POLITECNICO DI TORINO

Master's Thesis

The Surface Brazing effect of components for automotive applications

A Thesis in the Field of Materials for the

Degree of Master of Mechanical Engineering

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Abstract

The automotive industry can be considered one of the most important industries in this world. The sector is responsible for the transportation and logistics of humans and goods across the globe. In the previous decades, the automotive sector took over the railway industry in the US in both sectors of logistics and transportation. The sector has been booming ever since. Initially, a car was considered a luxury and has become a necessity. Recent history was really focused on the automotive industry being sustainable, but rather just a boom of cars. But we have come to realize now that there is a dire need to make the automobile more efficient in terms of fuel so that the car consumes less fuel and emits fewer gases. The automotive industry is keenly interested in figuring out ways and inventing new materials which provide the same strength to the vehicle but at a lower overall weight.

This thesis discusses the brazing procedure for brazing joining of aluminum alloys to low carbon zinc-coated steel with the filler material being zinc. The experiment conducted reveals some results about the strength of the brazed joint so that the automotive industry can replace all steel to maybe brazed portions of steel with aluminum for weight reduction. The methodology discusses the experiments in detail.

Acknowledgements

Although my master's degree will be completed with the completion of my thesis, I hope that this lifelong path of wisdom and knowledge will continue. I owe a great debt of gratitude to Politecnico di Torino's Department of Mechanical and Aerospace Engineering (DIMEAS) for allowing me to follow my aspirations and improve my talents. For me, being a member of a multicultural institution has been a life-changing experience. During my time at Politecnico, I met some of the most creative and extraordinary people. I'd want to express my heartfelt appreciation to my supervisor, Dr. Graziano Ubertalli and Dr. Sara Ferraris of DISAT at Politecnico di Torino, for their unwavering support and encouragement throughout my master's thesis in this unprecedented epidemic. In addition, I want to express my gratitude to my close friends, Bilal and Ifrah who have provided ongoing encouragement and motivation throughout my master's thesis and degree. Lastly, I want to convey my heartfelt appreciation to my parents, and siblings, who have been an integral part of my life and have always supported me. This work is dedicated to them in particular.

Muhammad Qasim Jadoon

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1.Introduction

1.1 Motivation

The number of vehicles has expanded tremendously as the automobile industry continues to flourish, and there are now more than 1 billion automobiles on the road globally [1]. The vehicle has evolved into one of the world's most important sources of energy consumption and pollution emissions, having a considerable influence on the environment and resources. Currently, all major nations have established severe rules to control motor fuel usage and carbon emissions.

In order to tackle the problem of environment change and global warming, the automotive industry has to come up with changes in their products in order to survive in this ever-changing race of technology. With time, an incredible change has been spotted in the automotive industry, in regard to every concerned aspect. Nowadays, the industry is looking into innovative methods that cater for the reduced fuel consumption of the vehicle while simultaneously increasing the efficiency of the vehicle. This can be achieved in several ways such as the use of different engineered fuels and introducing AI etc.

But if we go back to the fundamentals of the mechanics, reduced weight points mean reduced fuel consumption, which implies fewer CO_2 emissions, improved performance, and more shock absorption in the event of an accident. Not only can lighter vehicles save money on petrol, but they also lower greenhouse gas emissions.

The car industry is currently confronted with two significant challenges: improving fuel efficiency and reducing environmental pollutants such as CO_2 and Nox [2]. Light weighting a vehicle is one of the most important ways for achieving these aims since a vehicle with a smaller mass requires less power to accelerate or maintain motion.

Material substitution and design optimization can be used to create lightweight constructions [2]. The automobile industry has worked hard over the years to reduce vehicle mass by switching from ordinary steels to ultra-high strength steels (UHSS); or combining steels with light metals such as aluminum and magnesium alloys; or even using polymer composites.

Multi-material constructions are already in use in today's automobiles, and they are projected to become more common in the near future. However, production and joining techniques are currently being developed in order to meet safety criteria with high dependability at an affordable cost.

Multi-material vehicle designs can efficiently reduce vehicle weight while maintaining vehicle durability, safety, and essential performance. Mild steels in body-in-white (BIW), chassis, and closures have been replaced in modern automobiles by a combination of wrought and cast aluminum, high strength steels, ultra-high strength steels, and magnesium. Despite the numerous benefits of using multi-material constructions, the usage of this idea in real-world production vehicles is still restricted. This is because of its high production costs, incompatible material qualities, complicated joining technique, and poor joint dependability.

Joining is always a vital process in different industries. It can be thought of as the backbone of the mechanical industry specially when it comes to automotive sector. Engineers have been developing various techniques for a long time to figure out the best joining practices which provide the desired strength under extreme conditions. But they have been facing a problem to join different metals together using the conventional techniques. A lot of research has been done in the field of material sciences to go to the bottom of the problem to figure out the best and efficient metal joining techniques.

1.2 Objective

Conventional joining techniques have some limitations when it come to the joining of dissimilar metals and alloys. Thanks to the advancement in the materials world, now we have different hybrid techniques with which we can join various different metals using unique complicated joints.

One of the most used techniques for this purpose, which is also the main topic for the thesis is brazing. Brazing is a metal-to-metal bonding method that uses a filler metal with a melting (liquidus) temperature higher than 450 °C (840 °F) but lower than the base metal's melting temperature. Silver (Ag), aluminum (Al), gold (Au), copper (Cu), cobalt (Co), or nickel alloys

are commonly used as filler metals (Ni) [3]. The major advantage of brazing is the achievement of a sound joint at even lower temperatures than conventional joining techniques. In conventional joining techniques the base metal melts in order to join together whereas in brazing the base metal does not melt as the filler metal have low melting point so it melts in order to join the base metals.

In brazing the base metals are never melted, which is extremely important. Because the basic metals are not melted, most of their physical qualities are retained. All brazed joints, both thin-section and thick-section joints, have this base metal integrity. In addition, the reduced heat reduces the risk of metal deformation or warping. Consider that lower temperatures necessitate less heat, resulting in considerable cost savings.

Due to the differences in thermal and chemical properties of Steel and Aluminum, they cannot be joined by conventional joining methods. So, this thesis focuses on the experimental work for the joining of aluminum to Steel using the brazing procedure. Because the production of intermetallic compounds is critical for joint performance, scanning electron microscopy (SEM) was used for microstructural investigation, while energy dispersive X-ray spectroscopy (EDS) and X-ray diffraction analysis were used for phase determination (XRD).

The main objective of this thesis is to do detail research on joining of dissimilar metals by brazing with the help of a filler metal/material. As in today's world of competition we need to find smart and affordable ways of joining dissimilar metals. Specially in the field of automotive to reduce weight in order to get better efficiency and reduce risk related to environment because of the emissions of harmful gases, we have to substitute Steel with Aluminum.

2. Literature Review

This Chapter entails the discussion about the literature review for joining technologies in general and then focuses on the technologies envisaged for the joining mechanisms of aluminum and zinc coated steels. For this purpose, review and research articles are read, demonstrating the essential use in the industry, history of the process, and its usage.

Looking at the processes for joining of metals i.e., similar, and dissimilar, the literature provides us with a vast amount of information regarding all the types of joining which are further discussed below. To name a few, such as welding, mechanical joining and adhesive bonding can be regarded as the main branches of joining which are further split into different categories.

To further explain the branches of joining technologies, we need to take into account the types of joints that are required in different industries. The following section provides a slight overview on the typology of joints ad their usage.

2.1 Joining Processes

Joining involves a range of processes for assembling separate parts into a larger, more complex part or assembly. For each made item after the machining processes, there are some fundamental welding and joining strategies [4]. Whereas all these joining methods differ from each other in terms of properties, functioning and cost. The joints are found where the separate elements of an assembly connect.

Joints transfer or distribute stresses induced during service from one portion of the assembly to the other parts. Joint can be either classified as permanent or temporary [5].

The following are the several types of joints found in engineering assemblies:

- Temporary Joint: If the assembly can be removed without causing damage to the components, it is termed as temporary joint. The components should be able to be reassembled using the original or replacement fastenings. If we consider the simple

example of car, it is assembly of different thousand components, so some are temporary components that need be replaced with time. These components are joined by temporary fastenings such as bolts and nuts [6].

- Flexible Joints: A joint is called flexible if one component in an assembly may move relative to another component in a controlled manner, such as a hinge [6].
- Permanent Joint: If one or several of the components, or the connecting medium, must be destroyed or damaged in order to dismount the assembly, it is called permanent joint. Such kind of joints need to be brazed or welded together [6].

The joining procedures are primarily divided into three groups, additional classification of these joining processes is presented in figure 1.

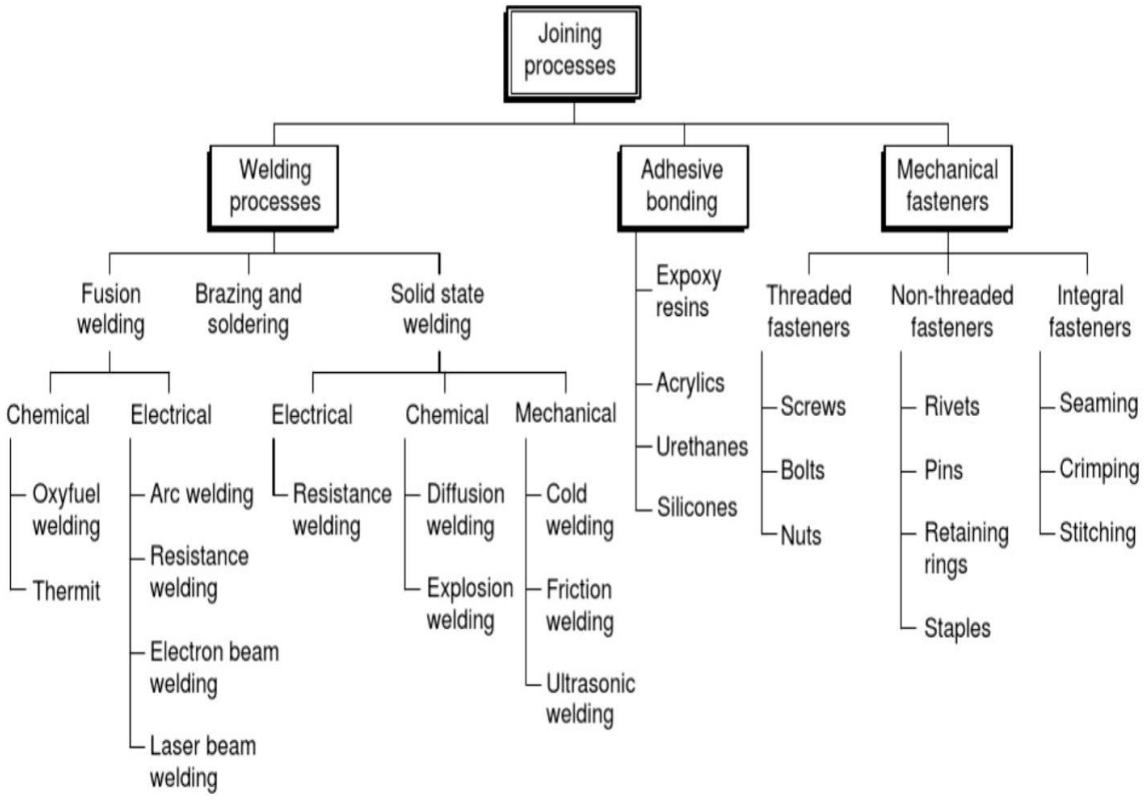


Figure 1: classification for the generic joining processes[7]

Butt, tee, lap, corner, and edge joints are the five most common types of joints. Figure 2 depicts the many types of joints. Several factors influence the joining procedure and joint utilized, including cost of manufacturing, manufacturability, dependability, aesthetics,

repairability, and so on. However, the kind of material, thickness, shape, and joint placement all influence the joining process.

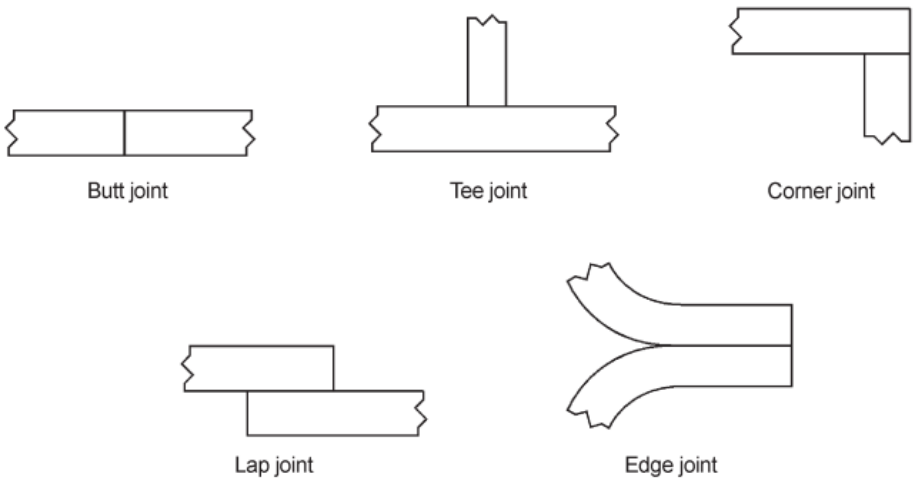


Figure 2: Joint Types [5]

The joints depicted in the figure 2 are some of the very basic configurations that can be made by using one of the above-mentioned joining technologies according to their usage and need of the assembly.

We further discuss the joining techniques of adhesive bonding and mechanical fasteners in detail before coming to the main topic of research to provide an insight and comparison on how the techniques work and are different from one another and whether can be replaced with each other to perform the same task.

2.2 Adhesive Bonding

One of the earliest assembling methods is adhesive bonding. Its growth expanded dramatically over the previous century, particularly in the aeronautics industry, which has a history that is intertwined with the two world wars [8]. In 1915, Fokker pioneered the use of adhesive bonding, paving the path for subsequent manufacturers. For the DH 98 Mosquito aircraft in 1940, adhesive bonds were utilized on wood spars (Adams and Cawley, 1988).

Adhesive bonding has progressed to the point that high-performance epoxy-based resins are now routinely employed in civil aircraft. Airbus, for example, began using adhesive bonding in 1972.

