

1 INTRODUCTION

This chapter covers cladding-related aspects, such as the necessity for cladding in various industries, classification, and the current cladding landscape. This chapter also highlights the uses, benefits, and drawbacks of friction stir welding and the need for dissimilar cladding.

1.1 Surfacing

Surfacing refers to the act of applying a surface treatment or coating to a material in order to enhance its performance, functionality, and aesthetics. Surface treatments can include chemical treatments, physical treatments, or coatings. The purpose of material surfacing is to either improve wear resistance, corrosion resistance or build-up formation for repair and restoration work. Material surfacing can also involve removing material from the surface to create a desired texture or finish. Surfacing has been performed on several materials, including metals, ceramics, polymers and composites, and numerous methods and techniques have been used to obtain the desired surface finish and properties. These methods include processes like electroplating, anodizing, powder coating, laser surface modification, and plasma treatment, among others. Material surfacing serves as a key factor in industries like aerospace, automotive, and manufacturing, where the performance and reliability of materials are critical.

With constant progress in the field of science and technology, there has been an increase in the demand for surfacing in industries. Currently, they are being used for:

Wear resistance: Industrial components are often subjected to high levels of wear and tear, such as mining equipment, through abrasion, impact, and friction. Surfacing can be used to add a layer of material to the surface of the component, improving its wear resistance and durability.

Corrosion resistance: Numerous industrial parts are subjected to severe environments where corrosion and deterioration may occur over time. Surfacing techniques can prove useful by offering a protective barrier against corrosion, enhancing the lifespan of components, and reducing maintenance costs.

Functional properties Addition: By applying the surfacing technique, one can add specific functional properties to the components, like resistance to chemicals, altered thermal conductivities, suitability for heat sinks, etc.

Aesthetic appeal: Surfacing can be used to improve the appearance of components, making them more visually appealing.

Cost effective approach: Surfacing can prove to be a cost-effective approach for repair and restoration work by adding suitable material to the component rather than replacing the entire product.

Environmental benefits: By utilising less material as a whole or avoiding replacements, surfacing can assist in lessening the adverse impact on the environment as well as improving the durability and longevity of components, thereby reducing the replacement and disposal requirements.

1.1.1 Prominent surfacing techniques

Surfacing plays a pivotal role in improving the performance and functionality of metallic materials across several industries. Depending on the utility, surfacing techniques have been broadly classified into hard facing, cladding, built up technique and buttering.

1.1.1.1 Hard facing

Hard facing is a material surfacing technique that involves adding a layer of hard and wear-resistant material to the surface of a softer material in order to improve its wear resistance and protect it from several forms of damage like wear, tear, and cavitation, as shown in Figure 1-1. This technique is commonly employed in industries like mining, construction, and agriculture, where equipment is subjected to harsh environments and heavy use. Hard facing has several advantages, such as extended equipment life and durability, reduced maintenance costs, and enhanced capability in demanding circumstances. Drill bits, buckets, blades, and rollers are among the few components where hard facing is commonly used.



Figure 1-1 Hard facing edges of the bucket to prevent excessive wear [1]

1.1.1.2 Built up technique

The built-up technique involves adding layers of material over the substrate to modify a surface for repair and restoration work or to create components with tailor-made properties. This technique is very useful for worn or damaged metal components and helps to restore the desired dimensions, maintain the functionality of the part, and restrict further damage. The material used for buildup can be the same as the original substrate material, or a material completely different from the substrate material can be used. In the latter case, the built-up material can be customised to provide enhanced properties, such as higher strength or wear resistance, as well. These processes are used for the repair of damaged components, such as worn shafts or cracked gears. This technique proves to be a cost-effective solution for a worn-out component, as it involves adding material to the damaged area rather than replacing the entire component.

1.1.1.3 Buttering

Buttering is a different surfacing method that involves depositing a layer on the substrate's surface to facilitate proper bonding of the weld overlay, as shown in Figure 1-2. Without buttering, the bonding between these base materials frequently deteriorates or becomes impossible. In contrast to the parent metal and weld metal, the buttering layer has a distinct composition. Buttering can be beneficial while welding two metals that have different expansion rates, as it prevents one metal from expanding into the other and causing cracking [2].

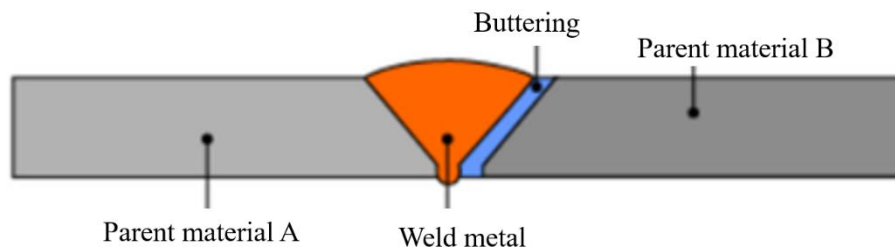


Figure 1-2 Schematic diagram of buttering phenomena [3]

1.1.1.4 Cladding

Cladding refers to the deposition of a corrosion resistant layer of material on the surface of another material to impart corrosion resistant properties. The clad layer is generally a corrosion-resistant material like copper or stainless steel, while the substrate is a corrosion-prone material like mild steel. There are a number of industries where corrosive environments are unavoidable, including the chemical and fertiliser industries, nuclear and steam power plants, food processing, and petrochemical industries, etc. In these industries, a number of process equipment and technical components are subjected to corrosive environments, which shortens their service lives. In such applications, materials with high strength and corrosion resistant

properties are desirable for the long-term reliability and performance of the whole system. However, materials possessing the above properties are costly and add to the overall cost of the system. This led to a rise in the need to improve the service life of a component while also keeping the cost of the material reasonable. For this, the process of cladding surface treatment is used. In this process, a corrosion-resistant metal is deposited on the base material, which imparts to the substrate the properties of resistance to corrosion. This clad layer acts as wall against corrosion. Hence, the property requirement for the material surface is met in a cost-effective way. Clad materials are expected to have the capability of serving their specific function in an aggressive environment for a sufficiently long time economically.

