

2 LITERATURE REVIEW

In this chapter, the discussion related to several aspects of cladding through commonly employed processes like arc welding processes, high energy density beam processes, and solid-state joining processes has been done. Discussion regarding dissimilar joining through friction stir welding, in butt and lap positions, and attempts at cladding through FSW has also been discussed. This chapter also finds a research gap based on the literature review.

2.1 Cladding

As discussed in introduction section 1.1.1.4, cladding refers to the surface treatment process that involves applying a layer of corrosion resistant material to the surface of another material, i.e., the substrate material. Here, a layer of corrosion-resistant material is placed on a cheaper substrate (mild steel) so as to increase the corrosion resistance of the engineering components, with the objective of increasing their service life. Thick cladding acts as a barrier against corrosion.

Weld cladding techniques were originally developed for the use of navy defence components by Strachan & Henshaw, Bristol, a major defence and nuclear engineering company. The developed cladding techniques were intended for use on parts of machinery that needed to operate in seawater with the least amount of maintenance while still being subjected to extremely high pressures and shock loading [50]. Additionally, cladding techniques were used on subsea components to make the

exterior layer corrosion-resistant to corrosive saltwater solutions [51]. Inconel 625 has also been used to coat a few areas of the submarine's pressure hull [52]. The pressure vessels used in power plants were clad to offer an anti-corrosive and durable surface layer to withstand harsh working conditions at high temperatures [53]. Several manufacturing processes have been used to deposit a thin or thick layer of material over another material, depending on its suitability.

The thick-cladding process can be broadly divided into:

- Arc welding processes: SMAW, GMAW, GTAW, and SAW
- High-energy beam processes: laser welding, electron beam welding
- Solid-state processes: roll bonding, explosive welding, and cold spraying

Despite advancements in the science of cladding, thick cladding still faces several challenges due to the complexity of the process. The different types of cladding processes, along with their advantages and disadvantages, are discussed below.

2.2 Cladding through arc welding processes

In all arc welding processes, an arc is established to melt the surface of the base material, usually in the presence of a shield gas. The clad material is then introduced in the form of filler material and is also melted by the arc, thereby forming the clad layer. The various approaches to arc cladding differ in details such as type of heat source, usage of the filler metal as the electrode, use of flux, or extent of penetration.

2.2.1 Cladding through shielded metal arc welding

Shielded metal arc welding (SMAW)/ manual metal arc welding (MMAW) is a labour-intensive arc welding process that uses a consumable electrode that is coated with a

layer of flux. This process has been widely used to weld a range of mostly ferrous materials. SMAW has been employed extensively in the construction of heavy steel structures and in industrial fabrication, along with maintenance and repair.

Cladding through manual metal arc welding is one of the most cost-effective methods available, along with having great flexibility to operate. This method provides the opportunity to use it in restricted areas with all position cladding. This method provides the opportunity for quick selection and change of stick electrode for cladding, which is not readily possible through other arc methods like GMAW or SAW.

Several authors have reported cladding of superior metal over other low-grade substrate materials. Singh et al. carried out the deposition of SS-316 stainless steel on mild steel by shielded metal arc welding and studied the corrosion behaviour of the clad material [54]. Cladding of 308L on ship building grade steel material through SMAW has been performed by Mohammed et al., where the authors reported that, while performing the bend test on the produced clad, the clad layer failed under tension at 60 degrees while survived under compression till 140 degrees, showing a somewhat acceptable bond integrity [55]. Buchanan et al. did the comparison of the iron-chromium hard-faced coating developed by SMAW and electric arc spraying. They also compared the abrasive wear behaviour of cladding produced by both the methods [56].

2.2.2 Cladding through gas metal arc welding

Gas metal arc welding (GMAW), among other weld cladding methods, is a cost-effective, user-friendly, and versatile method for protecting the surface of comparatively lower grade structural steels from corrosion by depositing high grade materials onto them [57] as shown in Figure 2-1. Welding current/wire feed speed,

welding speed, nozzle-to-plate distance, and shielding gas flow rate have been found to be the primary process parameters for cladding using the GMAW process [58]. To prevent any contact of the molten weld pool with the atmosphere, shielding gases like Ar, He, CO₂ or N₂, or their mixtures, are used, which prevent the hot molten metal from reacting and forming oxides and nitrides that could cause deterioration in the weld properties. As no flux is used, there are no chances of slag formation, which increases the quality of weld [59].



Figure 2-1 Thick cladding obtained by GMAW process [60]

Some initial work on cladding has been reported by Murugan et al., where stainless-steel cladding has been done on structural steel plates with an automated GMAW process [61]. Matias et al. performed multipass cladding of austenitic stainless steel on carbon steel by the GMAW process and observed the macrographs of the cladding. There was no evidence of cracking or disbanding [62]. Khan et al. performed cladding

of 309L stainless steel on mild steel using the pulse current GMAW technique. The authors reported that high heat input can deteriorate the clad properties, which could be overcome by the use of pulse-assisted GMAW [63].

Several attempts have also been made to simulate and optimise the process parameters of GMAW cladding using different algorithms. Palani et al. optimised welding process parameters for the cladding of stainless steel using Taguchi's method for the optimisation of cladding process parameters to obtain desirable weld bead geometry [58]. A genetic algorithm-based computational model for optimisation was used by Yogananda et al. for the optimization of GMAW process parameters for stainless steel cladding [64]. Shreeraj et al. did parameter optimisation of the GMAW process using neural networks and particle swarm optimisation algorithms to get the optimum dilution in stainless steel cladding of low carbon structural steel plates [65].

A review of cladding through GMAW with respect to anti corrosiveness has been reported by Singhal et al. [49]. Saha et al. [12] reviewed the GMAW process, highlighting the various parameters, their optimization and their impact on GMAW cladding. In spite of several benefits of cladding through GMAW, it still faces difficulties during thin section cladding. Compatibility issues between clad and substrate material and spatter control are other prominent constraints of the process. Dilution between clad and substrate material may deteriorate the clad material's original properties, hampering its functionality. The prolonged inhalation of toxic gases released during cladding through GMAW is another crucial factor that may adversely affect the health of workers.

2.2.3 Cladding through GTAW

In the gas tungsten arc welding (GTAW) process, the heat generated by the electric arc between the workpiece and tungsten electrode is used to melt the workpiece and the coating material. By maintaining process parameters within allowable ranges, a high-quality clad layer can be produced, as shown in Figure 2-2. Cladding through GTAW offers high quality, low distortion, and spatter-free cladding. This method enables precise control of welding heat, resulting in a lower dilution between the clad and substrate material.



Figure 2-2 Cladding obtained through GTAW process [66]

The cladding through GTAW has been found appropriate by several researchers for improving substrate properties. Chen et al. performed the deposition of multicomponent alloy filler on low-carbon steel substrates using gas tungsten arc

welding. The author stated that during the GTAW cladding process, the mixed metallic powder fillers were melted on the substrate surface and then rapidly solidified to form a dense cladding of 4 mm thickness, firmly bonding to the substrate [67].

Researchers tried using GTAW for depositing copper on a variety of steel substrates. Pooarporn et al. stated optimum conditions for the construction of vacuum systems, requiring materials to have sufficient mechanical strength, impermeability to gases, low vapour pressure and the ability to work under unfavourable conditions [68]. The authors joined oxygen-free thermal conductivity (OFHC) copper and 304 stainless steels for ultra-high vacuum applications through GTAW and reported proper welding. They found that the welding current had a significant impact on the depth of fusion, and a hook-like structure was formed in the weld zone, which strengthened the joint. The authors also stated that no microcracks or pores were found in the fusion zone, as confirmed by XRF mapping and optical SEM images. The authors reported that at the interface, dendrites were observed on the stainless-steel side, while small globules were reported along the copper side during solidification

A combination of MIG-TIG double-sided arc welding for copper-stainless steel was used by Cheng et al. [69]. This method seems to be gaining attention for dissimilar metal joining due to its low heat input and precise energy regulation. In this technique, a TIG torch without filler metal was placed on the rear of the workpiece, and a MIG torch was fixed to the top of the workpiece. The authors observed no pores, spatter, or cracks between the joints, demonstrating the great ability and flexibility of MIG-TIG with regard to various filler materials.

An extensive review of cladding employing the GTAW method for improving the surface properties of engineering materials has been carried out by Biswas et al. [70].

Although the capabilities of GTAW for cladding have been demonstrated, it encounters several shortcomings, like a lower deposition rate. This process is also less economical for thick cladding in comparison to processes that use consumable electrodes for cladding. Contamination of the clad layer may also occur due to tungsten inclusion if the electrode accidentally touches the weld pool.

2.2.4 Cladding through submerged arc welding process

In modern industries, cladding through submerged arc welding has been most commonly used, particularly for heavy section steels and for huge structure surfaces that need to be changed. Submerged arc cladding, in comparison to other cladding processes, offers very high deposition rates, larger layering capacities, and better bead characteristics with less sophisticated mechanised equipment [71]. The flux particles play a significant role in the submerged arc welding process. The arc is covered and shielded by flux in such a way that the wire and the arc are completely engulfed in the flux stream. Due to this, the SAW method produces a rather clean weld and emits almost no intense heat radiation, in contrast to the majority of traditional open welding methods. As it prevents any radiation loss, convection loss, or energy dispersion from wire to substrate, flux covering has the additional significant benefit of raising energy transfer efficiency to more than 90%, contributing to a high deposition rate and favourable weld reliability [72].

Several authors have reported successful cladding with submerged arc welding. Toit et al. enhanced the lifecycle of low-alloy steel continuous casting rolls facing extreme temperature fluctuations and harsh environments during service [73]. The authors clad the rolls through submerged arc cladding with nitrogen-alloy martensitic stainless steel. The authors additionally heated the martensite after the cladding

process to temper it to the desired hardness level. Lu et al. carried out the deposition of Fe-Mn-Cr-Mo-V alloy, which has been used as a cladding material on rollers, idlers, mine car wheels and similar equipment involving severe metal-to-metal wear (made of AISI 1045 carbon steel) by an automated submerged arc welding process. The authors investigated the effect of welding parameters on the microstructure and wear behaviour of the cladding [71]. SAW has proven itself to be beneficial for the repair of bulldozer rollers [74], rail parts [72], and many other intensive works. Efforts have also been made to increase the productivity of cladding through SAW through the application of multiple wire involvements and metal powder addition [75]. Dragan et al. explored the possibility of performing automatic submerged-arc welding and cladding using low density current for narrow-gap welding of plates and repair cladding of freight car wheel flanges [76].

Although high-deposition rate cladding is possible through SAW, this process is limited to ferrous alloys and has not been fully explored for non-ferrous materials. This process also suffers from troublesome flux handling systems and requires post-weld slag removal.

2.3 Cladding through high energy density beam processes

High-energy density welding processes are those that concentrate the energy required for welding in a very small region. Also, because of the extremely low overall heat input to the workpiece, the base metal's deterioration, residual stress, and distortion are greatly reduced. Laser and electron beam welding are the two popular high-energy-density processes. In comparison to other welding techniques, high energy density processes result in weld profiles with a high depth-to-width ratio, which makes them capable of weld much greater thicknesses, especially when using the EBW process

[77]. A detailed review of the high-energy density beam process for welding and additive manufacturing applications has been carried out by Patterson et al. [78].

