**KAUNAS UNIVERSITY OF TECHNOLOGY**

**FACULTY OF MECHANICAL ENGINEERING AND DESIGN**

**SAI VENKATESWARAN**

# SELECTION OF THE BEST WELDING TECHNIQUE FOR REDUCING MATERIAL WEAR AND CORROSION

Final Master Thesis

**Supervisor:** Assoc.Prof. Dr. Antanas ČIUPLYS

**Kaunas 2015**

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**Kaunas 2015**

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**FACULTY OF MECHANICAL ENGINEERING AND DESIGN**

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**INDUSTRIAL ENGINEERING AND MANAGEMENT 621H77003**

# Selection of the Best Welding Technique for Reducing Material Wear and Corrosion

**DECLARATION OF ACADEMIC INTEGRITY**

11th June 2015

Kaunas

I confirm that a final project by me, **Sai Venkateswaran**, on the subject "**Selection of the Best Welding Technique for Reducing Material Wear and Corrosion**" is written completely by myself; all provided data and research results are correct and obtained honestly. None of the parts of this thesis have been plagiarized from any printed or Internet sources, all direct and indirect quotations from other resources are indicated in literature references. No monetary amounts not provided for by law have been paid to anyone for this thesis.

I understand that in case of a resurfaced fact of dishonesty penalties will be applied to me according to the procedure effective at Kaunas University of Technology.

| | |
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**Venkateswaran S.** Selection of the Best Welding Technique for Reducing Material Wear and Corrosion. *Masters* final project / supervisor Assoc. Prof. Dr. Antanas Čiuplys; Kaunas University of Technology, Mechanical Engineering and Design faculty, Industrial Engineering and Management department.

Kaunas, 2015.72 p.

## Summary

This project is concerned with selection of the best method for the protection of material surface by coating it with an anti-corrosive and wear resistant material. Five welding methods likely laser cladding, overlay welding, roll bonding, explosive welding and friction-stir welding have been taken into accounts which are used mainly for coating an over-layer material. Different materials being used in each technique from various researches is studied and some important characteristics like heat affected zone which play an important part in overlaying of base material with a high performance material because they make the weld or clad weaker and vulnerable to wear and corrosion. In this project heat affected zone is studied in detail for each method mentioned above and the various outcomes on the material after cladding or welding is explained and the materials that can be used to reduce or avoid such problems on the weld is explained. Comparison is of each method is done to draw out outcomes such as advantages, disadvantages, place of application and the ways to reduce these effects on the weld materials. Material selection has an active role in preventing this effect, hence a detail study on the materials being used for each method for particular circumstances are mentioned and conclusions are drawn from it. After analyzing all the characteristics of each method, there different application and limitations, and the various materials being used for different reasons and also the price and other important characteristics of the methods are deduced and then the best method due to its advantages when compared to other mentioned method is selected.

***Keywords***: *Welding Technology, Weld coating, Heat affected zone (HAZ), Wear resistance, Corrosion resistance.*

**Venkateswaran, S**. Suvirinimo technologijų parinkimas siekiant padidinti atsparumą dilimui ir korozijai. Magistro baigiamasis projektas / vadovas doc. dr. Antanas Čiuplys; Kauno technologijos universitetas, Mechanikos inžinerijos ir dizaino fakultetas, Gamybos inžinerijos katedra.

Kaunas, 2015.72psl.

## SANTRAUKA

*Šis baigiamasis projektas yra apie geriausio suvirinimo metodo parinkimą, atsižvelgiant į medžiagos paviršiaus apsaugą, padengiant jį antikorozinėmis, atspariomis dilimui medžiagomis, siekiant padidinti įvairių detalių tarnavimo laiką. Tiriama terminio paveikio zonos įtaka, kuri yra matoma visose padengtose medžiagose, taip pat tiriamos naudojamos medžiagos bei palyginami nagrinėjami technologiniai procesai. Po išsamios analizės atsižvelgiama į privalumus ir trūkumus, bei rekomenduojamas geriausias suvirinimo metodas konkrečiam atvejui.*

***Raktiniai žodžiai**: Suvirino technologijos, Apvirinta danga, Terminio paveikio zona, Atsparumas dilimui,Atsparumas Korozijai.*

**KAUNAS UN IVERSITY OF TECHNOLOGY**
**FACULTY OF MECHANICAL ENGINEERING AND DESIGN**

**Approved:**

Head of Production Engineering Department _______________________________ *(Signature, date)*

_______________________________ *(Name, Surname)*

**MASTER STUDIES FINAL PROJECT TASK ASSIGNMENT**
**Study programme INDUSTRIAL ENGINEERING AND MANAGEMENT**

The final project of Master studies to gain the master qualification degree, is research or applied type project, for completion and defence of which 30 credits are assigned. The final project of the student must demonstrate the deepened and enlarged knowledge acquired in the main studies, also gained skills to formulate and solve an actual problem having limited and (or) contradictory information, independently conduct scientific or applied analysis and properly interpret data. By completing and defending the final project Master studies student must demonstrate the creativity, ability to apply fundamental knowledge, understanding of social and commercial environment, Legal Acts and financial possibilities, show the information search skills, ability to carry out the qualified analysis, use numerical methods, applied software, common information technologies and correct language, ability to formulate proper conclusions.

1. Title of the Project

| |
|---|
| Selection of the Best Welding Technique for Reducing Material Wear and Corrosion |

Approved by the Dean 2015 May 11 Order No. **ST17-F-11-2**

2. Aim of the project

| |
|---|
| The aim is to investigate the chosen welding method for material overlay coating to reduce wear and corrosion on the surface of the metal. The characteristics of the welding techniques are drawn and the best technique is recommended. |

3. Structure of the project

| |
|---|
| The final work will consist of Introduction part, Techniques for overlay weld part, where five welding techniques will be analyzed; comparison of different welding technique part, where the important factor like heat affected zone will be analyzed and the characteristics will be drawn, and finally the risks of the discussed welding techniques are analyzed and the necessary precautionary measures will be mentioned. |

4. Requirements and conditions

| |
|---|
| At least five welding techniques should be analyzed in the project; recommendation should be given for the best welding technique; the risks in performing welding should be analyzed; precautionary measures for risk prevention should be analyzed in this project. |

5. This task assignment is an integral part of the final project
6. Project submission deadline: 2015 June 1st.

Given to the student Sai Venkateswaran

Task Assignment received _____________________________ _____________________
(*Name, Surname of the Student*) (*Signature, date*)

Supervisor _____________________________ _____________________
(*Position, Name, Surname*) (*Signature, date*)

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# Introduction

Hardness is quite often used in the field of wear resistance as the criteria for judging alloys, castings, hard facings and overlays. The abstract is that harder the material, the greater the wear resistance. While this is technically correct, applying this principal across the board can lead to some catastrophic results. Wear is the interaction between surfaces and specifically the removal and deformation of material on a surface as a result of mechanical action of the opposite surface. The definition of wear may include loss of dimension from plastic deformation if it is originated at the interface between two sliding surface. Corrosion is a natural process, which converts refined metal to their more stable oxide. It is the gradual destruction of materials (usually metals) by chemical reaction with their environment. Rusting is the formation of iron oxides is a well-known example of electrochemical corrosion. This type of damage typically produces oxides or salts of the original metal.

Corrosion can also occur in materials other than metals, such as ceramics or polymers, although in this context, the term degradation is more common. Corrosion degrades the useful properties of materials and structures including strength, appearance and permeability to liquids and gases. Most ceramic materials are almost entirely immune to corrosion. The strong chemical bonds that hold them together leave very little free chemical energy in the structure, they can be thought of as already corroded. When corrosion does occur, it is almost always a simple dissolution of the material or chemical reaction, rather than an electrochemical process. Thus wear and corrosion in metals or material are more prominent since the materials become vulnerable to this surface abrasion. Abrasive wear occurs when a hard rough surface slides across a softer surface. Abrasive wear is commonly classified according to the type of contact and the contact environment. In order to avoid this kind of problem on the surface of metal different types of welding methods are introduced just to improve the surface of the material by coating it with a highly resistant material which in turn has less wear, corrosion or abrasion with the base material.

The welding methods which are taken into account in this paper are basically used methods for surface improvement to protect the base material by coating it with some high performance, less expensive alloys. The welding methods are laser cladding, overlay welding, roll bonding, explosive welding, and friction stir welding. The mentioned methods differ in the process of material coating and the material used. In laser cladding the process mainly constitutes a laser beam with a supply of filler material which is applied over the base material with lesser heat input and less distortion. But this method has some disadvantages which are can be avoided by the proper selection of coating material over the base which depends on the environment of metal being applied. While overlay welding is a method of horizontal welding on pipes and other components which serves the same purpose of laser clad to protect the expensive base material from corrosion by coating it with an inexpensive material. Roll bonding is the process of bonding two dissimilar materials with the help of two heavy rollers depending on the size of the material. In this paper accumulative roll bonding is considered to be the most efficient method of roll bonding of dissimilar materials. Explosive welding is similar to roll bonding where instead of rolling the metal, the materials are welded to other material by an explosion with no presence of heat affected zone since the process is quick. Friction-stir welding is also another kind of material improvement welding in which the material is welded by frictional process. From the above surface improvement techniques, there characteristics, the application of different materials for different environment of use, the advantages and disadvantages over the other methods are studied. The different researches carried out in each technique in terms of process, materials and alloys have been studied in detail and the best method for the specific type of material and for specific environment of use is discussed and concluded.

**Objective:** The main aim of the project is to investigate some chosen welding method for material overlay coating to reduce or remove wear and corrosion on the surface of the metal. The characteristics of the welding techniques are drawn and the best technique is recommended.

**Task:**

1. Investigate five welding techniques for overlay coating to reduce wear and corrosion on material surface.
2. Analyze the technique with respect to process, material used, and drawbacks.
3. Identify the important problems in overlay coated material after cladding or welding.
4. Investigate the problems further to draw out the cause for different materials for respective methods.
5. Solutions should be deduced from careful comparison of different techniques and other parameters.
6. The best welding technique should be recommended from the above analysis.

# 1. Techniques for overlay coatings

A welding operation can be defined as a method of fabrication intended to give physical continuity between the pieces to be joined. In the great majority of practical cases, this continuity is realised by local fusion [1]. There are different techniques in welding for joining two metals and also for protecting the metal from wear and corrosion. To overcome the problems of wear and corrosion on the surface of metal different methods have been introduced. In this paper five most prominently used techniques are considered due to its application in wide area and vast possibility of material application. The five welding technique are explained in detail below.

## 1.1 Laser cladding

Laser cladding or laser deposition is a processing technique used for adding one material to the surface of another in a controlled manner. A stream of a desired powder is fed into a focussed laser beam as it is scanned across the target surface leaving behind a deposited coating of the chosen material. This enables the applied material to be deposited selectively just where it is required.

The deposition of material by a powdered or wire feedstock material which is melted and bonded by the use of laser to coat on a surface of substrate. It is used to improve mechanical properties or to increase wear and corrosion resistance, repair worn out parts and fabricate metal matrix composites.

**Fig.1.1** Laser cladding

### Two-step process (pre-placed laser cladding)

In two step process the first step of the process is to place a layer of coating material before laser irradiating which is then melted with substrate material by the laser beam in the second step. In laser cladding, pre-placed laser cladding is a simple method used for coating and prototyping. The pre-placed powder particles have better bonding to substrate and also cohesion with each other. It is very important to avoid the powder particles on substrate from removing due to the gas flow during melting. To overcome this, the powder is mixed with a chemical binder to ensure its cohesion with the substrate during the process. There is some side effect of the chemical binder which is porosity in the clad layer due to evaporation [2].

In the second step of the process the following phenomena occur;

1. A melt pool of pre-placed powder is formed on the top surface due to radiation of laser beam.
2. Conduction of heat helps in expansion of melt pool to interface with the substrate.
3. Heat penetration causes a fusion bond to the substrate.

### One step process

In one step process an additive material is fed into the melt pool which can be supplied in the following forms like powder injection, wire feeding, and paste. Laser cladding is done by powder injection, in which powder particles are fed into the heat zone to produce cladded layer. By wire feeding, in which the wire is fed through a ceramic drum containing the desired material wire. To avoid plastic deformation and transport without vibration it is essential to use a wire that is straightened. In paste form, a stream of paste-bound material is deposited on the substrate which is bit ahead of the laser beam. The paste consists of hard facing powder with a suitable binder. The binder should be dried within a short while when the hard facing material is kept in a compact form, or else the powder particles are blown away by the shielding gas [2].

### 1.1.1 Process

Laser cladding is normally performed with powders which are of metallic nature, and is injected by either coaxial or lateral nozzles. The interaction between the laser beam and the metallic powder stream causes the melting of powder to occur, known as the melt pool. Thus moving the substrate allows the melt pool to solidify which produces a track of solid metal. The motion of the substrate is guided by a CAD system which interpolates solid objects into a set of tracks, thus producing the desired part at the end of the trajectory [3].

The laser technique that helps to enhance the surface properties by changing the composition of material in the surface can be distinguished by laser alloying, laser dispersing, and laser cladding. All three methods involve the formation of a melt pool. Depending on the degree of mixing between the clad material and the base material on the surface, one can distinguish from laser alloying, and laser dispersing as one and laser cladding as the other. The first two methods are characterized by making a complete mixture and/or reaction of the cladded elements with the base material. On the contrary, laser cladding generates a surface layer that hardly contains elements of the substrate on top of the base [4].

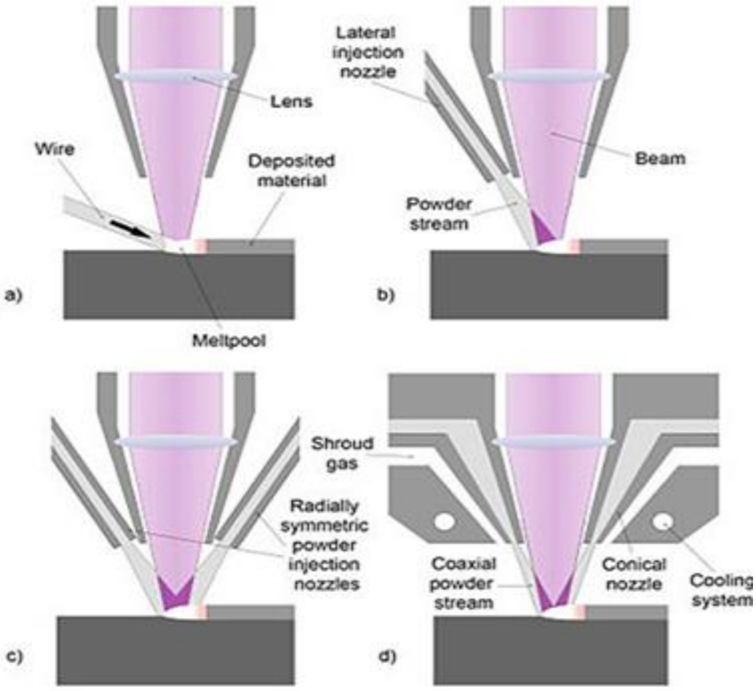


**Fig.1.2**.Process of laser cladding

Laser cladding as a repair and surface strengthening technology has advantages such as limited heat affect zone, small stress deformation, low dilution ratio and better metallurgical bonding with the substrate. It shows good prospects for improving the wear. Composite laser cladding is a good method of hard ceramic reinforcement in ductile metallic matrices which is currently attracting broad attention [5].

### Process advantages

- Flexibility of replacing desired material at any time.
- A very wide choice of different materials can be deposited.
- Deposits are fully fused to the substrates with little or no porosity.
- Narrow heat affected zone due tom minimal heat input.

- Minimal heat input also results in limited distortion of the substrate and reduces the need for additional corrective machining.
- Easy to automate and integrate into CAD/CAM and CNC production environments.

### 1.1.2 Materials of Laser clad

**Base metal and Base materials:** Plates, Forgings, stainless steel plates, Carbon steel, stainless steel, Alloy steel, copper, aluminium.

**Clad materials:** Copper, nickel, aluminium, copper alloys, nickel alloys, Nickel alloys: Alloy (200, 400, 600, 800, 625, 825, 900), alloys (C-276-22, C-2000), Hastelloys. Copper alloys: Copper nickel, Naval Brass, Aluminium, Aluminium bronze, Titanium, Tantalum, and Zirconium alloys.

There are two different kind of materials in powder form such as, Metal powders like chrome, nickel and cobalt base, nickel base and Fe base alloy powders, and the second type such as ceramic powder like WC (Tungsten carbide), SiC (Silicon carbide), TiC (titanium carbide), $Al_2 O_3$ and $ZrO_2$ (Zirconium dioxide) [6].

The most prominently used cladding materials are Fe based alloy, cobalt based alloy, nickel base alloy that are widely used in plasma and flame spraying technology. They are also used in laser cladding, because of their functional properties. The reasons for adopting the mentioned materials are due to its good wettability to carbon steel, alloy steel, stainless steel and various non-ferrous alloy metals [6].