In comparison to whole corrosion-resistant materials, cost benefits can be achieved by using clad materials with lower overall costs while maintaining consistent corrosion resistance. The materials used for cladding vary significantly depending on the application and the desired qualities required in the finished product. This process differs from surface hardening, which only requires altering the properties of the substrate's surface layer, while cladding involves the development of a new surface layer with a different composition than the substrate material. The most common clad systems on a tonnage basis are carbon or low-alloy steels clad with 300-series austenitic stainless-steel grades.

While cladding offers several benefits, there are also some limitations to its application. Like:

Compatibility issue: Compatibility issues can prove to be troublesome, as cladding materials must be compatible with the substrate materials and should have proper bonding between the two without any delamination.

Difference in thermal physical properties: Many times, huge differences in thermal, physical, and metallurgical properties prove to be a limiting factor in cladding.

Cost: Some cladding materials and methods can be expensive, which can again prove to be a limiting factor, forcing industries to opt for replacing components rather than going for cladding.

Desire performance: Many times, cladding can alter the performance of the component, which might prevent industries from accepting cladding as a suitable alternative.

1.2 Types of cladding

Depending on the thickness of the clad layer, the cladding process has been divided into two categories:

- a) Thin cladding/ film deposition
- b) Thick cladding

The details of the two different types of cladding are discussed below.

1.2.1 Thin cladding/ thin film deposition

The technique of depositing a thin layer of material (with a thickness ranging from a few microns to 1000 microns) on a surface is known as thin film cladding. This term is also sometimes referred to as thin film coating. Thin-cladding is comparatively easier to accomplish. Numerous industries, including electronics, optics, energy, and medicine, use thin film deposition. The process is popularly used to create thin films for computer chips, flat panel displays, medical implants, optical coatings, and semiconductors. Prominent thin film deposition techniques are physical vapour

deposition (PVD), chemical vapour deposition (CVD), electroplating, spraying, etc. A few prominent thin film deposition techniques are described below.

1.2.1.1 Physical vapour deposition

The physical vapour deposition technique requires condensation of the vapourised solid material on top of the surface of the solid substrate under the partial vacuum condition, as shown in Figure 1-3. The thickness of the film usually ranges from 1 to 10 μm . Prominent types of PVD methods are thermal evaporation, sputtering and ion plating. The substrate being coated is typically heated to a temperature between 200 and 400 $^{\circ}\text{C}$, which is far lower than the temperatures involved in CVD. However, the material to be deposited on the substrate needs to be vaporized. Depending on the material being deposited and the desired coating thickness, the PVD time cycle ranges from one to three hours. Coatings on gas turbine blades for corrosion resistance, wear prevention coatings for machine and press tools, and anti-reflective ceramic coatings for optics are a few examples where PVD techniques are frequently used [4].

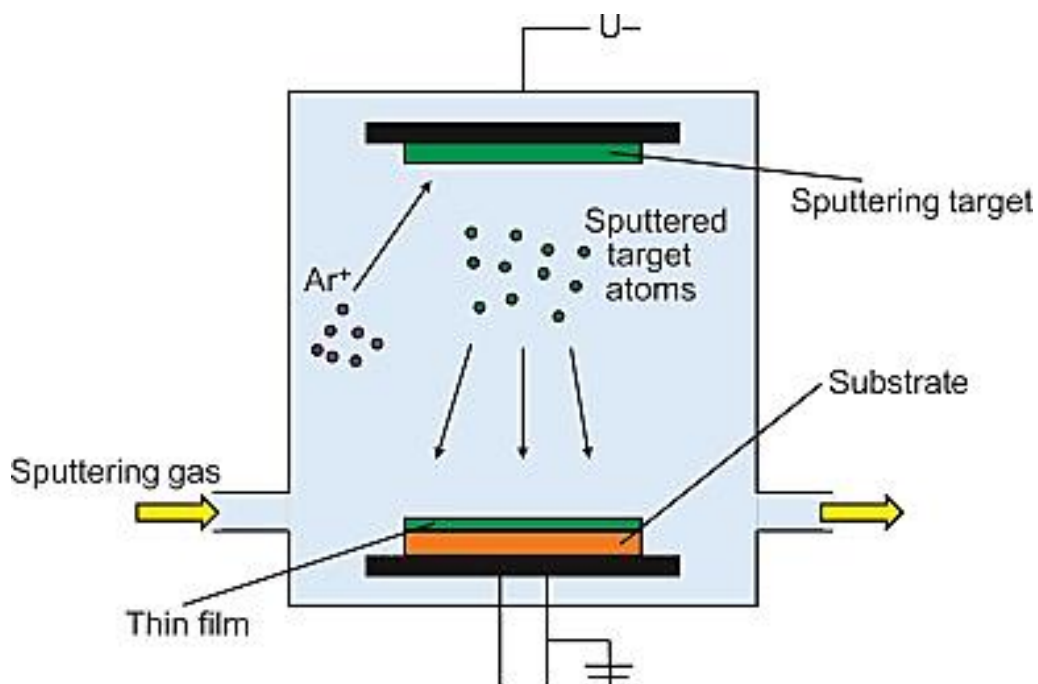


Figure 1-3 Schematic diagram of PVD process [5]

1.2.1.2 Chemical vapour deposition:

Chemical vapour deposition (CVD) is a generic term for the deposition of thin film via a series of chemical reactions [6]. CVD is a technique in which a volatile reactant is fed into a chamber and, when heated to a specific temperature, reacts or decomposes into the desired coating material and bonds to the substrate material, as shown in Figure 1-4 [7]. The quality of films produced during CVD is influenced by a number of process variables and chemical reactions between the reactant and substrate. By using the right combination of process variables, such as flow rates, pressure, temperature, chemical species concentration, reactor geometry, etc., the quality of the film can be controlled and modified [8].

