weld metal during solidification, leading to defects. This absorption is primarily due to inadequate gas shielding conditions. Porosity is a significant issue in aluminium alloys [91]. Porosity can occur when dissolved hydrogen in a liquid exceeds its solubility limit following solidification [91] . That is why purity of raw materials is crucial, particularly for aluminium alloys.

1.13.3 Cracks and delamination

Occurrence of defect is one of the common and critical problem in welded material. It might be either solidification crack or grain boundary crack [92]. depend on the material or its thermal characteristic. Solidification cracks are caused by the obstruction of solidified grain flow or high strain in the melt pool, while Grain boundary cracks occur because to differences in boundary morphology and precipitate formation/dissolution [92]

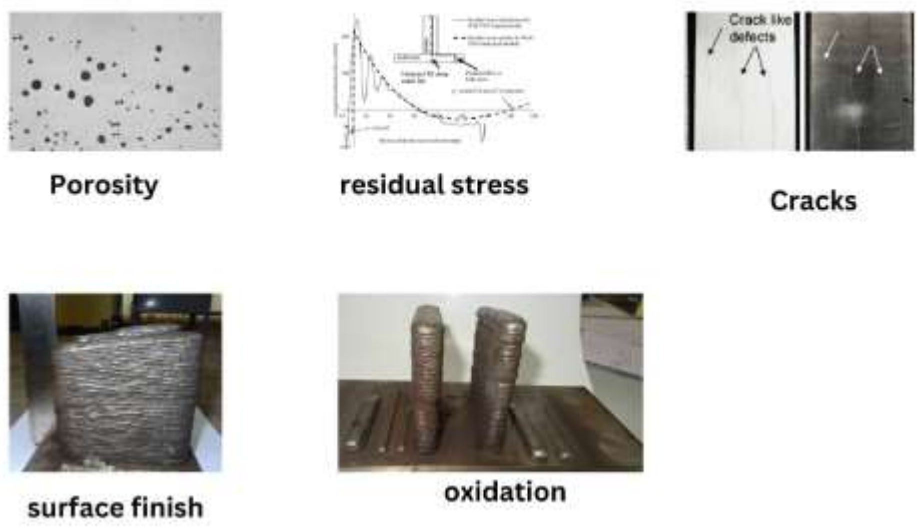


Figure1.12 (a) porosity, (b) residual stress [93], (c) crack, (d) surface finish, (d) oxidation

1.14 Application

Additive manufacturing is becoming increasingly popular in the manufacturing industry due to evolving customer demands and market competition, as it enables rapid mass customization. It is used to produce a wide range of products, from small piece to crucial spacecraft components. Recently sky root has developed a rocket with the help of additive manufacturing. Compared to standard machining, this approach involves fewer steps, saving time, money, and labour. Some common applications of additive manufacturing include the following

- Production of prototypes
- Manufacturing high complex geometry product
- Manufacturing of toy
- Being used in medical industries
- In nuclear industries
- In aerospace and automotive industries

2 TRIBOLOGY

Modern product development is driven by the desire to limit resource usage and reduce energy consumption, with the ultimate goal of achieving an industrial green transition. Wear and friction cause a large amount of the world's energy to be lost [94]. This emphasizes how crucial tribology is to almost every industry that produces technological items. Thus, a golden age of tribology is about to begin with research on lowering friction in the context of a green transition [95]. The scientific study of the interactions between solid contacting surfaces in relative motion is known as tribology [96]. When two solids come in contact the force of action and reactions takes place and phenomena can be said as the surface interaction.

2.1 Friction

Friction is not a new topic but one of the oldest subjects of research, playing a crucial role in engineering science. Friction results in significant energy and financial losses. Over time, many scientists have provided various definitions of friction. The earliest explanation of the friction force was based on the lifting of surface asperities. Friction between two solid surfaces opposes the tangential motion of one surface over the other and can occur in sliding, rolling, or rubbing contact. When the solid surfaces of two bodies come into contact, an adhesive force due to the interlocking of asperities creates resistance to motion [97]. The coefficient of friction (μ) is the ratio of the frictional force (F) to the normal load (W) [98]. Example is shown in figure 11

2.1.1 Types of friction of coefficient

There are two types of friction: one opposes the onset of relative motion, known as the static coefficient of friction, and the other opposes the continuance of relative motion once it has started, known as the kinetic coefficient of friction. line diagram is shown in fig 12