2.3.1 Cladding through laser energy

Cladding through laser has been tried and demonstrated by several researchers. High welding speed, a high degree of flexibility, ease of automation, and reduced distortion of the components due to lower heat input, are a few prominent advantages of laser welding and cladding. In laser cladding, fusion between the clad material and the base metal is obtained by the thermal energy obtained from a laser source. The schematic diagram of laser cladding has been shown in Figure 2-3. Joining through a laser provides high power density, along with the capability of locally restricting the heat energy input. This enables controlled distribution of heat with minimum exchange of joining materials, thus avoiding the formation of brittle intermetallics [79].

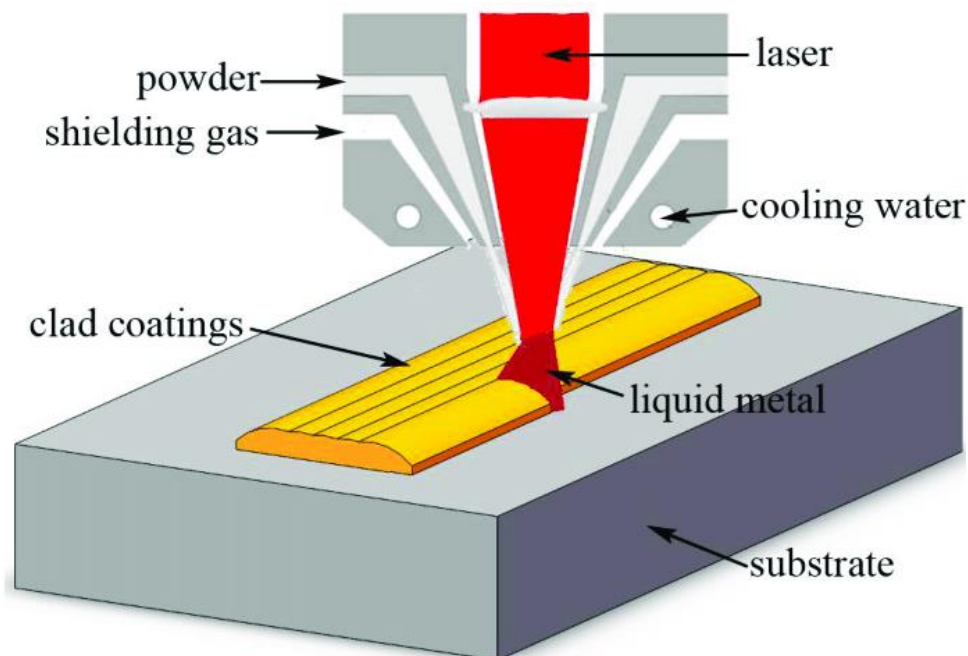


Figure 2-3 Schematic diagram of laser cladding process [80]

Arnold et al. studied the possibilities of laser powder technology for welding and cladding and highlighted that the maximum thickness that laser deposition offers can be in the range of a few millimetres [81]. The authors also added that sound bonding could be obtained between the coating and the substrate, and the possibility of pores and crack formation was lower in the process. They also added that during laser cladding, the bulk of the powder interacts with the laser beam before reaching the surface of the workpiece and depending on the composition, size, and density of the powder, the powder absorbs some of the laser's energy. The thin surface layer of substrate melts during cladding as only the leftover laser energy, which is neither absorbed nor scattered by the particles, eventually strikes the substrate.

A few initial attempts at cladding through laser have been attempted by Powell et al. [82]. Laser cladding has proven to be an appropriate method for creating precise, error-free coatings of different materials for increased wear and corrosion resistance. Laser cladding of Mg-Al alloys has been successfully reported by Wang et al. [83], while laser cladding of stainless steel on magnesium composites has been carried out by Yue et al. [84]. Laser cladding of cobalt-based alloys on copper bases has been successfully carried out by Yan et al. [85], and similarly, the cladding of nickel base alloys on copper has been carried out by Liu et al. [86]. Sampedro et al. carried out laser cladding of TiC on titanium components to reduce surface damage during contact loading [87]. Parekh et al. carried out a two-dimensional simulation of the laser cladding process to understand the influence of process parameters on clad geometry formation for better process optimization [88]. An interesting study on the design and development of nozzles for coaxial laser cladding has been carried out by Lin et al. [89]. Wang et al. studied the mechanism of crack formation during laser cladding by studying the

surface with the help of a novel acoustic emission technique and finite element analysis [90].

In an interesting work, Mai et al. performed laser welding experiments on three different metal combinations, i.e., Kovar-tool steel, copper-tool steel and copper-aluminium alloy and reported sound welding using a pulsed Nd: YAG laser. The authors reported that while joining dissimilar metals, precise control of the melting ratio of metals is very essential for defect-free welds [79]. Cladding a thick layer of copper on steel has been attempted using CO₂ laser system for plasma vertical stabilisation in the Tokamak operation. A 3 mm thick coating is found to be more suitable for those surfaces of vessel components that were plasma facing in advanced fusion reactors during plasma vertical stability when extracting excessive heat load from ITER reactors [91]. Yao et al. enlisted the several difficulties that arise during the joining of copper to steel through laser. The authors highlighted that the reflectivity of copper to a specific 10.6 μm wavelength CO₂ laser is very high (above 98 percent), which leads to a lower absorptivity of copper. The authors further added that solidification cracking can be generated due to the large differences in thermal expansion coefficient and thermal conductivity of copper and steel, resulting in large strain misfit residual stresses. They also emphasised the possibility of phase transformation due to high-temperature gradients and the possibility of porosity due to the high solubility of hydrogen in liquid copper. The authors further recommended scarf joint geometry during laser welding of copper on steel to overcome the temperature inhomogeneity, arising because of the high reflectivity of copper to the CO₂ laser and investigated the microstructure arising with different dilution ratios of copper [92].

Similarly, Phanikumar et al. performed continuous CO₂ laser welding of dissimilar Fe-Cu in a butt-weld geometry with inert gas shielding containing a mixture of helium and argon and obtained defect free welds [93]. The author added that the obtained welds were asymmetric at all traversing speeds, and as speed increased, the weld pool depth dimension decreased. The authors further added that microstructural bands were observed in the weld pool and at the interface along the steel side, which appeared smooth with a well-mixed iron-rich region, while the copper side interface seemed rough with a high copper-rich region, along with a high compositional gradient towards the copper side due to the high thermal diffusivity of copper, causing quick solidification.

Unlike other straight-line laser welding methods, Ciou et al. joined copper to stainless steel using zigzag and circular laser beam oscillation welding methods [94]. The authors reported that both oscillation welding modes obtained better grain refinement compared to conventional straight-line welding. The authors further added that circular oscillation motion proved to have a higher depth of fusion due to the greater overlap of the laser path during the process, resulting in better and more uniform mixing of the alloying elements within the weld pool. The authors found higher yield strength (YS), higher average microhardness for the circular laser welding, and a lower pore formation capacity in the weld pool.

An extensive review of the current scenario and progress on laser cladding has been nicely explained by Liu et al. [95] and Siddiqui et al. [96]. A review of the possibilities of in-situ repair through laser cladding technique has been dealt with by Raj et al., where the authors highlighted the pros and cons of repairing through conventional methods in comparison with laser welding [97]. Cladding with laser is marred by high

investment costs of the laser system, limited material selection, difficulty in handling powders, cracking during high build rates, complex control of process parameters, and high running costs.

2.3.2 Cladding through electron beam

With the demands for more reliable joints, electron beam welding (EBW) technology was initially used primarily in the nuclear, aerospace, and aircraft sectors. EBW works by using the kinetic energy of electrons as a heating source to melt the materials to be bonded. These electrons are produced by heating a negatively charged filament (cathode) to the temperature range at which it emits electrons via thermionic emission. EBW's capacity to accomplish deep penetration using the "key-hole mechanism" is one of its distinguishing characteristics, and electron beam weldments generally exhibit high depth-to-width ratios. Welding through EBW offers low total heat input per unit length of weld, resulting in a narrow weld bead and HAZ, lower residual stresses and minimal distortion. The controllable energy density enables the control of dilution as well. The main processing variables in the EBW are the welding speed, the vacuum level, the beam current, the beam accelerating voltage, and the focusing lens current (focal beam spot size) [98].

Yu et al. carried out cladding of AlCrTiNbMo, a high-entropy alloy coating on Ti 600 (titanium) substrate, by electron beam cladding and observed excellent wear-resistant capabilities of the same [99]. Yu et al., in their other work, deposited refractory high-entropy alloy coatings on top of Ti 600 substrate by electron beam cladding. The authors found sound metallurgical bonding with good surface formation with no cracks or pores. They further proposed that the improvement in surface properties was attributed to the solid solution, second phase and precipitation strengthening [100].

Klimenov et al. examined the possibility of deposition of Ti-Au over a Ti-6Al-4V substrate plate by the electron beam powder bed fusion method [101]. The clad layer, composed of titanium powders and gold foils, served as a feedstock, generally used for dental implants. The authors also observed that gold-containing intermetallic compounds formed throughout the cladding surface.

Sun et al. reviewed the application of electron beam welding for the joining of dissimilar metals [98]. Similarly, Weglowski et al. reviewed the current trends and foregoing advancements in electron beam welding [102]. A review on wire feed electron beam additive manufacturing has been carried out by Osipovich et al., where the authors elaborated on the structures and mechanical properties of additively manufactured components with a focus on post-processing of the same [103]. The process of EBW suffers from the inability to weld low temperature materials, the requirement of a vacuum chamber, less flexibility, high investment, and high skills to operate.

2.4 Cladding through solid state welding processes

Solid-state welding (SSW) refers to a group of welding processes that produce sound joints at temperatures that are essentially below the melting points of the parent materials. In SSW, bonding is accomplished through deformation and diffusion at specific pressures and temperatures using mechanical, electrical, or thermal energy. In these processes, bonding time can range from less than a tenth of a second for explosive welding to several hours for diffusion bonding. Solid-state welding may have its origins in ancient times before 1,000 B.C., when people joined metals by simply hammering them together, a process we now refer to as forge welding.

When compared to fusion welding methods, solid-state joints are typically free of various solidification flaws, such as gas porosity, hot cracking, and non-metallic inclusions. Solid-state welding does not require flux, filler metals, or shielding gas. Due to the absence of solidification flaws and heat-affected zones in the majority of these techniques, the metal being joined can have mechanical properties comparable to those of its parent metals. SSW proves to be ideal for combining dissimilar materials because issues with conductivity, thermal expansion, and chemical compatibility do not play a major role during these processes [104]. Solid-state bonding encompasses a broad range of techniques, including forge welding, ultrasonic welding, friction welding, friction stir welding, resistance welding, diffusion bonding, and explosive welding.