Metal matrix composite (MMC) is a combination of hard ceramic particles such as carbides pressed in a metallic binder. Laser cladding is capable of producing a wide range of MMC coatings. During laser cladding the melting of substrate and metal-ceramic composites powder is injected simultaneously into the molten pool. The metal powder with relatively low melting point melts and acts as a binder for the ceramic phase. Since the substrate melts faster, a strong metallurgical bond is formed between the substrate and coatings [7].

According to the purpose of usage, metal powders can be selected to satisfy the requirements such as wear resistance, erosion resistance and oxidation resistance. Metallic materials have high intensity, toughness and outstanding performance. But on the other hand ceramic powders have good wear resistance, heat resistance, erosion resistance, and chemical stability. When a metal substrate is cladded with ceramic layer the material will possesses both superior properties of metal and ceramics [6].

## Metal powders

### Fe-based Alloys

Fe-based alloys powder is cheaper and forms effective formative coatings TIC-VC ceramic particles which can be reinforced with Fe based coatings have been observed as high hardness and improved wear resistance over other coatings. However research on corrosion resistance of TIC-VC reinforced Fe-based coatings is limited [5].

Chromium is widely used as an effective alloying element and is well known for enhancing electrode potentials and corrosion resistance of iron and nickel based alloys. Chromium can form a passive film on alloy surfaces. They are commonly used as grain refiners during laser surface modification. An amount of rare earth elements in cladding can refine microstructure and thus reduce cracking and can significantly improve corrosion resistance, high temperature oxidation resistance and wear resistance [5].

Rapid cooling and the presence of carbide-forming elements in chromium favors cementite formation. The terminology used with cast iron varies among industries. On the basis of strength/cost, cast iron is second only to structural steel among metals and alloys.it has the advantage of good casting properties, and in the grey form, good machinability, which allows it to be used in component of complex shapes.

The higher carbon content of cast iron leads to a reduction in melting temperature in comparision with steels, which must be considered, when selecting laser processing parameters. A low melting temperature improves the castability of material

### Nickel based Alloy

Nickel based alloys are applied to parts that are exposed to very aggressive atmosphere at higher temperatures. They possess good high temperature corrosion and oxidation resistance. Nickel based alloys can be used an alternative for cobalt. Elements that are commonly mixed with nickel are chromium, boron, carbon, silicon, and aluminium [6].

Inconel 718, a nickel based super alloys, retains its strength and toughness up to temperatures of around 500ºC. Therefore it tends to form an ideal material for the aerospace industry and also applied in gas turbine components and jet engines. Generally nickel based super alloys are hard to machine because of their rapid work hardening ability during machining, segmentation resulting in high cyclical cutting forces and severe tool wear, and their high tendency to form a built up a edge by welding work piece material at high cutting temperature. Adhesive and abrasive wear are the dominant wear mechanism, flank wear and especially the notching wear are the main tool failure modes in conventional machining

Zinc-nickel based alloy with 8-15% nickel were electrochemically deposited onto stainless steel for increased corrosion protection. Alkaline deposition conditions were studied using ammonium hydroxide as the base source and a working pH range between 9.0-9.5. In the field of corrosion there is a constant demand for increased performance at a reduced cost. Steel is a common frame used in automobiles, planes, boats and ships but harsh environmental conditions lead to corrosion over time. To lengthen the life time of metals coatings are added that will protect by sacrificial corrosion protective coatings. Zinc alloyed with cadmium has shown improved corrosion protection, however it raises environmental concerns of toxicity associated with cadmium [8].

Zinc-nickel alloys were examined as a replacement since nickel is cheap easy to work with and the alloys offer comparable, if not better corrosion resistance than zinc-cadmium alloys. Zinc-nickel alloys have shown superior corrosion resistance compared to pure zinc coatings. The alloys are more electrochemically noble than the pure zinc, so the coating will sacrificially corrode to protect the steel but the corrosion at a slower rate. If the nickel content in the deposit becomes greater than 15% the coating becomes anodic in relation to steel. The coating is a good barrier but once damaged will no longer protect the substrate [8].

### Colmonoy Alloy

Laser cladding creates a true metallurgical bond between the two materials forming a much finer micro-structure than hand or arc welding. The process increases surface hardness, improves corrosion resistance and results in little or no distortion. Colmonoy 6 powder is self-fluxing Ni-Cr-B-Si system alloy, which is an industry mainstay because of its good welding and wear characteristics [9].

| **Elements** | C | Si | Mn | Ni | Cr | Mo | Co | B | Fe |
|---|---|---|---|---|---|---|---|---|---|
| **Colmonoy 6** | 0.73 | 4.28 | - | - | 14.56 | - | 0.09 | 3.37 | 3.80 |

**Table.1.1** Elements of Colmonoy alloy

MCrAlY (M stands for nickel or cobalt or both) alloys are commonly used as overlay protective coatings in gas turbine engine components against high temperature oxidation and corrosion. The protective effect of these alloys is due to the formation of a continuous thermally stable oxide layer on the coating surface. In this work several types of MCrAlY alloys differing in their elemental composition have been deposited on the austenitic stainless steel by means of laser cladding [10].

## Cobalt-based Alloy

Cobalt based alloy are widely used in wear related applications because of their inherent high strength, corrosion resistance, and retained hardness over a wide temperature range. Cobalt base super alloys (stellites) are very popular with regard to the improvement of the wear resistance of mechanical parts, especially in hostile environments. Mixture of cobalt powder is like nickel, chromium, tungsten, carbon and molybdenum. Chromium is added to form carbides to provide strength and resistance to cobalt. Tungsten and molybdenum have large atomic sizes and give, therefore, additional strength to the matrix. They also form hard brittle carbides. Nickel is added to increase the ductility [6]. Since cobalt is very rare and expensive element and very difficult to find, it is not extensively used in laser cladding instead nickel base alloy is used as an alternative.

## Ceramic powders

### Titanium Alloy

Laser cladding ceramic metal composite coatings onto titanium alloy substrate was the focus of various investigations owing to the higher, excellent metallurgical bonding in the interface and easy controlled process and the excellent wear properties of the ceramic coatings. In these studies most of transition metal nitrides and carbides are widely used as the coatings to improve the wear properties of titanium alloy for their high hardness and excellent wear properties. Especially titanium nitrides exhibiting also good corrosion resistances are widely used as a coating for cutting tool and wear parts [11].

TiC owes similar properties as TiN. However TiC is easy to break from the substrate due to its high brittleness property. Although TiN owes good toughness it also shows lower hardness which prevents it from being widely used to prolong the service deadline of the coatings. TiC coatings which owe the excellence both of TiC and TiN, within the frame of highly wear resistance coatings, TiCN has been proven as a good protective material especially due to its low friction high hardness and high melting point which makes it useful for wide application [11].

The versatility in terms of coatings architecture of the system is due to the fact that TiC and TiN are iso-structural and thus completely miscible via replacing C atom with N atom in the face centred cubic lattice. It is already well known that similar to other carbon containing coatings TiCN coatings presents low friction behaviour which might decrease or even eliminate the need for liquid lubrication [11].

## Aluminum Alloy

In most experiments of laser surface cladding, ceramic materials such as $Al_2O_3$ are often used as wear resistance coating materials owing to their ultrahigh hardness and superior wear resistance. However ceramic materials alone in the Mg matrix gave rise to poor interfacial strength and poor corrosion resistance. Al as an alloying element could enhance corrosion resistance and a good bonding at the interface with the added advantage of the improved anti-corrosion property [12].

Light alloy cladding material such as Al and Mg based alloy exhibits good physicochemical compatibility with Mg alloy substrates. To some extents it can improve the corrosion resistance of the substrates, but the mechanical properties of the clad layer are insufficient. One way to improve the mechanical properties of the light alloy cladding materials is to introduce some hard particles, forming hard particles reinforced composites. This process introduces cracking and porosity especially for cladding of large surfaces [13].

## Tungsten Alloy

In laser cladding the prominent hard -facing materials used are in powder form due to its high hardness application in which Co, Fe, Ni based alloy which contains hard phased carbides are commonly used. Tungsten carbides possess high coating hardness above 1000 HV. Thus commercial WC powders normally contain spherical micro particles of crushed WC agglomerates [14].

A common approach to the production of these hard-facing materials is the use of metal matrix composites, consisting of a mixture of hard ceramic phase immersed in a ductile metal matrix. In this sense mixture of Ni or Co based alloys are often used with tungsten carbides WC in the hard phase. Tungsten carbides are often commercially supplied as alloy powders consisting of bonded agglomerates of WC particles providing a particle hardness around 1500-2000 HV [14].

The high cooling rate between the ceramic and metallic phase is reported to be beneficial for wear resistance as this improves the bonding between the ceramic phase and the metal matrix. Tungsten carbide is often used as ceramic strengthening phase in laser cladded MMC coatings thanks to its combination of high hardness, certain plasticity, good wettability by molten metals and lower thermal expansion. The matrix material is usually a nickel or cobalt based alloy [7].

The structure of laser cladded nickel alloy tungsten carbide powders has been in several studies. The degree of dissolution depends on the laser beam composites interaction time, carbides particles size and volume fraction of carbides. Dissolution of WC particles in the matrix leads to secondary carbides dispersed in the matrix and around the primary carbides [7].

NiCrBSi alloy is a commonly used hard facing alloy that provides excellent hardness, wear and corrosion resistance at ambient and high temperature. Cracks however may occur in the coating during or after laser cladding caused by residual stresses occurred during rapid solidification. Tantalum (Ta) is a strong carbide formation element which can easily react with C to form tantalum carbide (TaC). TaC has some excellent properties such as high hardness, high melting point, high chemical stability, good resistance to chemical attack and thermal shock and corrosion resistance [15].

Laser cladding coatings consisting of various types of tungsten carbides embedded in a NiCrBSiCFe matrix are characterized. Friction and wear of machine components result in great loss of energy and materials. Surface technologies such as thermal spraying, laser cladding and arc deposition welding are able to produce thick wear resistance coatings on the surface of metal components. One approach to improve the wear properties of a metal surface involves the addition of hard particles (such as carbides, borides, nitrides, and oxides) to it [7].

## Problems in Laser Clad Technology

Many researchers indicate that in the melt–solidification layer, there exist tensile stresses. When the local tensile stress is more than the materials limit then a crack will come into being. Cracks appear mostly at the interface of dendrites, at gas porosity sites, at impurities and other areas of weakness [6].

Another problem is due to the different coefficient of expansion between the cladding layer alloy and substrate material. When the coefficient of expansion is too big tensile stress will come into being. When the tensile stress exceeds the utmost limit of tensile resistance at that temperature, a crack will appear. In addition rapidly heating and cooling occurs in the laser cladding layer as the life of the weld pool is very short. This always means that oxides and other kinds of impurities have not have much time to be emitted. Since they have retained in the clad, they can form into a crack [6].

### Porosity

The presence of holes in the clad layer is being referred to as porosity. Porosity can be caused by several reasons. First it may be the result of the formation of gas bubbles that are trapped in the solidifying melt pool. Secondly if solidification proceeds in different directions, some regions in the melt can be enclosed. A contraction occurs upon solidification of these enclosed regions. That contraction causes tensile stress in the layer and may even lead to the formation of holes. These two kinds of porosity are to be found in the clad layer [4].

Two other kinds of porosity are confined to the substrate clad interface. The first one is caused by the presence of minor flaws, such as grease which influences the surface tension and therewith the bonding of the coating material to the substrate [4].

**Advantages**

- Complex shapes can be coated with increase in life-time of wearing parts.
- Particular dispositions for repairing parts.
- Suitable technique for graded material application.
- Well suited for near-net-shape manufacturing.
- Low amounts of dilution between track and substrate.
- Lower the deformation of the substrate lower the heat affected zone (HAZ).
- Fine microstructure due to fast cooling rate.
- Wide variety of material application (metal, ceramic, even polymer).
- Cladded material is free of crack and porosity.
- Compact technology.

**Disadvantages**

- High equipment cost.
- High and skilled labor required.
- Selection of proper materials and gluing agent.

## 1.2 Overlay welding

A weld overlay is defined as the deposit of a dissimilar weld metal laid on the surface of a metal part. The technique of weld overlay is an excellent method to impart properties to the surface of a substrate that are not available from that base metal. The term weld overlay, also known as weld cladding, usually denotes the application of a relatively thick layer (3 mm or more) of weld metal to impart a corrosion, erosion, or wear resistant surface. A weld deposit of stainless steel laid on the surface of low alloy steel for improved corrosion resistance is an example of a weld overlay. In addition to weld overlays that develop a composite structure by a fusion welding process, there are many processes such as roll cladding, explosive cladding, sheet and strip liner cladding, braze cladding and thermal spraying, by which composite structures may be produced.

Moreover, by repairing an item with a damaged (e.g. corroded or worn) surface using overlay welding, it is possible to use the item repeatedly. As overlay welding can produce thicker layers than thermal spraying or plating and because it creates a metallurgical bond between the base metal and the overlay, it can provide high durability and significant surface modification effects. The procedure consists of the deposition of several weld beads arranged side by side, leading to the formation of a continuous surface layer.

The weld overlay technique can be classified according to the specific objective of the coating. Weld cladding corresponds to deposition of a corrosion resistant material, in general, measuring at least 3 mm (1/8 in.).

The below table shows the prominent materials used for overlay welding which consist of 3 main types namely iron based, Nickel-Cobalt based, Complex Carbide Alloys in which it has different types of material composition.

| | |
|---|---|
| **FE BASED ALLOYS** | Low alloy steel |
| | High alloy steel |
| | Stainless steel |
| | High chromium cast iron |
| **NI-CO BASED ALLOYS** | Inconel alloy |
| | Monel alloy |
| | Hastelloy alloy |
| | Colmonoy alloy |
| | Ni-Cr alloy |
| | Stellite alloy |
| | Tribaloy alloy |
| **COMPLEX CARBIDE ALLOYS** | Proprietary Super hard alloys |
| | Various carbides dispersed in a metal matrix |
| | Materials designed to match required performance E.g. Carbides: WC, NBC, CRC, and VC. |

**Table.1.2** Material used in overlay welding

Depending on the application method, the materials used for engineering parts have to possess an optimal combination of required properties. Some of these properties are pertinent to the bulk, for instance tensile strength, whereas other properties, such as corrosion and wear resistance are pertinent to the surface.

**Fig.1.3** Overlay Welding

The surface engineering technology offers a number of solutions to this problem. The great advantage of surface engineering technologies is that the surface properties can be modified without interfering with the bulk properties [16].

### 1.2.1 Materials

#### FE-Based Alloy

Overlay coatings are frequently deposited by welding and thermal spray techniques either to reclaim worn industrial components or to enhance surface properties of the component being produced. Most common hard facing alloys are iron-based and contain relatively large additions of chromium and carbon. The criteria applied to optimize the composition of welding materials usually include hardness, the requirement of specific composition on deposit and/or high abrasion resistance [16].

Iron-based hard facing alloys are widely used to protect machinery equipment exposed either to pure abrasion or to a combination of abrasion and impact. The specific wear behaviour of a welding alloy under the conditions depends on its chemical composition, the microstructure obtained after welding and finally the welding technology used to apply them respectively the parameter settings which strongly influence, for example, dilution with the base material or formation of metallurgically precipitated hard phases [17]. A new complex Fe–Cr–W–Mo–Nb alloy with high boron content was set into comparison with lower alloyed materials on basis Fe–Cr–B–C, a synthetic multiphase alloy on iron base with around 50 wt% tungsten carbides and a crack free martensitic Fe–Cr–C alloy containing finely precipitated Niobium carbides [17].

State of the art hard facing alloys comprise very cost efficient Fe–Cr–C or Fe–C–B systems on one hand, but on the other hand also more expensive synthetic multiphase composites reinforced with tungsten carbides for example are available [17]. Above that, complex Fe-based alloys with niobium, titanium, molybdenum in combination with boron and carbon gained importance by achieving wear resistance due to the precipitation of different abrasion resistant hard phases and by optimized matrix properties [16].

Mild steel is a material commonly used for structural applications. However, the resistance of this steel to this type of corrosion is poor. The method of enhancing corrosion resistance of such steel is in NaCl solution. The important issue is also the search for alternatives to electrodeposited hard chromium coatings because of the application of baths containing Cr(VI) in the galvanic process. Thermal spraying with subsequent fusion is considered as the alternative. Study showed that microstructure is the most important factor determining abrasion resistance of Fe-based hard facings and that carbon is the most important element. For materials of cast iron structure neither hardness nor chromium or carbon content can be treated as the criteria for materials though these processes are well known and materials used have high status [16].

## Low and High Alloy Steel

The term weld overlay, also known as weld cladding, may be accomplished by any one of the welding processes such as gas metal arc welding (GMAW), flux cored arc welding (FCAW), shielded metal arc welding (SMAW), gas tungsten arc welding (GTAW), plasma arc welding (PAW) and electro-slag welding (ESW). All metals that are used for welding fillers can also be used for weld overlay. With the exception of simple build-up situations where the overlay is used to restore the original dimensions of a worn or corroded part, the composition and properties of filler metal are often quite different from the base metal [17].