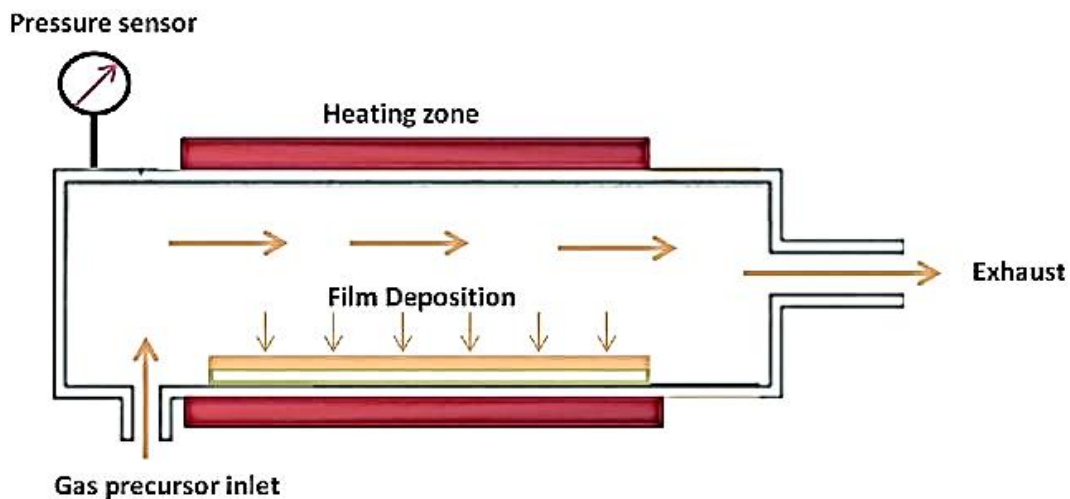


Figure 1-4 Schematic diagram of CVD process [9]

1.2.1.3 Electroplating

Electroplating is one of the oldest methods used for thin film deposition, which involves the process of coating a substrate with a thin layer of a specific material. In electroplating, the key steps include cleaning the substrate thoroughly to remove any contamination that might hinder the adhesion of the thin film. This step may sometimes be followed by pre-treating the substrate to activate its surface for improved bonding.

Next, the metal coating is applied to the substrate using an electrolytic technique. The substrate is submerged in an electrolyte solution that contains the desired coating material's ions. Under the application of a potential, the metal ions in the solution move and deposit on the substrate's surface, as shown in Figure 1-5. The tight control over film thickness and homogeneity provided by electroplating makes it useful for thin film deposition. However, electroplating also faces the possibility of coating contaminants, the need for specific electrolytes, and the constrained material selection that can be used [10].

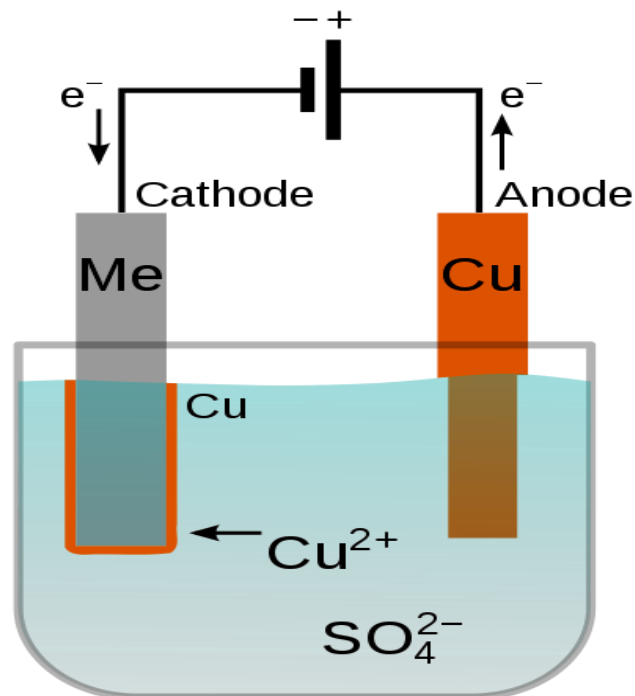


Figure 1-5 Schematic diagram of electroplating process [11]

1.2.2 Thick cladding

When the thickness of cladding ranges from 1 mm to several millimetres, it is termed thick cladding. Thick cladding is mainly used to protect the substrate materials from corrosion. Thick cladding poses more challenges because of the differences in the characteristics of the clad and substrate materials, i.e., physical, chemical, and

mechanical metallurgical properties. Thick cladding may allow the use of inferior and cheaper materials as substrates if they can be coated with a corrosion-resistant material. Thus, saving the cost and giving corrosion performance comparable to clad material. Prominent processes used to produce thick cladding are several arc welding processes, like shielded metal arc welding (SMAW), gas metal arc welding (GMAW), gas tungsten arc welding (GTAW), and submerged arc welding (SAW). High-energy density processes like laser cladding, electron beam cladding and a few solid-state cladding processes like explosive cladding, roll bonding and cold spraying.

1.2.2.1 Cladding through arc welding process

Several arc welding processes are commonly used to deposit a layer of material over another substrate material. Methods like shielded metal arc welding (SMAW), gas metal arc welding (GMAW), gas tungsten arc welding (GTAW), and submerged arc welding (SAW) are a few prominent methods being used currently. These methods offer a distinct set of benefits and limitations over other methods of thick material cladding. Cladding through SMAW offers cost effectiveness and versatility to tailor properties, and use it with ease for repair and restoration work. For cladding with GMAW, this method offers high deposition and production rates, all-position capability, compatibility for use with ferrous and non-ferrous materials, and ease of mechanisation at a low cost. This process is generally marred with dilution of the cladding material with the base material [12]. Cladding with GTAW offers lower dilution due to the quality of the clad layer by controlling the process parameters and keeping the shielding, electrode, and filler material separately. Submerged arc welding (SAW) is another arc welding method used for thick layer cladding, offering the highest deposition rate among all welding methods, enhanced bead properties, and seamless operation.