2.4.1 Cladding through explosive welding

Explosive welding is a solid-state lap welding process, showcasing the potential to join dissimilar material combinations with very different physical properties, like aluminium/copper [105, 106], aluminium/carbon steel [107], titanium/copper [108], brass/steel [109], nickel/aluminium [110], and aluminium/stainless steel [111], among a few. The principal mode of operation of explosive welding relies heavily on explosives, which, when detonated, create a compression force that is used to bond the overlapping metal sheets. The top plate to be joined (called the flyer plate) is tilted at certain degrees with respect to the other plate (called the target plate), and a layer of explosive is placed on the top of the flyer plate. Once the ignition takes place, the flyer plate is accelerated towards the target plate, which, upon impact, causes local plastic deformation of the contact area, resulting in continuous joining as shown by the schematic in Figure 2-4. The stand-off distance is the distance across which the flyer

plate can be accelerated to get the desired impact velocity. The interaction of mating surfaces, i.e., the flyer plate and base plate, produces a characteristic “surface jetting” effect, producing strong joints. The strength of the joint produced using explosive bonding surpasses the strength of the weaker mating material [14].

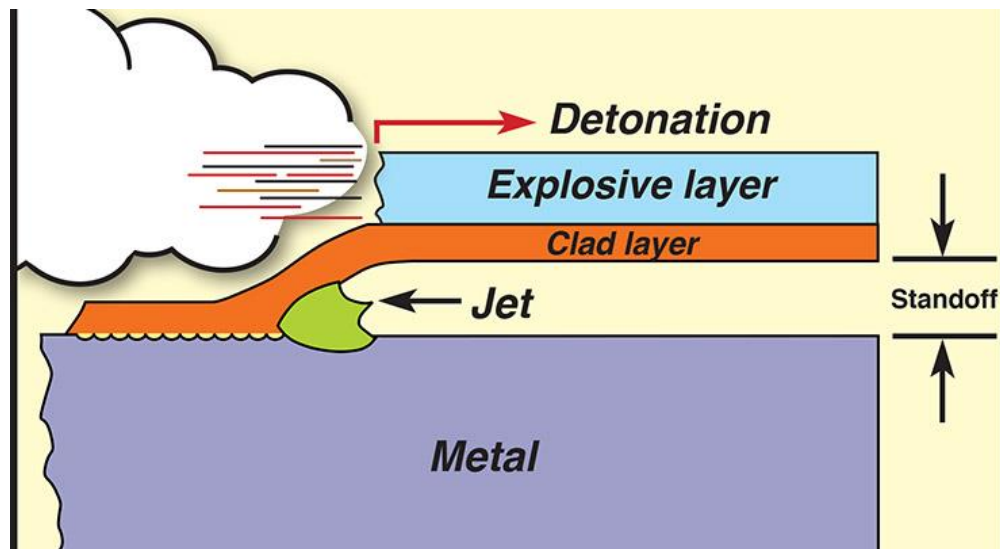


Figure 2-4 Schematic diagram of explosive cladding process [112]

An introduction to explosive welding and cladding was carried out by Bahrain et al. in 1964 [113]. Mroz et al. used explosive cladding for the production of Mg-Al bimetallic bars to counter the relatively poor corrosion resistance of magnesium with bimetal clad [114]. Xia et al. investigated the microstructure and mechanical properties of Ti/Al bimetals obtained through explosive cladding [115]. Saravanan et al. studied the influence of the interlayer of dissimilar metals during explosive cladding and stated that the interlayer, if not used judiciously, enhances loss of kinetic energy, leading to a defective explosive clad interface with a brittle interlayer [116]. Saravanan et al., in another article, developed a model to predict the rate of heat transfer during cladding [117].

Raj et al. performed the joining of dissimilar plates of mild steel with aluminium alloy through an explosive cladding approach with a detonation velocity of 3400 m/s [118]. The authors observed that the microstructure of the clad showed a uniform wave formation with the presence of intermetallics at the interface. The authors further observed that the tensile and shear strength of the cladded joint improved with a higher standoff distance between the flyer plate and base plate.

Durgutlu et al. reported successful welding of copper with steel using explosive welding and observed a flat joint interface at a low explosive ratio, while a wavy joint interface was observed at a high explosive ratio and a wider standoff distance. No evidence of intermetallic formation was reported by the authors [119]. Fabrication of a thick copper-stainless steel-clad plate for application in nuclear fusion equipment was carried out by Wang et al. through explosive welding [120]. The authors reported that the produced clad plates had the ideal joint interface with the desired wave shape, and there were no melting or intermetallic zones at the joint interface. The obtained clad sample, when subjected to bend and twist, respectively, showed no fracture, separation or tearing. Similarly, Raghukandan et al. carried out explosive cladding of copper on carbon steel using granular nitro-glycerine at 2500 m/s detonation velocity [14]. The authors suggested that flyer thickness, the loading ratio (explosive mass to flyer mass ratio), and the angle of inclination were the major parameters affecting the clad interface morphology. The area of explosive cladding is very vast and beyond the scope of this work. However, an extensive review of recent trends in this process can be seen in the works of Loureiro et al. [121] and Findik et al. [122].

2.4.2 Cladding through roll bonding

Roll bonding is a solid-state manufacturing process where cold or hot rolling of plates or sheets is carried out for lap joining of similar and dissimilar materials through the principle of severe plastic deformation [123]. The procedure involves bonding sheets by rolling them through a pair of rollers under sufficient pressure [124]. Based on the ranges of the processing temperature (with respect to recrystallization temperature), the process is divided into three types, namely cold, hot, and warm roll bonding [125]. A review of roll bonding processes and recent advances in this field has been nicely discussed in a paper by Zixuan et al. [126]. In the paper, they presented a detailed survey of roll bonding, with a focus on bimetallic bars and tubes as well as bonding models.

When the processing temperature is lower than the recrystallization temperature, the method is known as cold roll bonding (CRB) [127]. During cold roll bonding, a pair of rollers are rolled at room temperature over the stacked sheets, plates, or foils to generate the necessary deformation to achieve solid-state bonding between the parent materials, as shown in Figure 2-5 [128]. Akramifard et al. carried out the cladding of aluminium on 304L stainless steel by cold roll bonding [129]. Naseri et al. investigated the bonding behaviour during cold roll cladding of a tri-layer of Al/brass/Al composite [130], while Gholami et al. investigated the effect of microstructure evolution on the fracture toughness of a brass/low carbon steel/brass composite fabricated by cold roll bonding [131]. Li et al. fabricated Cu/Al-clad sheet by asymmetrical roll bonding with a higher mismatch speed ratio and stated that it causes severe shear plastic deformation of component metals. Additionally, according to the authors, roll bonding at higher speeds increases the final tensile strength, elongation, and peeling force of the clad

sheet while lowering the micro-hardness of the interfacial zone [132]. Liu et al. studied the effect of heat treatment on the mechanical properties of copper-clad steel plates by cold roll bonding and found that the maximum yield strength and ultimate tensile strength (UTS) of the clad plates were obtained along a tensile angle of 45 degrees [45]. The authors also found that ultimate strength and fracture elongation gradually decreased with the increase in annealing temperature, which they attributed to grain coarsening and interfacial delamination at high temperatures. Jamaati et al. carried out an extensive review of the cold bonding process and the effects of important parameters affecting the bond strength of cold-rolled materials [133].

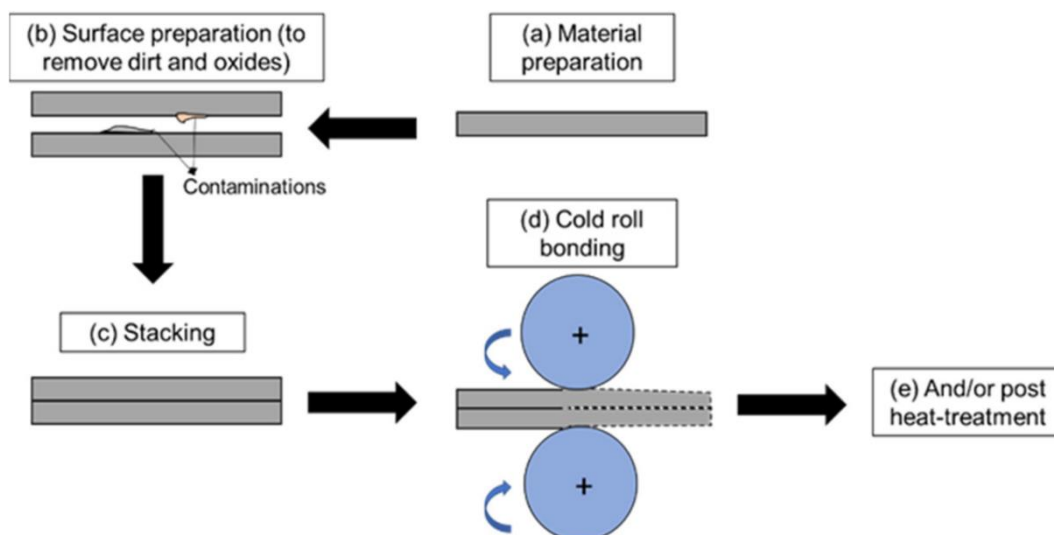


Figure 2-5 Steps involved in cold roll bonding process [123]

In contrast to cold roll bonding, when the processing temperature is higher than the recrystallization temperature, the process is known as hot roll bonding [134]. The process configuration is comparable to cold roll bonding, with the exception that the sheets are heated before going through the rollers, frequently in a vacuum environment. Wang et al. obtained clad sheets with a reasonable strength of Al/Mg through hot roll bonding [135]. Dhib et al. performed the cladding of low-carbon steel

with austenitic stainless steel by hot roll bonding [136]. The authors reported that the bond interface of the clad metals revealed a transitional zone with diverse microstructures between the clad layer and parent metal. Luo et al. improved the process and produced the clad of titanium/304SS by using vacuum hot roll bonding to bond a pure titanium plate to 304SS with a niobium interlayer in between [137]. The technique of cladding through roll bonding requires surface treatment before bonding, and surface contaminants can adversely affect the bonding quality. Lubricants such as grease, moisture or other chemical compounds may also act as surface contaminants, which act as a bonding barrier and adversely affect the bonding quality [138]. Furthermore, roll bonding is frequently restricted to cladding materials with comparable mechanical and physical qualities, and generally simple shapes can be formed. The interface quality can be impacted by changes in pressure, temperature, or rolling speed, which could lead to voids or delamination.

2.4.3 Cladding through cold spraying

In cold spraying, metal powders are sprayed at temperatures below their melting point at a very high velocity using a supersonic compressed gas jet (nitrogen or helium). Particles are bound to the surface by the impact, allowing for the quick accumulation of massive layers of deposited material, as shown in Figure 2-6.