In recent years, weld cladding processes are applied in numerous industries such as chemical, fertilizer, nuclear and steam power plants, food processing, and petrochemical industries. Various materials such as nickel and cobalt alloys, copper alloys, manganese alloys, alloy steels, ceramics and composites are used for weld overlay applications. The deposition of high hardness managing steel on 16Mn steel and 9Cr steel to improve the hardness, wear resistance and crack resistance. Microstructure and wear properties of Fe–Mn–Cr–Mo–V alloy cladding by submerged-arc welding on AISI 1045 steel substrate were studied [10]. The process of weld overlay cladding with iron aluminides to improve the corrosion and erosion resistance of 4 Cr–1Mo steel, 310 stainless steel and Inconel 600 [18].

The effect of process parameters on clad bead geometry and its shape relationships of stainless steel claddings deposited by gas metal arc welding were studied. The effect of welding conditions on microstructure and properties of 316L stainless steel submerged arc cladding on IS 2062 structural steel. High strength low alloy (HSLA) steels comprise a specific group of steels with chemical composition specially developed to impart higher mechanical properties such as greater resistance to atmospheric corrosion and low temperature notch toughness. Because of their low carbon content, they are readily weldable. Their development was spurred by the demand for strong, tough, weldable steels for natural gas transmission lines, ships and off-shore drilling platforms [18].

Growth in the production and application of these steels has mainly come about as a result of better under-standing of structure–property relationships as well as economic considerations. HSLA steels are subjected to cladding by one of the commonly used methods such as explosive cladding, roll clad-ding and weld overlaying. Weld overlay cladding can be successfully performed on components with intricate geometry and in areas of limited access where other techniques of cladding cannot be applied. At present, an attempt was made to develop weld overlay cladding of stainless steel. Quenched and tempered HSLA steel was used as the base plate. This steel was weld overlay clad with corrosion resistant stainless steel of AISI 347 grade. In general, only shear bond strength of the interface is evaluated for the clad joints as the thickness of the clad layer is only few milli-meters in thickness [18].

Certain critical defense applications need the clad interface to possess good tensile and impact properties. To facilitate evaluating these properties, a novel technique of friction welding was employed. Mechanical properties (tensile, notch-tensile, shear properties and charpy impact energy of the base plate as well as interface and micro hardness across the interface), optical and scanning electron microstructures and the compositional variations across the interface by electron probe microanalysis have been studied to obtain an understanding of the microstructure and mechanical properties in as clad condition [18].

**Nickel based alloys**

Nickel based alloys were developed in the 50’s for use in turbo superchargers and aircrafts turbine engines that required high performance at elevated temperature. Due to their high resistance to pitting and crevice corrosion many other industries make use of them such as the chemical industry, power generation, the automotive industries and the marine industry. Among different Nickel based alloy, alloy 625 is a high strength and high corrosion resistant Ni-Cr alloy widely used in the chemical industry due to its inherent resistance to a variety of severe corrosive environment [19].

In chloride and alkaline media there is almost no attack. In more severe environments the combination of Ni, Cr and Mo provides resistance to oxidizing and non-oxidizing acids. The use of Ni-Cr alloys for producing overlay welding coating on less noble substrates such as carbon steel is a cost effective method for producing protective coatings. This kind of coatings has a strong metallurgical bonding to the substrate providing good adhesion. Ni based alloys coating can be produced by different welding processes such as the gas tungsten arc, gas metal arc, shielded metal arc, etc. the lower coefficient of expansion of Ni alloys compared to stainless steel gives these alloys better resistance to cracking during welding and lower tolerance to contamination [19].

**Tribo-logical alloys**

Over the last years many studies have been undertaken on the corrosion resistance of nickel alloys in different environments. On the other hand, fewer studies of their tribo-logical properties and their tribo-corrosion behaviour are available. Gas tungsten arc welding (GTAW) process which is widely used in the material surface repairs for industrial and hydraulic handling components consist of nickel based alloys. The pseudo elasticity of TiNi intermetallic alloy provides excellent fatigue resistance and cavitation erosion resistance [9]. Trace titanium oxide formed during welding shows a hardness value of the overlay to 8.6 GPa, far higher than the TiNi rod source material[19].

It was commonly recognized that the nickel-based alloy coatings deposited by thermal spray or overlay welding techniques showed good surface finish, high hardness, and excellent wear resistance. However, the coarser microstructures of the nickel-based alloy coatings might result in more weight loss [20]. Therefore, several ways were used to refine their microstructures to increase their wear resistance, especially by adding $Al_2O_3$ particles in those coatings and the effect of the $Al_2O_3$ particles with different sizes on the microstructure and wear resistance of the nickel based alloy coating deposited by oxy-acetylene surfacing welding. It is understood that adding $Al_2O_3$ particles could refine its microstructure and increase its wear resistance. It is reported that the addition of $Al_2O_3$ particles influence the microstructure and wear resistance of the nickel-based alloy coating changes not only its microstructure but also change its phase characteristics, leading to increase in its wear resistance[20].

The study of previous research shows the works performed using Rietveld refinement method to study the effect of $Al_2O_3$ particles on the phase compositions and their mass fractions, especially to the mass fractions of the borides and the carbides, in the nickel-based alloy coating by now. It is said that the relative change in mass fractions of borides and the carbides have some essential effect on the wear resistance of the deposited coatings [20]. Moreover, it was reported that the wear resistance of the nickel-based alloy coating with nano-$Al_2O_3$ addition was higher than that of the nickel-based alloy coatings with micro or submicron $Al_2O_3$ addition. However, little attention has so far been paid to study the effects of nano-$Al_2O_3$ particles on the substructure of the nickel-based alloy coating. It is obvious that the substructure including dislocations and stacking faults have important effect on the wear resistance of the deposited coatings [20].

## Titanium Nickel Alloy

TiNi alloys are a well-known shape memory and pseudo elastic alloy. It has also shown great promise as a wear resistant material its excellent performance during cavitation erosion and water jet erosion. High resistance of TiNi alloy arises from its high work hardening rate and pseudo elasticity (reaching to 7-20% two orders of magnitude larger than ordinary elasticity) which enables its effective impact energy absorption properties with little damage from thermal elastic phase transformation deformation. Accordingly, TiNi alloy seems to be a good choice for hydraulic system applications [3].

In most cases, hydraulic machines are bulky and the TiNi alloy is expensive. Coating is a way to reduce the cost of TiNi alloy applications. As a result, explosively welded TiNi and thermal spray TiNi coatings have been studied. It was found that TiNi coatings could improve cavitation erosion resistance. Thin TiNi film coatings produced using cathode arc plasma ion plating has been proven to enhance the cavitation resistance of steel substrates [3].

## Colmonoy Alloy

Among the available hard facing alloys, nickel based ones have gained popularity in recent years owing to their excellent performance under conditions of abrasion, corrosion and elevated temperature with relatively low cost. Colmonoy 5, a cobalt free nickel based alloy is widely employed as hard facing material in applications like Petroleum, Chemical and other marine environments, Aircraft auto-motives, Paper and Pulp industries, Railways and Mining industries, Nuclear engineering, etc. among which chemical and marine environments are more vulnerable locations for pitting corrosion attacks [21].

Colmonoy alloys are machinable and have superior fusion characteristics. In many of the cases, such alloys are required over the surface as overlay to provide superior properties than the bulk material and a suitable low cost bulk material leads to economical solutions in many situations [21]. Normally, as the weld metals could have compositional and microstructural in homogeneity, they are more susceptible to corrosion where systematic and scientific based corrosion studies become inevitable.

The hard facing material can be deposited through various welding processes. But PTA process is preferred on many occasions due to its better process control, ease of use, high deposition rate and lower heat input. It achieves smooth and thin deposits of overlays through the controlled feeding of powder. In the present study, Colmonoy 5 was deposited on austenitic stainless steel 316 L plates through PTA hard facing [21]. The resulting overlays are of excellent wear resistant, corrosion resistant and high temperature properties with fabulous metallurgical bonding and low dilution. Dilution is an intermixing of hard surfacing alloy with base metal which degrades all the desirable properties of the overlay and spoils the ultimate purpose for which it is applied [21].

Moreover, development of mathematical models could be helpful to study the main and interaction effects of the significant process parameters affecting the pitting corrosion resistance of the weld bead. The literature available indicates that not many works have been carried out to develop mathematical models for studying the pitting corrosion behaviour of Colmonoy alloys influenced by the PTAW process parameters. Therefore, an investigation was carried out to develop a model correlating the process parameters to pitting potential [21].

The significant PTA process parameters chosen to carry out the PTA deposition of Colmonoy were welding current (A), Oscillation width (O), Travel speed (S), Preheat temperature (T) and Powder feed rate (F). The gas flow rate and Torch standoff distance were kept constant. The experiments were conducted based on the central composite rotatable design matrix. Regression analysis was used to develop the model and the analysis of variance method was used to test their adequacy [21].

**Stellite Alloy**

Stellite alloy is a hard facing alloy possessing excellent abrasion and corrosion resistance for applications such as pump sleeves, rotary seal rings, wear pads, expeller screws and bearing sleeves. It retains its hardness at temperatures in excess of 760°C (1400°F). It contains a high proportion of hard, wear resistant primary carbides. These render the alloy well suited to applications involving extreme low-angle erosion and severe abrasion, with some sacrifice in toughness. Compared to other Stellite alloys it is more crack sensitive, and care should be taken to minimize the cooling stresses experienced during casting and hard facing processes. Due to its high hardness and wear resistance, Stellite should only be finished by grinding. Stellite has good general corrosion resistance. The typical electrode potential in sea water at room temperature is approx. -0.4 V (SCE). Stellite corrodes primarily by a pitting mechanism and not by general mass loss in seawater and chloride solutions.

**Nickel-Tungsten Carbide Alloy**

Overlay welding is used to improve the wear resistance of surfaces on industrial parts by depositing a protective layer of abrasion and/or corrosion resistant weld metal onto a base material surface. The extreme wear decreases productivity and the useful life of equipment, as such overlay into the metallic matrix. As a result, WC particles are an ideal candidate for addition into Ni-based alloys as the reinforcing phase since the low melting point of NiCrBSi alloys (about 1025$^{\circ}$ C) allows tungsten carbide to endure the deposition process without degradation more readily than in Fe-based matrix alloys [22].

A central problem with plasma transferred arc welded (PTAW) Ni–WC overlays is the degree of dissolution of the WC particles. Dissolution results in lowered wear resistance as there is less WC reinforcing material remaining to offer protection from abrasive wear. In addition, the dissolved W, and C allow the formation of brittle secondary phases which may be detrimental to the abrasion resistance of the deposit. Particle dissolution occurs when excessive arc current provides sufficient heat to cause WC material to go into solution above a critical temperature.

In order to prevent precipitation of brittle hard phases during laser welding, it was found that alloys with low contents of carbon, boron, and chromium should be used. The diffusion coefficient of carbon in the matrix material is usually higher than the diffusion coefficient of the carbide forming metal. Thus, carbon diffuses much faster out of the carbide, allowing it to form mixed carbides. Laser cladding of a NiCrBSi alloy with WC particles resulted in a matrix microstructure similar to that processed with no WC particles present, since the dissolution of WC particles is very low (~5%) using the laser cladding process [22].

In addition, it is important to consider the formation of the phases in the matrix, since during abrasive wear the surface of a soft material is gouged out by the abrasive particles/phases of the harder material and produces wear chips when the abraded material is elasto-plastic or viscoelastic plastic. Abrasive wear involves subsurface plastic deformation (increases as wear particles themselves develop flat surfaces) in addition to cutting of the surface and generation of wear chips. It is generally understood that increasing the hard particle fraction will increase coating hardness and hence abrasive wear resistance.

It was studied that for laser deposited Ni-based alloys with WC particles, increasing the WC volume fraction from 0 to ∼50% did indeed show a linear dependence of hardness on the concentration of carbides but there was no correlation with the size of the particles [22]. This implies that the mean free distance between WC particles also plays an important role in wear resistance, where any dissolution of the WC material will be detrimental to the performance.

Alterations in the microstructure of chromium-rich irons and hard facing alloys through alloying additions, modifications in casting and cooling methods and heat treatments have resulted in surface distribution of carbide and ductile phases more prone to resist to particle impacts. However, no cast iron and carbide hard facing alloys developed so far have presented slurry erosion resistance exceeding a 50% improvement.

This work presents the research work carried out to develop a gas metal arc welding (GMAW) clad overlay that resists slurry erosion at low and high particle angles. The welding deposition parameters as well as the composition range in the Fe–Mo–B–C–Si system that lead to improved performance are exemplified [22].

**Complex Carbide Alloys**

Stellite Cobalt based alloys consist of complex carbides in an alloy matrix. They are resistant to wear, galling and corrosion and retain these properties at high temperatures. Their exceptional wear resistance is due mainly to the unique inherent characteristics of the hard carbide phase dispersed in a CoCr alloy matrix.

### Solid State Welding

**Solid state welding** is processes of producing coalescence at temperatures below the melting point of the base materials being joined, without the addition of any filler metal. In which pressure may or may not be used. They are otherwise called as solid state bonding processes: which includes processes like cold welding, diffusion welding, explosion welding, friction welding, and roll welding. The metals being joined by this process have lower heat affected zone problems even when there is base metal melting without change in its properties. When dissimilar metals are bonded thermal expansion and conductivity is given the least importance in solid state welding when compared to arc welding processes [23].

### 1.3 Roll bonding

Roll-Bonding, also called Roll welding, is a solid state welding process in which multiple layers of similar or dissimilar metals are stacked together and rolled to a certain degree to produce a solid state welding. A stack of desired material is fed through a cold rolling mill under sufficient pressure to produce significant deformation and thus performing solid state welding. Metals should be ductile, like copper, aluminium, low carbon steel, and nickel [24].

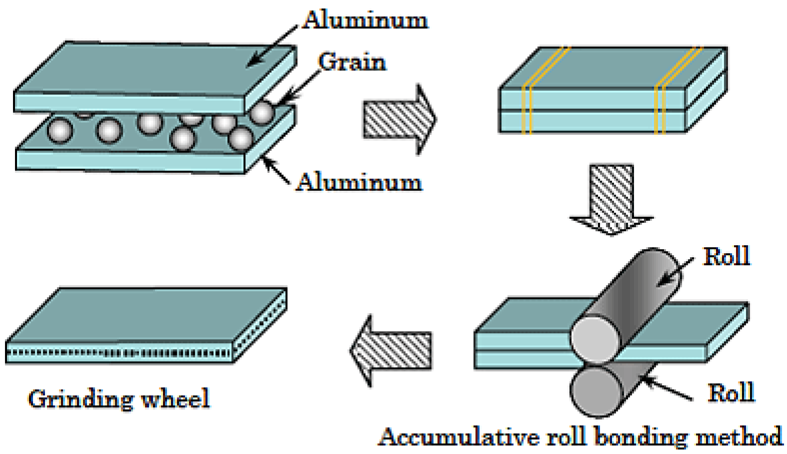


**Fig.1.4.**Roll Bonding [24]

### 1.3.1 Process of Accumulative Roll Bonding

Accumulative roll bonding process is one of the most prominent severe plastic deformation processes for obtaining sheet materials with ultrafine grained microstructure and high strength. The properties of such sheet differ significantly from those of conventionally rolled sheets. The process is based on the principle of stacking two sheets of materials and subsequently feeding them to a rolling mill where the thickness is reduced by 50%. As the geometrical dimension of the processed sheet remains more or less unchanged to the starting material, the process can be easily repeated. The major advantage of ARB process is that it can be easily integrated/adapted into existing industrial rolling trains without major modification and can be scaled up to produce sheet materials with UFG microstructures on an industrial scale. The repeated roll bonding of the sheets in the ARB process leads to substantial accumulation of plastic deformation resulting in a UFG microstructure. This UFG microstructure causes a significant increase by almost a factor of two in the strength of the material in comparison to the course grained counterpart. The application of ARB to low density sheet materials, like aluminium alloy can result in both high strength and high ductility of the material [23].