1.2.2.2 Cladding through high energy beam processes

High-energy beams, such as laser beam and electron beam, have been increasingly adopted in the industry for welding, cladding, and additive manufacturing. Both laser and electron beam cladding offer similar advantages, like high-quality cladding and ease of automation of the process, along with low base material deterioration and distortion. However, they differ in their energy sources and the way in which they deliver the energy to the workpiece.

1.2.2.2.1 Laser cladding

Laser cladding is used for depositing a desired material on the surface of the substrate material to enhance the surface properties of the substrate. In this process, a laser acts as a heat source to melt the substrate's surface and the material being deposited (usually in powder form), generating a melt pool and forming a clad layer. Using a laser beam as a heat source enables minimal dilution (high material purity), fine microstructure, and a small heat affected zone (HAZ) in the deposit layer [13].

1.2.2.2.2 Electron beam cladding

The energy source for electron beam cladding is an electron beam. The procedure entails introducing the cladding material while simultaneously concentrating a high-velocity electron beam onto the substrate's surface. The materials melt and fuse together due to the tremendous kinetic energy of the electrons. High-intensity electron beams enable thorough penetration and bonding between the substrate and the cladding material. Electron beam cladding can achieve higher deposition rates compared to laser cladding.

1.2.2.3 Cladding through solid state welding processes

Cladding through solid state welding processes has shown great potential for various similar and dissimilar material combinations because of the low heat input conditions, as the temperature remains less than the melting point of materials. A few of the prominent cladding techniques are explosive cladding, roll bonding, cold spraying, etc.

1.2.2.3.1 Explosive cladding

Explosive cladding is an unconventional solid-state process of depositing a flyer plate material on another substrate material with the use of explosives. The plates to be cladded collide at an angle with the substrate at a high speed, causing surface jetting and subsequent bonding to occur. The plate to be cladded is set as a flyer plate, which is propelled drastically by the detonation pressure of the explosive and flies speedily towards the substrate plate [14]. Cladding through explosive welding suffers from issues with the use of explosives and limitations for thin cladding.

1.2.2.3.2 Roll bonding

Roll bonding is another solid-state bonding process that can be used to bond two or more layers of similar or dissimilar materials. The process can also be used for cladding. In this process, the metal sheet to be cladded is piled on the substrate and then moved between the rollers in a rolling machine at a high temperature and pressure. The procedure thins the stacked material and permits atoms from various layers to diffuse into one another. Strong metallurgical bonds are produced by this diffusion between the layers. The requirement of surface treatment before bonding and surface contaminants can greatly affect the bond quality produced by roll bonding.

1.2.2.3.3 Cold spraying

Cold spray technology is a solid-state material deposition technique in which micron-sized feedstock powder particles are propelled by pressurised high-velocity gas towards the substrate. These powder particles, upon impact, form a layer of coating [15]. The cold-sprayed coatings have been proven to have minimal porosity, good adhesion, no phase transitions, and rapid deposition. The other benefit of this method is the avoidance of the adverse influence of high temperatures on the coating substance and substrate particles. The particles being coated experience significant deformation, which prompts intimate adherence of the deformed particles to the substrate and to one another [13].

1.3 Friction stir welding

Friction stir welding (FSW) is a solid-state welding process used to join two materials without melting. The process uses a rotating tool that is plunged at the joint between the two pieces of material to be joined and traversed in the desired welding direction, producing the weld as shown in Figure 1-6. FSW is widely used in numerous sectors like aerospace, automotive, marine, and construction industries, where it is used to join a range of materials, including aluminium, steel, titanium, and other ferrous and non-ferrous metals. FSW is a recently developed welding process, invented in 1991 when the TWI research team led by Dr. Wayne Thomas began exploring possibilities to join aluminium for ship panels that were earlier welded using traditional techniques such as MIG and TIG welding. FSW proved to be an efficient and cost-effective method of welding aluminium, and thereafter, it quickly gained popularity. FSW, underwent development and enhancement during the subsequent decades, and its usage marked its presence in sectors other than welding.

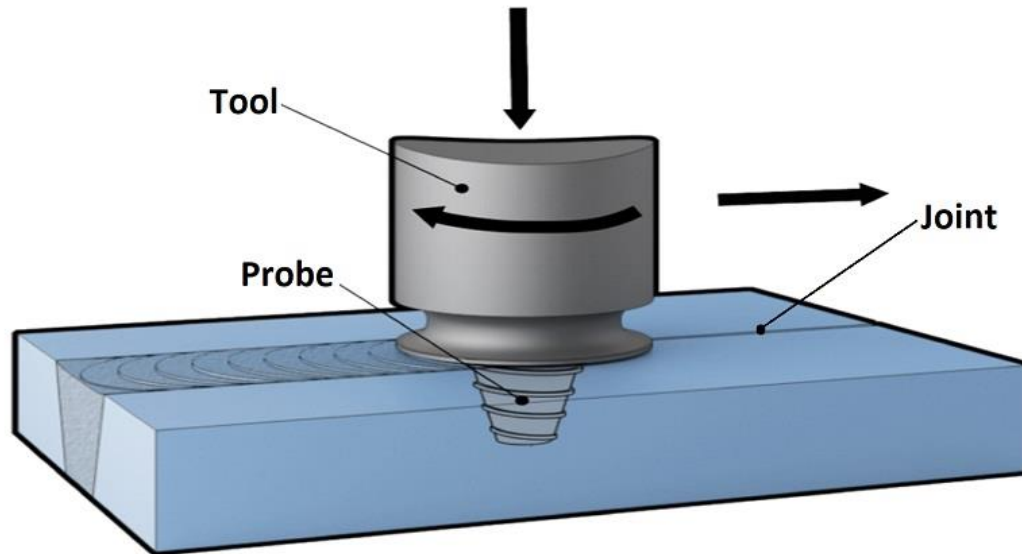


Figure 1-6 Schematic diagram of friction stir welding process [16]

Apart from joining, this process has shown potential for repair and restoration work [17], including underwater joining [18]. FSW is regarded as one of the important advancements in metal joining as it is a "green technology" because it is safe for welders and is energy efficient. As compared to conventional welding methods, FSW consumes considerably less energy. No flux or shielding gas is used in the process, nor does it generate fumes and ultraviolet radiation, which are typically observed in conventional welding processes, thereby making the process environmentally friendly. The joining also does not involve any sort of filler metal, and therefore the joint can be obtained without concern for the compatibility of composition, which is an issue in fusion welding processes [19].