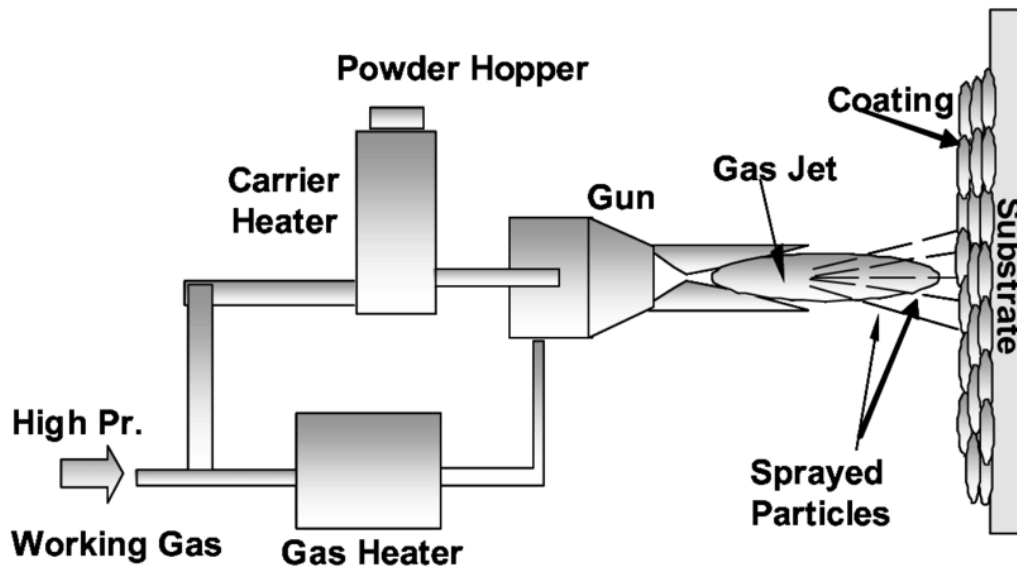


Figure 2-6 Schematic of cold spray process [139]

In the cold spray process, high-quality coating is possible with a low heating rate of powder. During cold spraying, the particle remains solid during deposition, and therefore, the process relies on high particle velocities for deformation upon impact with the substrate [140]. Singh et al. used the cold spraying method to deposit copper on SS 316L steel substrates and added that the electroplating of the substrate before cold spraying influences the adhesion strength of the copper coatings [141]. The author used nickel and copper as intermediate electroplating materials and found that the electroplating material had an affinity to share electrons with the steel substrate and had better adhesion strength and other properties. The author found that nickel electroplating had favourable metallurgical bonds and mechanical interlocking owing to its higher affinity to make metallic bonds with copper and steel elements. The author also reported that favourable metallurgical bonding was achieved with smaller copper particles compared to bigger sized particles. The cold spray method has also been proposed for manufacturing copper-cladded cast iron canisters for the long-term storage of spent radioactive fuel (containing a small amount of fissile nuclides from

reactors) [43]. Stoltenhoff et al. compared the coating of copper through cold spraying and thermal spraying [142]. The author added that in thermal spraying, the coating's conductivity is mainly reduced by non-metallic bonds at internal interfaces and trapped oxides, while in cold spraying, almost no oxidation of the coating material occurs during spraying. The authors found cold-sprayed coatings showed a more uniform microstructural appearance, higher electrical conductivity and higher hardness. A critical review of corrosion protection by cold spray coating has been done by Gangaraj et al. [143], while a review on the influence of cold spray parameters on bonding mechanisms has been done by Singh et al. [144].

2.4.4 Friction stir welding and friction stir cladding

Friction stir welding is a well-known solid-state joining process that has been widely used for the welding of similar and dissimilar metals [145] or for the processing and fabrication of surface composites [146]. In this process, joining takes place below the melting temperature of the joining materials. When a rotating tool pin gets inserted between the faying surfaces, heat is produced due to friction between the tool shoulder and the workpiece. As a result, the material beneath the tool shoulder becomes plasticized and moves from the front of the tool to the back of the tool through the retreating side. Kulekci et al. conducted a comprehensive examination of friction stir-based manufacturing processes, highlighting their past, present, and projected futures as well as the method's benefits and drawbacks. Friction stir-based techniques can be employed for microstructure refinement, property enhancement, welding, riveting, cladding, hardening, and channelling [147]. FSW has proved to be very useful in welding components with relatively flat geometry.

Friction stir welding offers a number of advantages over conventional arc welding processes. It can produce defect-free joints with low distortion as joining occurs in solid state, thus avoiding defects arising during the solidification of the liquid weld pool. Dilution control and thin section cladding through GMAW are challenging, while a low deposition rate makes GTAW not feasible for thick cladding. Limited material selection options, cracking during high deposition rates, and very high running costs, impose serious limitations on cladding with LASER. On the flip side, FSW offers flexibility in diverse-thickness cladding. FSW also serves to be cost-effective as it does not require consumables like shielding gas or filler wire.

The FSW process also differs from other solid-state joining processes in that it offers better process control than handling explosives, as in explosive cladding. Similarly, roll bonding cladding works best for thick cladding, but FSW allows for cladding in a variety of thicknesses.

2.5 Friction stir welding of dissimilar materials

FSW has been widely used for joining similar materials like Al, Mg, Ti, copper-based alloys, steels and dissimilar alloys like Al/Cu, Al/Mg, Al/steel, etc. Initially, the process was used for joining nonferrous metals with low melting points [148]. Joining copper to steel has been tried by FSW popularly in butt joint or lap joint configurations and has been described below.

2.5.1 Friction stir welding of dissimilar metals in butt position

The majority of joining through FSW has taken place in the butt position, where the abutting edges are brought close enough and the rotating tool pin plunges and travels through them. The friction between the shoulder and workpiece surface and the plastic

deformation of the weld metal generates enough heat to create the weld. Figure 2-7 shows the schematic representation of the FSW butt joint.

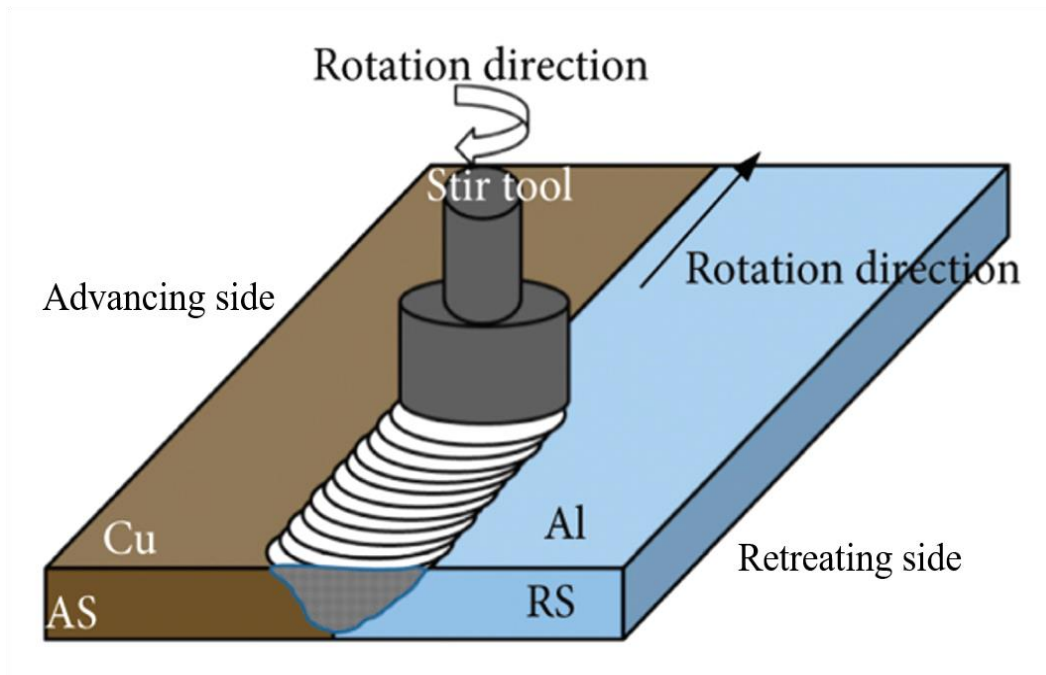


Figure 2-7 Schematic illustration of dissimilar butt welding using FSW process [149]

Butt-position joining of different grades of dissimilar metals has been carried out by friction stir welding. Joining of dissimilar materials with preferable positioning of the tool pin towards one side has also been tested by many authors, like Xue et al., who carried out the joining of 5 mm-thick 1060 aluminium with commercially pure copper plates through FSW [150]. The tool was purposefully offset on the aluminium side, and they obtained sound bonding with the formation of a continuous and uniform IMC layer of 1 micron thickness. The weld also remained intact in the 180-degree bend test. Aonuma et al. carried out the joining of magnesium alloy with titanium using FSW in a butt joint configuration with the pin offset towards the softer magnesium side and were successful in obtaining a sound joint [151]. Li et al. performed dissimilar FSW of Ti-6Al-4V alloy and Al-6Mg alloy employing a modified butt joint configuration

where the tool shoulder and pin barely made contact with the butt-side of Ti alloy and the tool pin was completely inserted on the aluminium side [152]. Butt joint with interface layer has been tested by Li et al. to join copper/titanium (Ti6Al4V) with and without an intermediate layer of Ag and observed interface layer composed of Ti₂Cu, TiCu and Ti₃Cu₄ on both cases with a thickness of 1-3 microns [153].

Although dissimilar thickness butt joining is difficult through FSW, Beygi et al. made modifications in the clamping design for butt joints of 5 mm aluminium to 3 mm thick carbon steel, as shown in Figure 2-8, using a tool steel material support plate below the steel part to compensate for the difference in base plate thicknesses. The authors reported that an intermetallic layer of FeAl with a 3 µm thickness was obtained along the bond line [154].

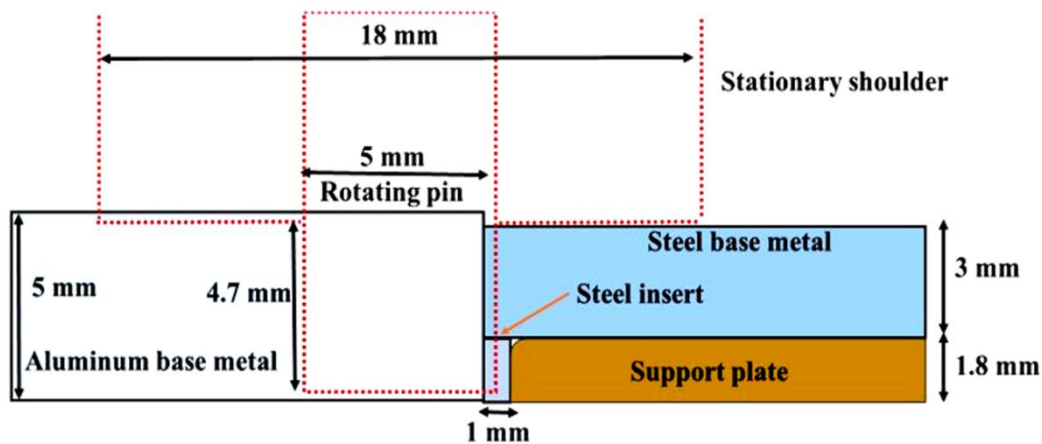


Figure 2-8 Schematic representation of the arrangement of plates to produce butt joint in plates of dissimilar thicknesses [154]

Sato et al. carried dissimilar FSW of 6 mm thick aluminium and magnesium alloys in butt welding position at a very high rotational speed of 2450 RPM, travel speed of 90 mm/min, and tilt angle of 3 degrees [155]. The authors reported that a sound weld was obtained when a magnesium plate was placed on the advancing sides of the rotating

tool, and vice versa, resulting in a poor-quality joint. The authors proposed that, generally during dissimilar FSW, the two base materials alternately create bands in the weld centre due to plastic deformation and observed similar bands of Al and Mg. They also added that due to the simultaneous heating of the weld during FSW stirring, Al and Mg atoms mutually disperse at interfaces between the alternating bands. The authors suggested that constitutional liquation could have taken place during stirring in FSW.