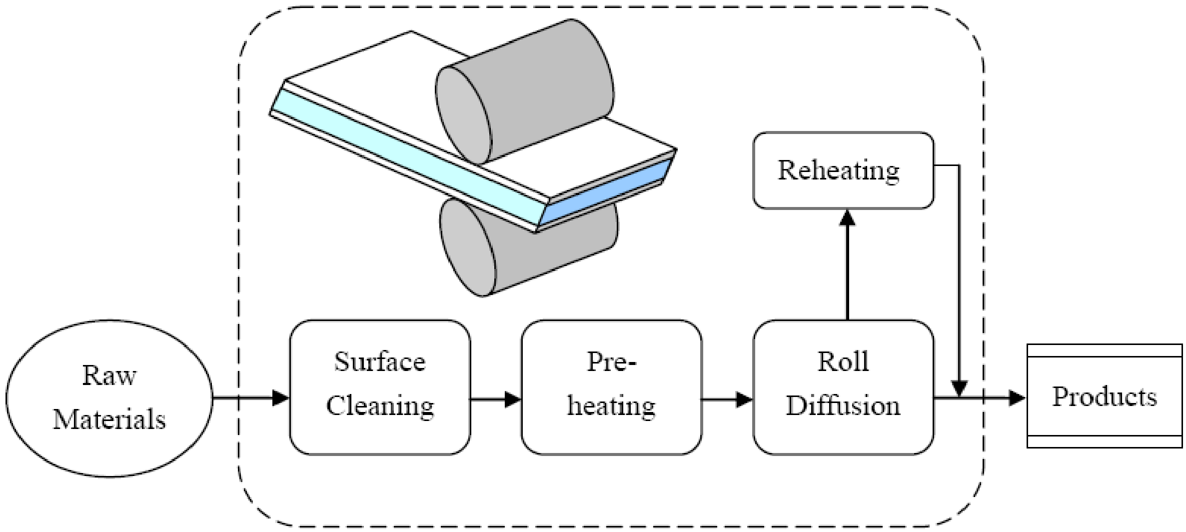


**Fig.1.5** Process of Roll Bonding [23]

ARB process itself involves a multitude of parameters e.g. rolling speed, friction between the rolls and the feedstock, number of rolling passes, and stacking and rolling direction, which can have a considerable effect on the properties of the roll bonded sheet. Comparing the conventional rolling process, the role of such process parameters is either significantly enhanced in ARB due to high thickness reduction and repeated stacking of roll bonded sheets in every pass. Sheared surface layers give rise to characteristic through thickness strain gradient in the roll bonded sheet. With repeated cutting and stacking, the shear profile changes substantially, leading to different rates of microstructure evolution along the thickness of the sheet. The anisotropic in the roll bonded sheet is thus not just a function of microstructure, but also the strain gradient and the number of rolling passes. It is thus expected that the properties of ARB sheets differ appreciably from those of conventionally rolled sheets, and additionally, can significantly impact further application of the roll bonded sheet [23].

### 1.3.2 Materials

Metal Matrix composites are of great interest in automotive and aerospace application due to their superior properties that help in designing light weight structures. As light metals, Al and its alloys have been widely applies in various fields, such as aerospace, automobiles, but from a metal forming point Mg, Ti their alloys have limited applications due to their poor plasticity. However it is expected that a light metallic multi-layered composite may utilize advantages of three light metal components through the balance design and appropriate processing. Thus the production of such a light metallic composites becomes an important issue [24].

Al/Ti/Mg multilayer composite has a great potential for industrial applications due to their excellent mechanical properties combined with low density. These composites are economically more attractive than monolithic AL, Mg, Ti. Moreover Mg/Al/Ti composite is less expensive than Ti. Accumulative roll bonding linkage as one of the most economical method of producing composites sheet is well known [24].

With the development of modern technology, single material hardly satisfies the increasing demands of properties. Laminated metal composites consisting of two or more metals have been developed due to their improved fracture toughness, bending behaviour, impact behaviour, corrosion, wear and damping capacity. A number of techniques have been developed to manufacture LMC such as explosive welding, roll bonding, diffusion bonding. However, roll bonding is extensively used because of its efficiency and economy [25].

Multi-layered Al/Cu/Mn composites are produced from aluminium 1100 strips, commercial copper foils and manganese powders, through accumulative roll bonding (ARB). Metal matrix composites are known as key engineering materials in industry. Some of them, including aluminium-based metal matrix composites because of their outstanding properties such as appropriate electrical and high thermal conductivity, low density, and high wear resistance and corrosion resistance. One type of these materials called metallic multilayer composites (MMCs) consisting of alternative metal, reinforced metal layers and metal powder, dramatically improve a range of mechanical properties. Various methods including electro deposition, ion sputtering, evaporation, and magnetron sputtering deposition have been used to fabricate thin metallic film multilayer or multi layered composites [26].

Metal matrix composites (MMCs) are engineering materials to which ceramic particles, particularly $Al_2O_3$, SiC are added to obtain the desired mechanical properties. Recently, metal matrix composites have gained a lot of attention due to their accessibility to different types of reinforcements having competitive prices, successful development of production processes and the possibility of obtaining the desired structured by standard methods of mechanical working. There are different methods to produce the MMCs such as powder metallurgy, squeeze casting, spray forming and accumulative roll bonding (ARB) processes. The yield strength compressive strength and Young's modulus of metal matrix composites have been shown to increase by the addition of non-metallic phases. It has been shown that with increasing the number of ARB cycles, the uniformity of the $Al_2O_3$ in the aluminium matrix is enhanced; the $Al_2O_3$ particles become finer, the porosity of composite is decreased and the mechanical properties of composites are improved. Composites with metallic matrix have been successfully used in applications such as aerospace and transportation. Therefore, wear resistance is one the important characteristics that should be considered. Lack of wear resistance leads to deprecation, which is failure followed by serious damage to the industry. There are several mechanisms of wear including seizure, melting, oxidation, adhesion, abrasion, delaminating, fatigue, fretting, and corrosion. Wear can be reduced normally by using a lubricant with appropriate anti-wear additives, changing the materials, and/or the operating parameters affecting the wear rate [27].

The composites and nano-composites have higher strength in shear and compression and higher temperature capability because they are a combination of metallic properties and ceramic properties. Interstitial free (IF) is a recently developed steel product with a very low free carbon and nitrogen level. This steel is used widely in the automotive industry because of its excellent form-ability and high planar isotropy. However, the IF steel in the coarse-grained (CG) condition possesses high ductility but low strength. Low strength in automotive body panel materials gives rise to the need for thicker sheets in order to maintain desired crash safety and panel rigidity, which cause heavier vehicles, and consequently higher fuel consumption. In addition, low strength of IF steel limits its broader applications in conditions where high strength is needed in addition to high formability. Considering the single-phase ferritic microstructure of IF steel, strengthening methods to enhance its mechanical properties are limited. Continual annealing and roll bonding (CAR), and cold roll bonding (CRB) processes for fabrication of high strength metal matrix composite. Therefore, fabrication of metal matrix composites and nano-composites via ARB process seems to be the suitable methods [28].

Commercially pure titanium (CP Ti) is one of the most important titanium alloys due to its relatively high strength-to-weight ratio, excellent corrosion resistance and biocompatibility. It is widely used in many fields such as chemical, nuclear and biomedical industries. In fact, the corrosion resistance of CP Ti is excellent, but its strength is lower than that of other titanium alloys. This relatively low strength limits the use of CP Ti in many cases, especially where the combination of high strength and corrosion resistance is required. Enhancement of CP Ti mechanical properties by means of grain refinement through severe plastic deformation (SPD) techniques has been widely investigated by different researchers [29].

ARB process has been successfully used for improving mechanical properties of Ti alloys or fabricating high strength multi-layered structures systems, including Ti, such as Ti/Al, Ti/Al/Nb. In 2007, ARB process was applied to commercially pure titanium by Terada et al. They showed that the tensile strength and the total elongation of the CP Ti specimens ARBed above 5 cycles were equivalent to those of Ti–6Al–4V [29].

The mechanical properties of MMCs are highly dependent on the size, fraction and the distribution of reinforcement and also, the reinforcement/matrix bond strength. In conventional MMCs processing procedures, usually, the reinforcement tends to agglomerate, leading to the non-uniform distribution. Also, the poor wettability of reinforcement oxides has a kind of harmful influence on the reinforcement/matrix bond strength and consequently, the mechanical properties of the resulting composites. To overcome the above problems, a new technique was developed for manufacturing high-strength and highly-uniform metal matrix composites via repeated roll bonding process. In this method, reinforcements were added uniformly between the two strips after surface preparation and before roll-bonding. The mechanical properties of Titanium alloys can be improved by reinforcing them with ceramic particles. In previous works, different particles such as TiC, TiN, and SiC were used as reinforcement of titanium alloys. SiC establishes a high strength and stronger specific Young’s modulus and so, it is nowadays widely used as the reinforcement of Ti alloys and Ti aluminide matrices [29].

Copper are extensively used in industrial applications, corrosion prevention, power generation, and heat exchanger tubes. The passivation behaviour of copper in the alkaline solutions is very important because of the scientific importance of this phenomenon. Indeed, the passive film provides an efficient barrier against the metal dissolution. In a lot of extensive research, little research has been focused on the passivation behaviour of UFG copper and copper alloys. It is found that the corrosion resistance of UFG metals and alloys is worse than that of its coarse grained counterpart, due to the higher defect density. It is reported that the corrosion resistance of UFG Al–Mn alloy that was highly deformed by the ARB method was improved by decreasing the size of $MnAl_6$ particles. Moreover, it is reported that the pitting of 5052 Al alloy produced by ARB was increased. Also, other results indicated that the formation of a passive film is difficult by increasing the cold deformations. This phenomenon can be correlated to the enhanced dislocation density and number of defects in the material [30].

Magnesium alloys are the lightest-weight metal commercially available today, having various advantageous properties in terms of specific strength, damping capacity, electromagnetic shielding, and dimensional stability. Actual industrial application areas of Mg alloys are, however, quite limited due to their inherent drawbacks in relation to poor corrosion resistance, formability, and surface quality. In order to expand the applications of Mg alloys, various types of clad Mg alloys have been developed by bonding with other alloys such as stainless steels and Al alloys to complement the drawbacks of Mg alloys. Direct solid-state bonding between Mg and Al alloys is, however, seriously restricted due to limited formability of Mg alloys at low and intermediate temperatures. Various solid-state bonding processes of Mg/Al sheets have been developed to date including roll-bonding, friction-bonding, diffusion-bonding, and explosion-bonding. Among these, roll-bonding is the most widely used process for fabricating Mg/Al clad sheets, considering economic advantages in terms of convenient utilization of conventional rolling facilities, productivity, and easy combination of clad metals. A warm roll-bonding is generally used to circumvent the poor room temperature formability of Mg alloys followed by subsequently annealing treatment to control mechanical properties of clad sheets [31].

Advantages in comparison to overlay welding:

- Improved surface conditions
- No dilution from the base material
- Homogenous chemical composition

Advantages in comparison to explosive cladding:

- Higher bonding quality
- Reduction of weld length due to larger dimensions
- Use of thinner clad material is possible
- No welds in the claddings for wide plates

### 1.4 Explosion welding

Explosion welding is a solid state welding process in which coalescence is affected by high-velocity movement together of the parts to be joined produced by a controlled detonation. Even though heat is not applied in making an explosion weld it appears that the metal at the interface is molten during welding [32].

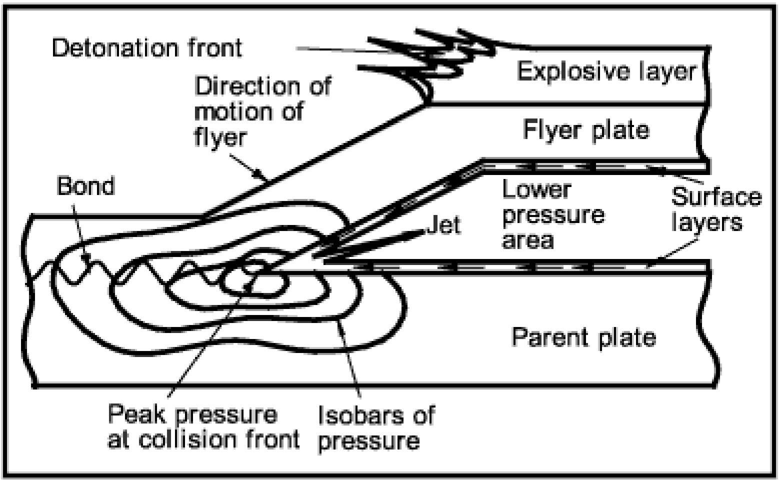


**Fig.1.6** Explosion Welding [32]

This heat comes from several sources, from the shock wave associated with impact and from the energy expended in collision. Heat is also released by plastic deformation associated with jetting and ripples formation at the interface between the parts being welded. Plastic interaction between the metal surfaces is especially pronounced when surface jetting occurs. It is found necessary to allow the metal to flow plastically in order to provide a quality weld [32].

Explosion welding creates a strong weld between almost all metals. It has been used to weld dissimilar metals that were not weld-able by the arc processes. The weld apparently does not disturb the effects of cold work or other forms of mechanical or thermal treatment. The process is self-contained, it is portable, and welding can be achieved quickly over large areas. The strength of the weld joint is equal to or greater than the strength of the weaker of the two metals joined [32].

The resultant composite system is joined with a high-quality metallurgical bond. The time duration involved in the explosive welding event is so short, that the reaction zone between the constituent metals is microscopic. During the bonding process, several atomic layers on the surface of each metal become plasma. The collision angle between the two surfaces (typically less than 30°) forces the plasma to jet ahead of the collision front, effectively scrubbing both surfaces and leaving virgin metal.

The remaining thickness remains near ambient temperature and acts as a huge heat sink. Therefore, the bond line is an abrupt transition from the clad metal to the base metal with virtually no degradation of their initial physical or mechanical properties. The obvious benefit from this process is the joining of metallurgically incompatible systems. Any conventional cladding method, which uses heat, may cause brittle intermetallic compounds to form [32].

Explosion welding has not become too widely used except in a few limited fields. One of the most widely used applications of explosion welding has been in the cladding of base metals with thinner alloys. Another application for explosion welding is in the joining of tube-to-tube sheets for the manufacture of heat exchangers. The process is also used as a repair tool for repairing leaking tube-to-tube sheet joints [32].

### 1.4.1 Process Control

Cladding multi-laminates by explosive welding involves a working knowledge of the process phenomena and the ability to utilize them efficiently to create quality composites. In order to produce a quality weld, the variables affecting the weld formation must be tightly controlled. The amplitude and periodicity of the wave pattern formed during explosive welding can be controlled by adjusting three major parameters: detonation velocity (Vd), explosive load, and the interface spacing. The wave pattern formed at the bond line is most often described as resulting from a fluid flow collision. The two constituent metals can be considered to act as viscous fluids in the reaction zone and, just as in describing laminar or turbulent flow, a Reynolds number can be determined for the system [33].

It is also important to know the metallurgy involved in a particular system when selecting bonding parameters. In every turbulent wave patterns, localized melt pockets can occur at the "crests" of the waves. These melt pockets can contain a variety of binary alloys, rapidly-solidified microstructures and intermetallic compounds. Some systems that form a very stable intermetallic compound may form a continuous layer of that compound at high bonding pressures. Such a bond, with a continuous intermetallic layer, usually shows very high tensile strength, but low ductility and impact resistance. It will also react poorly to thermal cycling [33].

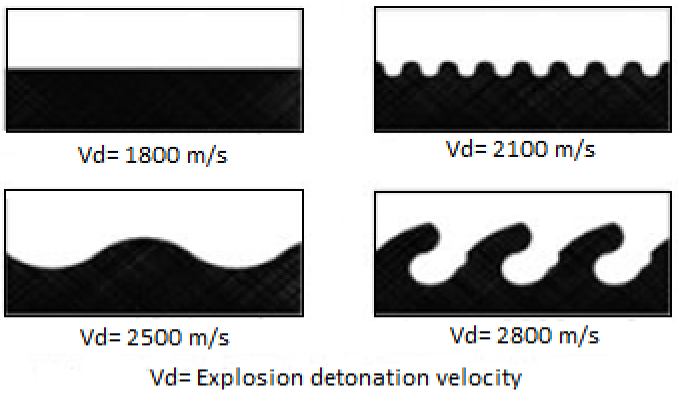


**Fig.1.7** Wave forms in Explosion weld [33]

**Interlayers**

The problems of extreme metallurgical incompatibility may be overcome with the addition of an interlayer. The interlayer is chosen for improved compatibility with both of the constituent metals or because it allows thermal excursions which otherwise may lead to service problems. High melting temperature interlayers allow transition joints to be conventionally welded to their respective parent metals without the concern of diffusion related failures or bond degradation [33].

Explosively welded multi-laminates come very close to achieving ideal composite conditions i.e. a sharp transition between layers; physical and mechanical properties which are constant or enhanced throughout individual layer thickness; and a metallurgical bond between layers. These composites are available for a wide variety of industrial and strategic applications. The high integrity of the bond allows design engineers to utilize the specific desirable properties of metals more efficiently [33].

Transition joints between metals with widely differing melting temperatures can be produced with the appropriate diffusion barrier interlayer. Thin, exotic metals with unique desirable properties can be metallurgically incorporated externally or within a metal matrix. This process allows the economical use of strategic metals, while mitigating design constraints common with mechanical joining methods [33].

Cladding metal or cladder is the thinner plate that is either in direct contact with the explosive, or is shielded by a flyer plate from the explosive. Flyer plate is a sacrificial plate placed between the cladder and the explosive to protect the clad metal. Interlayer is a thin (typically 0.01–0.03 in.) metal layer that is sometimes placed between the cladder and base plate to enhance joining. Base plate or backer is the plate that the cladder is being joined to. Anvil is the surface on which backer rests during the joining operation. Standoff is the distance between the cladder and base plate prior to the joining operation. Bond window is the range of process variables, such as velocity, dynamic bend, and standoff distance that result in a successful weld. Bonding operation is the detonation of the explosive resulting in a weld [33].

### 1.4.3 Materials

Ordinary TiNi alloy is connected to other alloys by laser or plasma welding. However the strength and functional properties of these objects are not so good due to the formation of precipitates such as $TiFe_2$, TiFe, TiC, and $Ti_3Ni_4$ in the heat-assisted zone. Meanwhile Prummer and Stockel showed that the bimetal composite of TiNi alloy–stainless steel may be produced by another type of joining: explosion welding. S. Belyaev et al found that the formation of brittle inter-metallics and non-metallics particles was not observed in TiNi–stainless steel composite produced by explosion welding. Moreover it was shown that the width of the mixture zone between the steel layer and the TiNi one was very narrow and did not exceed 6 μm. It was found that a martensitic transformation in the TiNi component of bimetal composite was strongly depressed by plastic deformation imparted to the TiNi alloy during an impact with a steel plate. Belyaev et al found that the kinetics of a phase transition may be restored by subsequent annealing of the composite [32].