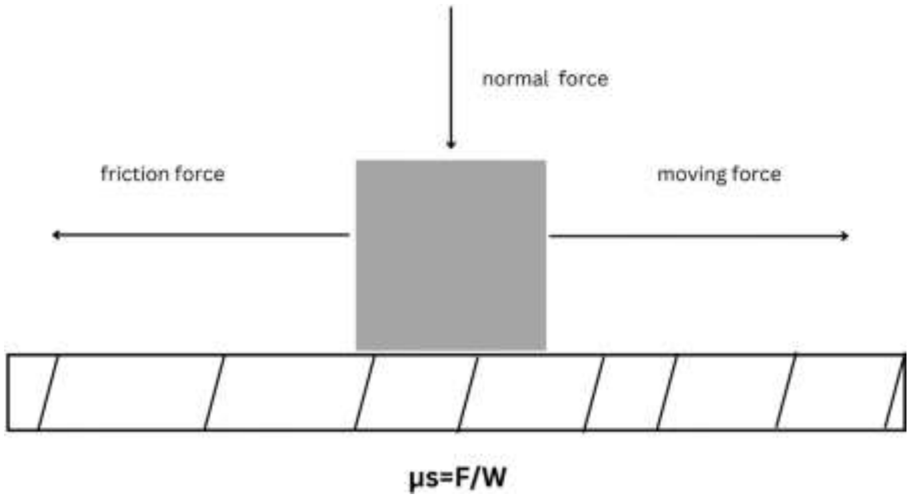


Figure 2.1 shows the friction force

2.2 Wear

The American Society for Testing and Materials (ASTM) defines wear as the slow loss of material from a solid surface produced by relative motion with a contacting substance or substances. The two surfaces may be impacted by this. The wear rate is defined as the reduction in volume, weight, or height and serves as an indicator of wear [99]. Wear studies are often undertaken for one of the following reasons:

- To analyse wear behaviour of a certain material family.
- Optimizing or selecting materials for specific applications.
- To analyse how different variables impact a certain wear mode or process.
- To support in the creation of prediction or descriptive models for wear in certain tribo systems [100]

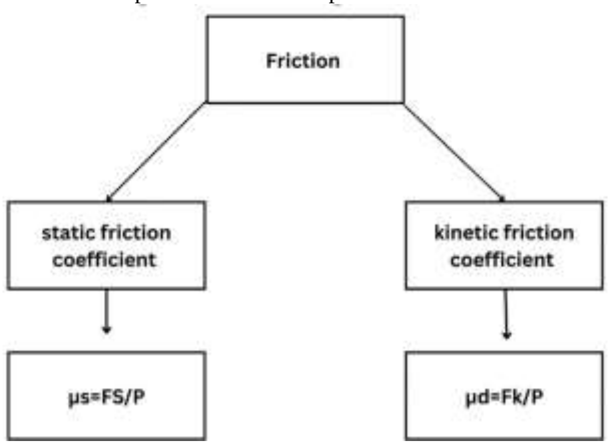


Figure 2.2 shows the types of coefficients of friction

2.2.1 TYPES OF WEAR

2.2.1.1 Adhesion Wear

Shearing of solid welded asperity joints causes material to be transferred from one surface to another, resulting in adhesive wear. It causes surface holes, voids, caverns, or valleys [101]. The adhesive bond is the cause of this wear. The adhesive bond of the Pair's weaker substance is stronger than the cohesive bond at the contact points. Adhesion often happens when two metals with comparable chemical compositions come into touch with one another. The adhesive wear mechanism of steel against indium pair is shown in Fig. 13.

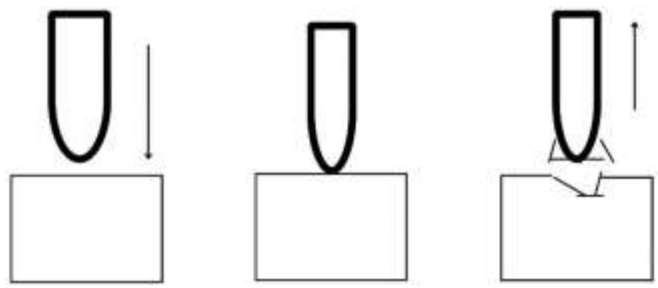


Figure 2.3 shows the adhesion wear

2.2.1.2 Abrasion

Wear happens when hard particles slide over a softer solid surface, leading to both plowing and wedging. During the plowing process, material is pushed to either side, forming a groove that may either remain or be removed. Figure 14 depicts the main processes involved in abrasive wear. Abrasive wear is categorized into two types: single-body wear and two-body wear. In single body marks will occur on the one body while in two body marks will occurs on both the surfaces. After a certain length of sliding distance, the ridges created by the abrasion or ploughing process flatten and finally break as a result of repetitive cycle stress [102,103] Moreover, it results in the developments of surface and subsurface cracks as well as subsurface deformation. For many pure metals, experimental data shows that In two-body abrasion, the wear rate is directly proportional to the normal load and the size of abrasive particles, but inversely proportional to the material's hardness. [104].

2.2.1.3 Erosive wear

Erosive wear occurs when liquid or solid particles impact a solid surface, causing mechanical contact. When particles repeatedly strike a metal surface at a certain velocity, pits and significant subsurface deformation develop.