Adhesive bonding is a method of attaching two or more components that involves the solidification or hardening of a non-metallic adhesive substance that is put between the parts' faying surfaces[9]. The process has many advantages over its counterparts, the main one being the development of continuous bonds between the two surfaces being joined instead of localised point contacts [10]. What this continuous bonding does is that it leads to a structure that has a greater uniform distribution of stress and a higher stiffness. Other several advantages also include the over the competing processes include process temperatures that are lower than that of welding and brazing processes and also the ability to connect different components together only using one operation. Normally, while using the technique under discussion for joining two components, joint design should be kept in mind so that the loading stresses are directed along the greatest strength lines, meaning that the peel mechanism should be minimised. Also, it is a good practice to prepare two surfaces beforehand for bonding by removing surface contaminants, which is generically done by degreasing with the help of a solvent and abrasion process.

Adhesive bonding can generally be described by dividing it into two categories that are the following:

1. Structural adhesive bonding
2. Non-structural adhesive bonding

Talking about the first category, structural adhesive bonding processes involve a chemical reaction and include anaerobic, cyanoacrylates, acrylics that are toughened, also polyurethanes and epoxies. Structural adhesives are utilized when the bonded structure is subjected to increased stress but beneath the yield point.

Whereas the non-structural adhesives are usually set by a range change that is physical and includes the use of hot melts, plastisol, rubber-based adhesives and also pressure sensitive adhesives [10]. Non-structural adhesives, as compared to structural adhesives are weak adhesives that cannot withstand larger stresses; yet they may maintain light materials together when combined.

Usually, talking about the joints that use adhesive bonding, most of them perform the best and are strongest while undergoing shear, compression, or tension stresses, but are considerably weak when they are subjected to peel or cleavage type of stress. The following figure 3 describes the types of loading conditions discussed in the above paragraph.

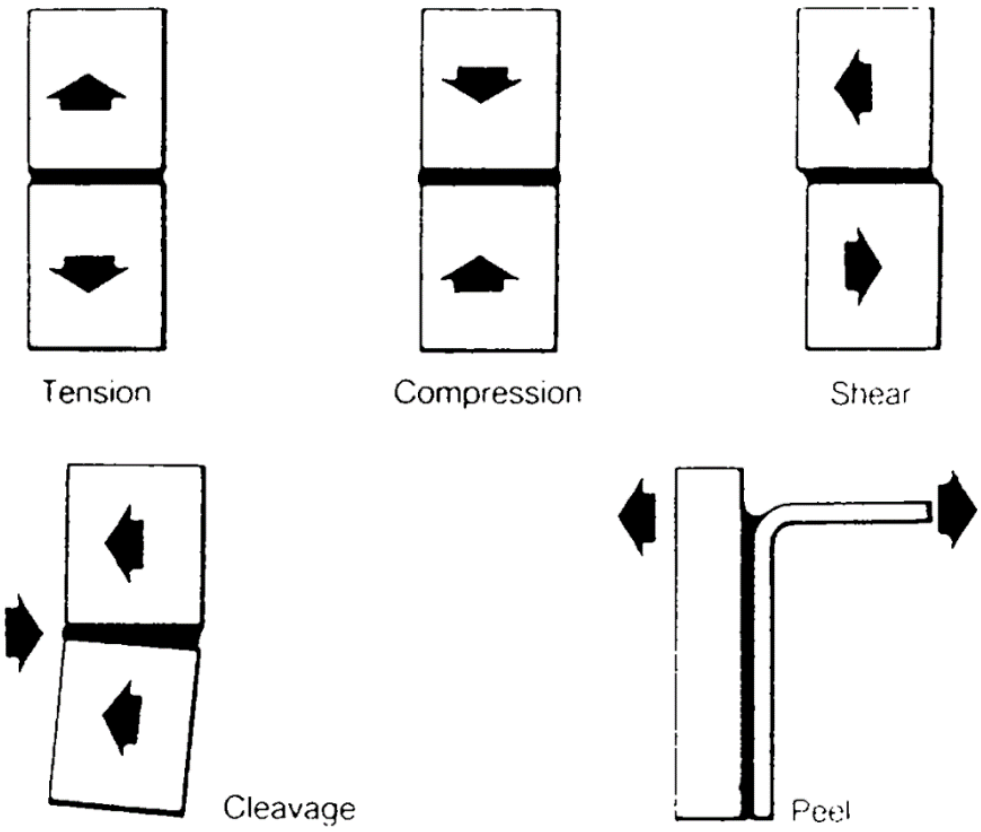


Figure 3: loading conditions for adhesive bonded joints [10]

Concluding our discussion about adhesive bonding, they can be regarded better than other joints in terms of weight reduction characteristics, corrosion resistant and providing a greater uniform distribution of stress. However, the technique also has some disadvantages which makes its usage in the industry limited. These include a large amount of curing time, after which the final strength of the bond is achieved. Also, the ageing mechanism affects the bond strength over time, the strength of the bond depends on various physical and chemical actions in the environment such as ultraviolet light and presence of moisture. Also

contributing to this phenomenon is the working temperature limitation of the adhesives that are utilised during procedure.

Hence the most efficient usage of adhesive bonding in any manufacturing operation is dependent on the optimisation of the selection of the adhesive, the design of the joint and the conditions of the process [10].

2.3 Mechanical Fasteners

In industry, mechanical fastening is the most prevalent way of combining numerous materials. It was originally developed for metal joining, but it is now widely used to link plastics to one other and to other materials [11]. Permanent and non-permanent industrial fasteners are the two basic types. Non-permanent fasteners include screws, which may be removed, replaced, and reused. Due to the increased assembly time, these pieces raise the product cost and are more difficult to handle and align. Screws are a dependable and economical mechanical fastening technique. They don't need moulded-in threads or threaded inserts, which saves money on moulding and assembly. Dissimilar materials can be bonded, and the joint can be disassembled and reassembled several times, typically up to 10 times [11].

Connections are formed in certain areas of the component and have a high impact resistance. No specific application equipment is required, and full-strength joints can be produced instantly without the cure period associated with adhesive bonding. Non-permanent fasteners like screws, nuts, bolts, and washers are dismantled and reassembled until the material being attached fails.

Permanent fasteners, such as snap fits, which are embedded into parts by direct moulding, are more durable and less likely to come free. Due to these characteristics, the use of permanent fasteners is increasing in the industry.

Talking about the type of fasteners as mentioned in the figure 1, there are many types which are categorised under permanent and non-permanent fasteners. Threaded fasteners such as bolts, screws and nuts and non-threaded fasteners such as pins, retaining rings etc are categorised as non-permanent fasteners and most commonly used for assembly of

components due the fact that they are easy to be installed and uninstalled according to the need of the situation.

Whereas, if we talk about the permanent fasteners, such as rivets, once removed, they cannot be reused. Their usage pertains to a number of industries but are specially known for their usage in the to join sheet metals and plates. Another example of the permanent type of fasteners is nails. Once used, they cannot be reused and removing them may cause permeant damage to the joint.

But talking about the usage and advantages of mechanical fastening, it is vital that we also talk about the disadvantages of mechanical fastening. Mechanical fasteners add extra weight to the assembly, they also usually require holes that area cause to weaken components, and also leave extremely visible bond lines. One of the major disadvantages of mechanical fastening is that the distribution of stress is not uniform on all the part rather they are concentrated on specific points, contributing to the overall fatigue of the joint and the assembly. Also, the fact that they do not help in separation of dissimilar materials that can be a vital contributor for corrosion of the assembly [11].

After discussing adhesive bonding and mechanical fasteners, we come to the welding technologies for joining. Welding technologies are another method of joining metals with each other for production of assembly. Welding processes can be categorised further into fusion welding, brazing, and solid-state welding. The following section talks about the welding procedures, specifically brazing which is the main topic of discussion of our thesis.

3.2 Welding Processes

Welding is defined as the method or technique used for joining metallic parts via the application of heat. To get into more details, we also cater for the pressure and the filler materials used during the process. A more precise definition would also involve the above mentioned two factors. So, in essence the process of welding can be elaborately defined as the amalgamation of metals produced by providing heat to a suitable temperature with or without the application pressure and with or without the use of filler materials.

The following sections discuss the different types of welding procedures that are used in industries and the market. The sections provide a brief overview of the practices and then caters for the main topic of brazing as it also a part of the welding procedures.

3.2.5 Fusion Welding

Talking about the most common type of welding, that can be regarded as fusion welding, the heat source is responsible for generating a sufficient amount of heat that creates and also maintains a molten pool of metals of the required size [12]. This amount of heat can be supplied from an energy source that can be electricity of by a gas flame. The methods have significant differences and are used according to the need and requirement of the joint to be formed. For example, the arc welding process which uses electricity reaches an extremely high temperature of around 6000^{o}C and produces a strong joint. On the other hand, the surface finish produced is not of significant degree and requires some cleaning while welds produced by gas welding can join dissimilar metals in some cases as well and provide for a very clean surface finish.

Talking about the same category of welding processes, electric resistance welding can also be counted as fusion welding. Electric resistance welding is a process in which metals are joined together by applying pressure and conducting a strong electric current through the metals in contact to heat up the joint until it melts, forging them together. There are also a lot of types of electric resistance welding, but spot welding is a worthy mention while talking about electric resistance welding.

Resistance spot welding has been widely used in the automotive industry and aerospace industry for joining of steel and aluminum alloys respectively. It can be considered one of the oldest and simplest forms of resistance welding technique in which a weld nugget is created by passing electric current between the two metals when they are being held together in between copper-based alloys electrodes. The electrodes are made of typically copper-based electrodes due to copper's superior conductive properties.

As figure 1 indicates, laser beam welding and electron beam welding technologies are also considered to be a part of fusion welding. This is due to the fact that both these procedures while producing a welded joint, create some kind of molten metal due to extremely high temperatures reached.

Going into some details about the laser beam welding, it is a fusion welding process which involves two metal pieces joined together by the use of laser. Laser beam, that is responsible for providing a concentrated heat source, is focused on the cavity between the two metal pieces that are to be joined[13]. The procedure is commonly employed in high-volume, automated applications, such as the automobile sector. Welding in the keyhole or penetration mode is used. The capacity to melt the region located at the borders of the joint without impacting a vast area of the component is the major benefit of laser welding, which is attributable to its high energy density [13]. The figure 4 on the next page provides with a schematic for the Laser beam welding.

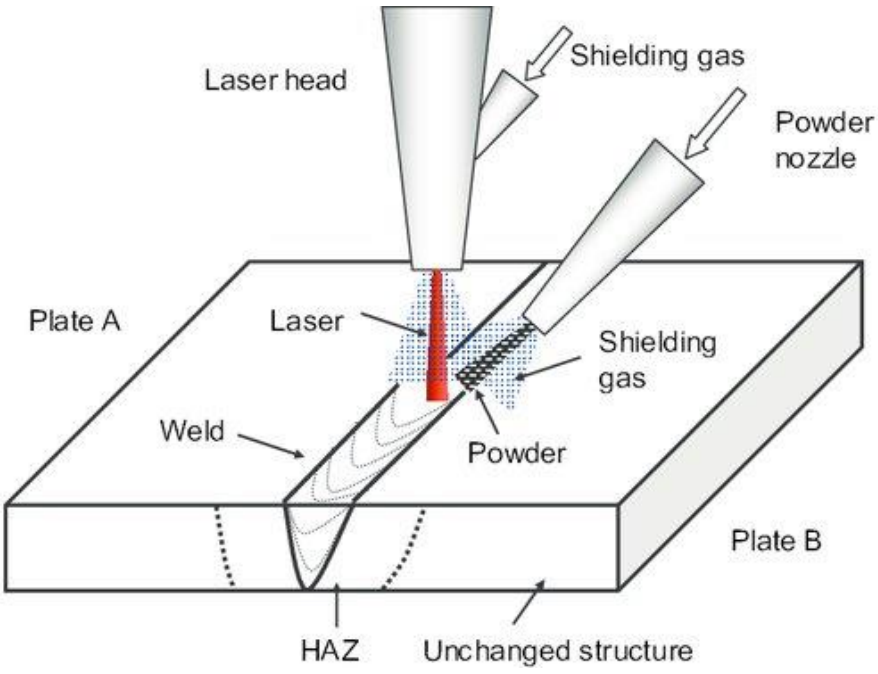


Figure 4: Laser Beam Welding

When compared to arc welding, laser welding is a high-power-density fusion welding technology that creates high aspect ratio welds with a comparatively low heat input. Furthermore, compared to previous joining methods, laser welding may be done “out of vacuum,” and the fibre-optic transmission of near-infrared solid-state laser beams allows greater flexibility.

Electron beam welding can also be considered as a type of fusion welding, is a high-energy density fusion process that uses intense, strongly focused beam of electrons that are accelerated to 0.3 to 0.7 the speed of light to be bombarded on the joint to be welded [14]. The rapid conversion of these electrons’ kinetic energy into thermal energy as they contact and penetrate into the work piece leads the weld-seam interface surfaces to melt, resulting in the desired weld-joint coalescence. Electronic beam welding (EBW) can be used to weld any metal that can be welded by the use of arc welding and is with a few exceptions, always carried out in vacuum.

Electron beam welding (EBW) is particularly well adapted to forming connections in one or two passes of heavy section materials (about 50 mm). It tends to cool quickly, resulting in substantial ferrite content in the melt zone, especially in thin sections. The following figure illustrates the usage of electronic beam welding.

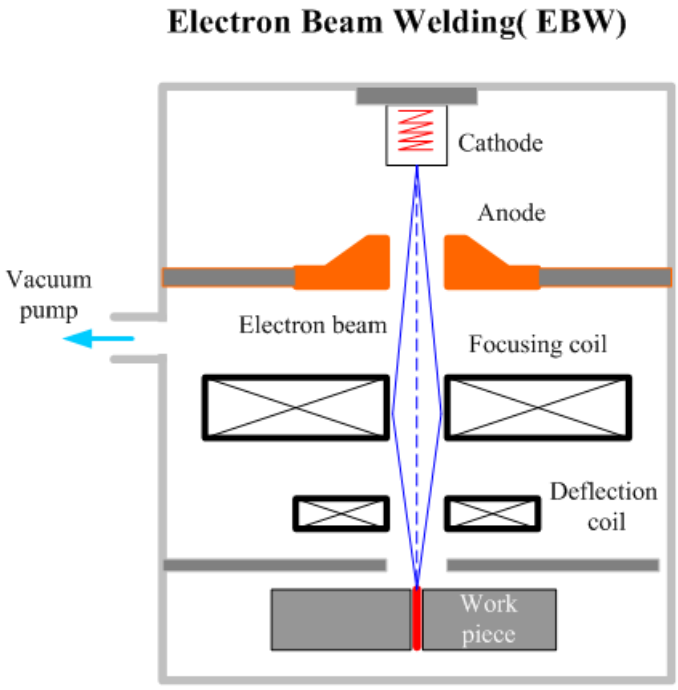


Figure 5: Electron Beam Welding

Modern electron beam welding machines are controlled by PLCs with working tables or numerically controlled welding positioners, allowing for the automation of welding processes, as well as various control and safety systems aimed at maximizing the operator's radiation protection and allowing for technological processes to be carried out in the vacuum [15].