However for application of bimetal composite it is very important to study not only the kinetics of martensitic transformation but also the functional properties. It is known that the behaviour of actuators depends on the relation between the ability of the bias element to accumulate an elastic energy and the ability of the shape memory alloy to recover a strain. Thus, in the case of actuators created on the base of bimetal plate, the properties of the actuator should depend on the ratio of the thickness of the TiNi layer to that of the steel one. However the ability of the sample to accumulate stress is determined not only by the thickness of the steel layer but also by the level of preliminary strain of the bimetal composites [32].

Current developments in advanced technologies are required for new materials with superior properties such as corrosion, wear resistances for industrial applications. Therefore, numerous works have been carried out to develop new materials for such purposes. As low carbon steel has low corrosion resistance therefore, it may be cladded with the materials such as aluminium, titanium and stainless steel that can be suitable for using in corrosion environment. Explosive welding is a well-known for its capability to directly join a wide variety of both similar and dissimilar combinations of metals that cannot be joined by any other techniques. Furthermore, the process is capable of joining with high surface areas due to its ability to distribute the high energy density through explosion. Similar metals (low carbon steel, steel to steel, Al–Al, stainless steel to steel), dissimilar metals such as steel and aluminium, steel and titanium, nickel film and aluminium alloys, iron and copper, aluminium, copper and magnesium, copper, titanium and steel, aluminium and copper and also metallic glasses were cladded successfully [33].

Explosive welding parameters of steel parts and their effects on micro-hardness and shear strength were investigated by Acarer. 6061 T0 aluminium alloy was joined to 6061 T0 aluminium alloy by explosive welding. This is a process in which the controlled energy of a detonating explosive is used to create a metallic bond between two similar or dissimilar materials. The welding conditions were tailored to produce both wavy and straight interfaces [33].

Titanium’s superior corrosion resistance is ideal for many process applications. Process industries choose titanium as the material of construction for piping, tanks, pressure vessel, autoclaves and heat exchangers. When pressure and/or temperatures and size demand very thick plates, the titanium equipment can become considerably more expensive than units constructed from lower cost, lower performance materials. Titanium clad steel provides lower cost than many other materials as indicated [34].

The explosive welding of two different kinds of metallic sheet is accomplished by the exhaustive deformation owing to high pressure and high temperature created at the collision place. Particular explosive welding operations have been completed without any interlayer. Nevertheless, depending upon the material couples, the third material was presented as an interlayer [35].

For instance, when an Al bush-bar in an Al refining factory is welded by an explosive welding process, a titanium interlayer plate is placed between the steel and the Al to repress the generation of the brittle intermediate phase which performs a fatal influence on period of the cladded artefact. It is also extremely hard to weld exactly the unification of Al alloy and stainless steel plates. For this combination Hokomoto et al. employed the other stainless steel plate as an interlayer in welding an Al–Mg alloy and a stainless steel plate, and the inter-layer manage to variations in morphologies and mechanical features of interface [35].

The system of materials Ti-Al has been extensively studied in recent decades. Many researches note that titanium aluminide forming in this system are characterised with high hardness, corrosion resistance, heat resistance, and low specific gravity. Of the great number of the possible inter-metallics forming between aluminium and titanium, the largest interest is attracted to $Al_3Ti$. A unique set of mechanical properties renders titanium tri-aluminide a prospective material for aircrafts engineering. The main drawback of the inter-metallics is their high brittleness, and therefore various composites reinforced with titanium tri-aluminide are usually suggested for industrial application [36].

Of the other titanium tri-aluminide based composites the class of multilayer metallic-intermetallic laminate composites should be specifically emphasized, which possess a unique set of mechanical properties. An important advantage of the multilayer composites is the possibility of combining the properties of both the hard and refractory inter-metallics and the ductile matrix. Beryllium and its alloys are the only metallic materials of higher specific stiffness [36].

Titanium is suitable for chemical and aerospace industries because of their excellent corrosion resistance and specific strength compared to steel. Q345 steel has good strength and excellent cost advantage over Titanium. It is difficult to join Ti (or its alloys) to steel due to great differences in thermal, physical, and chemical properties. According to the Ti–Fe binary phase diagram, the solubility of Fe in Ti is very low (0.1 at%, at room temperature). Intermetallic phases TiFe and $Ti_2Fe$ begin to form when beyond its solubility. , thermal stress mismatch between the two materials is another important factor resulting in cracking. It has been acknowledged that direct joining of Ti to steel is very difficult even under solid state joining method. Cu, Cr, Ni were frequently used to prevent the formation of brittle inter-metallics between Ti and steel in diffusion bonding method [37].

Thermites are commonly referred to as highly exothermic reactive mixtures of metal powder fuels (i.e., aluminium, magnesium, titanium, zinc) and metal/non-metal oxides (i.e., boron oxide, silicon dioxide, chromium oxide, iron (II, III) oxide, copper (II) oxide). Once initiated the exothermic reduction-oxidation (redox) reaction proceeds rapidly and releases substantial heat, which is sufficient to boost the combustion temperatures up to ~4000 K. Such thermite systems hold great promise for a variety of applications, including extracting pure metals from ores, joining of materials. Recently, a new class of thermite reactions, known as super-thermites, attracted great attention for preparation of energetic nano-composites [38].

**Applications**

- Joining of pipes and tubes.
- Major areas of the use of this method are heat exchanger tube sheets and pressure vessels.
- Tube Plugging.
- Remote joining in hazardous environments.
- Joining of dissimilar metals - Aluminum to steel, Titanium alloys to Cr – Ni steel, Cu to stainless steel, Tungsten to Steel, etc.
- Attaching cooling fins.
- Other applications are in chemical process vessels, ship building industry, cryogenic industry, etc.

**Advantages**

- Can bond many dissimilar, normally un-weldable metals.
- Minimum fixturing/jigs.
- Simplicity of the process.
- Extremely large surfaces can be bonded.
- Wide range of thicknesses can be explosively clad together.
- No effect on parent properties.
- Small quantity of explosive used.

**Limitations**

- The metals must have high enough impact resistance, and ductility.
- Noise and blast can require operator protection, vacuum chambers, buried in sand/water.
- The use of explosives in industrial areas will be restricted by the noise and ground vibrations caused by the explosion.
- The geometries welded must be simple flat, cylindrical, conical.

### 1.5 Friction welding

Friction welding is one of the effective joining techniques. Friction welding is a solid state welding and it offers an alternative welding process for joining the parts in particular electrical appliances, engine parts etc. the welding takes place when two surfaces, subjected to the joining, get in mechanical contact and the surfaces are heated to the desired temperature through frictional heat generation and later a forging pressure is introduced to weld the parts. Many ferrous and non-ferrous alloys can be friction welded. Friction welding can be used to join materials of different thermal and mechanical properties. The combinations of material cannot be joined by other welding techniques because of the formation of brittle phases which make the joint poor in mechanical properties. The sub-melting temperatures and short weld times of friction welding allow many combinations of material to be joined [39].

#### 1.5.1 Process overview

Friction stir welding is a solid state joining process that creates extremely high quality, high strength joints with low distortion. A non-consumable spinning tool bit is inserted into the work piece. The rotation of the tool creates friction that heats the material to a plastic state. As the tool traverses the weld joint, it extrudes material in a distinctive flow pattern and forges the material in its wake. The resulting solid phase bond joins the two pieces into one [40].

The process use no outside filler material, no shielding gases, and requires low energy input when compared to other welding processes. The solid phase bond between the two pieces is made solely of parent material. The grain structure in the weld zone is finer than that of the parent material and has similar strength, bending, and fatigue characteristics [40].

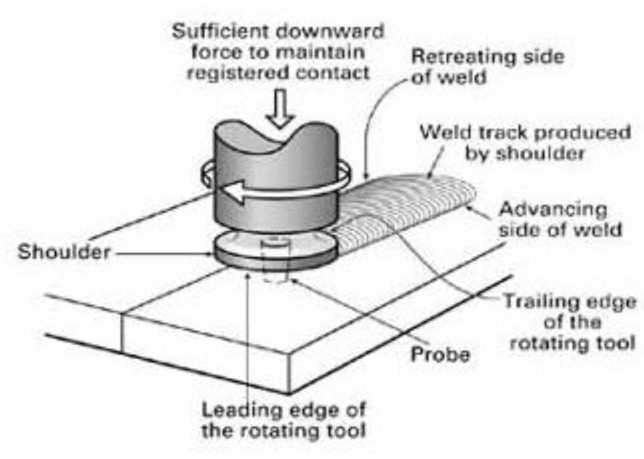


**Fig.1.8.** Friction-stir welding [40]

### 1.5.2 Materials

Austenitic stainless steels are the most popular type of stainless steels with wide applications in different industries, from low-end to advanced applications like aerospace vehicles. Although austenitic stainless steels possess high corrosion resistance, good formability and suitable welding properties, their relatively low hardness and yield strength have limited their wider applications. Improving the mechanical properties of austenitic stainless steels have therefore become a critical concern, and advanced thermo mechanical processing based on hot deformation or cold rolling annealing is one of the most industrially applicable methods to produce nano or ultrafine grained (UFG) austenitic stainless steels, which were found to exhibit high strength and ductility. FSW has been successfully applied to aluminum as well as magnesium alloys, but in comparison with these light alloys, limited research has been performed to study its applicability in high-temperature alloys such as steels, possibly due to the lack of suitable tools found for the FSW of such alloys [39].

The co-existing application of aluminium alloy and magnesium alloy can alloy further design flexibility and achieve a combination of individual properties. Friction stir welding offers a potential way to individual properties. Friction stir welding offers a way to obtain high quality joint of Al to Mg alloys since the formation of IMCs is limited due to the relative low processing temperature, and the distribution of IMCs is dispersed under the combined action of high strain rate and severe plastic deformation during welding. The welding conditions, such as material position, tool offset, rotation rate and traverse speed, significantly influenced the weld properties of Al-Mg dissimilar metal FSW joints [40].

High strength 7000 series aluminium alloys are widely used in critical condition in aircraft and aerospace structures. Along with 2000 series aluminium alloys, it is considered relatively difficult to weld using fusion welding techniques because of the crack sensitivity and severe mechanical property decrease. Nevertheless, FSW shows a great potential in welding 7000 series aluminium alloys according to Hwang and Chou (1997). However, limited work has been published on SSFSW joint of 7000 series high strength aluminium alloys [41].

Uzun et al. (2005) joined 304 stainless steel to Al 6013 with the thickness of 4 mm and the joint strength can achieve 70% of the base aluminum alloy. Tanaka et al. (2009) did FSW of Al7075-T6 to mild steel with the thickness of 3 mm and reported an exponentially increasing relationship between interface strength and the reducing thickness of IMC layer. Liu et al. (2014) studied the effects of different process parameters on FSW for joining TRIP 780 steel to Al 6061 and a maximum strength of 85% of the base aluminium alloy [42].

Magnesium and aluminum alloys are continually increasing in importance as lightweight structural materials for automotive applications. The application of both aluminum alloys and magnesium alloys simultaneously provides greater design flexibility and improved mechanical response with reduced weight. Combining these dissimilar alloys demands a reliable joining process; however welding magnesium and aluminum alloys still faces many challenges. These alloys can be joined using a wide variety of processes, but conventional processes have exhibited some disadvantages such as a large heat affected zone (HAZ), solidification cracking, porosity, evaporative loss of the alloying elements, and high residual stresses. Friction stir welding (FSW) is an alternative method, which could overcome the above disadvantages. Since FSW is performed below the melting temperature of the material to be welded, and it produces pore-free joints and smaller temperature gradients than conventional arc processes. It was later utilized for joining other metals including magnesium, copper, titanium and steel alloys. Recently, FSW has been used to join dissimilar metal combinations, such as Al/steel, Mg/steel, Al/Ti, Al/Mg and Al/Cu [43].

The physical and mechanical properties of both metals are significantly different. As a consequence, some challenges still exist in the dissimilar welding. The major problem arises from the chemical affinity at temperatures higher than 120 LC, which could lead to the formation of the Al/Cu brittle intermetallic phase and low melting point eutectics. Thus, the solid joining processes have been considered as the qualified welding methods for these metals. During this welding process the peak temperature is lower than the metal melting point, and it has the excellent ability to weld dissimilar metals. Abdollah-Zadeh et al studied the microstructural and mechanical properties of friction stir welded aluminum/copper lap joints. They observed the various microstructures with different morphologies and properties in the stir zone. It is found that $Cu_9$ $Al_4$, CuAl and Cu $Al_2$ are the main intermetallic compounds formed in the interfacial region. A high heat input could increase the amount of intermetallic compounds and then decreased the mechanical properties [44].

Cracking tends to incidence in intermetallic-rich zones, which is the major reason for the pre-mature failure of dissimilar Al/Cu friction stir welds temperature and the length of the incubation period, respectively. Low welding temperature and short incubation time could contribute to decrease the amount of the brittle intermetallic compounds [44].

FSW has offered a great welding quality to the joint of aluminum, magnesium, titanium, copper, and steel. Due to the different chemical, mechanical, and thermal properties of materials, a dissimilar material joining presents more difficulties than similar materials joining. Development of sound joints between dissimilar materials is a very important consideration for many emerging applications including the chemical, nuclear, aerospace, transportation, power generation, and electronics industries. However, joining of dissimilar materials by conventional fusion welding is difficult because of poor weldability arising from different chemical, mechanical, thermal properties of welded materials and formation of hard and brittle intermetallics in large scale at weld interface. As FSW operates in the solid state, it was naturally extended to joint dissimilar reactive materials, with the aim of reducing the amount of intermetallics, because too thick layers of intermetallic are indeed deleterious for the mechanical behaviour of the joints [45].

Although it was reported that the formation of a thin intermetallic layer along the Al/brass interface may increase the mechanical properties of the dissimilar welds, it is different to control the layer thickness and an increase in the layer thickness will result in the crack formation and the mechanical properties decrease significantly. However both Al and Cu can produce the formation of alloys with Zn according to the phase diagrams. Zn could act as filler which contribute to the intimate contact or effectual mutual diffusion between the base metals [45].

FSW of steels has only been recently realised primarily as a result of issues in tooling material selection and development. The tool must exhibit high strength, wear resistance, fracture toughness and a resistance to chemical degradation all at the high temperatures associated with FSW. However, composite polycrystalline Boron Nitride/Tungsten–Rhenium (pcBN/W–Re) tools are now becoming commercially available and facilitate FSW of steels. There is significant demand to adapt the FSW technology to carbon and stainless steels and it is therefore envisaged that there will soon be an increasing requirement for producing T-joints in steels. As discussed by Steel et al, the shipbuilding industry would find significant application for such advancement in the attachment of longitudinal stiffeners to plate, where low distortion and minimal reworking is key and hence the FSW process would be ideally suited [46].

In solid state welding, the formation of IMCs (inter-metallic composites) can be well controlled by avoiding the melting of materials and controlling heat input, resulting in an improved mechanical property [47].

**Advantages**

- Provides opportunities for new solutions to old joining problems**.**
- Virtually defect-free welding
- Versatile applications by welding all joint geometries including complex contours
- Limitless panel length and width
- Superior mechanical characteristics
- Join dissimilar alloys

**Drawbacks**

- Large forces: order of magnitude 10kN
- Rigid clamping system needed
- Hole at the end of the weld
- Problem if weld gap is less than 10% material thickness.
- Investment cost
- Other weld flaws are possible.

## 2. Comparison of different Welding Techniques

The main area of comparison of the different welding techniques has been discussed taking some features into consideration. The features taken into consideration bonding strength, Dilution, Coating material, Coating thickness, Repeatability, Heat affected zone (HAZ), controllability, and Cost play an important role in the development of the technique itself in which Heat affected zone and Dilution are explained in detail. The welding techniques mentioned here are laser cladding; overlay welding, solid state welding like roll bonding, explosion welding, and friction stir welding. Firstly laser cladding is discussed since it is more prominently used in all industrial application to improve performance more cheaply than by making the entire item out of expensive metal. Laser cladding in short is the deposition of material by powder or wire feedstock, melted and consolidated by use of laser. Laser cladding is one of the laser surface treatments. The positive effects of laser surface treatments are based on a change of the microstructure or the material composition of the surface layer due to a thermal cycle which is induced in the laser source.

The bonding strength of welds in laser cladding is observed to be stronger than any other welds methods. Different materials show different bonding strength due to the varying properties of the metal or materials which are cladded. The bonding strength of the material is observed to be consisting of little or no porosity which in some cases are negligible.

Dilution is an important factor to influence the properties of laser cladding. To get high quality clad layer low dilution is required. During laser cladding, heat will accumulate near the melt poo before quasi-steady state is reached. Laser power, temperature of the base metal and the cladding speed are the important parameters to influence dilution. Dilution becomes larger with increase in laser power and decreases with increase in cladding speed. With the increase of preheating temperature, dilution increase.