A few of the common sectors where FSW has been commonly employed are mentioned below:

Marine: FSW has become widely accepted over the past decades as a highly efficient substitute for conventional MIG welding for maritime applications, particularly as the industry shifts towards higher usage of aluminium. As FSW is best suited for long straight welds, a significant portion of shipbuilding, such as floors, decks, etc., is

welded by the FSW process. Pre-fabricated wide aluminium panels for high-speed ferry boats have also been produced by FSW, serving as a more cost-effective and efficient solution for boat making [20].

Aerospace: Aluminium and other lightweight materials are frequently joined with FSW in the aerospace sector, especially when making aeroplane wings, fuselage panels, and engine parts.

Automobile industries: Many automotive industries use FSW to join aluminium and other lightweight materials for vehicle components, including body panels, engine blocks, and transmission cases.

Rail: FSW has been used for the construction of container bodies, high-speed trains, underground carriages, and rolling stocks for railways. The process is also used to manufacture roof and floor panels.

Defence: The defence industry has seen a rise in joining materials through FSW for military vehicles, including armour plating and vehicle structures. The construction of lightweight military tanks using high-strength aluminium alloys is another application for FSW.

Electronics: In the electronics sector, FSW is used to join copper and aluminium for producing heat sinks and other electrical components.

1.3.1 Advantages of FSW

As mentioned above, FSW is a green manufacturing process. Apart from this, FSW offers several other advantages over traditional welding methods. Here are some of the most significant advantages of FSW.

No melting: FSW, being a solid-state joining process, does not involve melting the components being joined. As a result, there is no molten metal to cool and solidify, which eliminates the possibility of flaws like porosity and hot cracking.

Low distortion: The FSW process produces low distortion due to the low heat input. The use of the process lowers the risk of warping or distortion in the weld produced.

Reduced post-weld processing: No or minimum post-welding treatment like cleaning, flux removal, grinding or polishing is required after FSW, as this process gives clean, smooth welds.

Versatility: FSW can join a wide range of materials, including aluminium, magnesium, copper, steel, titanium, and many others. It can also be used to join dissimilar materials, such as aluminium to steel, aluminium to copper, copper to steel, etc., which is often not possible through conventional arc welding processes.

Better mechanical properties: FSW produces welds with superior mechanical properties in the stir zone in comparison to the fusion zone of other conventional arc welding processes. The heat-affected zones are also usually devoid of coarse-grain heat-affected zones.

1.3.2 Limitations of FSW

While friction stir welding (FSW) offers several advantages over traditional welding methods, there are a few limitations to the process like:

Limited joint configurations: FSW has traditionally been used for flat or curved surfaces. Joint configurations that are highly curved or complex are more challenging

to weld. Similarly, making fillet welds is also challenging and may require special fixtures.

Tool requirement: A dedicated tool is required each time to weld a specific thickness. Plates with other thicknesses cannot be welded with a ‘general’ tool. Also, the problem becomes more challenging if plates of different thicknesses are being welded in butt welding configuration.

Mobility: While other welding machines are somehow portable, the FSW machine generally remains fixed on the shop floor, and specimens need to be carried to the machine site.

1.3.3 Microstructural Zones in FSW

Welds during FSW are non-uniform on the two sides of the abutted edges because of the different flow of materials, which results in two different sides of welds named the advancing side and the retreating side. The advancing side is the side where the tangential velocity of a point on the tool surface is parallel to the traversing direction of the tool. While the retreating side is on the opposite side, where the tangential velocity of a point on the tool surface is anti-parallel to the tool traversing direction. The flow of material takes place from the leading edge of the tool to the trailing edge via the retreating side and thereafter fills the advancing side through centrifugally forged action. Unlike conventional arc welding processes, FSW develops four distinct welding zones, known as the weld nugget (or the stir zone), the thermo mechanically affected zone (TMAZ), the heat-affected zone (HAZ), and the unaffected base metal, as shown in Figure 1-7. The weld nugget comprises the region travelled by the tool pin, which undergoes intense stirring and high temperatures, resulting in dynamic recrystallization and the formation of new (usually smaller) grains. Adjacent to the

weld nugget zone, on both sides, is the thermally mechanically affected zone (TMAZ), where the amount of stirring and thermal effect is less. TMAZ is generally observed to be composed of deformed grains. Next to TMAZ lies the heat-affected zone (HAZ), where only the effect of heat from welding can be observed. Generally, the temperature in the HAZ is not high enough to cause the coarsening of grains. Beyond the HAZ is the base metal, which has remained unaffected by tooling action and where no influence of heat or mechanical deformation can be found.