The categories discussed up till now can be considered as electrical fusion welding. Fusion welding has also a chemical portion which consists of mainly two subcategories. The categories are thermit and oxyfuel welding.

Coming towards the latter type of welding that is oxyfuel welding or commonly known as gas welding, is a process that joins metals by using combustion of fuel gas, and air in a nozzle that is directed at the work surface. Acetylene is the most often utilized fuel gas. The base metal, filler metal, and fluxes all contribute to the gases produced during this method of welding. However, the amount of fumes created is small, and the temperatures produced are far lower than those produced by arc welding. Because the equipment is inexpensive, this method is frequently utilized in auto body and house repair. Because the weld quality is lower to that of arc welding methods, it is not widely employed in industry. Instead of connecting metal, the process can also be used to cut it e.g., oxyfuel cutting [16].

The other technique is chemical fusion welding is the thermite welding. The process uses heat from an exothermic reaction, to produce coalescence between the metals to be joined. The name comes from the term "thermite," which refers to a process involving metal oxides and reducing agents. The thermite mixture is made up of metal oxides with low temperatures of formation and metallic-reducing agents with high heats of formation when oxidized. The surplus temperatures of reaction product creation serve as an energy source for forming the weld. This is a particularly effective welding technique for joining huge steel pieces together, such as elements of a stern structure. In fact, it's frequently used to repair castings and forgings of this type[17]. The welding mechanism is greatly used in welding sections of rail rack with each other in the railway industry. The following figure shows the use of thermit welding in the railway industry for the welding of tracks.

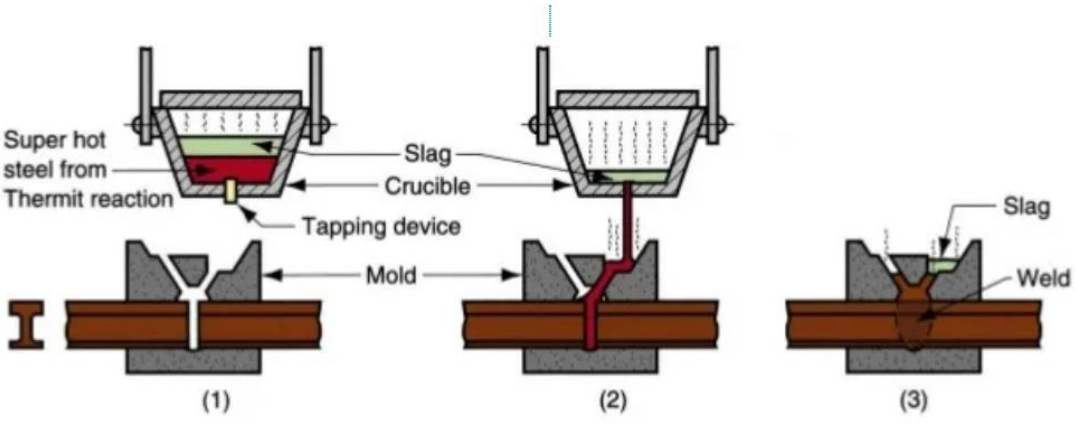


Figure 6: Use of Thermit Welding

Thermit welding is a quick and easy way to combine metals that are similar or different. This procedure is inexpensive since it does not need the use of a pricey power supply.

The following sections covers a brief overview of the solid-state welding procedures that are in use in the industry as depicted in figure 1 mentioned above.

2.4.2 Solid State Welding

Solid-state welding is a collection of welding methods that generate coalescence without the need of brazing filler metal at temperatures virtually below the melting point of the base materials being connected. They are a diverse set of welding methods that rely on various Multiphysics phenomena [18]. The category is further divided into three components that are electrical, chemical, and mechanical.

Coming to the mechanical category of solid-state welding, firstly we talk about friction welding. Friction welding is a type of solid-state welding. The heat created by friction at the rubbing surfaces causes coalescence by raising the temperature at the interface to a point where the two surfaces are welded together under high pressure.

The process is commercially established that is frequently used for joining similar and dissimilar materials such as polymers and metals/alloys. Some of the types of friction welding include rotary friction welding, linear friction welding, friction stir welding, and friction stir spot welding. The quantity of the heat required to generate the weld between the two metal components determines the speed at which the relative motion occurs, and the pressure supplied to the workpieces. Friction welding produces temperatures ranging from 900 to 1300 degrees Celsius in steel. The following figure represents a schematic for frictional welding.

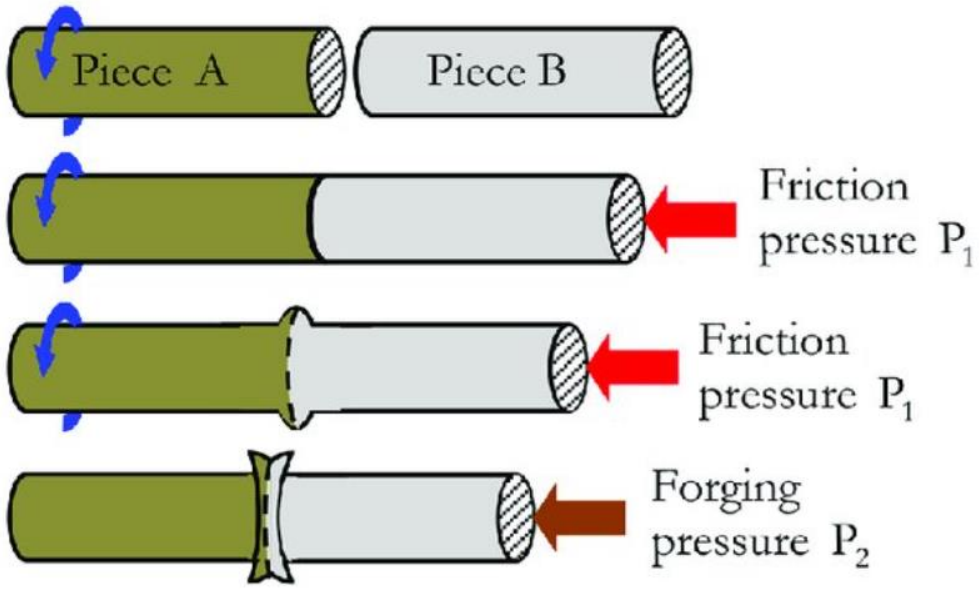


Figure 7: Friction welding schematic[19]

Talking about some advantages of the process, the technique allows the joining of dissimilar metals, for example, aluminum to steel, cooper to aluminum, and nickel alloy to steel. Generally speaking, every metal that is forgeable can be friction welded. There is no need for an external heat source, keeping the process easy and less messy. The process is relatively fast and does not require surface preparation.

Another form of solid-state welding is cold welding. Cold welding (CW) is a type of welding that does not need the use of heat. The two pieces being linked are subjected to external pressure, resulting in significant plastic deformation [20]. As a result, one of the essential requirements of CW is that at least one of the joining materials is ductile and does not exhibit considerable work hardening. As a result, commercially pure aluminum and several of its

alloys are ideal for CW. Both butt and lap joint configurations can be conducted using cold welding. The process can ensure fast and strong joints in wires and is commonly used with aluminum, brass, copper, and gold. Cold welding is also good for joining dissimilar metals that are otherwise difficult to be welded. The following figure 8 depicts the schematics for cold welding.

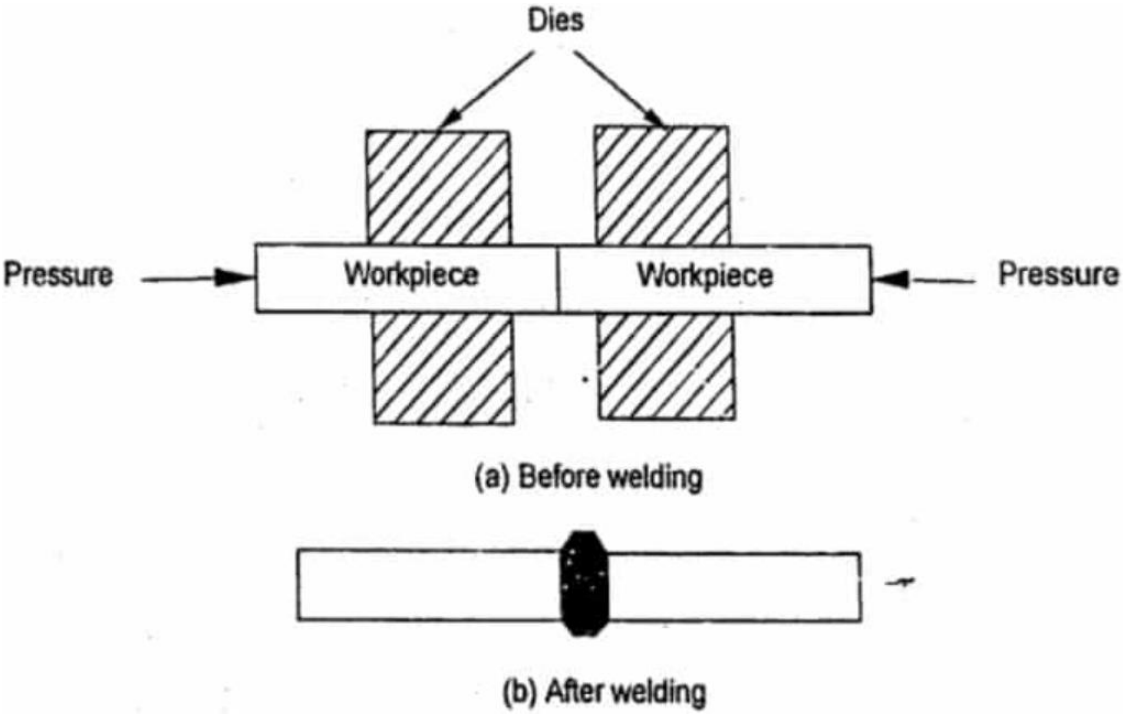


Figure 8: schematic for cold welding

The above-mentioned solid-state welding types correspond to mechanical solid-state welding. Solid-state welding also entails chemical welding which is discussed below. Chemical solid-state welding involves explosion welding as a category. Explosion welding is basically a solid-state welding process, in which explosives are used to accelerate the parts to be joined into a high velocity oblique collision. The process has a great potential for joining dissimilar material combinations with extremely different physical properties such as aluminum to copper, aluminum to carbon steel and stainless steel. Briefly skimming over the process, the process is mainly used for cladding processes. This method may be used to combine nearly any metal or alloy that allows for more than 5% strain[21]. The explosion of explosives creates a compression force that is utilized to attach overlapping metal sheets in explosive welding. The connecting components are angled 1–15 degrees toward each other, depending on the

material and procedure, and a coating of explosive is applied on top. Following ignition, the connecting portions are accelerated against each other [21]. Local plastic deformation of the contact region causes continuous joining. The following schematic 9 describes the explosion welding in more detail.

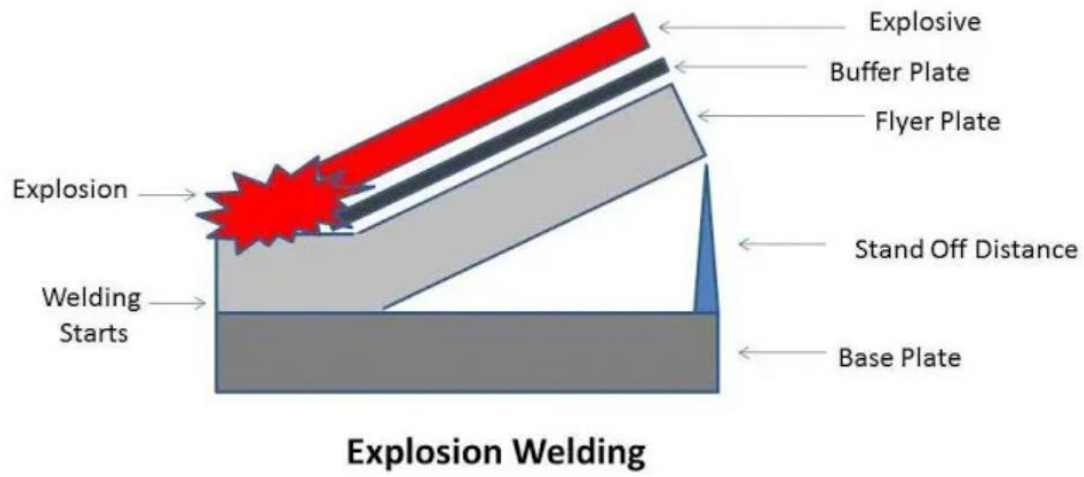


Figure 9: explosion welding schematic[22]

Coming to the last category of solid-state welding to be discussed, that is diffusion welding. Diffusion welding is a solid-state welding method for joining two metals together. Diffusion is the movement of atoms across a joint as a result of concentration gradients. The two materials are squeezed together at a temperature that is generally between 50 and 70% of their melting point. The pressure is utilized to fill any voids that may form as a result of the various surface topographies. N.F. Kazakov, a Soviet physicist, devised the approach in 1953. To match the welder to the workpieces, specific equipment is designed for each welding application.

Diffusion welding has many types and is widely used technique in the industry. Some of the types of diffusion welding include laser welding, auto-vacuum welding, transient-liquid phase (TLP) welding etc [23]. The procedure has many advantages over traditional welding technologies. Some of the advantages include clean joints, of all quality, and free from

brokenness and porosity. Diffusion welding reinforces materials, and they represent the same physical as well as mechanical properties as the base fabric. The technique can be utilised for joining comparable and disparate materials; hence it is broadly used. Also, the plastic distortion of the material reduces below the diffusion.

Some of the disadvantages of the process include an extremely high start-up cost. The process is time consuming, planning the work piece is a hard task, and the procedure has no application for mass production [23].

Before going to the next chapter, we briefly provide an overview for brazing and soldering. Brazing is a metal-joining method that involves melting and flowing a filler metal into the joint, with the filler metal having a lower melting temperature than the neighbouring metal. Brazing differs from welding in that it does not require the workpieces to be melted[24]. Whereas Soldering is a method of joining two or more metal objects together by melting and flowing a filler metal into the junction, with the filler metal melting at a lower temperature than the workpiece. Soldering differs from welding in that it does not require the work parts to be melted. The filler metal melts at a greater temperature than the workpiece metal in brazing, but the workpiece metal does not melt [25].