Several researchers have attempted to join copper with stainless steel in butt configuration and obtained a sound joint, like Shokri et al., who welded 4 mm thick duplex stainless steel with copper through FSW and studied the effect of parameters on final properties [156]. According to the authors, the appearance of a brittle intermetallic at the interface was found, and the mechanical properties were significantly influenced by heat input. The authors added that low heat inputs resulted in inadequate mixing of the two sides, leading to weak metallurgical bonding, while high heat inputs caused a thick layer of intermetallics, leading to early failure. The authors obtained optimum welding conditions with a rotational speed of 1200 rpm and a travel speed of 30 mm/min.

Wang et al. carried out butt welding of 6 mm thick copper and 316 SS by FSW using a tungsten rhenium tool with a rotational speed of 400–500 rpm, a tool travel speed of 25–50 mm/min, and a tilt angle of 2.5 degrees with an offset of 2 mm towards the copper plate [157]. Copper sheet was put on the retreating side and steel sheet was put on the advancing side, and a sound bonding at the interface was observed. The authors found out that steel grains were refined to a greater extent than copper grains, and the grain size at the interface was intermediate between the grain sizes of refined copper

and steel. According to the authors, intermetallic compounds were not produced because of solid-state bonding, due to the synergistic effects of high temperatures and significant plastic deformation. The authors also added that the welded joint failed through the stir zone (SZ) in the processed copper region during the tensile test due to the stress concentration.

Joshi et al. moved a step further and compared conventional FSW with FSW assisted by heating and cooling for dissimilar joints made of copper and stainless steel [158]. A conventional GTAW torch with currents varying between 20, 40, and 60 A was used as a heat source ahead of the FSW tool. While compressed air came out of the back of the tool on the joint line with a flow rate varying between 15 and 30 psi, water with a flow rate of 75 ml/min was used behind the FSW tool for cooling-assisted FSW. A cryogenic-treated tungsten carbide (WC) refractory tool was used to carry out the experiments with a rotational speed of 1500 and a feed rate of 31.5 mm/min with a tilt angle of 2 degrees. Researchers discovered that the conventional FSW of a copper to stainless steel joint was superior in comparison to aided methods. The authors reported that copper showed significant deformation in the microstructures of the heating-assisted FSW in comparison to the conventional FSW and the cooling-assisted FSW. Also, surface oxide layers were observed for heating and cooling-assisted FSW. According to the authors, conventional FSW had the maximum tensile strength, and, as the cooling conditions got severe, the tensile characteristics worsened.

To understand the effect of the number of passes on the properties of the obtained joint, Jafari et al. carried out welding of 304L stainless steel to copper using the FSW process, where the optimal parameters for welding were finalised using response surface methodology (RSM) [159]. The UTS of the weldment was considered as the

response parameter. The optimal welding parameters were obtained based on the results of the tensile test using RSM. The range of rotational speed was varied from 760 to 1450 RPM, while the traverse speed was varied from 25 to 60 mm/min. However, the tensile properties obtained for the friction stir butt-welded sample were lower than those of the base materials, and the grain size of copper in the TMAZ and HAZ regions was larger than that of the base material. The authors also performed repeated passes of FSW and reported that as the number of welding passes increased, the strength and ductility of the friction stir-welded samples dropped.

Investigation by offsetting the pin away from the butt line during FSW of 3 mm thick copper and 304 SS was carried out by Imani et al. [160]. The authors conducted four experiments with zero offset variation in the butt line: 0.6 mm offset towards the steel side, 0.6 mm offset towards the copper side, and 0.9 mm offset again towards the copper side. The experiment was carried out with a spindle rpm of 1000 and a travel speed varying between 14 and 112 mm/min. The authors reported that out of the four conditions, sound welds were obtained with the tool offset towards the copper side. The authors added that with a low welding speed of 14 or 20 mm/min, high heat input hampered the joint strength, while a high welding speed of 112 mm/min resulted in poor joint strength due to insufficient heat. Optimum joint strength was obtained at 40 mm/min. The authors also reported that the tensile strength of joints was lower than that of the base materials due to the formation of brittle intermetallic compounds, which acted as crack initiation sites.

Najafkhani et al. used the FSW process for butt joining of a 5 mm-thick pure copper plate to a 316L stainless steel plate with a moderate spindle speed of 720 RPM and a very low travel speed of 16 mm/min. The authors observed coarse copper grains in the

HAZ of copper. The authors reported that the UTS of the dissimilar joint was lower than the base copper, and all samples fractured in the HAZ of the copper side during the tensile test [161].

2.5.2 Friction stir welding in lap position

Although friction stir welding was first developed for producing butt welds, its variants are being used for processing the top layer of material [25] and for producing lap joints [162, 163]. The procedure for creating lap joints differs from that of a butt in terms of the positioning of the plates. In a lap joint configuration, the plates are placed one over the other. Since the tool needs to pierce both sheets for appropriate stirring action, the tool used for lap joints has a longer pin sufficient to penetrate the top plate and some portion of the bottom plate. Thus, the pin length is larger than that used for a butt joint [164]. A schematic diagram representing the FSW lap joint has been shown in Figure 2-9.

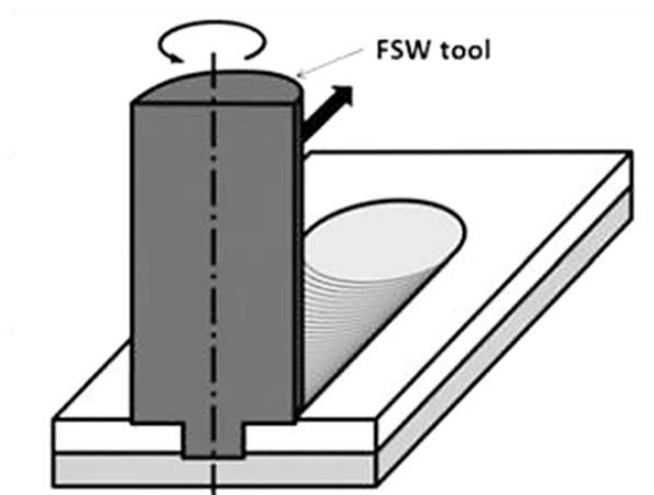


Figure 2-9 Schematic configuration of FSW lap welding [165]

Argade et al. carried out friction stir lap welding of 2.7 mm thick austenitic stainless steel on a plain carbon steel substrate to enhance corrosion properties [166]. The

experiment was carried out with a PCBN tool with a pin length 1 mm longer than the clad material thickness. The spindle speed of 500 RPM and the tool travel speed of 25.4 mm/min were used. The authors reportedly achieved solid-state cladding of austenitic stainless steel on a carbon steel substrate with corrosion properties nearly similar to those of stainless steel.

Friction stir lap welding of 3 mm brass on steel was carried out successfully by Gao et al. with a WC-Co tool with a concave shoulder and a tool tilt of 3 degrees [167]. The authors reported that with a travel speed of 250 mm/min, excess heat input caused larger burrs and groove defects on the surface of the joint, while good-quality joints were obtained with a regular surface and a smooth interface when welding at speeds of 400 and 500 mm/min. The authors also reported that no intermetallics were traced out at the joint interface, but mutual diffusion of elements was confirmed at the interface.

2.5.3 Friction stir cladding

Although extensive work has been carried out using FSW for joining, processing, and composite manufacturing, very little work has been carried out using the FSW process for cladding. Attempts have been made to clad a material over another substrate material through multi-pass FSW. The sheet that needs to be cladded is put over the substrate plate, and both are clamped firmly. A non-consumable rotating FSW tool penetrates from the top and executes several passes with a predetermined overlap distance between subsequent passes, as shown in Figure 2-10. However, work on using the process of friction stir welding for cladding is limited.

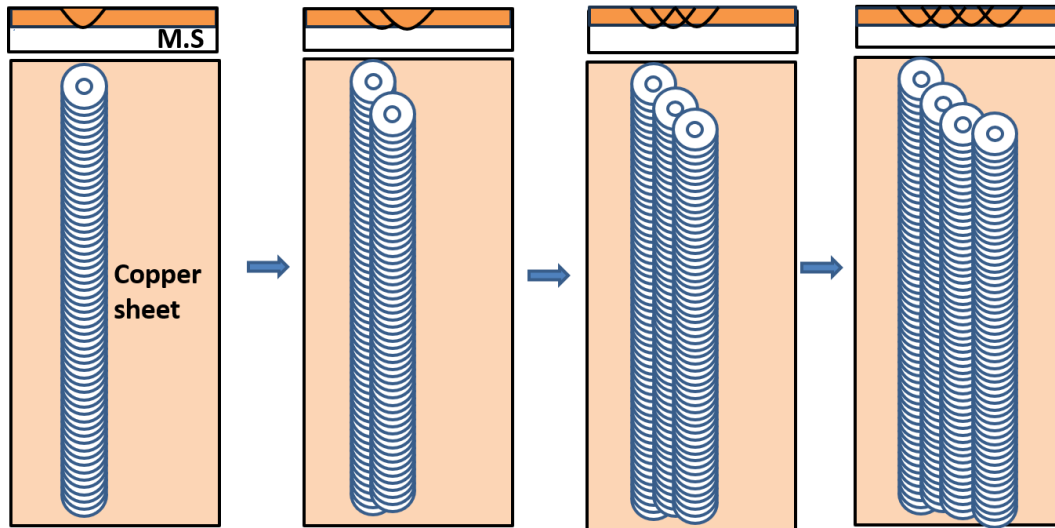


Figure 2-10 Cladding scheme with copper sheet on top of steel substrate

The friction stir cladding process differs from the MELD process as, in the MELD process, the material to be deposited is attached to the centre of the tool, as shown in Figure 2-11. As the tool rotates, under the combined action of force and rotation, the consumable solid bar material attached to the centre of the tool extrudes and gets deposited over the substrate material.

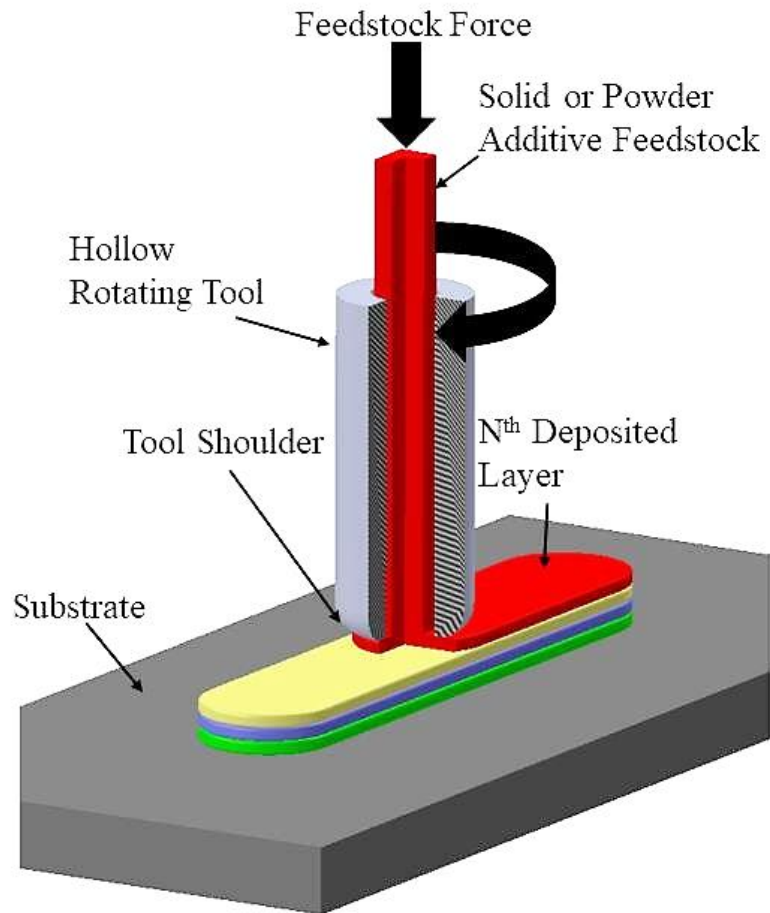


Figure 2-11 Schematic illustration for MELD process [168]

Tavassolimanesh et al. used FSW for manufacturing copper-clad aluminium bimetallic tubes [169]. The author suggested that better bimetallic tubes were manufactured by FSW compared to other methods like severe plastic deformation (SPD). The authors claimed that using higher rotational speeds during welding resulted in the generation of excess heat, reducing the weld surface quality and strength of tube joints.