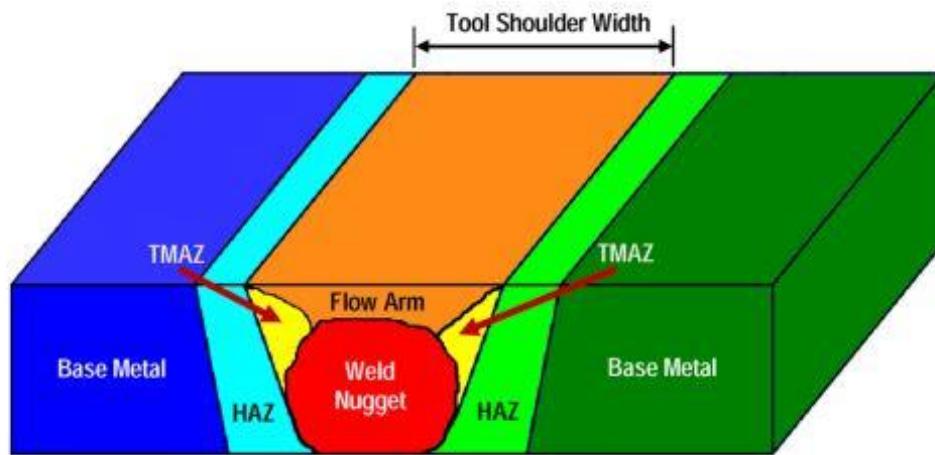


Figure 1-7 Various zones obtained in friction stir welding process [21]

1.3.4 FSW parameters

Similar to other welding processes, the selection of FSW parameters needs to be done wisely to obtain defect-free welds. A few prominent parameters for FSW are tool rotational speed, tool travelling speed, tilt angle, and tool geometry.

Rotational speed: The speed at which the FSW tool rotates is called rotational speed. Rotational speed influences the amount of frictional heat generated, the extent of plastic deformation of the material, and forces on the tool. A higher rotational speed produces a higher heat input to the joint. This may lead to increased tool wear because of the high rubbing action, leading to premature tool or pin failure. On the other hand,

very low rotational speed may lead to less heat generation, resulting in poor bonding [22].

Welding speed: The rate at which a tool travels through a workpiece's joint line is known as the welding speed or travel speed. Optimum welding speed is very important for obtaining a good quality weld. A very high welding speed can produce low heat input and may result in incompletely welded interfaces. Conversely, too slow a welding speed may result in excessive heat input, which may damage the tool and cause the base material to melt. It can also lead to the production of intermetallics [23]. High heat input excessively softens the material, which may cause the plasticized material to flow turbulently.

Tool tilt angle: The angle at which the FSW tool is positioned in relation to the top surface of the workpiece is known as the tool tilt angle. Tool tilt is provided to consolidate the flowing material beneath the tool shoulder. The tool tilt angle helps to prevent expulsion of the flowing material. Tool tilt is generally provided between (0 to 5) degrees. A higher tilt angle may increase the tool wear rate and promote breakage of the tool pin. A higher tilt angle leads to a significant increase in thrust and forging forces at the tool-workpiece contact point [24].

Tool geometry parameter: The FSW tool is one of the most important parameters that needs to be well designed for successful welding. A tool is comprised of a shoulder and a pin, which are usually integral to the tool. The tool pin first gets plunged between the abutting edges of the plates to be welded, followed by the tool shoulder getting plunged. Friction between the revolving tool (pin and shoulder) and the material of the workpiece produces heat, which causes the region of the material below the shoulder to soften. This softened material is easily stirred during the travel of the tool in the

welding direction. The FSW tool may have a shoulder with a convex, concave, or straight profile. Similarly, the tool pin may be either cylindrical, threaded, or of another profile.

1.4 Variants of FSW

Several friction stir welding (FSW) variants have evolved over time and are used in various applications, depending upon their suitability. The most typical FSW variations include:

1.4.1 Friction stir processing

Based on the fundamental ideas of FSW, friction stir processing (FSP) was developed as a material processing method in 1999. In FSP, a tool with a short pin is used for localised surface microstructural modification for specific property enhancement, as shown in Figure 1-8. FSP has definite advantages over conventional metalworking processes. FSP is a solid-state, single-stage processing method that maintains the size and shape of the processed metallic materials while providing grain strengthening, homogeneity, and grain refinement. With proper control of the tool design and FSP settings, it is possible to precisely control the microstructure and mechanical characteristics of the processed region. In this method, the depth of the processed region can be controlled by controlling the tool pin length. The pin length may range from zero to a few millimetres [25]. An extensive review of the influence of FSP on the microstructure, mechanical and corrosion behaviour of steel has been carried out by Merah et al. [26] and an excellent review of FSP technology has been carried out by Ma et al. [25].

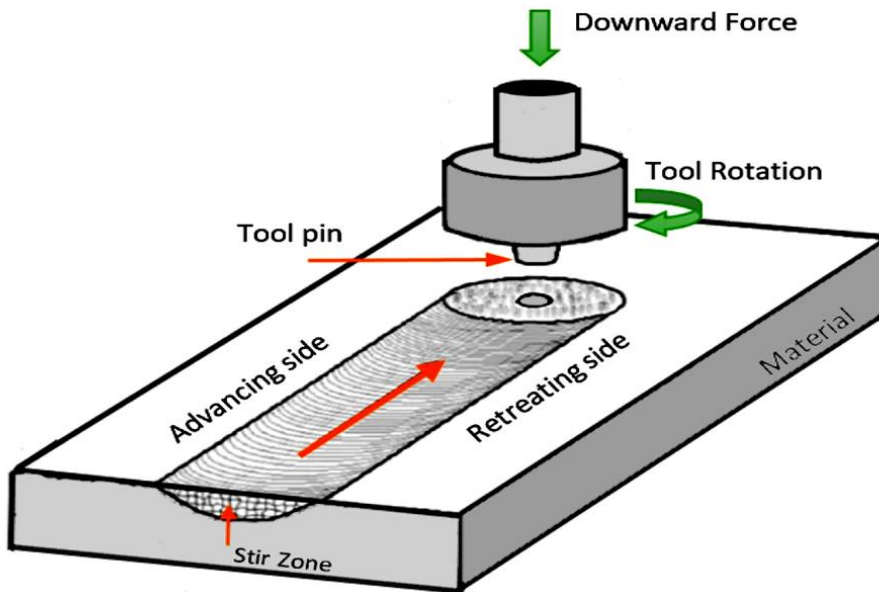


Figure 1-8 Schematic illustration of friction stir processing method [26]

1.4.2 Friction stir spot welding

In friction stir spot welding, two similar or dissimilar plates are arranged in a lap joint configuration, and a rotating FSW tool is inserted from the top at the location where a spot weld is desired. The tool pin reaches up to the required depth, which is slightly more than the thickness of the top lapped plate, and the shoulder contacts the plate. The tool keeps rotating for a specific period of time called, holding time. The plunging action of the tool in a downward direction and the shoulder rubbing produce heat through friction and plastic deformation, resulting in the softening of the material around it and thus creating a strong bond, as shown in Figure 1-9. Following this, the tool retracts back from the specimen, leaving a solid-state bond between the two plates and the keyhole. Unlike the FSW process, the plunging tool does not traverse in a linear direction and thus results in the formation of only spot welds [27]. An extensive review of the friction stir spot welding process has been carried out by Shen et al. [28] and Pan et al. [29].