Repeatability or test–retest reliability is the variation in measurements taken by a single person or instrument on the same item and under the same conditions. A less-than perfect test–retest reliability causes test–retest variability Repeatability in laser cladding is from moderate to high level which depends on the laser power and the accuracy of the weld. Heat affected zone in laser cladding is narrow by minimizing the heat input. Less heat affected zone (HAZ) also results in limited distortion of the substrate and reduces the need for additional corrective machining.

Controllability of laser cladding ranges from moderate to high. The maximum coating thickness of laser clad ranges from 50µm to 2.5mm. Laser cladding technique has a major drawback of cost of laser being used which is inevitable, thus research is going on to find the cheapest laser to improve the overall efficiency of laser cladding.

The next welding technique is overlay welding in which, deposit of a dissimilar weld metal laid on the surface of a metal part. The technique of weld overlay is an excellent method to impart properties to the surface of a substrate that are not available from that base metal. As overlay welding can produce thicker layers than thermal spraying or plating and because it creates a metallurgical bond between the base metal and the overlay, it can provide high durability and significant surface modification effects. Bonding strength of weld overlay is considerably high but not as laser cladding which depends on the material being weld and base metal which is overlaid. Dilution also plays an important role in overlay welds which has similar conditions as the laser cladding. High deposition rate process may appear to be fast, but if the heat input is too high, excessive dilution with the underlying base metal may mean that a second layer is required. It may be possible to deposit two layers faster than a single layer with a slower low heat input welding method but, if the final deposit depth is greater, then the material cost will be higher.

Repeatability of overlay welding is moderate in nature. When compared with laser cladding it is seen moderate. Heat affected zone in overlay welding is high when compared with laser cladding. Controllability of overlay welding is comparatively lower with laser cladding due to high heat affected zones, and high heat inputs. Coating thickness of overlay welding ranges from 1mm to several milli-meters. Cost of overlay welds is moderate when compared with laser cladding because of the use of inexpensive materials to overlay the expensive material to save the material from corrosion. The equipment cost for overlay welding is less expensive than the laser cladding technique.

Roll-Bonding, also called Roll welding, is a solid state welding process in which multiple layers of similar or dissimilar metals are stacked together and rolled to a certain degree to produce a solid state welding. The stack is fed through a cold rolling mill under sufficient pressure to produce significant deformation and solid state welding. Bonding strength of roll bonding method is moderate when compared with other techniques discussed above. The bonding strength depends on the type of material used for bonding. Materials with less tensile strength tend to break with the application of pressure. Thus the choice of roll bonding is limited. Dilution of roll bonding is lower than overlay weld method, since there is no dilution in the base metal which influences the increase in dilution. The heat input in roll bonding is less and hence the dilution ratio is less. Repeatability of roll bonding technique is high, since the repeated roll bonding of the sheets in accumulated roll bonding process leads to substantial accumulation of plastic deformation resulting in a UFG microstructure. This UFG microstructure causes a significant increase by almost a factor of two in the strength of the material in comparison to the course grained counterpart. Heat affected zone in roll bonding is very high compared to laser welding due to superior heat conductivity of material. Controllability of solid state welding method like roll bonding is lower due to high heat affected zones and high heat inputs. Coating thickness of this technique ranges from 1 mm to several mm. Cost of this technique is less because of the lesser material cost and lower cost of filler material.

Explosion welding is a solid state welding process in which coalescence is affected by high-velocity movement together of the parts to be joined produced by a controlled detonation. Even though heat is not applied in making an explosion weld it appears that the metal at the interface is molten during welding. Bonding strength of explosion weld is higher, during the bonding process, several atomic layers on the surface of each metal become plasma. The collision angle between the two surfaces (typically less than 30°) forces the plasma to jet ahead of the collision front, effectively scrubbing both surfaces and leaving virgin metal. Dilution of explosion weld is low as similar to the roll bonding, since the welding procedure takes a shorter time. The time duration involved in the explosive welding event is so short, that the reaction zone between the constituent metals is microscopic. Repeatability of explosion welding ranges from low to moderate, since the explosion time is short and quick. There are no heat affected zones in explosion welding, only minor melting. Material melting temperatures and coefficients of thermal expansion difference do not affect the final product. Controllability of this technique is low due to the quick bonding of the material. Coating thickness of explosive welding ranges is similar to roll welding. Cost of explosion welding depends on the amount of explosive used which depends on the thickness of the material. Higher the thickness of material, higher the amount of explosives creates higher cost.

Friction welding is one of the effective joining techniques. Friction welding is a solid state welding and it offers an alternative welding process for joining the parts in particular electrical appliances, engine parts etc. The welding takes place when two surfaces, subjected to the joining, get in mechanical contact and the surfaces are heated to the desired temperature through frictional heat generation and later a forging pressure is introduced to weld the parts. Bond strength of friction stir welding is high like other welding methods. Since the process uses no outside filler material, no shielding gases, and requires low energy input when compared to other welding processes. The solid phase bond between the two pieces is made solely of parent material. The grain structure in the weld zone is finer than that of the parent material and has similar strength, bending, and fatigue characteristics. Dilution in friction stir welding is low, since there is no filler material and the heat input does not affect the base metal. Friction stir welding has excellent repeatability. Heated affected zones in friction stir welding are lower due to low heat distortion. Controllability of friction stir welding is lower like the other solid state welding techniques. Coating thickness range is similar to other solid state welding technique. Cost of this technique is high due to high investment cost, extensive clamping is required for holding the material. A backing support is required for holding the stir.

| Features | Laser cladding | Overlay welding | Roll bonding | Explosion welding | Friction stir welding |
|---|---|---|---|---|---|
| **Bonding strength** | High | High | High | High | High |
| **Dilution** | Low | Low | Low | Low | Low |
| **Coating material** | Metals and ceramics | Metals | Metals and ceramics | Metals | Metals |
| **Coating thickness** | 50µm to 2.5mm | 1 mm to several mm | 1 mm to several mm | 1 mm to several mm | 1 mm to several mm |
| **Repeatability** | Moderate to high | Moderate | High | Low to moderate | High |
| **Heat affected zones (HAZ)** | Low | High | High | No HAZ | Low |
| **Controllability** | Moderate to high | Low | Low | Low | Low |
| **Overall Cost** | High | Low | Low | High | High |

**Table.2.1** Comparison of different techniques and its properties

From the above comparison of different techniques, Heat affected zone and Dilution effect on the base metal, the corrosion and wear characteristics of the overall material of these welding techniques have been studied and the conclusions have been drawn.

## 2.1 Heat-Affected Zone (HAZ)

A heat-affected zone (HAZ) is the portion of the base metal that was not melted during brazing and cutting/welding, but whose microstructure and mechanical properties were altered by the heat. This alteration can be detrimental, causing stresses that reduce the strength of the base material, leading to catastrophic failures.
The HAZ occurs inside the metal and cannot be seen. The HAZ may need to be partially or completely removed (by grinding or some other process) before the metal part can be used.

Preferential corrosion of a heat-affected zone is a widely known phenomenon. High temperature exposure and welding can significantly affect the microstructure and properties of the heat-affected zone that makes them more susceptible to corrosion. The microstructural changes that occur in heat-affected zones include carbide precipitation and intermetallic phase formation.

Heat affected zones can be of varying size and strength. The extent and magnitude of the HAZ is inversely proportional to the thermal diffusivity and cooling rates of the material:

- Where thermal diffusivity and the material cooling rate is high and the HAZ is small.
- Where thermal diffusivity is low, the cooling rate is slower and the HAZ is larger.

The extent and magnitude of property change depends primarily on:

- Base material
- Weld filler metal
- Amount and concentration of heat input by the welding process

The width of the HAZ is influenced by:

1. Cut speed - In general, faster speeds result in a smaller HAZ.
2. Amperage (when using plasma) - For a given thickness of metal, a higher amperage (and consequently a faster cut speed) results in a smaller HAZ.
3. Type of metal being cut - Increased temperatures and longer cutting times will result in a wider HAZ.

All thermal cutting processes create a heat-affected zone in the cut metal. The amount of heat inputted by the welding process plays an important role:

The heat from the welding process and subsequent re-cooling causes change from the weld interface to the termination of the sensitizing temperature in the base metal. These changes can be minimized by following proper welding procedures and using low-carbon stainless steel alloys.

The changes induced by heat can include: Altering the microstructure of particular steels, leading to an increase in the hardness of the cut edge relative to the un-cut metal, altering the microstructure of particular steels, leading to a decrease in the strength of the cut edge. The formations of nitrides on the cut edge, which can affect the weldability of the cut face. HAZ width is influenced only by the thermal history of the metal. While the change in the coloration of the metal may by chance approximate the width of the heat affected zone, heat-tint width can be either larger or smaller than the HAZ. Different metals transfer heat at different rates and respond to differently to elevated temperatures. Increased temperatures and longer cutting times will result in a wider HAZ. Another thing to note about the HAZ is that when cutting thicker metals the width of the zone may be smaller at the top of the cut edge and wider at the bottom.

**Weak point**

HAZ is a region that can become the weak point in a weld that, under normal conditions, would be strong enough. This is common in carbon steels where the HAZ is usually less resistant than the metal, but it may be the source of welding defects and the origin of failure.

Even being less resistant than the weld metal, the qualification of a welding procedure should generally ensure that heat affected zone is enough resistant or at least maintain the properties of the parent metal.

**Reasons for its typical weakness**

Some of the reasons for the weakness of the heat affected zone of carbon steel may be found below:

- Grains in the HAZ grow due to the input but especially to the peak temperature reached. Microstructures with coarser grains have lower toughness at temperatures, and are generally less corrosion resistant.
- Heat also promotes coalescence and spheroidizaition of steel components such as cementite, thus reducing its mechanical strength.
- A typical thermal cycle of welding and its rapid cycles of heating and cooling of the HAZ, can create a brittle and hard crystalline microstructure known as martensite.
- The martensite structure generated is essential for hydrogen cracking. This crack is usually not visible to the human eye but can severely comprises the performance, safety or just reduce the useful life of the equipment.
- The hardness increase caused by the new martensitic microstructure decreases the corrosion and impact resistance.

### 2.1.3 HAZ in Laser clad

Laser cladding operations, which is heated partially and quickly, the molten pool, is small and the temperature is very high. Thermal physical properties of the material vary with temperature rapidly. At the same time there are phenomena of molten and phase change. It is difficult to measure the temperature and shape of molten pool in the test. Therefore a numerical simulation is used in this paper which can provide the flow field thermal field and thermal properties parameters for a certain model, the multi factors of model can be controlled and compared easily. The temperature field and the size of the heat affected zone are affected by laser power. In order to study laser cladding with powder feeding, the temperature field and the shape of the molten pool were simulated by a two dimensional heat transfer models and the effect of the process parameters on the surface quality was analysed. The relationship between laser processing parameters such as distribution of the temperature field, pool temperature, the maximum temperature and the maximum cooling rate, the width of the clad layer were simulated and analysed. Based on the charged couple device technique for high temperature measurement, the molten pool of the laser cladding with synchronous powder feeding and re-fabricated powder on NI base alloy was studied and the shape of the molten pool and the distribution of temperature field were obtained under different powers. An AZ91 magnesium alloy was studied by a pulse laser and numerical analysis [53].

Laser cladding is a complex process which has a lot of process parameters and includes the heat conduction, thermal radiation, melting and solidifying of metals, the stress and deformation of cladded layer and other physics and chemistry phenomena [53].

As seen from the figure as the laser power is small the decalescence of cladded layer is also small and the alloy powder of surface melts incompletely, and the size of the heat affected zone is small. With the laser power increasing, the heats and poo temperatures increases, the alloy powder melts completely, the surface is relatively smooth, and the heat affected zone enlarges [53].

**Microstructures of the clad layer and HAZ**

The zone immediately next to the base metal is the chilling zone, where the grains are very fine. Then the solidified zone is the columnar zone, where the grains grow directionally from the base metal towards the centre of the molten pool. The microstructure of the clad layer is austenite as shown in fig.2.1 [54].

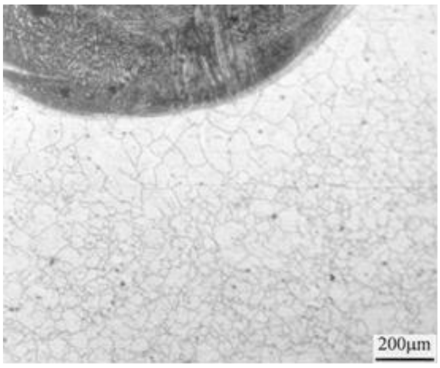

**Fig.2.1** The microstructure of clad layer [54]

The grains immediately next to the melt pool grow large. The width of the zone where grains grow large is about the size of several grains. The grain size of HAZ is related to the cladding speed and cladding time, as shown in fig.2.1. With the increase of cladding speed or decrease of cladding time, the grain size of HAZ is smaller. This indicates that the cooling rate near the melting line (boundary between melt pool and base metal) increases with the increase of cladding speed or with the decrease of cladding time. The microstructure of HAZ is austenite as shown in fig.2.2 [54].

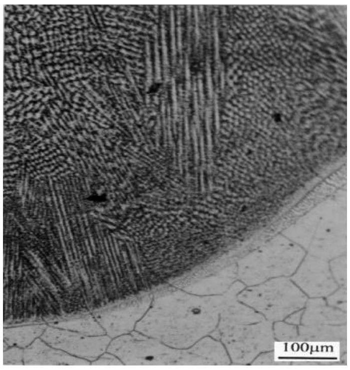

**Fig 2.2** Microstructure of HAZ [54]

The hardness of melt pool metal is higher than that of the HAZ metal. This is because the cooling rate of melt pool, which has a high cooling rate, results in fine microstructure. With the increase of the cladding speed, the hardness of melt pool increases. The hardness of HAZ is lowered because (a) the growth of the grain sizes, (b) the disappearance of work hardening effect, and (c) there is no transformation of microstructure. The degree of lowered hardness of HAZ is proportional to the temperature distribution in HAZ. The hardness immediately next to the melting line is the lowest. With the increase of the cladding speed, the degree of lowered hardness decreases. These results indicate that with the increase of the cladding speed, the cooling rate of the melt pool and HAZ increases fig.2.3 shows the hardness distributions of melt pool and HAZ at different cladding speed [54].

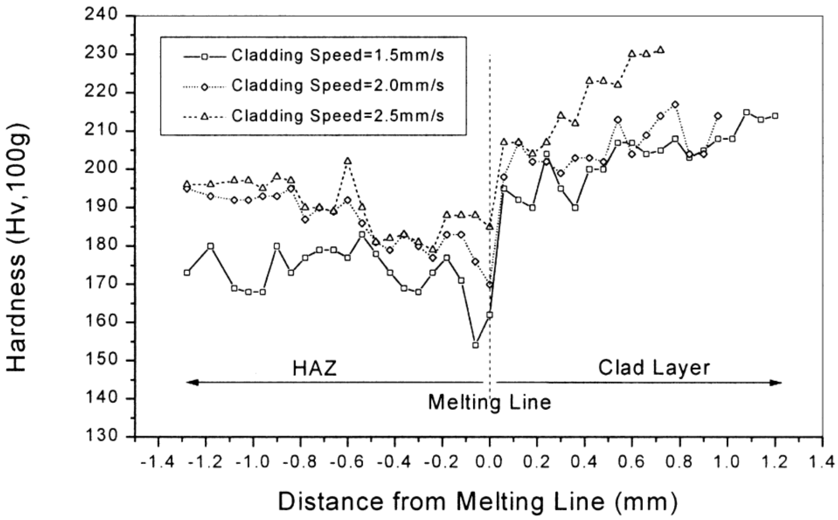


**Fig.2.3** The hardness distributions of melt pool and HAZ at different cladding speed [2]

Micro-hardness of heat-affected zone (HAZ) of the Ni45 + 5.wt%Ta composite coating is lower than that of Ni45 coating. This is due to the different thermal conductivities of the coatings. The thermal conductivities of Ni and TaC are 0.91 W/cm K and 0.22 W/cm K, respectively. In situ synthesized TaC particles decrease the thermal conductivity of the composite coating. Therefore, cooling rate of HAZ of Ni45 coating is faster than that of the composite coating, resulting in a greater thickness of the quenched zone of the HAZ of Ni45 coating with respect to that of the composite coating [15].

Laser welding has been widely used in automobile industry because of its great advantages: high welding speed, high weld quality, narrow heat affected zone (HAZ) and very low distortion. The HAZ, which lies between the base metal and weld metal, consists of coarse grained region, fine grained region and incomplete recrystallization region, Fig.2.4 [55].