Ibrahim et al. performed the cladding of a 2 mm-thick Al5052 alloy on ASTM 516 steel through friction stir diffusion cladding, similar to the friction stir cladding process [35]. The cladding was performed with a H13 tool steel tool with an adjustable pin and a tool shank made from 4140 alloyed steel with concentric circular grooved features on the shoulder to increase the surface contact area, enhancing the frictional heat

generation and material flow. The authors performed the cladding with 0% overlap and reported successful cladding of aluminium over steel. The authors also reported that optimum properties were obtained at a combination of rotation and travel speeds of 500 rpm and 50 mm/min, respectively.

Li et al. deposited 2 mm of aluminium over a 6 mm Ti-6Al-4V alloy substrate by using multi pass friction stir lap welding under an atmosphere of pure argon gas to prevent possible oxidation of the Ti alloy substrate with a tool rotation speed of 1200 RPM and a welding speed of 60 mm/min [170]. A tool with an Inconel shoulder and a WC-Co pin was used with an offset of 33% (5 mm) to cover the entire plate. According to the authors, the stir behaviour at the Ti/Al interface, friction-heat generation between the rotating tool and its surrounding metallic components, and downward force generated by the tool-shoulder served as critical parameters for a strong cladding structure. Al cladding without any cracks, porosities, or voids with an onion ring pattern in the Al region was successfully obtained. The authors found Ti/Al interdiffusion near the interface region with an interlayer thickness of 45 microns.

Deposition of copper has also been tried by a few researchers on different substrate materials. Osman et al. carried out multipass FSW of Cu on Al substrate at different overlap conditions of 0%, 50% and 100% overlap and observed weak interface bonding for 0% overlap, while intensive liquation, IMC formation and grain coarsening at 100% overlap were due to increased temperature at the intersecting zone [171]. A 50% overlap resulted in good mechanical interlocking and bonding, along with excellent shear and peel strength among all.

Lakshminarayanan et al. carried out cladding of 2 mm thick copper on top of 5 mm thick austenitic stainless steel with various overlaps of 0, 25, 50, 75 and 100 percent

and evaluated the influence of the extent of overlap on the microstructure and bond strength of copper [172]. The authors reported no surface defect in any overlap condition and reported that samples with a 0% shoulder overlap ratio demonstrated a fully bonded interface with a clearly visible pin-influenced zone and TMAZ. The author added that with increasing overlapping passes, a ratio of 25% and 50% wider dynamically recrystallized zones of austenitic grains around the deformed copper were observed. While for the sample with a 75% overlap ratio, copper grains showed grain coarsening due to the higher reprocessed zone. The sample with 100% overlap was reported to have thin alternate layers of SS and copper at the top. The authors also evaluated the effect of overlap ratio on interface bond tensile strength and found that clad joints fabricated at 0% overlap ratio exhibited the lowest joint strength among the samples due to the wider unprocessed area and weaker interface bonding, while the highest clad strength was observed for 50% overlap due to strong bonding interface.

Shen et al. used FSW to clad a sheet of 2.1 mm thick copper with a 25 mm thick plate of steel and compared the same with the weld obtained through GMAW [28]. The tool used during FSW consisted of a Co-WC cermet with a 12 mm shoulder and 2.1 mm of pin length, i.e., equal to substrate length, with tapered pin geometry and an offset distance variation of 3 mm between the passes. The authors observed copper sheets bonded to the steel with minimal flash and found a 'hook' type feature in the microstructure and gross displacement of steel into the Cu area, resulting in enhanced mechanical interlocking at the interface.

Guo et al. deposited a layer of 2 mm thick copper on top of 4 mm steel using the friction stir additive manufacturing process, similar to the friction stir cladding process [173]. The tool was made of tungsten rhenium alloy, having a 10 mm shoulder and a

3.1 mm long pin with a tapered geometry. A medium speed of 600 RPM and 50 mm/min with a tool tilt of 2 degrees and overlap of 50 percent was used to carry out the passes. The authors reported a successfully clad joint without any pores or cracks in external surfaces and discovered a wave-like interface that enhanced the bonding characteristics of steel and copper in a favourable way.

2.6 Optimization of FSW tool geometry

An FSW tool plays an important role during welding and needs special care during the selection of the tool geometry. Tool geometry accounts for one of the main parameters, controlling the material flow and heat input, and hence the weld quality [174]. The thermomechanical deformation and workpiece frictional heating required for friction stirring are greatly affected by the FSW tool geometry.

Commonly used FSW tools can be classified as fixed, adjustable, bobbin type or pinless, as shown in Figure 2-12. The fixed pin tool corresponds to a single piece comprising both the shoulder and pin, which can weld a workpiece with a constant thickness due to the fixed pin length. The adjustable tool consists of two independent pieces, i.e., a separate shoulder and a pin. The pin length is adjustable to allow welding of workpieces of different thicknesses. The bobbin-type tool comprises three parts: the top shoulder, pin and bottom shoulder, and the bottom tool eliminates the requirement of a backing plate for welding. The pinless type of tool design is mainly used for friction stir processing and surface property modification [175].

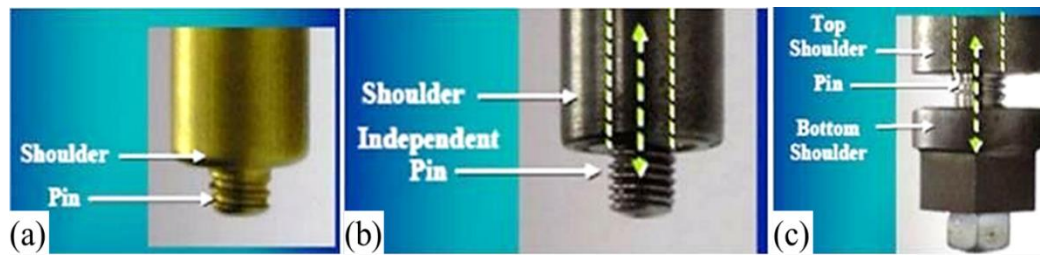


Figure 2-12 Types of FSW tool (a) fixed (b) adjustable (c) bobbin type [175]

The FSW tool consists of mainly two parts: a pin or probe and a shoulder. The pin is the part of the tool that makes initial contact with the plate and plunges through the thickness of the plate until the shoulder comes into contact with the plate. Rubbing of the plunged pin with the workpiece gives rise to frictional and deformational heating, which leads to the initial softening of the workpiece material. The contact of the shoulder with the workpiece increases the heat input, expands the zone of softened material, and limits the deformed material flow. This step is generally followed by an initial dwell period where the tool only does rotational motion, which further increases the volume of deformed material. Once the dwell time has elapsed, the tool begins to move in a forward direction, along a predetermined path, producing the weld.

2.6.1 Design of tool shoulder

Tool shoulder diameter and profile are important aspects of tool design in FSW. The shoulder's primary job is to keep the deformed material contained in the weld zone, and its secondary function is to generate frictional heat to soften the material ahead of the probe. A major amount of heat is produced during rubbing between the workpiece and the tool shoulder. The tool shoulder produces the downward forging action necessary for weld consolidation. Several designs have been tried by researchers to obtain good welds. The fundamental geometries of shoulder design are concave, convex, and straight.

Concave shoulder: Among all profiles, the concave profile is the most commonly used design in FSW. The shoulder concavity is produced by a small angle between the edge of the shoulder and the pin and ranges between 6 and 10 degrees. The hollow portion thus created due to the concavity of the shoulder serves as a reservoir for the displaced material. Forward movement of the tool forces new material into the cavity of the shoulder, pushing the existing material into the flow of the pin, and helps to accomplish complete consolidation by bringing material back near the probe. A schematic illustration of a concave shoulder has been shown in Figure 2-13.

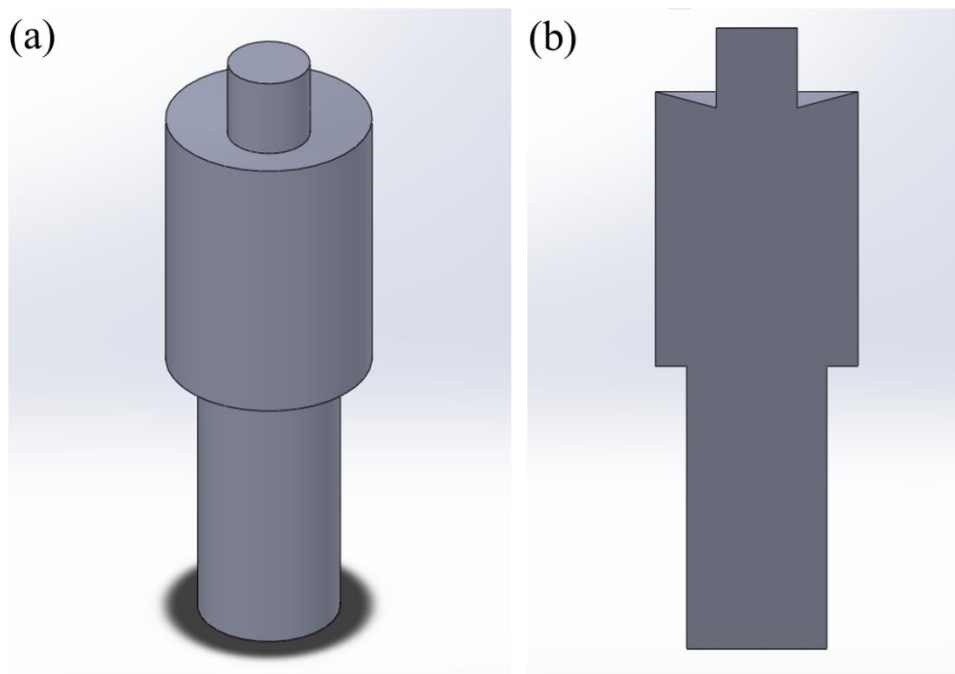


Figure 2-13 Schematic illustration of concave shoulder

Convex shoulder: A convex profile shoulder represents the state where an obtuse angle is made between the shoulder face and the pin. The convex surface pushes material away from the pin. Initial attempts by TWI (The Welding Institute) reported failure

with this tool profile; however, many other researchers later found success with this profile. A convex shoulder has been shown in Figure 2-14.