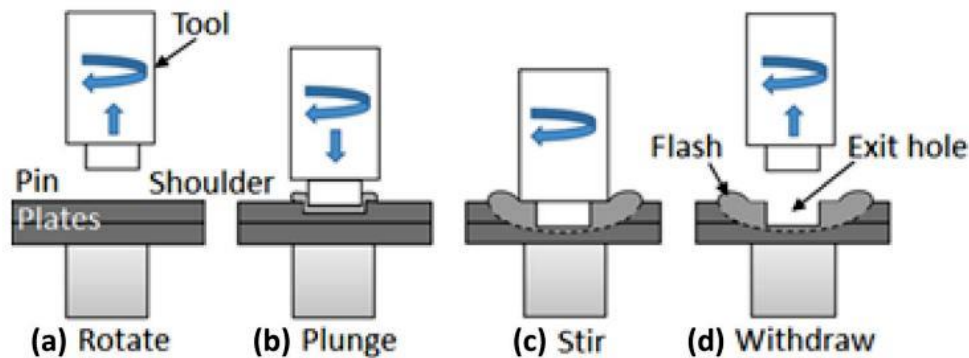


Figure 1-9 Pictorial representation of friction stir spot welding process [27]

1.4.3 Bobbin tool friction stir welding

A specially designed tool with two shoulders (one above and one below the workpiece) is used in the bobbin tool FSW process. Throughout this welding process, a pin in the centre joins the two shoulders and penetrates through the thickness of the workpiece [30]. The method is useful for joining closed sections when using a well-supported backing bar is challenging or impossible. The bobbin tool produces a full penetration weld and eliminates the possibility of kissing bond defects. During this process, the plates are clamped from the sides without a backing plate, and the tool stirs the material between the shoulders of the bobbin tool, as shown in Figure 1-10. Unlike other FSW variants, this process involves zero vertical force [31]. An extensive review of the bobbin tool FSW has been carried out by Fuse et al. [32]. Another review on the relationship between welding forces and defect generation in bobbin tool FSW has been carried out by Liu et al. [33].

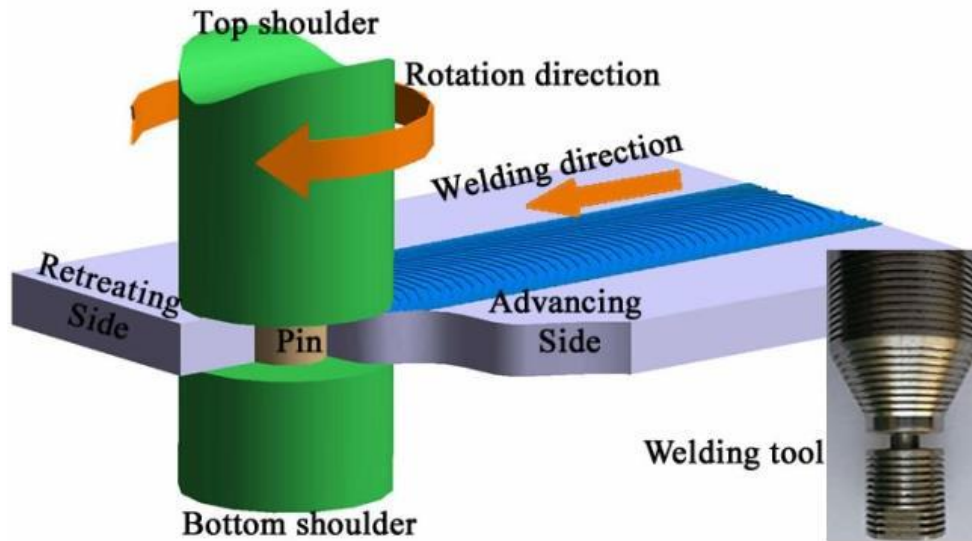


Figure 1-10 Schematic illustration of bobbin tool friction stir welding process [34]

1.4.4 Friction stir cladding

Friction stir cladding is a variant of FSW where a corrosion-resistant material is deposited onto the top surface of another material through repeated welding passes. In this process, the clad material is placed on top of the base or substrate material. Some of the commonly used clad materials are copper, stainless steel, aluminium or titanium. Both plates are securely clamped in the FSW table, and a rotating tool plunges from the top, piercing the clad material and reaching the substrate material, executing an FSW pass. Adjacent to the previous pass, multiple passes are made, covering the entire substrate plate, as shown in Figure 1-11. This process is frequently applied to enhance a component's corrosion resistance.

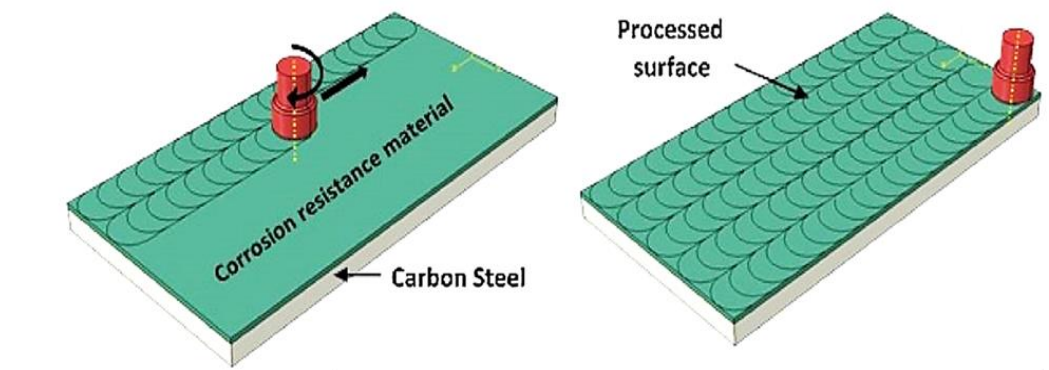


Figure 1-11 Schematic diagram of friction stir cladding process [35]

1.5 Advantages of friction stir cladding

Friction stir cladding has several benefits over conventional cladding processes, like:

Better control over the thickness of the cladding layer: Cladding through the FSW process allows precise control over the thickness of the clad layer, which is difficult to control through other cladding techniques.