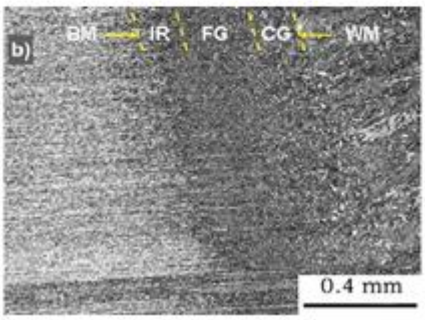


**Fig 2.4** Shows the very low HAZ in the laser weld [55]

For the P22 steel substrate, fig.2.5 shows the average coating hardness was about 600 HV for 1 kW and about 500 HV for 1.8 kW heat input. However, the higher heat input resulted in a wider HAZ and lower average heat affected zone (HAZ) hardness. The HAZ hardness was lower than the coating, but higher than the substrate. The coating on P91steel substrate showed a lower coating hardness of about 550 HV for 1.0 kW and about 500 HV for 1.8 kW in fig.2.6. The HAZ hardness was generally lower than that of the coating, but higher than the substrate. The hardness of the unaffected substrate was about 225 HV, compared to 250 HV for the P22 steel [56].

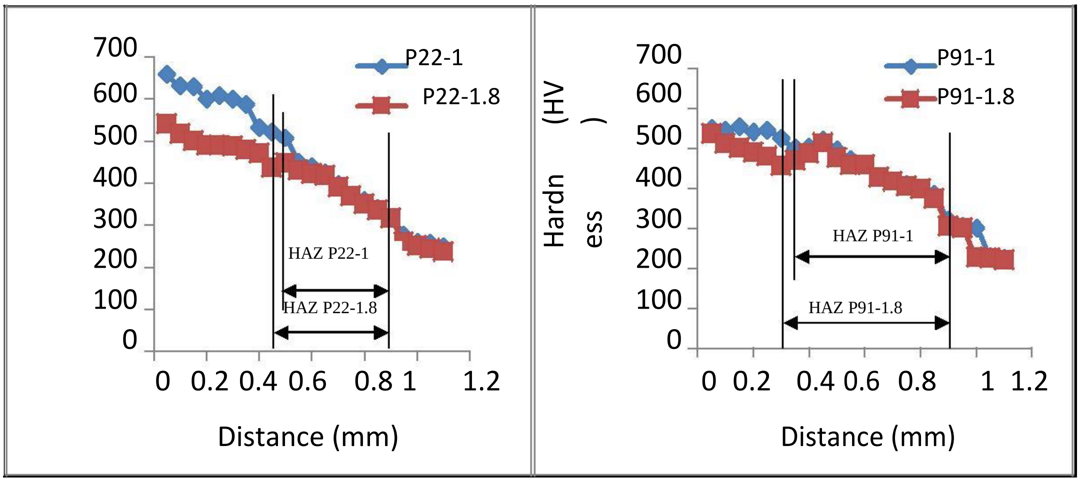


**Fig. 2.5 & 2.6** Micro-hardness profiles for the two Stellite 6 weld samples [56]

The micro hardness varies from cladding coating to transition layer then to heat affected zone and substrate along a gradient. The gradient distribution of micro hardness near bonding interface provides a matching between the coating and substrate, which releases stress concentration, avoids the formation of cracks and realizes better metallurgical bonding between the coating and substrate. Owing to high energy density laser beam, the heat source is more focused. Heating and cooling rates are more rapid. Cladding layer has good re-melting performance. Less distortion happened on work pieces. The heat affected zone is narrower [6].

### 2.1.5 HAZ in overlay weld

The manufacturing of components by welding can produce high residual stresses and microstructures that are susceptible to cracking in the HAZ. In order to reduce residual stresses and increase toughness of the HAZ, post weld heat treatments (PWHT) must be performed immediately after welding [57].

The HAZ hardness reveals certain fluctuations due to the thermal history imposed by multiple welding. The HAZ in the vicinity of the fusion boundary exhibits a peak in hardness and the hardness decreases with increasing distance from the fusion boundary [57].

Before overlay welding, the residual stresses in HAZ are similar to those in the weld metal. The root still has larger radial and hoop stresses of 125MPa. But the difference is that the peak drop stress is about 150 MPa shown in the surface rather than the root as shown in Fig.2.7, the residual stress along P4 in HAZ before and after overlay welding [58].

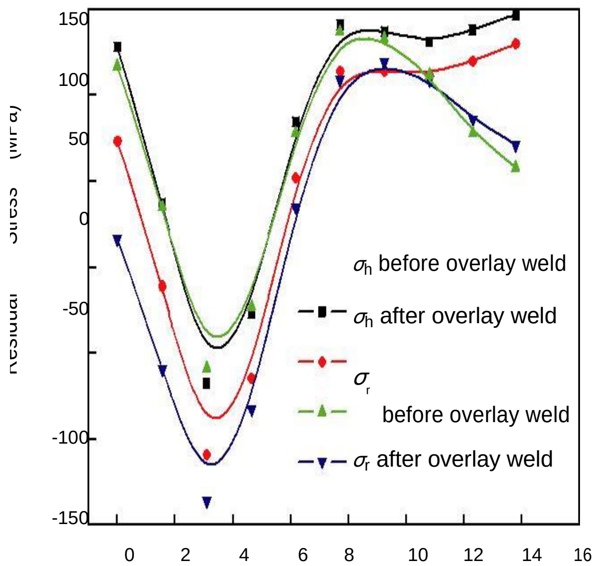


**Fig.2.7** Effect of overlay welding on residual stress along P4 in heat affected zone [58]

Composition differences and microstructural differences can promote localized corrosion of weld metal, heat affected zones (HAZ), or base metal immediately adjacent to heat affected zones. Even though the composition of the weld heat affected zone is the same as the composition of the adjacent base metal, the different microstructures in each area have different resistance to corrosion. The effects of microstructural differences are difficult to eliminate, although microstructures can be influenced by adjusting weld procedure heat inputs, inter-pass temperatures and, when necessary, post weld heat treatment Fig 8. shows that, for steel assemblies that are stress relieved after welding, the stress relief heat treatment can also produce some beneficial modification of weld zone microstructures in addition to relieving stress. However, that the corrosion resistance of many CRAs (corrosion resistant alloys), including most austenitic stainless steels and some Ni-Cr-Mo alloys can be significantly degraded by exposure to stress relief temperatures typically applied to mild steel and low alloy steels. For those alloys, post weld heat treatments designed to solution anneal the weld zone are preferred, but are generally impractical and uneconomical to perform in the field. Solution annealing is sometimes performed as part of manufacturing since it not only makes the HAZ microstructure more similar to the base metal microstructure, but it also improves the corrosion resistance of the weld metal by making the distribution of the alloying elements within the weld metal more homogenous [59].

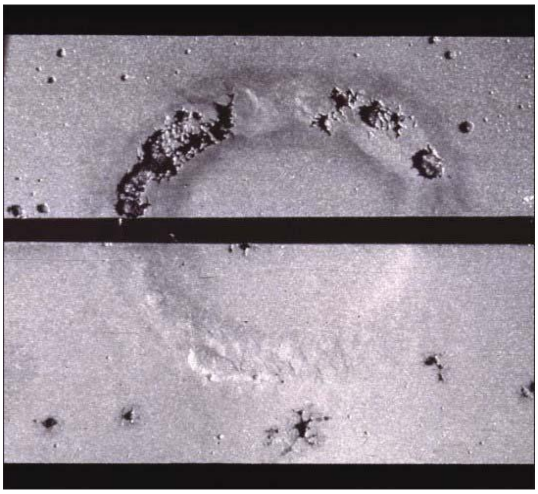

**Fig 2.8** Comparative corrosion resistance of the weld zone in a low alloy steel test sample containing a circular weld bead on the opposite side of the sample [59].

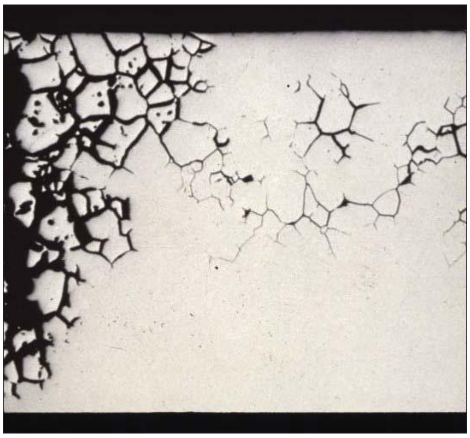

**Fig 2.9** Ni-Cr-Mo alloy pipe showing inter granular cracking of the HAZ after excessive weld heat inputs caused inter granular carbide precipitation [59].

To avoid hydrogen cracking and related problems in the weld heat affected zone, ensure that the hardness does not exceed a threshold "safe" hardness. The acceptable hardness varies depending upon steel composition, as expressed by the carbon equivalent or "CE", and the hydrogen content of the deposited weld metal. As weld metal hydrogen contents decrease, for example by using low hydrogen welding processes, higher heat affected zone hardness can be tolerated. Likewise, for a given weld metal hydrogen content, the acceptable hardness is greater for steels of higher CE. Susceptibility toward the formation of hard heat affected zones varies inversely with weld cooling rate; faster cooling rates increase susceptibility toward forming hard microstructures. In turn, fast cooling rates are promoted by low weld heat inputs, and higher heat sink capacity of the pipe material [59].

The low overall heat input of the laser cladding process, coupled with rapid solidification rates serve to limit the dilution of the base material and prevent degradation of the wear and corrosion performance of the overlay. Additionally, the small HAZ associated with the overlay means that the substrate properties are relatively unaffected with negligible part distortion.

### 2.1.6 HAZ in roll bonding

The distribution of hardness along the centre line of the weld in the vertical direction is indicated in Fig 2.10. As seen the hardness decreases gradually to the minimum (66.4 HV) from the top surface of aluminium sheet to the Al/Fe interface, then increases dramatically to the maximum (349 HV) at the layered structure in the Al/Fe interface, and then drops to another minimum (182.3 HV) in the heat affected zone (HAZ) of the steel, and then increases to the steel hardness of up to 200 HV.

Being a non-heat treatable (or work-hardened) aluminium alloy, the mechanical properties of Al5754 are greatly influenced by dislocation contribution (i.e. density) and grain size refinement rather than precipitates in the structure. Therefore, softening in the Al sheet can be attributed to the fact that the recovery occurs and the grain sizes near the Al/Fe interface was coarser than that on the upper surface of the Al. Meanwhile, the variation of hardness in steel also can be attributed to the variation of grain size as a whole (see Fig. 2.11), and softening in the HAZ of the steel sheet can be attributed to the tempering of the martensite islands in that base material [60].

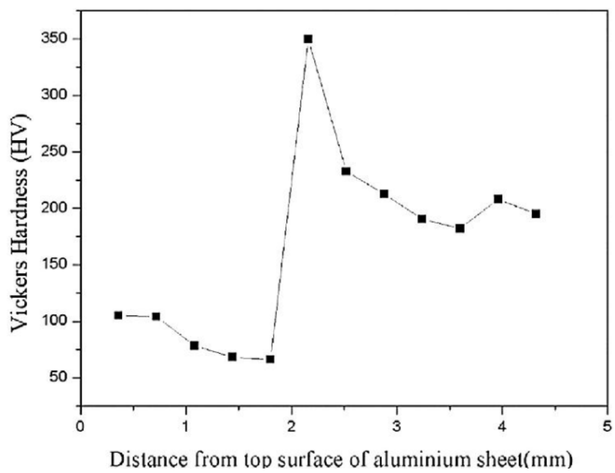


**Fig 2.10** Hardness distribution along centre line of the weld in the vertical direction [60]

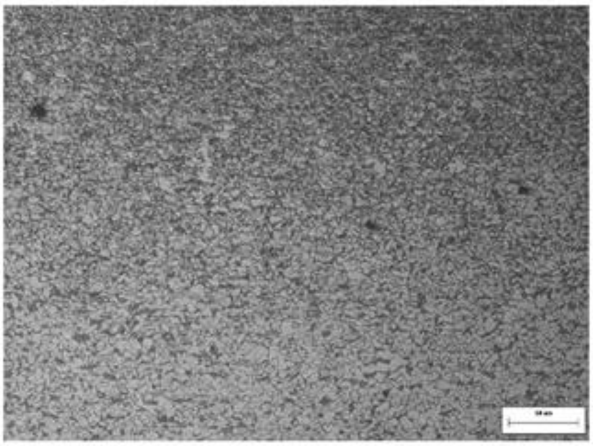

**Fig.2.11** Microstructure of steel directly under the tip of pin [60]

The heat affected zone in Magnesium containing alloys in particular has usually the worst microstructure with respect to corrosion resistance due to the high precipitation density, which limits the application of the welded structure obtained in the particular in higher temperature applications, typically above 80ºC. The cladding remains solid and essentially undisturbed during welding in the region near the heat affected zone. Thus after welding a good anodic protection is obtained for the critical heat affected zone due to the presence of zinc. Additionally the cladding provides an anodic corrosion protection to the structural component which is not affected due to the welding [60].

### 2.1.7 HAZ in Friction stir welding

Previous work on both aluminium and steels has studied the influence of residual stress fields on fatigue crack growth behaviour, and has also examined the relative importance of residual stresses, HAZ microstructures and hardness levels. These studies are confined almost exclusively to fusion welds, rather than solid state processes. The studies to date indicate that the residual stress field plays the dominant role. For cracks propagating perpendicular to the weld and subjected to weld induced longitudinal tensile stresses of at least 0.5 yield, crack growth rates have been measured to be between three and seven times greater than those found in parent plate. As the crack grew the stresses relaxed and crack growth rates reduced. For cracks initiating in the weld HAZ, with compressive residual stress fields, crack growth rates were correspondingly slower. In some cases crack arrest has been observed. For cracks propagating parallel to the weld, and introduced into the weld metal, growth rates were comparable with those in the parent plate. In the HAZ, crack growth rates were much reduced, compared with the weld metal and parent plate values [49].

HAZs in FSWs of 2024-T351 aluminium contain large variations in residual stress, hardness and micro-structure as the weld line is traversed. Microstructure, hardness and residual stress distributions in the FSW HAZ are all complex. The studies in this work show each of them has three regions. The nugget region has a fine re-crystallised grain structure, with hardness values between 110 and 140 Hv1. On the PJL within the nugget, residual stresses are low (8 MPa) parallel to the weld but large and tensile (174 MPa) perpendicular to the weld [49].

Immediately outside the nugget, the thermo-mechanically affected zone consists of highly elongated and deformed grains, which comprise the softest (102 Hv1) part of the HAZ. This is the region with the highest recorded residual stress in the longitudinal direction of 264 MPa, and only 5 MPa in the transverse direction. Residual stress distribution, microstructure changes and hardness in the HAZ will be related to one another. The exception is for cracks growing parallel to the weld, at 28 mm from it, in regions of HAZ remote from the softened zone where plastic strain and stress relief will occur [46].

Then investigation on the effect of welding speed and rotation speed on microstructures and mechanical properties of underwater FSW 2219 aluminium alloy. The results reveal that the precipitate deterioration in the thermal mechanically affected zone and the heat affected zone is weakened with the increase of welding speed, which leading to a narrowing of softening region and an increase in lowest hardness [46]. It is also found that the joint welded at lower rotation speed tends to be fractured in the stir zone, and at higher rotation speeds, the hardness increase in the stir zone (SZ) makes the fracture locations of defect-free joints move to the thermal mechanically affected zone (TMAZ) or heat affected zone (HAZ).

Considering the first three welds where the rotational speed was maintained as constant and the traverse speed was incrementally increased, the parameter variation effects may be observed. The heat affected zone (HAZ) region becomes progressively narrower as the traverse speed is increased. The variation is most apparent when considering the change from W2 at 200 rpm and 140 mm/min to W3 at 200 rpm and 160 mm/min respectively where a much narrower HAZ is evident in W3 at 200 rpm and 160 mm/min [6]. This is particularly noticeable on the advancing side of the weld in W3 at 200 rpm and 160 mm/min where the HAZ outside of the thermo-mechanically affected zone (TMAZ) is considerably reduced.

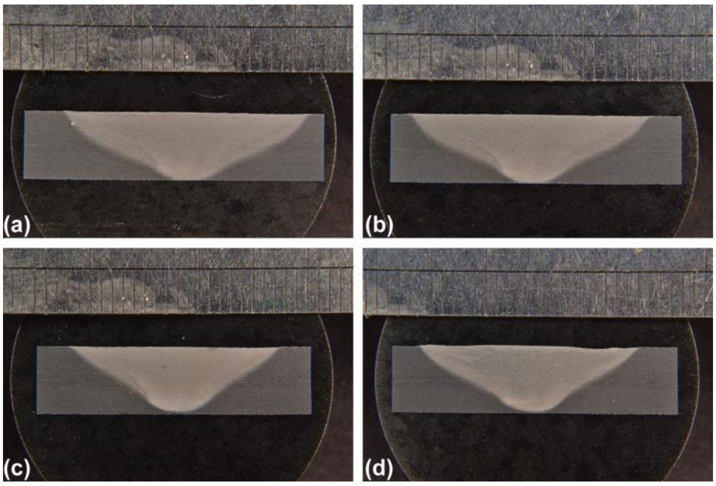


**Fig.2.12** Shows the HAZ in welds W1, W2. W3, W4 [6]

The HAZ only underwent a heat cycle which is insufficient to make an apparent effect on the constituent particles. Constituent particles have an incoherent interface with the aluminium matrix and are too coarse to interfere with dislocation movements.