2.2 Joining of Aluminum and Steel

So far, we have provided a brief overview about the joining technologies being used in the industry. Here in this chapter, we discuss the joining of aluminum and steel, specifically zinc coated steel. Joining aluminum to steel has always been a crucial problem in the industry, especially automotive and aerospace. Conventional joining techniques such as resistance spot and gas welding are not really acceptable because these techniques had a plethora of metallurgical issues. Other techniques than welding can easily help us join steel to aluminum like adhesive bonding and mechanical fastening, but these methods just are not feasible if we take into account the strength that we require, and in the end want to further make the assembly lighter in weight.

2.2.1 An Introduction

But first we should make clear that why do we need to weld these two metals together. Aluminum and its alloys are much lighter than steels and have a density of around 2.70 g./cm^3 whereas, steel has a density of 7.75 to 8.05 g/cm^3. This means that a comparable volume of steel weighs roughly three times as much as an equivalent volume of aluminum [26]. Steel is used in a variety of sectors for structural purposes. Steel, on the other hand, has a high density and hence has a considerable weight penalty. New environmental legislation is requiring the transportation industry to adhere to rigorous greenhouse gas emission restrictions. Reducing the weight of a vehicle's construction is one approach to help cut emissions. The use of aluminum alloys to replace various steel constructions is becoming increasingly important in industry. Because it is not always possible to replace the complete steel structure with aluminum alloys in many applications, the two materials must be joined.

2.2.2 Fusion Welding of Aluminum and Steel (Electric Resistance Spot Welding)

Due to the different melting temperatures, thermal conductivities, expansion coefficients, and tendency to generate brittle intermetallic compounds, applying fusion welding methods to combine steel and aluminum is well-known to be challenging. This is due to the fact that ferrous solubility in aluminum is rather low (around 0.04wt%), at temperatures that are higher than 350^{o}C, so when Fe diffusion into aluminum becomes significant, aluminum-ferrous compounds start to precipitate. And this precipitation can be of a significant level even at lower temperatures than the melting point of aluminum (660^{o}C for pure aluminum). Hence the fusion welding approach for joining the two metals together is logical and is likewise not used in the industry.

For many years, electric spot welding has been employed in the automotive industry. Although the process is good in welding of steel and body sheet components, difficulties arise when the process is applied to low resistance metals, in our case aluminum. It is also a well-documented fact that spot resistance welding between dissimilar metals, like steel and aluminum is a reason for the creation of IMC's (Inter Metallic Compounds) due to alloying

between two metals which have different properties. These new created compounds are a problem for the industry as they are especially brittle and cause a decrease in mechanical strength of the component rather than fortifying it. Focusing on the welding process, for combining steel with aluminum, current conditions are restricted by electrical and thermal qualities, making it even more difficult to achieve a sound weld.

But in the recent years, the demand for joining dissimilar metals has skyrocketed, especially in auto-motive industry due to the fact that the industry is in a race to reduce the overall weight of the car, increase efficiency while still maintaining the mechanical strength of the body. Hence there is a demand to join aluminum sheets with steek sheets. Results of the peel tests of experimentation conducted on the dissimilar metals joined by spot welding revealed that the creation of the weld button was achieved effortlessly when peeling was performed between the sheets of steel and aluminum. [27].

To define peel tests in more detail, they measure the strength of the bond between a substrate and the material being peeled off (known as the adherend). This peel strength is expressed as the load required to separate the adherend from the substrate, per unit width of the bond.

Coming to the results of the above-mentioned experimental observations. The following figure 10 represents the microstructure of aluminum/steel weld.

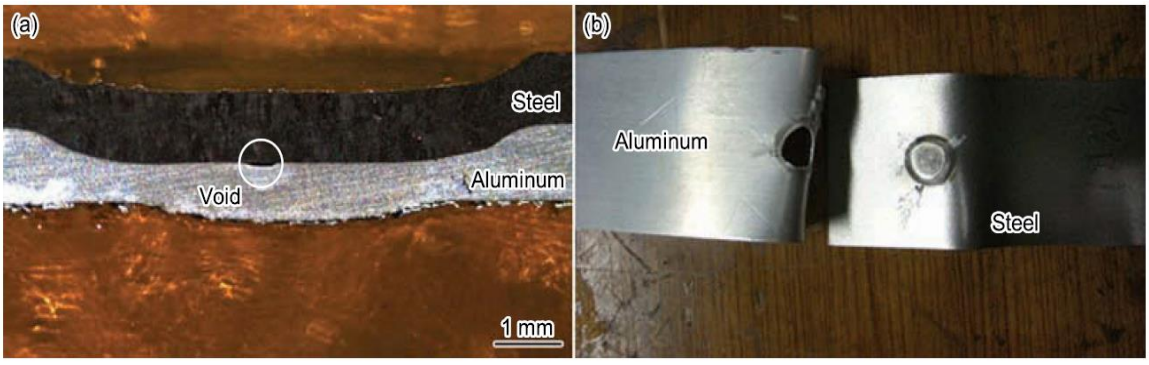


Figure 10: resistance spot welding specimen (a) formation of the IMC layers and voids (b)button fracture of aluminum [27]

As shown in figure 10, pores and gaps are apparent at the interface of joining of two metals. Shrinkage stresses are responsible for the existence of weld discontinuities at the aluminum/steel contact. The aluminum next to the aluminum/steel contact is the last to harden during the welding process. Voids can form as a result of shrinkage strains mixed with restraint from the neighbouring solid metal as shown in figure 10(a) which are more often

than not demonstrated as pores and solidification cracks. The following image shown in figure 11(a) taken from a scanning electron microscope clearly distinguishes the interface of aluminum and steel.

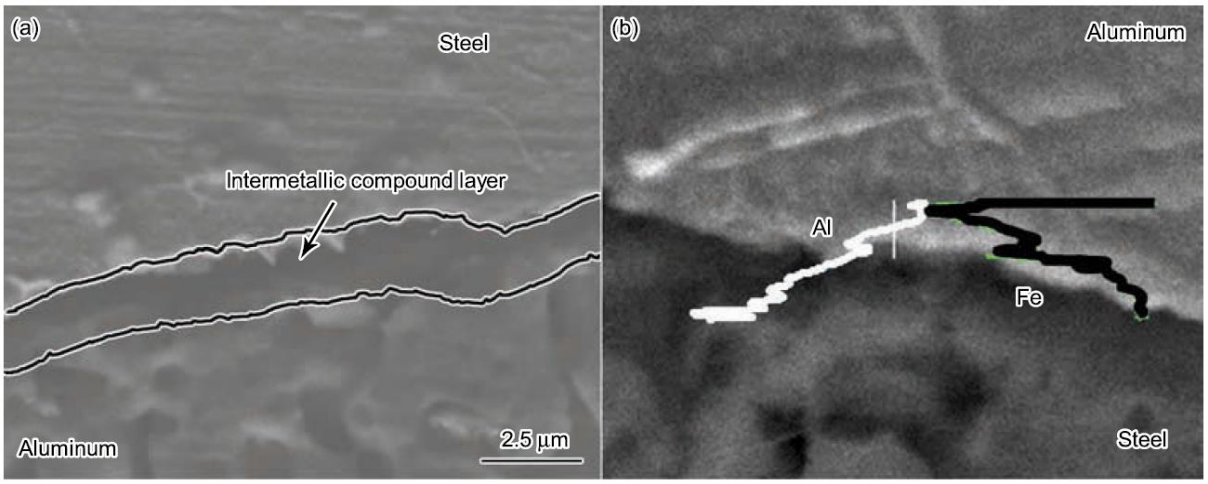


Figure 11:microstructures of spot welding (a) SEM images for IMC layers, (b) EDX analysis crossing the IMC layer [27]

During the process of resistance spot welding of aluminum and steel, aluminum melts quickly due to the high energy density of welding heat, but still the pool of molten metal will be restricted to a small size. As seen in figure 11(b), this generates an accelerated diffusion of iron atoms in the liquid like pool of aluminum atoms. Here at the interface, the Fe-rich IMCs could result in improved strength of the joint. With time, the thickness of the IMC layer increases post welding. But after conducting lap shear and peel tests, it was discovered that failure often occurred at the interface of the metals. It is important here to mention that during the tests, a tear failure during lap-shear tests always followed in the interface in the aluminum side. [27].

To conclude the experiment, resistance spot welding is one way of joining aluminum with steel but certainly not the best way. The improvement of bond strength depends on the longer diffusion time of Fe atoms into liquid aluminum. However, that is not always the case, as a recent study by Rathod et al. on joining low carbon steel with aluminum concluded that as the thickness of the IMC layer increased, the amount of AL- rich IMC was increasing the amount of Fe-rich IMC decreased, which caused a drastic decrease in the strength of the joint.

Therefore, more investigation is required to fully understand the increase in peak load with longer post weld time.

2.2.3 Resistance Spot Brazing using filler materials (Hybrid Joining)

As stated earlier in this study, traditional resistance spot welding is ineffective for connecting dissimilar metals due to metallurgical issues. As a result, the focus has shifted to hybrid joining techniques, which are a combination of brazing and spot welding mixed with high mechanical qualities to link aluminum to steel. The topic is still under constant investigation in the industry to obtain optimal results. Here are some key points that were observed in an experiment[27]. Firstly, the experimentation was conducted using different filler materials for the brazing technique.

In the first attempt, a plastic like paste material was developed to be used as a filler material. The paste was made by grounding the aluminum alloy (Al-12Si) to micro sizes bits and then mixed with a flux, which then was ready and regarded as the filler paste material. The second approach did not involve a complicated procedure of fine grinding the aluminum alloy and mixing with flux, rather a thin sheet of aluminum (Al-12Si) was used with a measured thickness of 0.7mm. This filler material was then placed between the two metals to be welded that are aluminum and steel as shown in the figure.

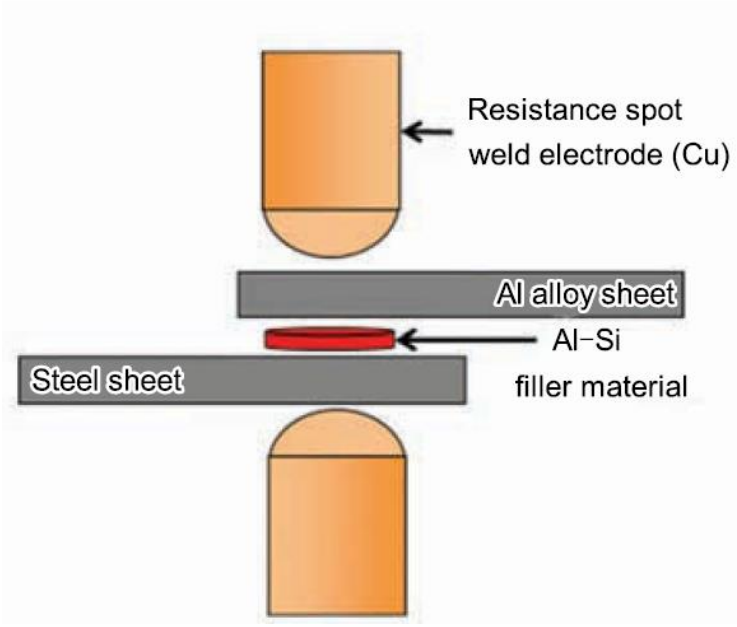


Figure 12:schematic drawing of specimen using filler metal for resistance spot brazing[27]

Before the starting of the procedure, the sheet type filler metal was treated with the flux material.

Briefly discussing the experiment conducted by using the filler paste metal, prior to using the paste, welding of Al/Al and steel/steel was carried out with and without the paste. This was done in order to compare the peak load for joining the metals in two different conditions. The results revealed that there are no advantages of using the paste type filling for resistance spot welding. The mechanical properties did not enhance, and the joint had point contact between the two metals. So, we can deduct from the experiment that filler metal for resistance spot brazing is not beneficial. [27]

Hence, the focus has now been shifted to the sheet metal filler for resistance spot welding. The experiment conducted helps us in concluding that the bong strength obtained is not substantial for joining the two metals. However, the usage of sheet metal as a filler provides us with a rather interesting result. The experiment revealed that the sheet metals interacts with both the metals to be joined and caused in a identical coating at the joint surface. The following figure shows the results obtained. It reveals a microstructure of the interfacial layer which is formed between the filler sheet metal and the steel sheet [27].

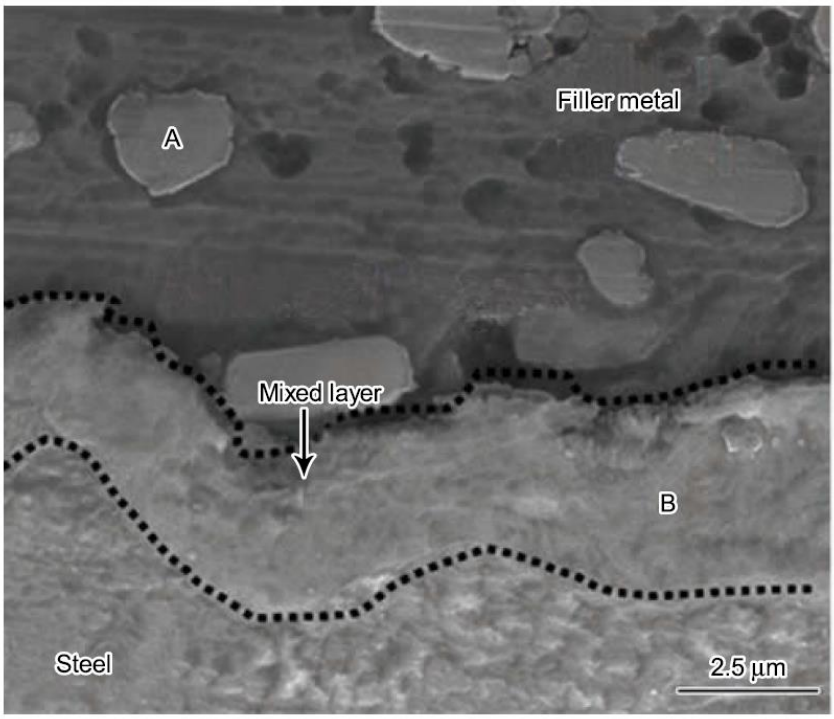


Figure 13: Microstructure of interfacial layer between the filler metal layer and steel sheet for resistance spot brazed [27]

The figure clearly depicts a uniform mixed layer marked as B forming on the interface of the steel sheet and the filler metal. Because filler metal sheet can attain the greatest temperature due to high contact resistance during the early stages of joining, filler metal should become liquid first. The EDX analysis (Energy Dispersive X-Ray) reveals that the layer is a mixture of 20wt% Aluminum and 80wt% ferrous. Because most breakage occurs at the Al/filler metal interface, it is assumed that this mixed layer has a high binding strength, which might be attributable to Fe-rich IMC. The particle (mark A) found in the filler metal layer has 36wt % Silicon and 2wt% ferrous, with the rest being Aluminum. This finding implies that owing to silicon segregation during filler metal solidification from a liquid condition, spherical type Si-rich particles can develop [27].