Improved bonding: Friction stir cladding often results in a stronger bond between the clad material and the substrate material due to strong mechanical and metallurgical interactions between the clad layer and the substrate, compared to other processes.

Reduced dilution: Friction stir cladding often produces less or no dilution of the cladding material and can thus preserve the original properties of the clad material.

Reduced distortion: Being a solid-state joining process, cladding through FSW typically produces less distortion. The residual stress has been found to be compressive in nature or of lesser magnitude tensile when compared to other cladding techniques.

Wide range cladding potential: High-quality deposits on a wide range of substrate materials, including incompatible materials (like copper on steel), can be obtained using FSW, which are difficult to obtain through other cladding processes.

1.6 Dissimilar cladding

In recent years, industries have placed an increased emphasis on sustainable development, which requires reducing costs and boosting the effectiveness of metallic materials derived from limited resources. Moreover, it has become very difficult to meet the wide variety of demands for a single material. As a result, clad metals, which combine two or more metals, have become popular due to their distinct qualities [36]. Clad materials are increasingly being used for several applications, particularly in automobiles, cookware, electrical distribution systems, energy storage and catalytic converters [37]. Copper and copper alloys rank as one of the most important materials based on their high thermal conductivity, strong corrosion resistance, and mechanical workability. They are predominantly used in condenser and heat exchanger tubes and other applications requiring corrosion resistance [38]. As the use of copper and its alloys in industries has increased, so has the demand for joining this metal with similar or dissimilar materials.

In order to increase the acceptability and applicability of inferior or diverse properties-enabled materials, many materials have been joined with copper, like steel, titanium, aluminium, and magnesium, to name a few. Copper clad aluminium is used for the construction of heat sinks, which combine the benefits of the high thermal conductivity of copper with the high heat capacity of aluminium [39]. Cladded bus bars with superior properties like structural rigidity are also replacing pure copper bus bars.

Cladding of corrosion-resistant materials like copper and stainless steel has been carried on top of mild steel to prevent the base mild steel substrate from environmental degradation. During the cladding of stainless steel over mild steel, it faces carbon migration from the mild steel side to the stainless-steel side, which reacts with chromium, forming the harmful chromium carbide, which weakens the bonding strength and destroys the corrosion resistance [40]. Also, when the stainless-steel-clad plate interacts with a hydrogen-containing environment, the absorption of hydrogen takes place. Researchers reported that residual stresses can promote hydrogen diffusion, which can cause interface debonding, hydrogen embrittlement and hydrogen-induced cracking [41]. Similarly, when cladding copper on mild steel, particularly by conventional welding processes, brittle intermetallics form, which deteriorates the properties of the clad layer obtained.

Copper is a highly corrosion-resistant material. It forms a protective oxide layer (patina) over time, which avoids further corrosion, while certain grades of corrosion-resistant stainless steel may be susceptible to localised corrosion in specific environments. Additionally, copper has a better thermal conductivity than stainless steel, which makes it appropriate for use where heat transfer efficiency is crucial, like heat exchangers or heat-dissipating devices. The electrical conductivity of copper is also excellent. Therefore, copper-cladded steel may have potential applications in making bus bars. Compared to stainless steel, copper is more ductile and malleable, making it easier to form into complicated shapes. Copper also has anti-microbial qualities that prevent the growth of bacteria, fungi, and other microbes on its surface. Therefore, this challenging task was undertaken to provide a solution for cladding the copper layer on mild steel.

Cladding of copper on steel combines the high tensile strength of steel with the corrosion resistance of copper and is used for a wide range of applications. Copper-cladded steel is being increasingly used for electrical components such as fuse clips, connectors, circuit breakers, etc. Low-cost copper-clad steel wire is being used especially for high-frequency power transmission, wherein the high mechanical strength of steel is combined with the high electrical conductivity of copper [42]. Copper-clad steels are used for producing cannisters for storing nuclear leftovers [43], along with having usage in ITER blanket system operations [44] and Bundy tubes [45].

Joining copper with steel is a hard-hitting task. The diverse crystal structures of both materials restrict their solubility limits. The science of thin-film deposition of copper on steel is well established, but the deposition of thick copper material (greater than 2 mm) on top of steel has always faced numerous difficulties because of the wide differences in their properties (physical, chemical, mechanical, metallurgical, and thermal), and it prohibits uniform and favourable joining of these dissimilar materials. The clad layer is marred by interlayer formation and thermal fatigue arising due to the wide thermal expansion coefficient of dissimilar joining metals [46], interface diffusion control during high heat [47], poor mixing, porosity, microcracking [48], etc.

Each fabrication method and each set of materials face a distinct set of challenges. Fusion welding processes have the inherent problem of dilution of the clad material with the substrate material. Solid-state welding processes like roll bonding and explosive welding, although superior to fusion welding processes, have their own limitations [49]. Laser cladding of copper has reflectivity issues, owing to which proper clad material is hard to produce. The friction stir welding (FSW) process has been used for a long time for welding and surfacing applications. Previous researchers

working in the area of FSW have mainly attempted either lap joining, butt joining or processing, but only a handful of researchers have attempted friction stir cladding for the deposition of thick material on substrate material.