Precipitates play the most important role in the strengthening of AA7075-T651 through their reaction with dislocation motion. According to the results, the precipitation transformation is the predominating softening mechanism that resulted in the fracture at the HAZ. Due to the various strengthening effects from different precipitates, the yield strength of various locations in the SSFSW joint is considered to be different. It was reported that the HAZ and the nugget zone in FSW joint exhibited low yield strength compared to the base metal of 6005-T6 aluminium alloy. High temperature leads to the growth of precipitates in the HAZ and results in severe strength decrease [41].

Defect-free joints of aluminium 7075-T651 with smooth surface can be manufactured by SSFSW. The narrow TMAZ and HAZ surrounding the nugget zone and are fairly symmetrical in the transverse section. The nugget zone and the TMAZ consist of fine equiaxed and bended grains respectively, while there is no evident difference in the grain structure in the HAZ and Base metal. Constituent particles are homogenously distributed in the nugget zone. In the HAZ and the TMAZ, the spacing and distribution of constituent particles are similar with that in Base metal. Precipitates dissolved in the nugget zone during the welding process and phase is the dominating precipitates in the HAZ [41].

High tool rotational speed or high welding speed result in stronger joints due to the competition between the re-precipitation of GP zones and the growth of precipitates. The precipitates evolution and constituent particles redistribution lead to the decrease of the toughness of the HAZ and the nugget zone (NZ) [47].

In the hardness profile measured of Al plate, it is observed that there is insignificant decrease of hardness in the stir zone when the rotation speed is 1200 rpm. Indeed, the area where the hardness measured is actually the heat affected zone (HAZ), and the HAZ softening occurs there. A more important factor is observed that there is a significant hardness increase at the edge of the stir zone because of the extruded Zn based alloy. And the highest hardness shows large difference because of the variably complexity of the contents [47].

### 2.1.8 HAZ in Explosion welding

Cladding of plates and concentric cylinders constitutes the major commercial application of explosive welding. Advantageous features of explosive cladding include: the joining of dissimilar metals together. The bonding of thin sheet with thick plates, the welding of heat treated and cold worked metals together without charge in their mechanical properties, the absence of heat affected zone in the clad plates and the simplicity and speed of operation for having coalescence with cost reduction and strength or corrosion properties. Since there is no thermal effect in explosive welding, it does not show the characteristics of other welding methods such as brazing, hot rolling or molten welding. There is no heat affected zone in this welding method, so very thin plates can be welded with this method. Explosive welding method can be used to bond similar and dissimilar plates and also to produce fibre reinforced composites materials.

# 3. COMPARISON OF MATERIALS

## 3.1 Laser cladding materials

The materials prominently used in laser cladding are Base metal and materials like stainless steel plates, Carbon steel, stainless steel, Alloy steel, copper, aluminium. Clad materials like Copper, nickel, aluminium, copper alloys, nickel alloys, Nickel alloys: Alloy (200, 400, 600, 800, 625, 825, 900), alloys (C-276-22, C-2000), Copper alloys: Copper nickel, Aluminium, Aluminium bronze, Titanium, Tantalum, and Zirconium alloys. There are two different kind of materials in powder form such as, Metal powders like chrome, nickel and cobalt base, nickel base and Fe base alloy powders, and the second type such as ceramic powder like WC (Tungsten carbide), SiC (Silicon carbide), TiC (titanium carbide), $Al_2O_3$ and $ZrO_2$ (Zirconium dioxide. The reasons for adopting the above mentioned materials are due to good wettability of these alloys to various carbon steel, alloy steel, stainless steel and various non-ferrous alloy metals. According to application or purpose of usage, metal powders are selected to satisfy the requirements such as wear resistance, erosion resistance and oxidation resistance. Metal materials have high intensity, toughness and outstanding technology performance. But on the other hand ceramic powders have good wear resistance, heat resistance, erosion resistance, and chemical stability [6].

### 3.2 Overlay weld materials

The material used overlay welding are Iron-based alloys like low and high alloy steel, nickel based alloys like colmonoy alloy, titanium-nickel alloy, stellite alloy, and some complex carbide alloy like tungsten carbide alloy. Iron based alloys have specific wear behaviour under the conditions depends on its chemical composition. In iron based alloys carbon content is the important element. Lower the carbon content in the alloy tends to be readily weldable [17]. Nickel-based alloy coatings deposited by overlay welding techniques shows good surface finish, high hardness, and excellent wear resistance. Nickel alloy in combination with chromium is a cost effective method for producing protective coatings. This kind of coatings has a strong metallurgical bonding to the substrate providing good adhesion. Lower coefficient of expansion of Ni alloys compared to stainless steel gives these alloys better resistance to cracking during welding and lower tolerance to contamination [19]. Titanium-nickel alloy is otherwise called as tribo-logical alloy provides excellent fatigue resistance and cavitation erosion resistance over carbon steel [3]. Colmonoy 6 alloy results in excellent wear resistant, corrosion resistant and high temperature properties with fabulous metallurgical bonding and low dilution [21]. Stellite alloy contains a high proportion of hard, wear resistant primary carbides. These render the alloy well suited to applications involving extreme low-angle erosion and severe abrasion.

### 3.3 Roll bonding materials

The materials being used in roll bonding are metal matrix composites. Metal matrix composites consisting of some light alloys like aluminium and its alloys with the combination of titanium and magnesium provides excellent mechanical properties with low density [27]. Laminated metal composites consisting of two or more metals are developed due to their improved fracture toughness, bending behaviour, impact behaviour, corrosion, wear and damping capacity [25]. Ceramic particles like $Al_2O_3$, SiC are used to obtain the desired mechanical properties [27]. Composites and nano-composites have higher strength in shear and compression and higher temperature capability because they are a combination of metallic properties and ceramic properties [28]. The mechanical properties of Titanium alloys can be improved by reinforcing them with ceramic particles. The combination of metallic materials and ceramic materials has more prominent application in roll bonding technique [29].

### 3.4 Explosive welding materials

In Explosion welding similar and dissimilar metals are used. Similar metals (low carbon steel, steel to steel, Al–Al, stainless steel to steel), dissimilar metals such as steel and aluminium, steel and titanium, nickel film and aluminium alloys, iron and copper, aluminium, copper and magnesium, copper, titanium and steel, aluminium and copper and also metallic glasses were cladded successfully [35]. Thermites are highly exothermic reactive mixtures of metal powder fuels (i.e., aluminium, magnesium, titanium, zinc) and metal/non-metal oxides (i.e., boron oxide, silicon dioxide, chromium oxide, iron (II, III) oxide, copper (II) oxide) [38].

### 3.5 Friction stir weld materials

Friction stir welding technique can be used to join similar and dissimilar materials. Magnesium and aluminium alloys have an increasing importance as lightweight structural materials for automotive applications. It provides greater design flexibility and improved mechanical response with reduced weight [43]. FSW is also used for joining other metals including magnesium, copper, titanium and steel alloys. Austenitic stainless steels being the popular type of stainless steels with high corrosion resistance, good formability and suitable welding properties, their relatively low hardness and yield strength. This welding technique produces ultrafine grains of austenitic stainless steel which exhibits high strength and ductility [39].

| Welding Techniques | Laser cladding | Overlay welding | Roll bonding | Explosive welding | Friction stir welding |
|---|---|---|---|---|---|
| Complexity of shape of the component | Complex components are cladded | Only pipes or circumferential parts are welded | Horizontal bonding of plates | Horizontal welding with an explosion of dissimilar metals | Simple components with flat shapes |
| Complexity of process | Higher complexity due to its amount of heat input | Simple process | Simple process with lower heat input | Simple and quick process with no heat affected zone | Process is similar to overlay weld with |
| Position of weld or clad | All position cladding possible | Horizontal welding | Horizontal bonding | Horizontal and vertical position | Horizontal position |
| Porosity | Two kinds of porosity<br>-Bubbles in melt pool<br>-Enclosed melt regions | Lower levels of porosity compared to laser clad | No porosity | No porosity | Lower levels of porosity |
| Surface finish of material | Poor surface finish | Smooth surface finish depends on material of use | Smooth surface | Smooth surface | Surface finish depends on the speed of weld |
| Size of the equipment | Laser equipment is compact and expensive | Depends on the welding technique selected for overlaying | Depends on the size of the material | No large equipment necessary | Smaller equipment when compared to laser cladding |
| Materials | Dissimilar materials can be cladded with help of adhesive | Dissimilar materials can be deposited | Dissimilar materials can be joined | Dissimilar materials can be joined | Similar metals with no filler material requirement |
| Labor Skills | Highly skilled labor required | Skill required on different welding technique | Less skill | Less skill | Basic skill about the technique is required |

**Table 3.1** Characteristics of each welding technique discussed

# 4. Risk Assessment

Welding is a potentially hazardous activity and precautions are required to avoid electrocution, fire and explosion, burns, electric shock, vision damage, inhalation of poisonous gases and fumes, and exposure to intense ultraviolet radiation. Radiation hazards emitted from electric arc and laser welding have the potential to cause eye disorders and skin burns such as 'arc eye' or 'welder's flash'.

Radiation from laser welding is less obvious than from electric welding arcs, but both are serious hazards. Workers directly involved in welding processes are at the greatest risk but other workers could also be exposed to harmful radiation [64].

Risk is the possibility that harm (death, injury or illness) might occur when exposed to a hazard. Depending on the levels of risk, different levels of precautions are required to be considered.

The risk management process involves four steps:

1. Identify the hazards - this is known as hazard identification.
2. Determine how serious the problem is - this is known as risk assessment.
3. Decide what needs to be done about the problem - this is known as risk control.
4. Review the control measures to make sure they are working as planned.

## 4.1 Identify Hazards

Identifying hazards involves finding all of the things and situations that could potentially cause harm to people. Hazards generally arise from the following aspects of work:

- The physical work environment
- The equipment, materials and substances used at the workplace
- Work tasks and how they are performed
- Work design and management.

Methods that can be used to identify hazards in your workplace include:

- Inspecting the workplace and observing how work tasks are performed
- Consulting your workers about any health and safety problems they have encountered in doing their work
- Analysing your records of workplace incidents, near misses and worker complaints

- Reviewing any information and advice about hazards and risks relevant to your particular industry or the type of work that you do e.g. information provided by industry associations, manufacturers or suppliers.

### 4.2 Assess Risks

A risk assessment should be done when:

- There is uncertainty about how a hazard may result in injury or illness
- The work activity involves a number of different hazards and there is a lack of understanding about how the hazards may interact with each other to produce new or greater risks
- Changes at the workplace occur that may impact on the effectiveness of control measures.

Assessing risks involves considering:

- how severe the harm caused by the hazard could be, including [64]:
- how hazards may cause harm, including:
- the likelihood of harm occurring, including:

The level of risk will increase as the likelihood of harm and its severity increases.

### 4.3 Control Risks

The ways of controlling risks are ranked from the highest level of protection and reliability to the lowest. This is known as the hierarchy of risk control.

One must work through the hierarchy of control in order and, where possible, implement risk controls high in the order as follows [64]:

1. ***Eliminate*** - remove the hazard completely from the workplace e.g. removing trip hazards on the floor or disposing of unwanted chemicals. This is the most effective control measure and must always be considered before anything else.
2. ***Substitute*** - substitute or replace the hazard with a less hazardous work practice e.g. replace solvent-based paints with water-based paints.
3. ***Isolate*** - as much as possible, separate the hazard or hazardous work practice from people by distance or using barriers e.g. placing guards around moving parts of machinery.
4. ***Engineering controls*** - these are physical control measures e.g. use a trolley to lift loads.
5. ***Administrative controls*** - these should only be considered when other higher order control measures are not practicable. These are work methods or procedures that are

designed to minimise the exposure to a hazard e.g. developing a procedure on how to operate machinery safely or use signs to warn people of a hazard.

6. ***Personal protective equipment (PPE)*** - this should be the last option. PPE, such as hard hats, gloves and protective eyewear, relies on the proper fit and use of the PPE, but does nothing to change the hazard itself.

In some cases a combination of control measures may need to be implemented to provide the highest level of protection that is reasonably practicable. When selecting and implementing a combination of control measures it is important to consider whether any new risks might be introduced as a result [64].

### 4.4 Review Control Measures

Control measures that have been implemented must be reviewed, and if necessary, revised to make sure they work as planned.

There are certain situations where you must review your control measures, including:

- when the control measure is not effective in controlling the risk e.g. when an incident occurs
- before a change at the workplace that is likely to give rise to a new or different health and safety risk that the control measure may not effectively control
- If a new hazard or risk is identified
- If the results of consultation indicate that a review is necessary
- If a health and safety representative requests a review.

| | **Laser cladding** | **Overlay welding** | **Roll bonding** | **Explosive welding** | **Friction-stir weld** |
|---|---|---|---|---|---|
| **Risk assessment** | Level of risk is high | Level of risk is low to medium | Level of risk is from low to medium | Level of risk is from medium to high | Level of risk is low |
| **Maintenance cost** | High | Low | Low | Medium | Low |
| **Cost of equipment** | High equipment cost | Cost depending on selection of technique | Cost depending on the size of roller | Low | Moderate |

**Table 4.1** Comparison of welding techniques based on risk and other parameters

## Noise Risks

All welding and cutting processes generate noise but methods like explosive welding are much noisier than others. Exposure to noise over a period of time can result in impairment or loss of hearing. It is also possible that permanent hearing damage can be caused by a single, intense impact noise [65].

## Assess Risk

To assess the risk, account must be taken of the welding process to be used, the general and intermittent noise levels in the work area, the duration of exposure to noise and the protective equipment available. In most cases the following steps will be necessary to carry out a risk assessment.

1. When noise level exceed allowable levels laid down in health and safety legislation, warning notice will be required either at the machine or if excessive generally throughout a workshop at all entrances.

2. Noise level measurement in dB may need to be taken to identify where noise levels are excessive and also which operations are producing the highest noise level [65].

## Control Measures

1. Ear protection equipment is the most prevalent risk control measure used to reduce personal exposure to noise. Ear protection device must be in good condition and have sufficient noise attenuation properties. Not using ear protection increases the risk of hearing impairment over a period of time.

2. Segregation of noisy process to one area of the workshop, away from the general work area, can be used as a control measure to reduce exposure to noise for the majority of workers. In the segregated area, there is high risk of exposure to loud noise, but outside the area there should be lower risk of exposure to continuous noise [65].

## Maintenance of laser cladding

Preventive maintenance serves to guarantee that the laser and accompanying peripheral equipment always produce respectively the right laser beam and correct material supply during production in the working place. For preventive maintenance;

- An overview of maintenance activities and the right settings of the laser equipment, provided by supplier.
- A staff member within the company who is responsible for the maintenance scheme.
- An annual planning of the maintenance inspections that is linked to the production planning.
- A maintenance procedure including the parts and components that should be checked, maintained, replaced and cleaned [65].

## CONCLUSIONS

The different welding techniques which are extensively used for material surface repair, or enhancing the corrosion and wear resistant properties of base material is studied in detail and the following conclusions are drawn. The common factors in the above techniques are the surface enhancing purpose at different levels with different materials.

1) Laser cladding being the expensive technique of all has more advantages. Laser cladding is used for repairing complex components for e.g. turbine blades with less distortion and low heat affected zone i.e. with no damage to the base material. It is seen that laser cladding shows narrower or less heat affected zone because of low heat input and low cooling rate.
2) Overlay welding is mainly used for protecting expensive base material from corrosion and wear resistance by overlaying an inexpensive material or a filler material on it. Overlay welding provides long life and high reliability corrosion resistance to harsh environment application but limited to perform only in horizontal position.
3) Roll bonded clad plates are the economical alternatives to expensive high alloy solid plate. The mechanical properties of the base material and the corrosion resistance of cladding material results in optimum combination and forms better surface finish than overlay welding.
4) Friction stir welding provides low distortion and shrinkage, even in long welds, and can operate in all position with no porosity.
5) Explosion welding is simple where large surface can be bonded with wide range of thickness. Only small quantities of explosives are used and has no heat affected zone.
6) By high resistance material to surface, we can make the surface to high corrosion resistance, a high abrasive resistance, a high heat resistance and reinforce the weak point of the product more strongly. Based on these techniques, we can reduce the cost of material by 50%.

## Recommendations

After taking into consideration the above techniques and studying them in detail about the process involved in, and the materials used for it the following recommendations are given. Laser cladding being the most expensive technique because of its equipment cost, it can be used for very complex component and can be performed in any position. With less heat affected zone and low cooling rate the properties of the material are not adversely altered and the process is quick with less distortion, but on the contrary other method like overlay welding is less expensive and have limited application for complex components with considerable change in properties of base material. This method is mostly used in systems carrying corrosive substance which needs coating of anti-corrosive materials.

Roll bonding and explosive cladding are commonly used in simplified components to make materials of dissimilar metals with limitation of positions. Hence these methods being less expensive and negligible heat affected zone can be used for joining dissimilar metals without altering its properties in a very easier way. Friction stir welding is mainly recommended for materials with longer welds with less distortion and the ability to weld in any position. Hence from the above methods laser cladding and friction stir welding has more advantages than other methods even-though they seems expensive. Limitations which are more prominent in these two methods can be avoided or reduced with the help of selecting the optimum material for coating and deciding the best way for coating.

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