2.2.1.4 Fretting Wear

Fretting wear is the result of small-amplitude oscillatory or reciprocating action between two surfaces. It operates in two steps. The rubbing of two surfaces initially causes adhesive wear, which is followed by oxidation [105].

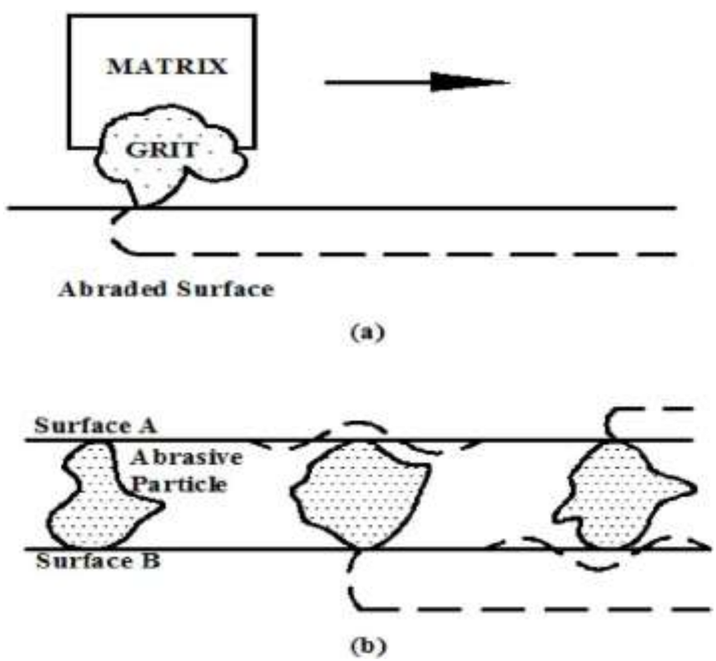


Figure 2.4 abrasive wear (a) single body abrasive wear, (b) two body abrasive wear [105]

2.2.1.5 Corrosive wear

When sliding arises in an environment that is oxidative or corrosive, corrosive wear results. with dry sliding, the solid surface may interact with ambient gases such as oxygen from the surrounding air. this wear can also occur due to the excessive use of anti-wear chemicals or other chemical compositions. Oxygen can react with a sliding surface at high temperatures to create oxides known as oxidative wear.

3 Stainless steels

A unique family of steel alloys noted for its ability to resist corrosion is called stainless steel. To be classified as stainless steel, an alloy must meet two criteria:
1. It must contain a minimum of 10.5% chromium and 50% iron.
2. It must resist corrosive attack from normal atmospheric exposure [106].

For the purposes of heat treatment and application stainless steels are categorized into five general families or groups. These categories are austenitic, martensitic, ferritic, duplex, and precipitation hardening.

3.1 Austenitic stainless steels

Among the most popular grades of stainless steel are austenitic stainless alloys. These are categorized using AISI 200- or 300-series designations; the 200-series denotes a range of compositions in which manganese and/or nitrogen partially replace nickel, and the 300-series grades are chromium nickel alloys. The austenitic grades exhibit good strength at high temperatures, exceptional cryogenic capabilities, and a very high resistance to corrosion [107].

Grade 304 is the basic grade of austenitic stainless steel. The incorporation of different alloying elements into 304 creates various grades of austenitic stainless steel, as shown in Figure 15. In the grade designation, "L" indicates a low percentage of carbon. These grades are used to improve weldability whereas high-carbon stainless steels are used in applications where increased hardness is required.

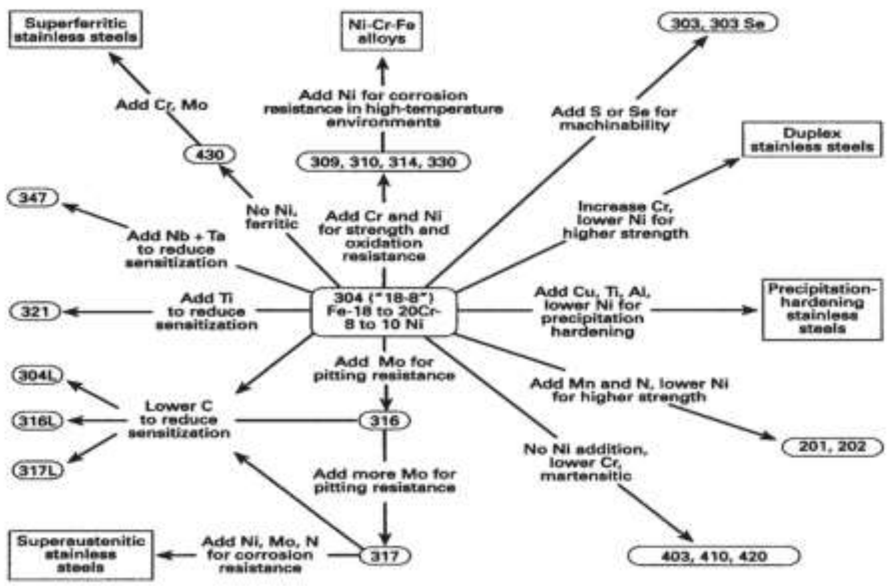


Figure 3.1 Composition and property linkages in the stainless-steel family of alloys [108]