The contact between filler metal and steel has a homogeneous layer, whereas the interface between filler metal and aluminum sheet does not. It can be seen in the following figure that no distinguishing layer was found on the interface between aluminum and filler material.

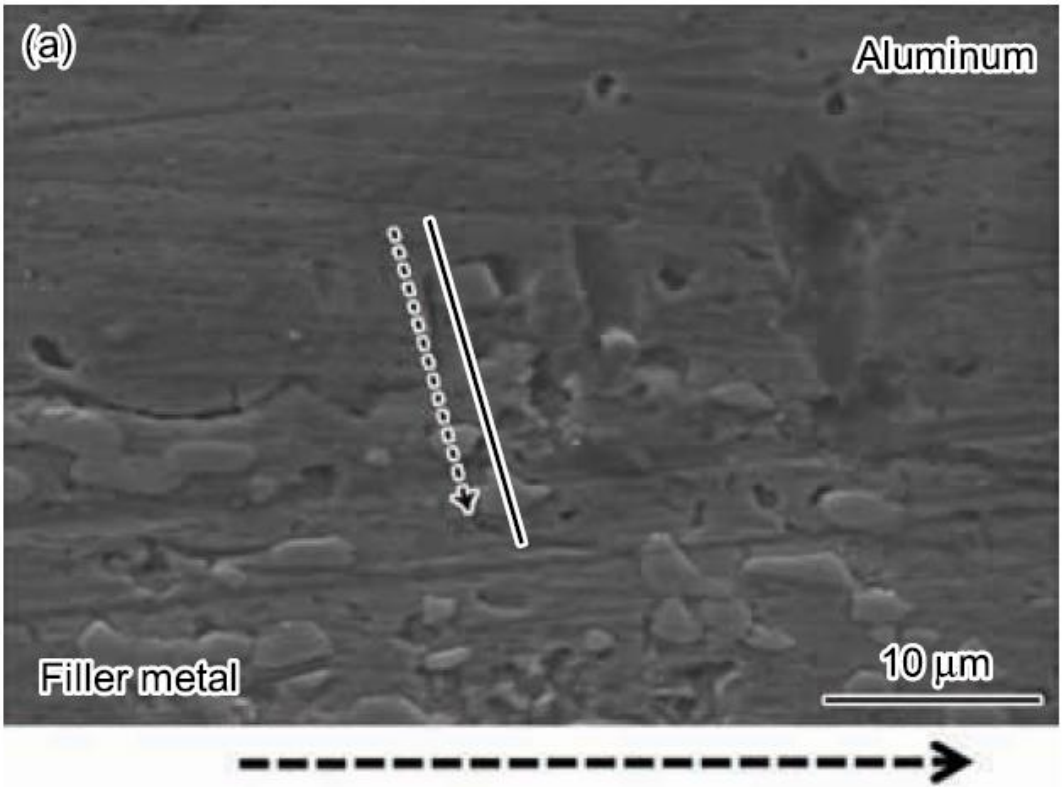


Figure 14:Line scanning of EDX analysis of interfacial layer [27]

The EDX analysis revealed that the silicon rich particles are able to penetrate into the aluminum side, hence there is zero interaction of layers on the said side of the joint. This is a consistent observation with the failure of the joint with aluminum side having a weak bond strength [27].

We can reach the following conclusion after conducting the above two experiments:

1) The bond formed between aluminum and steel using filler metal is electric resistance spot brazing is rather weak and does not provide with any mechanical advantages.
2) However, the consistent blended layer formed on the interface between the sheet type filler metal (Al-12Si) and the steel sheet is expected to increase the bond strength while using the filler paste in tandem for resistance spot brazing.

2.2.4 Laser Welding-Brazing

Another approach can be the use of lasers to create a brazed type of joint between the two metals, which is more logical rather than fusion welding. The laser application is a reasonable step, as the high intensity of heat is generated in a smaller area and provides a stable environment for brazing that can be locally generated, and a joint can be created with minimum time for diffusion to drive intermetallic compound formation [28]. The Fe-Al phase diagram depicts a variety of hard intermetallic phases that may be generated, including Fe3Al (892HV), FeAl (470HV), FeAl2 (1060HV), Fe2Al5 (1013HV), and FeAl3 (1013HV) (892HV). Extremely high hardness, near-zero ductility, and low fracture toughness characterize these phases. As a result, if a thermally generated junction between steel and aluminum must contain any or all of these phases, the intermetallic compound layer thickness should be as thin as feasible if the joint is to have high mechanical performance. When arc welding steel with aluminum, certain procedures must be followed in order to avoid the creation of intermetallic compounds. The first is to cover the steel with an aluminum layer. This is accomplished by immersing the steel in molten aluminum (hot dip aluminising). The aluminum can be arc welded to the coating after it has been coated. The coated aluminum must not be heated to an excessive temperature by the arc; otherwise, intermetallic compounds may occur[28].

When fusion welding is to be carried out between the two metals, bimetallic transition inserts are another way to decrease intermetallic development. Rolling, explosion welding, friction welding, flash welding, or hot pressure welding are used to join the inserts, which are made up of one part aluminum and one part steel.

When combining these materials, the major goal is to keep the welding temperature as low as possible while limiting the amount of time the weld is exposed to elevated temperatures. This is why bimetallic transition inserts between aluminum alloys and steel bulk components are made using procedures like friction welding (especially rotary friction welding).

The application of heat and the inclusion of a filler metal are used in the brazing process to unite two pieces of metal. This filler metal is either pre-placed or injected into the joint when the pieces are heated, as it has a lower melting temperature than the metals to be connected. Capillary action allows the filler to flow into the joint in brazing pieces with narrow clearances. The molten filler used for brazing has a temperature of above 800° F (430° C). Soldering, a similar technique, keeps the filler metal below that temperature. Soldered joints are weaker than brazed ones [29].

The automobile industry is becoming increasingly interested in combining dissimilar materials because to the superior mechanical qualities and high corrosion resistance of stainless steel in conjunction with the low specific weight and excellent corrosion resistance of aluminum alloys. As mentioned previously, joining these two metallic compounds is a problem due to the differences in their melting points. Brittle Fe-Al compounds are formed which influence the joining strength of the joint. Hence another method to join these two metals is essential specially in the automotive industry as to reduce the overall weight of the assembly while not compromising on the overall strength. This is where brazing becomes exponentially effective. In compared to welding, brazing allows for the production of several high-quality joins with complicated geometry in one stage at lower temperatures [30]. Good mechanical qualities can be achieved by employing a short brazing duration and a local heat input. Induction brazing, in particular, meets these requirements. Filler application on stainless steel, such as paste or filler cladding, is a significant factor in mass manufacturing of components.

Experimental Study

In an experimental study[30], aluminum alloy and austenitic stainless steel were joined using the brazing process. Following figure provides with the different joining setups.

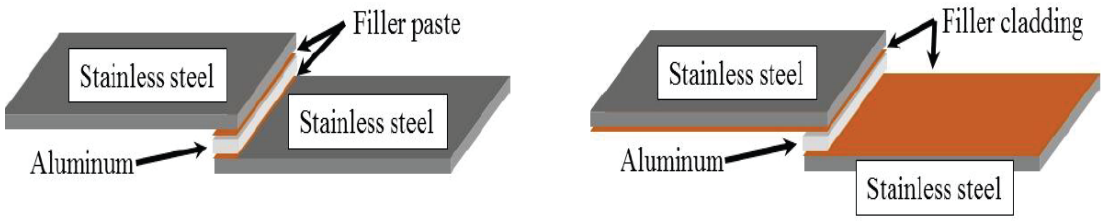


Figure 15: different setups for brazing joints[30]

The filler used for brazing was the AlSi10 (AA 4045) filler was applied in the joining in two different ways: such that as a conventional paste or as the filler cladding on the stainless steel. Both of these configurations are shown in figure 15. The thickness and the layer structure of the filler paste were specially taken care for.

The shear tests performed under tensile loading of the brazed samples are presented in the following figure.

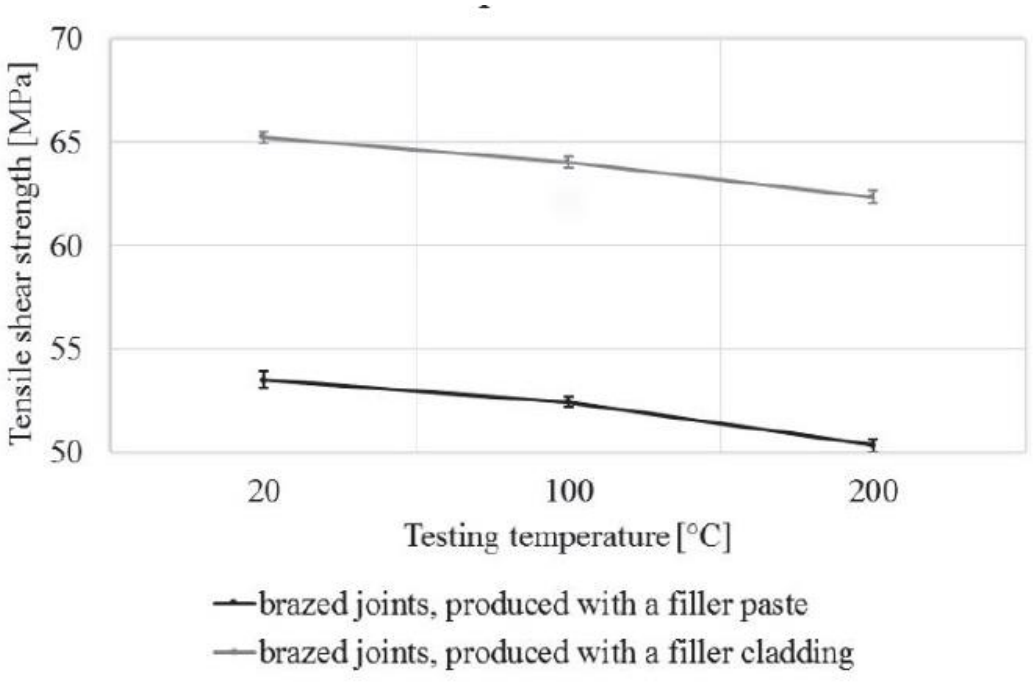


Figure 16: tensile test results of the sample[30]

The brazed joints generated with a filler paste have a tensile shear strength of 53 Mpa and the brazed joints created with a filler cladding have a tensile shear strength of 65 Mpa at ambient temperature. The findings (21 Mpa) of Roulin, who brazed aluminum/stainless steel joints in a furnace at 600°C with a holding duration of 10 minutes, are much higher [30].

With brazing, the requisite joint quality may be obtained with relatively modest external impacts on the materials joined: a temperature below the aluminum alloy's solidus temperature and a negligible compressive force for creating a capillary gap between workpieces. When steel is wetted and a liquid filler metal is used to fill the capillary gap, a reactive intermetallic layer forms, which has a significant impact on the brazed joint's characteristics. Many variables influence the chemical composition and thickness of this brittle transition layer, including the brazing consumables' composition (filer metals and reactive fluxes), the brazed joint's temperature–time parameters, and so on. Great-temperature brazing using Al–Si system filler metals, which have high strength and corrosion resistance, may be used to create various sorts of joints between aluminum and stainless or galvanized steel.

The results obtained while using zinc coated steel and a zinc-based filler are even better than the joining of aluminum and steel using laser welding-brazing. The discussion regarding the zinc-coated steels will start in the next chapter of the literature review followed by a comparison table which will depict the advantages and disadvantages of zinc-based alloys in brazing technologies.

2.2.5 Friction Welding for joining aluminum and steel

Automobile businesses have been under intense pressure since the dawn of the twenty-first century to meet environmental standards as well as user-driven demanding criteria such as low cost, safety, exhaust emissions, fuel economy, drivability, comfort, and more interior space. Reduced fuel usage is one option for addressing some of these difficulties, and it is therefore critical for all automotive manufacturers to make progress in this regard. To lower fuel usage, several techniques such as engine modifications and hybrid systems are being researched. The major emphasis area, however, is vehicle weight reduction, which is

considered one of the most efficient ways to reduce fuel consumption by substituting steel with aluminum. To state some figures, at present, the aluminum weight per vehicle is around 180 kg/vehicle with the aim of increasing the total weight to 250 kg/vehicle by 2025 [31].

This section describes the analysis of friction stir welding technique for joining aluminum to steel. To further explain the process of friction, stir welding, figure 17 illustrates the usage of a rolling pin to friction weld the two metals together.

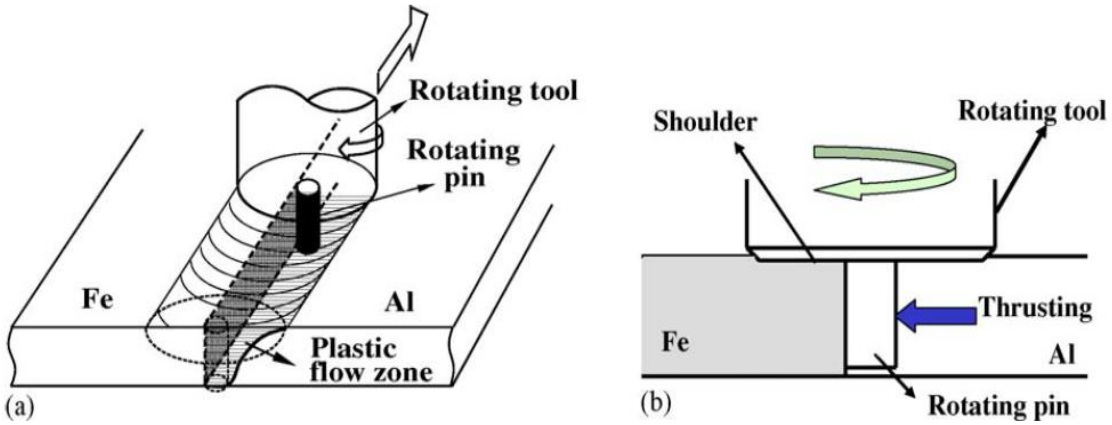


Figure 17:Rotating pin position: (a) birds eye view, (b) cross-section view perpendicular to the weld surface [32]

Initially a rotating pin is pushed into the aluminum metal with the help of a rotating tool. Then the pin is pushed towards the interface of the two metals to interact with steel. Here, the oxide layer formed is automatically removed by the motion of the rotating pin rubbing motion. Due to the friction developed by the rotating tool, the aluminum metal transforms into a fluid-like plastic state, and its starts holding on to the activated faying surface to the steel metal. Hence the joining of the two metals is achieved. An important point of the process is that since the pion is plunged into the softer metal of the two, that is aluminum, is suffers less wear.