Figure 2-14 Schematic illustration of convex shoulder

Flat shoulder: A flat shoulder profile is generated when the shoulder face is perpendicular to the pin axis. Several authors have reported successful welding through the use of flat shoulders. A schematic illustration of a flat shoulder has been shown in Figure 2-15.

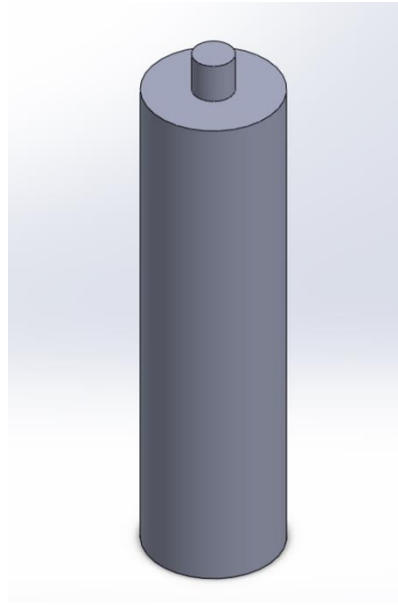


Figure 2-15 Schematic illustration of flat shoulder

Apart from the plain shoulders, many shoulders contain features to assist in material deformation and distribution produced by the tool shoulder, resulting in better mixing and hence weld quality. These features may consist of scrolls, ridges, grooves, or concentric circles. These profiles are generally machined onto the tool surface. Scrolls are among the most commonly reported features. The feature consists of a flat surface with a spiral channel from the outer edge of the shoulder moving towards the pin centre. This spiral channel directs the deformed materials from the edge of the surface to the pin. A schematic illustration of a scrolled shoulder has been shown in Figure 2-16.

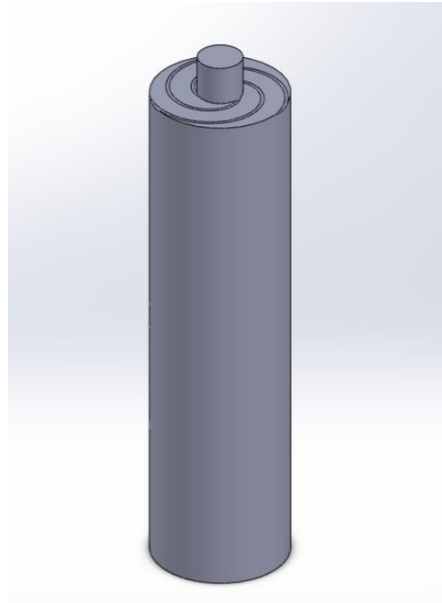


Figure 2-16 Scrolled shoulder feature

2.6.2 Design of tool pin

For a successful weld, the FSW tool pin plays an important role, as maintaining pin dimensions intact while welding is crucial. The tool pin produces deformation and the necessary heat for the welding. The FSW tool pin also shears the material from the front of the tool to the back of the tool. Several geometries of tool pins have been reported, like cylindrical, triangular, square, pentagonal, hexagonal, etc., as shown in Figure 2-17. Among these geometries, the cylindrical profile of the tool pin is the most commonly used.

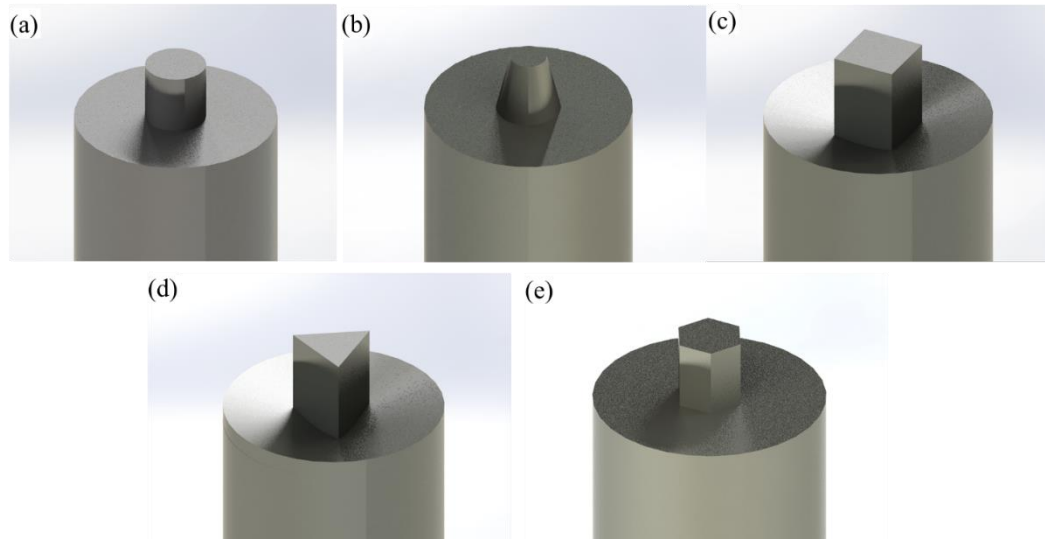


Figure 2-17 Different basic pin geometries (a) cylindrical (b) cylindrical taper (c) square (d) triangular (e) hexagonal

Several profiles have also been engraved on pin geometries like threaded and stepped, as shown in Figure 2-18. Smooth probes without any features have also been successfully used by several researchers. Threading of the pin helps in providing excellent flow of the material, offering better consolidation and recrystallization, and reducing the chances of the occurrence of defects [176]. Several researchers have also used tools made up of a combination of different sets of materials, i.e., a shoulder of a different material and a pin of a different material. For example, to join copper to SS 304 in butt position, Jafari et al. used a welding tool comprising a shoulder made of heat-treated M2 steel and a pin made of tungsten carbide [159]. Najafkhani et al. used a hybrid tool comprising a tool pin made of tungsten carbide, and a tool shoulder made of molybdenum to sustain high temperatures while joining copper with 316L steel for a thickness of 5 mm [161].

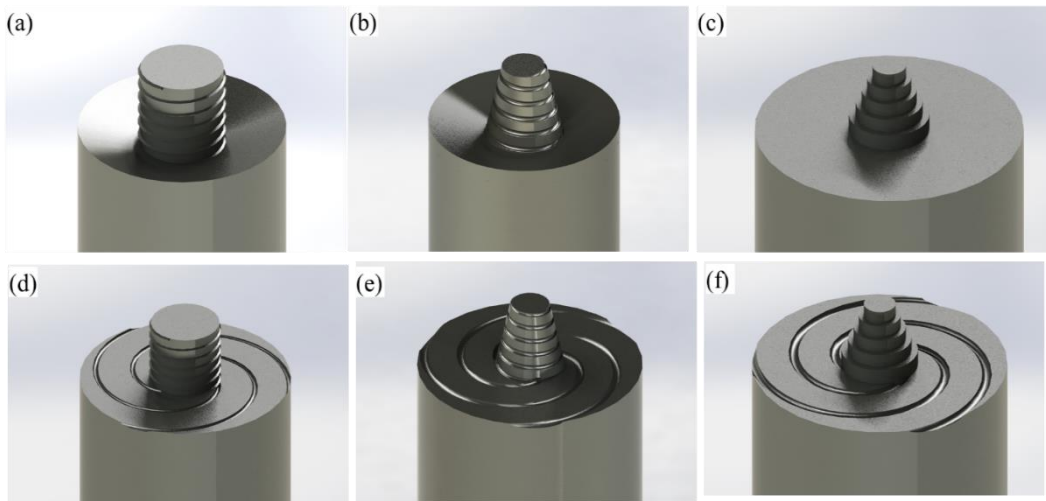


Figure 2-18 Different pin profile (a) cylindrical threaded (b) cylindrical tapered threaded (c) stepped cylindrical (d) scrolled shoulder cylindrical threaded (e) scrolled shoulder with cylindrical tapered threaded (f) scrolled shoulder with stepped cylindrical threaded

Material flow during welding is significantly affected by tool pin geometry. During the tool stirring process throughout welding, cylindrical or conical tools remain in continuous contact with the material, while tools with flat faces (e.g., square pins, triangular pin and four slotted pins) strike the material and produce a pulsating-stirring effect during revolution. The material flow is strongly impacted by this pulsating-stirring action. By multiplying the quantity of flat faces by the rotational speed of the tool per second, the pulsating-stirring action of the pin profile can be determined [177].

The swept volume ratio also serves as a crucial parameter for material flow. Static volume is the actual volume of the tool pin in stationary condition (the volume of the pin itself), and dynamic volume is the volume of material that gets displaced because of tool pin rotation (the volume swept by the pin during rotation) [178].

$$\text{Swept volume ratio (SVR)} = \text{Dynamic Volume (V}_d\text{)} / \text{Static Volume (V}_s\text{)} \dots \dots \text{eq (1)}$$

The swept volume ratio for some commonly used pin geometries is 1.0 for cylindrical and cylindrical tapered pins, 2.4 for triangular pins, and 1.57 for square pins. A higher ratio of the dynamic volume swept by the tool to the static volume of the tool results in an easier flow of material around the tool [179]. A tapered cylindrical pin offers an additional downward force to the plastic material that results in an improvement in the flowability of the bottom metal [177].

During welding, the plates' upper surface is subjected to more stirring and friction during tool stirring than their lower surface. This occurs because the shoulder also helps in the stirring of the material on the top surface, which is in contact with the tool shoulder, while the lower surface is in contact with the pin surface only. Moreover, the loss of heat during the process is due to both thermal conduction and convection. Loss through conduction mode takes place through the backing plate and the lower surface of the workpiece, while heat loss through convection takes place between the top surface of the workpiece and the atmosphere [177].

2.7 Defects formation during FSW

Like all other welding processes, joints produced through FSW may also have welding defects, but since the FSW process works below the solidus temperature of the material, several defects that are more easily found during fusion welding are automatically eliminated, like spatter, porosity, inclusions, and hot cracking.

The occurrence of defects is more pronounced in the FSW of dissimilar materials, primarily due to differences in their solidus temperatures, miscibility, metallurgy, chemistry, thermal conductivity and flow stress that may impair proper material flow and result in non-uniform heat distribution [180]. The selection of optimum FSW

process parameters may avoid the occurrence of some of these defects, but it is also very unlikely to completely remove all the defects from occurring. A few of the commonly observed FSW defects are:

Voids and tunnel defects: The inadequate material flow and poor mixing of materials may cause tunnel flaws and voids, which are often observed in butt weld joints on the advancing side at the bottom of the weld nugget. They may occur as a result of insufficient forging pressure, poor workpiece clamping or very high welding speeds [181]. During FSW, it is required that the tool fill the deformed material in the void produced by the traversing pin. When improper tool geometry is present, the tool is not able to apply the sufficient forging force required to flow the deformed material properly. Similarly, when the welding speed is too high, the deformed materials cool quickly before filling the region, causing voids to appear [182].

Joint line remnant: A semi-continuous layer of oxide throughout the weld nugget zone is called a joint line remnant. This may form because of insufficient cleaning of the workpieces before welding or insufficient deformation of the joining surface due to mispositioning of the tool pin with respect to the joint line [181].

Incomplete root penetration: This sort of defect arises due to a thickness mismatch between the plates, poor alignment of the tool relative to the joint interface, or a shorter tool pin length. Too low plunge depth, or low heat input may also result in incomplete root penetration [183].