3.2 TERATOLOGICAL PROPERTIES OF 304L

3.2.1 Effect of Sic particle impact nano-texturing

Study concludes that impact texturing of 304L stainless steel with Sic particles significantly improves its tribological performance, particularly under dry and lubricated conditions at higher loads. The friction coefficient was reduced from 0.7 to 0.15, and wear was reduced by up to two orders of magnitude compared to an untextured surface [109].

3.2.2 Tribology of 304l under dry and polyalphaolefin lubrication conditions

Higher grain boundaries in nano-grained CR 304L stainless steel make it more susceptible to oxidative wear in dry environments. However, under PAO4 lubrication, the samples have better wear resistance due to their high microhardness from extreme plastic deformation. This study demonstrates the transition of wear mechanisms from severe oxidative wear to mild adhesive wear, highlighting the material's capabilities under different lubrication conditions. [110]

3.2.3 Tribo-Behaviour and Corrosion Properties of Welded 304L and 316L

The current study reveals that 316L stainless steel has better wear and corrosion resistance than 304L stainless steel. The greater molybdenum and chromium content of 316L contributes to improved performance in both tribological and corrosive conditions. Characterization tests demonstrated that distinct phases and intermetallic compounds developed during welding, which influenced mechanical properties. Overall, 316L is more robust and trustworthy for applications that demand great resistant to wear, corrosion [111]

3.2.4 Effect of nano crystallized surface on the Tribo corrosion behaviour of 304L SS

The study concludes that nano-scale surface peening improves the tribo corrosion behaviour of 304L stainless steel. Mechanical resistance improves with continued sliding while corrosion resistance remains unchanged. The nano crystallized layer and enhanced hardness play important roles in this advancement. Intermittent sliding improves both corrosion and mechanical resistance by forming a nano crystallized top layer loaded with Cr and Mo, which strengthens the protective passive film and work-hardened surface [1]

3.2.5 Wear performance of AISI 304L stainless steel at different ambient temperatures

The wear parameters of AISI 304L stainless steel vary dramatically with temperature, with the friction coefficient decreasing from 25°C to 150°C due to the production of oxide layers and increasing at 200°C due to abrasive wear mechanisms. Nano-scale surface peening improves mechanical and corrosion resistance during intermittent sliding by forming a nano crystallized top layer rich in Cr and Mo. Improved surface characteristics reduce wear and increase the service life of steel components. These findings imply that proper surface treatments can maximize the performance of stainless steel under varied operational situations [2]

3.2.6 Wear in WAAM fabricated material

The wear rates of 3D-printed stainless steel varied dramatically along the print route, with the maximum wear rate occurring at the start and decreasing towards the end of the sample. This wear resistance gradient is statistically significant, indicating a relationship with material microstructure [112].

3.2.7 WAAM parameter affecting wear properties

The wear rates of 3D-printed stainless steel varied dramatically along the print route, with the maximum wear rate occurring at the start and decreasing towards the end of the sample. The heat input influences the material properties, as higher temperatures can result in reduced hardness and an increased wear rate. This occurs due to the deposition technique in WAAM, where each new layer acts as a heat treatment for the previous layer, thereby altering its properties. Consequently, the microstructure and hardness of the material are altered, affecting its overall wear resistance. [112]

Conclusion

This review examines the advancements and challenges associated with Wire Arc Additive Manufacturing (WAAM) of 304L stainless steel components. WAAM provides several advantages, including high deposition rates and cost effectiveness, making it an appealing technology for creating complicated geometries and bespoke components. However, the procedure is not without problems. Residual stress, porosity, cracking, and other flaws are serious challenges that can compromise the mechanical qualities and lifetime of produced components. To eliminate these problems, welding settings, heat input, and post-processing treatments must be effectively controlled.

WAAM-fabricated 304L stainless steel can have its tribological performance greatly improved by surface treatments such as SiC particle impact texturing and nano-scale surface peening. These treatments increase wear resistance and minimize friction, making the material ideal for a variety of applications, including hostile conditions.

Future research should focus on improving WAAM process parameters and creating new post-processing procedures to improve material qualities.

Overall, WAAM is a promising solution for the efficient and cost-effective fabrication of high-performance stainless-steel components, assuming that the process's constraints are adequately handled.

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