Friction Stir Welding (FSW) is usually done by stirring the weld line of butted base plates with a revolving pin placed around the centre of the weld line. But in this approach, welding is not achieved as the rotating pin gets worn out in a short duration due to constant interaction with steel and causes insufficient stirring between the two metals [32].

Experimental Study

The experimental study for the process talks about the friction stir welding process for the joining of the two metals [32]. The results provide a clear picture about the usage of friction stir welding and whether it is feasible to be used for the joining of the two metals. The experiment was conducted using a pin with a rotation speed which was variable and an offset of 0.2mm. The speed and location affects the weld properties significantly. For example, when the rotation speed of the pin was 100rpm, the pin worn out quickly, due to low heat generation which resulted in greater wear. On the contrary, a pin rotation speed of 250rpm at the same offset, resulted in a good joint which had a maximum tensile strength of around 86% of the Al base metal.

In comparison, at the rotation speed of 500 to 800rpm, the weld surface structure was similar top on obtained at 250rpm, however, the speed caused some defects to occur in the Al matrix which reduced the tensile strength of the specimen. At an even faster rpm, of 1250, burning of the specimen occurred during the welding process due to Magnesium in Aluminum matrix and the resulting tensile strength was negligible as the weld was not completed. The following figure 18 shows a graph that depicts the tensile strength obtained at various rotational speeds of the rotating pin.

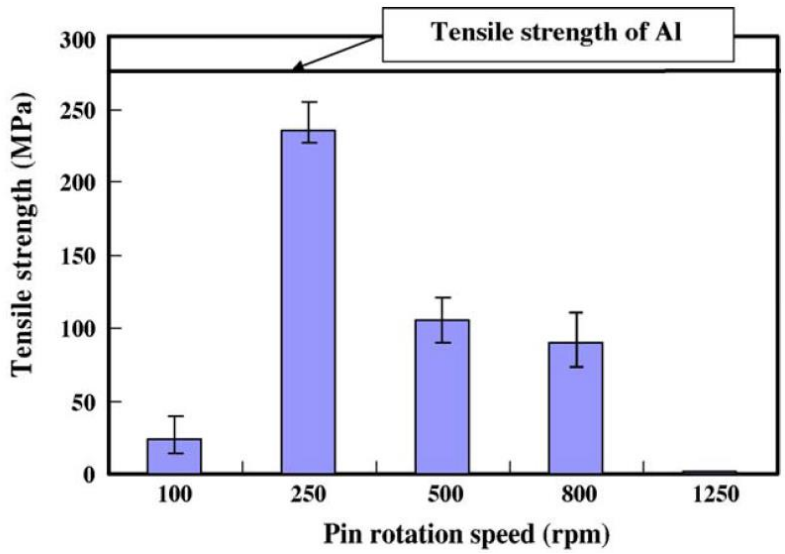


Figure 18: relation between pin rotation speed and tensile strength of the joint [32]

Further deductions were deduced after conducting the experiment. Some of them included the following:

1) The position of the rotating pin is a crucial factor that plays a vital role in determining the strength of the joint. The pin is plunged into aluminum which is softer of the two metals and then an offset is provided for optimal results. Figure 19 shows the offset of the rotating tool.

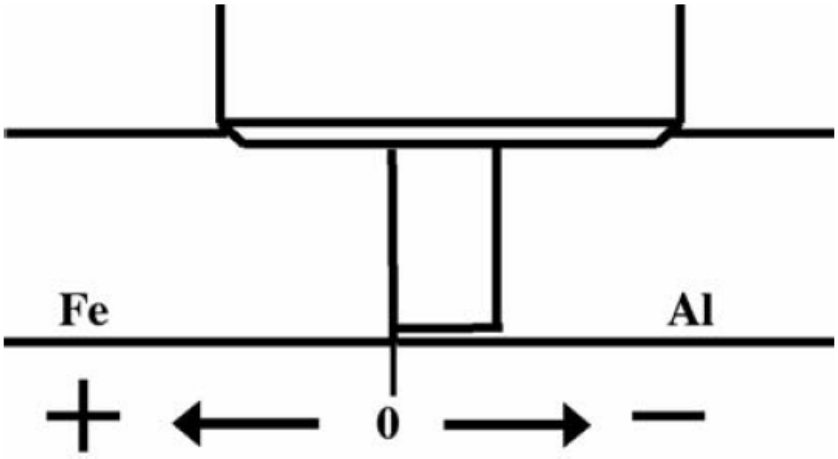


Figure 19: Offset of the Rotating tool

At different offsets, which may vary from specimen to specimen, the tensile strength of the joint changes. In the experiment, at a larger offset, steel pieces started to scatter into the Al matrix which resulted in the decrease of the tensile strength. The pieces were reported to become larger as the offset was increasing.

2) At the contact between the steel and aluminum alloy, no intermetallic compounds developed. However, a little amount of intermetallic compound was found towards the weld's top, where the temperature was highest due to the heat generated by the spinning tool shoulder. As a result, these intermetallic compounds, which develop at the Fe/Al interface's upper region, reduce joint strength.
3) The removal of the oxide coating from the steel faying surface by rubbing with a revolving pin was demonstrated, and the removed oxide was transported away with steel fragments into the aluminum matrix. Furthermore, welding aluminum alloy to steel with a counter clockwise rotation of a pin is difficult. The last fact can be explained by understanding the motion of the pin and the activated faying surface of the steel metal. The diagrams in figure 20 can help us understand the reason.

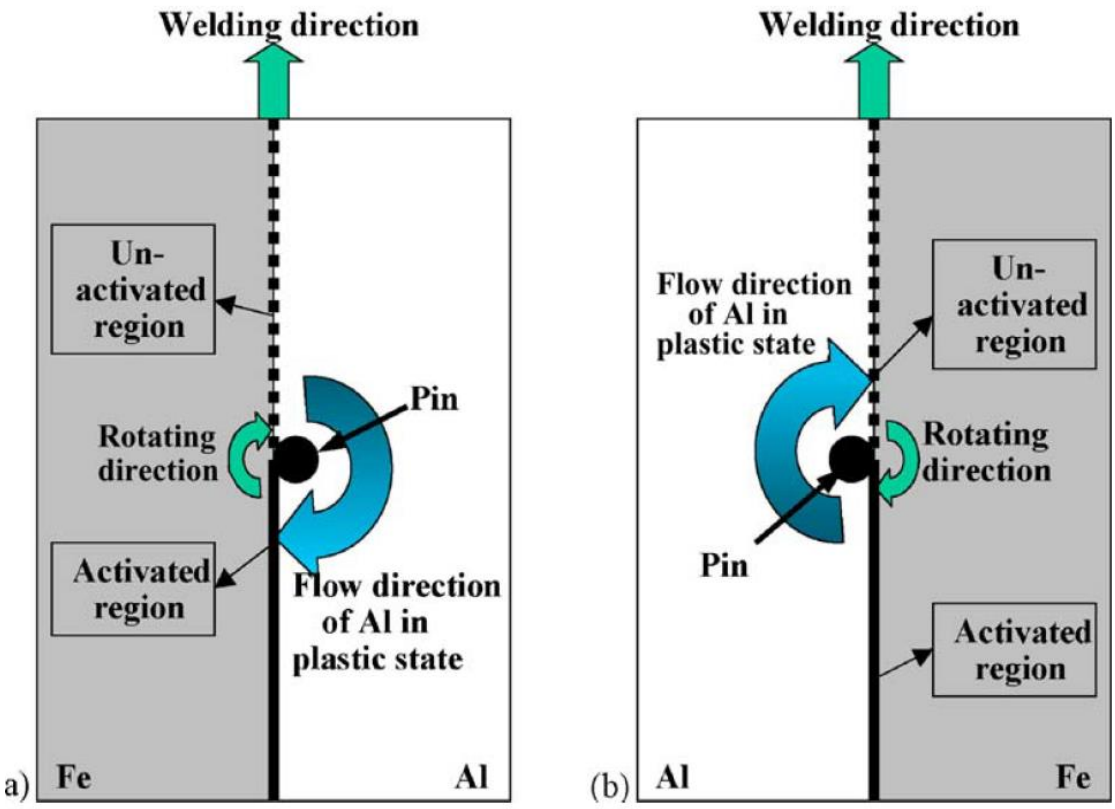


Figure 20: schematic representation of the rotating direction of the pin and activated surface of steel [32]

The illustration depicts a situation in which the clockwise rotating pin is welding the Fe plate on the left side and the Al plate on the right side, both of which are facing the welding direction and the part b depicts the case where the pin is rotating counter clockwise. When the pin turns clockwise, the spinning Al in a fluid-like plastic condition is forced against the Fe faying surface (shown by a bold line) that has already been activated by the revolving pin's rubbing action and attaches to the Fe, resulting in welding both plates. When the welding direction is reversed, as illustrated in (b), the spinning Al in a plastic flow condition is forced against the Fe faying surface (shown by a bold dotted line) that has not been triggered by the revolving pin, resulting in no welding [32].

In the end of this chapter, we construct a table (Table 1) that compares the three technologies that are discussed for joining process of aluminum and steel. The table contains the advantages and disadvantages primarily of using the discussed methods among others in whether to use the joining process for a specific kind of task.

Technique	Materials	Brazing Condition	Advantages	Disadvantages
Resistance Spot Welding	Al-alloy, Steel, Al-12Si (filler)	Resistance Spot welding, overlapped joint	Increased bond strength when paste filler material is employed	Formation of IMC's that can cause cracking
Laser Welding-Brazing	aluminum alloy austenitic stainless	Laser welding, controlled heating of the assembly, overlapped joint	More control over welding, increased strength	
Friction Welding	Al- steel	Rotating pin friction welding, butt joint	Increased high strength, less formation of IMC's	Requires equipment accuracy, can only weld in one direction

Table 1: Comparison of the Joining Techniques

2.3 Brazing with Zinc based Alloys

The previous chapter provides an overview of the welding technologies for aluminum and steel. It discusses some of the methods adapted by the industry for the joining of these two metals. The chapter also talks about the usage of brazing in those specific technologies which improves the quality of the joint in some of the methods.

Currently, in this chapter, we will discuss the effect of Zinc based alloys in brazing technology. The effect will be discussed in detail for a few technologies of joining that permit the usage of zinc and the advantage it offers over its counterpart processes which do not make the use of zinc-based alloys.

2.3.1 An Introduction

Zinc is added in some brazing filler metals in order to help lower the melting point temperature of the particular filler metals. Zinc is an amazingly effective “temperature depressant,” such that it can effectively lower the melting temperature of usually silver based filler metals to which they are added and also help them to become “wet.” Wetting means to be able to diffuse into spread over and out) on the clean base-metal surface that are being brazed. Zinc in its nature is very volatile and can outgas the filler metals that it is being added to. Let us discuss some of the types of brazing and the advantages of zinc while brazing.

2.3.2 Laser Brazing and Welding

As mentioned previously, Aluminum and steel when joined together, produce brittle inter-metallic compounds which weaken the strength of the joint. Hence, the industry is looking for alternative methods that can be used for joining of the two metals as it is a key parameter to lose the weight of the assembly while still maintaining the strength. For this purpose, diverse types of welding procedures are being investigated to form durable joints [33] In the literature it is well established that a relatively long wetting length is important to achieve a joint with good mechanical properties for dissimilar metals.

The zinc layer of zinc-coated steel is recognized to have a key role in the spread of liquid aluminum on the coated surface. In many circumstances, these zinc-coatings allow for flux less joining of aluminum and steel during industrial brazing and welding procedures. To study the role of zinc in detail, the following experiment was conducted by researchers in Germany.

Experimental Study

A solid-state laser was used to perform both bead-on-plate laser beam brazing and overlap laser welding operations. The following figures depict the joining nomenclature of the brazed joint.

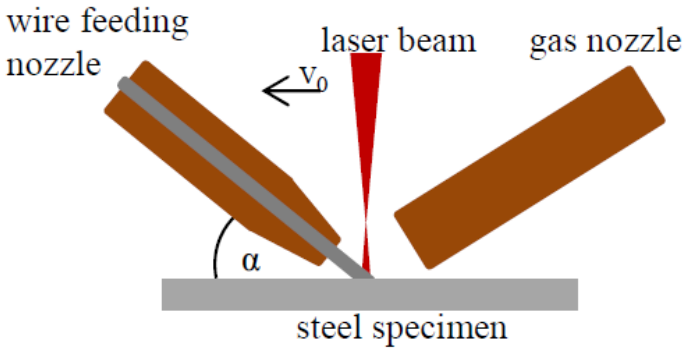


Figure 21:Setup for bead-on-plate laser brazing [33]

Base Material	Coating Specification	Type	Specimen Thickness [mm]	Measured coating thickness [µm]	Avg, coating thickness [µm]
DC04	+ZE50/50	Electrogalvanized	0.7	5.0-7.0	6.0
DC04	+ZE75/75	Electrogalvanized	0.8	4.0-9.0	6.5
DX56	+Z100	Hot dip Galvanized	0.8	6.0-8.0	7.0
DX56	+Z140	Hot dip Galvanized	0.81	10.0-11.0	10.5

Table 2: List of zinc-coated low-carbon steel sheets used for the brazing and welding experiments.

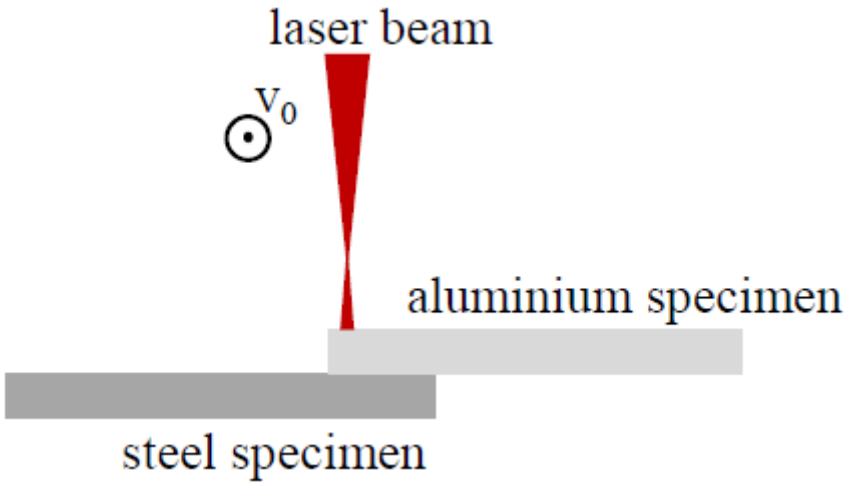


Figure 22: setup for laser beam overlap welding [33]

For all connecting geometries, four different types of commercial galvanized zinc-coatings of low-carbon steel sheets were studied, including electrogalvanized and hot-dip galvanized coatings, with a length of 140 mm, a width of 30 mm, and almost the same thickness. The following table shows the thickness of the specimen along with the thickness of the measured-zinc coating thickness.