Flash: Flash is another type of defect that occurs due to the very high plunge provided to the tool. When the tool surface touches the workpiece, this excessive plunge causes the deformed material to extrude back from the sides, resulting in projections arising from the periphery of the tool diameter called flash. The defect is further aggravated if

the heat input is also very high. This type of defect could be avoided by maintaining optimum heat input combined with the correct plunge distance.

Exit hole: Once the weld is completed, during the retraction of the tool pin, a hollow recess is observed, which is the replica of the tool pin, causing a defect, termed an exit hole defect. This hole will have a high stress concentration and may cause the weld to fail. This defect could be eliminated by placing the exit hole in the sacrificial plate or run-off wedge.

IMCs formation during dissimilar welding: In the dissimilar joining of materials in FSW, the probability of the development of intermetallics at the weld interface is very high. The thickness of the intermetallic layer has been reported to be crucial, as lower IMC thickness enhances the joint strength up to a certain point, but surpassing the critical height, these IMCs are generally brittle and decrease the joint efficiency [156]. During dissimilar welding of aluminium to magnesium through FSW, Sato et al. reported the development of $Al_{12}Mg_{17}$ intermetallic in the weld centre, resulting in higher hardness in the weld compared to base materials [155]. Dehghani et al. carried out the joining of aluminium to steel through FSW and reported the formation of Al_5Fe_2 and Al_6Fe at the weld interface and nugget. The authors found that a very low welding speed of 14 mm/min led to high heat generation. As a result, a wide IMC region was observed in the weld nugget, which gradually decreased as the welding speed increased to 28 mm/min and 40 mm/min. The amount of IMCs decreased significantly due to lower heat input [184]. Similarly, Xue et al. carried out dissimilar FSW of aluminium and copper and obtained Al_2Cu and Al_4Cu_9 IMCs at the interface. It was reported that due to the very low thickness of the IMC layer, i.e., 1 μm , the enhanced metallurgical bonding strength could still be obtained [150].

In a dissimilar FSW joint, due to diverse physical and mechanical properties, flow behaviour on the two sides becomes significantly different. For example, for steel and copper, inhomogeneous material movement in the weld zone is likely to occur. This inhomogeneous movement of material may act as a source of defect formation. Researchers have used different methods to mitigate the effect of intermetallic (IMC) formation during welding. Liu et al. obtained Al-Fe bimetallic components through friction stir additive manufacturing and attained nanoscale intermetallic joints between the layers. While Beygi et al. used stainless steel as a buttering material between aluminium and steel to mitigate the thickness of IMCs during FSW. The author claimed a significant improvement in tensile strength and fracture elongation was obtained due to the thinning of IMCs from 5 μm to 2 μm , along with the nano crystallinity of IMCs due to the lower nucleation rate [185].

2.8 Corrosion protection through cladding

Corrosion refers to the electrochemical degradation of materials as a result of a reaction with their environment. Corrosion is a natural process that takes place to decrease the energy of the system. The rate of corrosion is greatly influenced by many factors, such as the type of material, its microstructure, environmental factors, design factors, surface finish, time of exposure, and stress assistance. Several broad forms of corrosion are:

- i. Uniform corrosion
- ii. Galvanic corrosion
- iii. Crevice corrosion
- iv. Pitting corrosion
- v. Dealloying

- vi. Intergranular corrosion
- vii. Erosion corrosion and
- viii. Stress assisted corrosion

Uniform corrosion refers to the state of corrosion when corrosion uniformly progresses throughout the surface towards the depth of the material. The form of corrosion proves to be indicative, as one can observe how long a material can sustain. Opposite to this, pitting corrosion is that form of corrosion where corrosion is localised in several regions while others remain relatively uncorroded. Austenitic stainless steel has a tendency to pit, while mild steel does not show a pitting effect. Crevice corrosion forms at some openings, where solutions go in and remain stagnant. Galvanic corrosion refers to the corrosion occurring between two dissimilar materials, where a galvanic couple forms and one metal proves to be superior in corrosion resistance in comparison to another, and corrosion occurs more heavily in the anode material than it would all by itself, while the other becomes the cathode and corrodes slower than it would alone. Dealloying, or selective leaching, is a form of corrosion where one of the alloy elements preferentially dissolves. Intergranular corrosion refers to the localised attack along the grain boundaries, or the region immediately adjacent to the grain boundaries, while the bulk of the grains remain largely unaffected. Erosion corrosion is a state of corrosion that occurs due to a combined action involving corrosion and erosion and may be caused by the rapid flow of any turbulent fluid on a metal surface.

Corrosion has also proven to be beneficial in certain conditions, like the revealing of microstructure during etching or the operating mechanism inside a battery, which also takes place due to corrosion only. Similarly, the fabrication of porous silver that has potential applications in molecular adsorptions and medical materials is obtained by

dealloying, where corrosion proves to be beneficial [186]. However, generally, corrosion is one of the major issues responsible for the degradation of materials, and if proper concern is not given, it may result in catastrophic failures. Literature suggests corrosion has always posed limitations in widespread applications of mild steel due to its excessive corrosion rate. Corrosion costs the global economy \$2.2 trillion annually, which is more than 3% of global GDP [187]. It is also estimated that employing available corrosion management techniques results in savings of between 15 and 35 percent of the cost of corrosion.

Several methods for corrosion prevention are prevalent and are used depending on their suitability. One commonly used method is the application of protective coatings by paints, which act as barriers against corrosion [188]. Another method is to use a sacrificial material, which makes the metal intended to be protected as the cathode and protects it from corrosion while the sacrificial material corrodes as the anode. This method is mostly used in marine applications or underground construction where sacrificial Zn or Mg is used [189]. Similarly, another important corrosion protection method is to use corrosion inhibitors, which minimise the corrosion rate by adding specific chemical compounds to the corrosive environment [190]. Anodic protection is another technique to reduce corrosion on metal by polarising it to its passive region and maintaining it there, which helps in the formation of a passive layer, reducing corrosion damage [191].

Cladding is another protective method that can safeguard material from corrosion. It improves the durability of the underlying substrate, which is vulnerable to corrosion. The cladding material can be coated, sprayed, or deposited on the substrate, depending on the process used. Several authors have deposited corrosion-resistant material over

corrosion-prone material through GMAW, GTAW, LASER, or the explosive method, as discussed throughout the literature section. Deposition of stainless steel or copper has been employed by many researchers to safeguard the mild steel beneath. In this work, cladding of 3 mm-thick copper over a mild steel substrate has been deposited through multi-pass FSW. This cladding can protect the steel material beneath it from corrosion. Cladding through FSW faces lesser chances of material delamination or peeling off as mechanical and metallurgical bonding takes place over here.

Braithwaite et al. reported the corrosion rate for AISI 1018 for nuclear waste cannisters in brine solution to be 7 mm/yr and in seawater to be 11 mm/yr, which prohibits widespread usage of this material for diverse employments [192]. Deployment of copper cladding on mild steel can protect the substrate steel from severe degradation, as it does not face a corrosive environment directly. Thus, this work is an attempt to clad copper on top of the steel substrate using multipass friction stir cladding.

Yaghoubi et al. studied corrosion behaviour in a 3.5 wt.% NaCl solution for friction stir welded copper plates after welding them with shielding gas in different welding conditions [193]. It was reported that the grain size of the stir zone was very small in comparison to the base material and the other zones of weld due to recrystallization, while the grain size of HAZ was larger than the base material. Upon increasing the number of weld passes, the grain size further reduced significantly, and the density of the passive layer increased, decreasing the effect of the destructive chloride ion more effectively and consequently increasing the corrosion resistance. Similarly, Alhosseini et al. studied the corrosion behaviour of FSWed pure copper in a 3.5 wt.% NaCl solution [194]. The author reported grain refinement after FSW and stated that corrosion behaviour improved with decreasing grain size. They also suggested that X-

ray diffraction patterns indicated the absence of unwanted phases, including oxides. Although several studies have been carried out to study the corrosion behaviour of copper post-different manufacturing operations, limited attempts have been made to study the corrosion behaviour of copper post-FSW.

Based upon the above discussion, it can be concluded that covering the steel substrate with copper through FSW effectively protects the beneath surface from corrosion. However, due to the wide differences in properties of steel and copper, a defect-free, favourable joint is hard to achieve. Moreover, a lack of literature for thick cladding through FSW was also observed. Hence, in this work, after carrying out the cladding work successfully, attempts have also been made to study the corrosion behaviour of the obtained clad material (copper top) and compare the results with the corrosion properties of base steel and base copper strip.

2.9 Literature gap

Cladding copper on steel faces several obstacles due to the diverse set of properties of the clad copper and steel substrates. Moreover, many industries are looking forward to opt a cost-effective, suitable method to clad copper on steel, which can offer flexibility to clad diverse-thickness copper without the use of any shielding gases or the generation of harmful gases. The flexibility to perform cladding with the least intervention of a skilled operator is another advantage that industries look upon. As for other welding methods, highly skilled operators are needed to obtain good-quality welding.

After carrying out an exhaustive literature survey on the dissimilar material cladding techniques for thick copper on steel, it was found that processes like GMAW, GTAW,

SAW, laser and several other solid-state bonding methods suffer limitations like poor bonding, delamination, brittle intermetallic formations, grain coarsening, powder handling, and the inability to control clad thickness on the steel substrate.

The following gaps have been identified in the literature review that has been carried out:

- FSW has been widely used to carry out welding in lap or butt joint configurations but has not been explored extensively to execute cladding. Furthermore, very limited work is available for the friction stir cladding of copper on steel.
- Various challenges that can be encountered during the cladding of copper on steel have not been reported in detail in any literature.
- The study of tool pin offset on the clad layer obtained using FSW process has not been studied in detail.
- Only a handful of literature are available to evaluate the effect of process parameters and selection for cladding copper on steel using the FSW process.
- The behaviour of tungsten carbide tool material when carrying out FSW cladding has not been explored by previous researchers.
- There is a lack of comprehensive work on the evaluation of the properties of clad obtained through friction stir cladding.
- No literature was found where corrosion tests of friction stir-cladded samples of copper on steel have been carried out.

2.10 Objectives

The prime objective of this present work is to efficiently clad a 3 mm-thick copper plate on top of a steel substrate using the optimum tool offset distance between passes to clad the entire plate in the minimum amount of time.

Thus, the detailed objectives of the present research work are:

1. To develop the technique to deposit 3 mm-thick copper on top of steel substrate through multi-pass FSW.
2. To carry out a critical evaluation of various hindrances that arise while cladding copper on steel.
3. To perform a critical assessment of the behaviour of tungsten carbide tool material towards FSW cladding.
4. To determine the best combination of process parameters that can be used to perform friction stir cladding of copper on a steel substrate.
5. To determine the optimum tool pin offset distance between two adjacent passes for efficiently cladding the entire substrate material in the smallest number of passes.
6. To evaluate the cladded sample for defects, tungsten carbide inclusion and unbounded regions through non-destructive tests like X-ray radiography.
7. To evaluate the bonding characteristics of the cladding through optical and SEM evaluation and analyse the bonding effectiveness of the cladded sample through mechanical tests like tensile, hardness evaluation, fractography analysis, and bend tests.
8. To assess the corrosion behaviour of copper-cladded steel and compare it with base copper and base steel.