Both the experiments used aluminum wires as filler metals but of different compositions. Argon was used to cover the process in both the processes to make the environment inert around the experiment.

The brazing procedure was done on a partly zinc-coated steel sheet to highlight the general difference in wetting behaviour on a zinc-coated surface vs an uncoated steel surface. As illustrated in Fig. 23, the brazing process began on the coated section and progressed to the uncoated area of the steel surface.

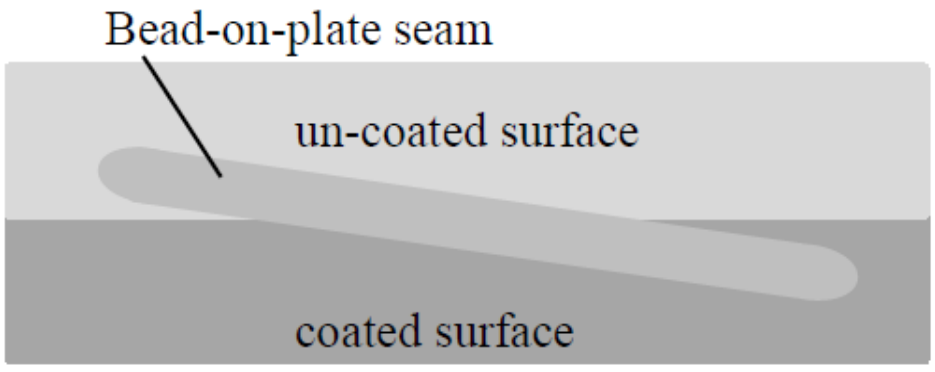


Figure 23:partially coated specimen[33]

The braze seam may be separated into three regions, each with its own set of wetting characteristics: a fully zinc-coated zone, an uncoated zone, and a transition zone in the centre [33].

To conclude the experiments, bead-on-plate brazing tests on a partly zinc-coated steel surface proved the capacity of a thin zinc coating on top of a steel surface to facilitate the wetting of aluminum without the need of flux. When the aluminum melt propagates from a zinc-coated to an un-coated steel surface, the overall wetting capacity changes dramatically. When the aluminum melt reaches the de-coated steel side of the surface at the start of the transition zone, it immediately stops spreading. The fact that the wetting duration and angle are dependent on the coating thickness is an intriguing finding that only emerges in bead-on-plate brazing. In both circumstances, heat is removed from the liquid aluminum mostly by heat conduction through the coated steel surface. As a result, our findings show that the zinc coating plays a role in the total energy exchange. A potential explanation for the relatively thin zinc layers' influence on heat transmission during bead-on-plate brazing might be a large transfer of latent heat to melt and evaporate the zinc coating.

Because the evaporated zinc is irreversibly removed from the aluminum-steel interface, the quantity of latent heat of evaporation might grow up to the point where it could have a detectable influence on total energy dissipation and hence the wetting length and angle. Thicker coatings may consequently result in larger volumes of evaporating zinc, resulting in faster heat removal from the aluminum melt. As a result, the solidification temperature is attained sooner, halting the spreading process.

However, in the case of overlap welding, when no such reliance is found, the influence of coating thickness on the resultant wetting length and angle appears to be minor. This might be explained by a shift in the heat transmission conditions in general. The increased heat sink provided by the aluminum layer is projected to make a significant contribution to total heat dissipation.

Although a higher laser power is utilized in overlap welding, it is possible that less heat is delivered to the zinc-layer melting or evaporation, and therefore the zinc layer's influence on overall heat exchange becomes less essential. The first removal of the oxide layer from the aluminum surface is a necessary prerequisite for a successful wetting between steel and

aluminum. The oxide layer can be ruptured in the absence of flux owing to thermal expansion of the melt or mechanical forces.

The steep feeding angle of the wire helps appropriate breaking of the first oxide layer in bead-on-plate brazing tests because it induces a greater distortion of the molten aluminum when it meets the steel surface. It is hypothesized that following the first cracking of the oxide layer, the aluminum is intermixed with the liquid zinc, blocking further oxidation of the aluminum at the steel interface, due to the low melting temperature of the zinc.

According to this theory, the lack of wetting seen during overlap welding might be caused by an oxide layer that is not entirely broken throughout the whole liquid aluminum

surface during the operation. As a result, the oxide layer may only be broken along the initial laser beam axis, where the greatest temperatures and hence thermal expansion occur. This means that, in addition to the good effects of zinc-coatings, adequate preparations for total breakage of oxide layers must be made in order to obtain complete wetting on the coated surface.

2.3.3 CMT Brazed Lap joints between aluminum and zinc coated steel

Cold Metal Transfer welding is a modified MIG welding technology created by Fronius in Austria and based on a short-circuiting transfer procedure[34]. The sole difference between this technique and MIG/MAG welding is the sort of mechanical droplet cutting technology used, which has never been seen before. By combining a unique wire feed system with high-speed digital control, Cold Metal Transfer delivers a regulated way of material deposition with minimum heat input. The wire feed rate and arcing phase of the cycle are both managed to ensure that enough energy is generated to melt both the base material and a globule of filler wire.

The CMT process has two key characteristics: one is the formation of a short circuit with low current matching to low heat input, and the other is the occurrence of a short circuit in a steady regulated way. When the electrode wire tip makes contact with the molten pool in the

CMT process, computerized process control reverses the servomotor of the 'robacter drive' welding torch. This causes the wire to retract, allowing for droplet transfer. The current reduces to near-zero during metal transfer, preventing the formation of spatter. The arc is re-ignited, and the wire is fed forward with predetermined welding current reflowing once the metal transfer is complete.

Experimental Study

The aluminum alloy sheet (AA6061) with a thickness of 2 mm and low carbon steel with thicknesses of 0.7 mm and 1.2 mm were used in studies to assess joint strength and examine failure mechanisms [34]. To evaluate the shear strength and failure mechanisms, the testing pieces were cut off from the brazed joints after brazing, as illustrated in figure.

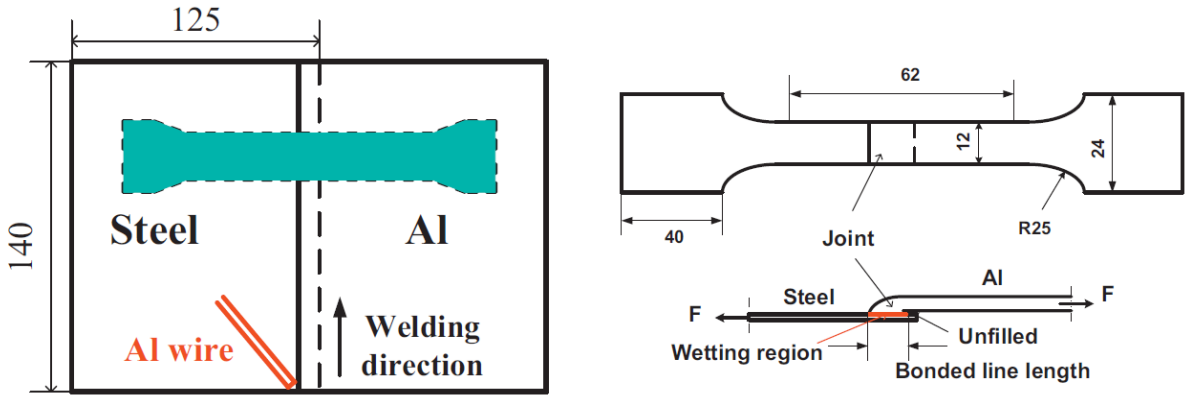


Figure 24: Shape and dimension of sample for lap-shear test [34]

The overlap between the aluminum and steel sheets was fixed at 8 mm or 15 mm. The overlap length had little effect on the bonded line length, which was around 6 mm. By varying the thickness of the steel sheet and the space between the aluminum and steel sheets, several CMT lap joints were constructed for the observation of failure mechanisms. The following table displays the experimental findings under shear stress. In both cases, CMT brazed lap joints failed. Interface failure was one, while fusion line failure was another. The contact layer between aluminum and zinc-coated steel failed, causing the collapse [34].

Case	Steel Strength grade	Thickness (mm)	Shear Strength
1	Low Carbon steel (270 Mpa)	0.7	2.1
2	Aluminum	1.2	≥ 2.5

Table 3: experimental finding under shear stress for failure

The following figures depict the failure modes for the two interfaces.

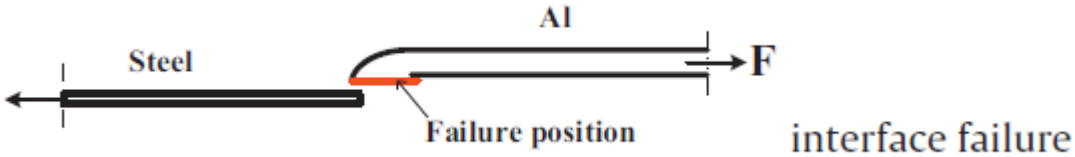


Figure 25: Depiction of failure mode[34]

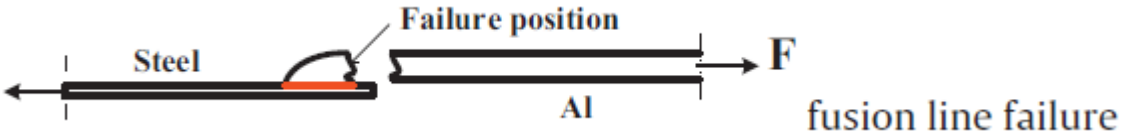


Figure 26: Depiction of Failure Mode[34]

In the cross section of the joint after brazing, there were several micro flaws such as porosity and an unfused root as shown in the figure 27.

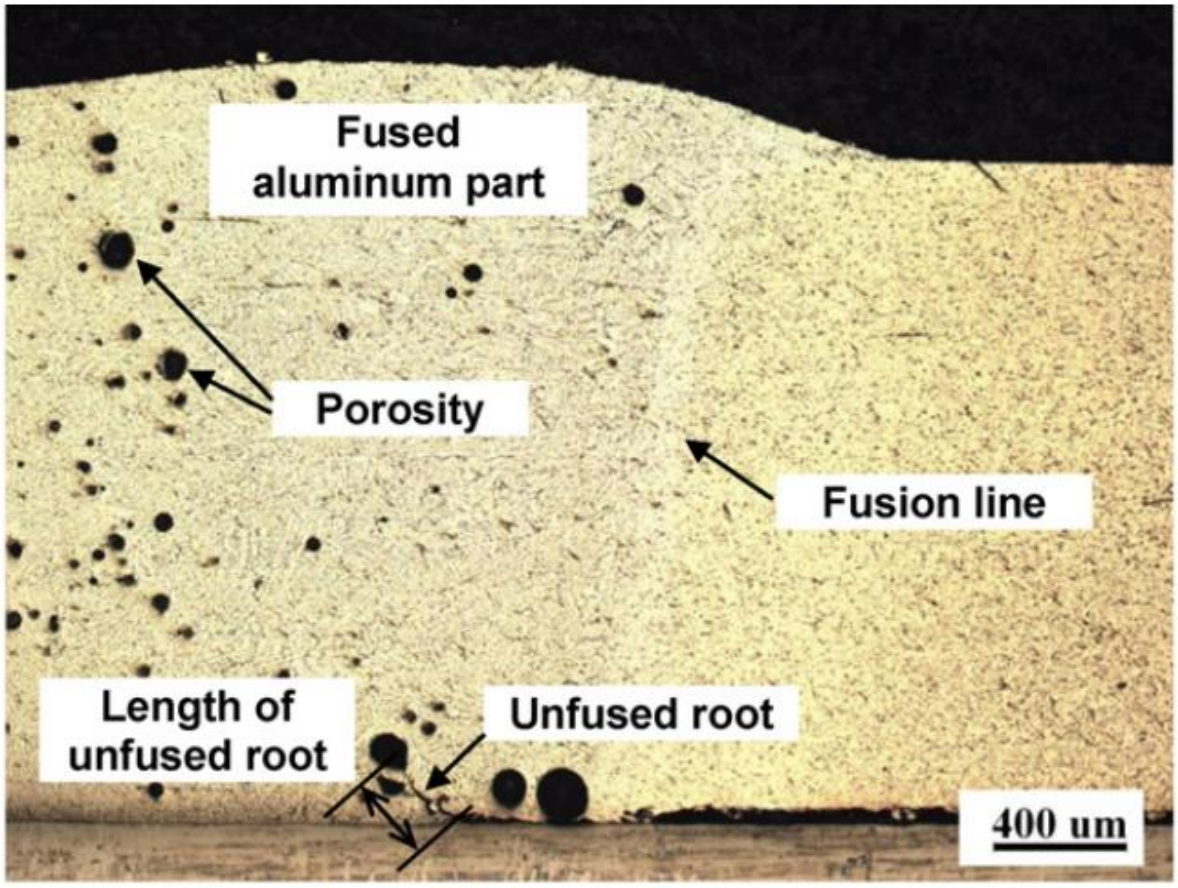


Figure 27: micro defects in cross-section [34]

The production of the porosity and unfused root will need to be researched more in the future, as it may be related to molten metal flow in the space between steel and aluminum sheets. Because micro flaws in CMT joints are particularly difficult to eliminate in CMT brazing, they can be acceptable for products if the strength of CMT joints is higher than standard spot welds or meets the deigned strength. The following points help us conclude the experiment performed for the shear strength analysis of the joint between aluminum and zinc coated steel.

1. CMT brazed lap joints of aluminum alloy and zinc coated steels with high strength or thick plate show a higher shear strength and fusion line failure.
2. Only when aluminum was brazed with low strength (270 Mpa) and thin steel sheet did shear strength and interface failure occur (0.7 mm).
3. The maximal principle stress and deformation energy were recommended as interface failure criteria, while plastic strain was presented as a fusion line failure criterion.

4. Using specified criteria for different CMT brazed lap junctions of dissimilar materials under shear stress, the two failure modes and shear strength were very effectively replicated.

2.3.4 Role of Zinc as Filler Material

This chapter discusses the use of Zinc in filler materials used in brazing. Brazing industry has used zinc due its various advantages. The usage of zinc in the filler material helps in reduction of the melting point and improves the wetting of the ferrous surface. One of the most important aspects of using zinc is its compatibility with aluminum. However, that being said, where there are advantages of using zinc, one cannot just overlook the disadvantages at the same time. To point out a few, zinc is susceptible to corrosion, produces somewhat toxic fumes, at higher temperatures, it may boil and present voids of cracks in the joint.

The role of zinc along with other elements to be used as a filler material specially in the automotive industry to join the dissimilar metals of aluminum and steel is under detailed investigation. This is vital as every 1% reduction in the weight of the vehicle reduces the fuel consumption by 0.75% [35]. The replacement of steel, which is quote heavy, with aluminum promises a solution which can be viable for the industry. The hybrid structure which the Al/steel structure provides reduces the total weight of the assembly which reduces emissions of polluting gases.

Hence the investigation that is being conducted in the industry tests several different filler materials for the welding-brazing of the two metals. For this purpose, laser welding has attracted special attention due to the high joining efficiency. The technology provides accurate melting locations for the weld, less deformation and a thin inter metallic compound thickness. But in the case of laser welding-brazing, the filler material that is used for the brazing process holds special importance as it greatly influences the formation of the interfacial IMC.

Up to date, the Zn-based eutectic (Zn-Al2-Zn-Al4, Zn-Al15 and Zn-Al22) and aluminum-based eutectic (Al-Cu6, pure Al, Al-Si5. Al-Si10-Mg and Al-Si12) are selected as filler materials for the

joint. Research is continuously being conducted on the influence of the alloying elements (Si, Cu, and Zinc) on the interfacial reaction mechanism for the formed IMC [36].

To provide an example, for the element of silicon Si, Spring et al [37]. Held the view that the presence of silicon element at the joint interface of the Al/Fe, would actually reduce the reaction rate between the two joining elements, and help in reduction of the formed IMC. As for the Cu elements, it was found that the copper elements would replace some of the existing Fe elements which would help in reduction of the hardness of the IMC and hence the interface would be less prone to cracks.

But as for the investigation carried out for the element of zinc, the influential mechanism on interfacial reaction has been reported to be different by Dharmendra[37]. He, in his experiments discovered that Al element has a higher affinity towards Zn rather than Fe. This affinity was considered to be responsible for the presence of Zn elements in the IMC phases formed at the interface. Zn presence in the phases of the IMC specially this dispersive distributive δ-$FeZn_{10}$ provided a low hardness and increased ductility. The same phase was then responsible for the increases crack resistance which would later lead to increased joint strength under tensile loading[36].

Apart from being used as filler material in alloyed forms for brazing, zinc element proves to be beneficial as a coated layer on the steel surface as well. The element provides galvanization of the steel surface and hence provides extra protection from rust. Apart from that, the zinc layer provides a better wettability for the welding process for the filler material to reach all end of the joint and increases the strength.

Following is some research on the topic that points out some experimental studies conducted while using zinc in the filler material. It advantages and disadvantages are discussed in the conclusion.

Effects of Zinc on laser welding of aluminum allow and galvanized steel

Zinc as mentioned above, can prove beneficial in the welding of dissimilar metals, especially aluminum and steel. It can be thought of as catalyst, that helps in making the joint by reducing

the melting temperature, improving the wetting characteristics of the surface of the metals. In a study conducted in China's Changchun University, revealed the advantages of using zinc in the filler material. The experiment conducted was to join aluminum alloy (AA6061) with galvanized high-strength steel (DP590) using laser welding technology. The filler material used were zinc and aluminum alloy in powdered form.

70–110 µm diameter pure Al powders, 1.5 mm thick A5052-H34 Al alloy sheets, and 0.8 mm thick ST07Z hot-dip galvanized steel sheets with a 10 µm thick Zn coating on both sides were used as the experimental materials. The aluminum alloy was overlapped to the galvanized steel, and the lap joint was set at a 60-degree angle to the laser beam and feed head. The following figure depicts the placement of aluminum and steel [38].

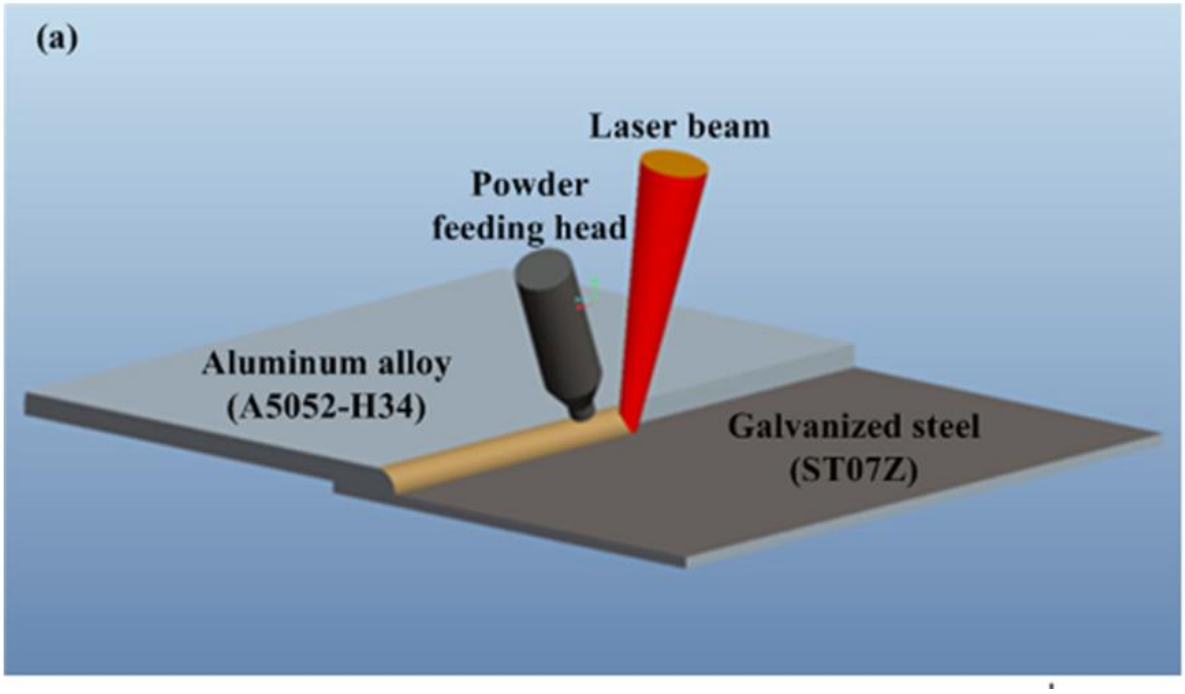


Figure 28: 3-D schematic view of the welding process [38]

The experiment conducted also involved the welding of non-galvanized steel in order to compare the results. Also, the experiment was conducted twice, once with filler material and once without it. Some conclusions reached in the experiment clearly exhibit the advantages of the use of zinc during the joining of dissimilar metals.

1. The results of laser welding an aluminum alloy to galvanized steel with and without a filler powder were compared, and it was discovered that filler powders might increase the energy utilization rate in the laser fusion-brazing process, lowering laser power needs. The following image depicts the advantages of using filler material.

Figure 29: Surface morphologies of the joints produced by laser welding without filler powder and without filler powder[38]

2. The zinc coated layer produced a good wetting effect by changing the types of materials that come into contact with the liquid aluminum, reducing the brazing temperature from near the melting point of Fe (1535.0 C) to that of Al (660.4 C), according to comparative results of laser welding with filler powder to join an aluminum alloy and a galvanized or non-galvanized steel.

The following table provides an overview of the advantages for using zinc for the brazing of dissimilar metals which in our case are aluminum and steel.

Technique	Materials	Brazing Condition	Advantages	Disadvantages
CMT Brazing	Al alloy (AA6061), low-carbon steel, (zinc coated)	Lapped Joints, Cold Metal Transfer	Increased shear strength was observed with less IMC formation	Multiple breaking criterions were observed.
Laser-Welding	Zinc, Aluminium, Galvanized Steel	Usage of filler material (zinc) on galvanised steel	Increased strength, less power usage for laser, increased Wetting effect, increased crack resistance	Intense surface cleaning, volatile and not to be used in vacuum. (ZINC)

Table 4: Comparison of Zinc as brazing filler for dissimilar metals

3 Experimental Work

The section for experimental work has been divided into two sections of materials and methodology. This is done due to the fact that material selection is an important procedure in our experimentation and has a direct influence on the result. It can also be a determining factor in the type of experiment that we are going to perform and can dictate the methodology of the experiment as well. Below, we first discuss the materials of the experimentation in this section and then will move on to the methodology part.

3.1 Materials

This section deals with the materials used in the experimentation analysis of the joining of aluminum to steel. Obviously, the main materials to be used can be categorised as the metals aluminum and steel that are to be joined together. The third material can be filler material that is used for the brazing of these two metals, which in our experiment was zinc and it alloys.

The aluminum metal used was in form of different alloys. For our first experiment, we used aluminum 6016. 6016 aluminum is a 6000-series aluminum alloy with substantial magnesium and silicon alloying, and it is designed for primary shaping into wrought products. The Aluminum Association (AA) has given this substance the name 6016. It is designated as EN AW-6016 under European standards. The UNS number is A96016. Furthermore, AlSi1,2Mg0,4 is the EN chemical designation. Among the 6000-series alloys in the database, it has the maximum ductility [39].

The composition of 6016 aluminium is unique among wrought aluminium alloys for being a relatively high percentage of silicon (Si). Silicon is used to improve strength while sacrificing ductility. It also decreases the melting temperature and improves the alloy's fluidity.

The aluminum alloy presents with a medium to good strength, while the corrosion resistance is quite good. The weldability and brazability of the alloy are categorised is good in the manuals and can also be machined well as compared to other aluminum alloys. The UTS (ultimate tensile strength of the material is listed around 310Mpa.

Coming to the applications of the Aluminum 6016, it is widely utilised in spacecraft components and aircraft fuselage frames, rotors, wall panels, landing gear pillars, and other key lightweight structural components due to its heat treatment and pre-stretching procedure.

It may be employed in a variety of car components and bodywork. The bending limit is a significant parameter for determining the hemming performance of 6016 aluminium sheet. In general, 6016 aluminium with an O temper is acceptable for bending applications.

Coming to the manufacturing process of the 6016 aluminium's, it will go through the natural ageing process, annealed 6016 aluminium undergoes age hardening, and the hardness value

has a propensity to considerably reduce and then increase. After applying "annealing treatment + natural ageing" to 6016 aluminium alloy sheets in industrial production, the best application time is two months later.

The Figure 30 represents some of the properties for the aluminum 6016.

Chemical Composition

Alloy	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Standard(wt%)
6016	1.0-1.5	0.50	0.20	0.20	0.25-0.6	0.10	0.20	0.15	EN/GB

Mechanical Properties

Alloy	Temper	Tensile strength Rm(Mpa)	Yield strength Rp0.2(Mpa)	Elongation at Break A80(%)	Uniform Elongation Ag(%)	Plastic Strain Ratio	Strain Hardening Exponent	Yield Tensile Ratio
6016	T4/T4P	205-240	85-130	⩾24	⩾20	⩾0.6	⩾0.26	≤0.55

Size

Alloy	Temper	Thickness	Width
6016	T4/T4P	0.5-1.5	1200-2650

Figure 30: Properties for Aluminum 6016

Other than the aluminum alloy discussed in the above section, other alloys were also tested during the testing phase of the experimentation. For example, aluminum Al5182 was also tested under similar conditions in an effort to braze join the two dissimilar metals of aluminum and low carbon steel.

Magnesium and manganese are minor components in the 5182-aluminium alloy. In the car industry, 5182 aluminium alloy is used to make numerous elements of automobiles. Aluminum 5000 series alloys are mostly utilised in sheet or plate form, but extrusions are also available. Aluminum alloy 5182 is a wrought alloy with excellent corrosion resistance. Aluminium 5182 alloy is regarded as having good weldability and corrosion resistance. The Table 3 records the chemical composition of the aluminum 5182 alloy.

Element	Content %
Aluminum (Al)	95.2
Magnesium (Mg)	4.5
Manganese, (Mn)	0.35

Table 5: Chemical Composition of Al5182

The table 4 lists the physical parameters of the aluminum 5182 alloy.

Properties	Metric	Imperial
Density	2.65 g/cm^3	0.0957 lb/in^3
Melting Point	577-638^{o}C	1070-1180^{o}F

Table 6: Physical Properties of Aluminum 5182 [40]

The above-mentioned properties of the aluminum alloy depict a picture of its chemical and physical properties which are a vital help in choosing the alloy for the brazing joining process.

The methodology and the results of the experiments will be discussed in the coming sections in detail. The sections will go over the type of experiment, the performing procedure, and the preparing methods of the metal samples for all the experiments.

Coming to the Interstitial free Zinc Coated Steel (C < 0.06) used for the experimentation. The vehicle's interior and exterior are both made of low-carbon steel. Clutch housings, suspension components, control arms, brackets, and other items are examples. Wheel rims, covers, screws, washers, bolts, nuts, fasteners, and other ornamental items may also be used. All of these are necessary for maintaining a vehicle's structure and stability.

The steel sample is the one which is also used in the automotive industry for car body manufacturing. Since the main purpose of this experimentation is the joining of the two dissimilar metals, it is rather necessary that we also discuss the low carbon steel properties. The automotive industry is trying to reduce the usage of low carbon steel for increasing performance and fuel efficiency of the automobile. Hence, it is vital and holds utmost importance that some material be developed that can replace the heavy low carbon steel while maintaining the same strength or somewhat similar to the existing value.

The brazing joining of the two metals provides us with a midway to increase the fuel efficiency of the vehicle by reducing the overall weight while still maintaining the integrity and overall strength to similar levels. The brazing material used for the experimentation was zinc and its alloys. Zinc provides quite some benefits during the experimentation as a filler material. Both pure Zinc and its alloy (ZAMA) was used in the experiments. The alloy used was ZAMA. The name originates from the main elements which are Zinc, Aluminum and Copper in various percentages. The advantages of Zama are both, in terms of quality and financially. The allow is responsible for improving the wetting properties of the joint. That means that the filler material is spread all over the joint and provides a better connection between the two metals.

In experiments conducted using aluminum 6016 with pure Zinc as filler and aluminum 5182 with Zama as filler material, both pure zinc and its alloy (ZAMA) as a filler material demonstrates good interface reactivity on cleaned surfaces [41]. Hence it is used for joining of the two dissimilar metals. It can also be noted that different preparation techniques are required for the usage of different aluminum alloys and also the brazing material. Hence in the end, we are left with various combinations that are tested in order to find out the best one.

3.2 Methodology

The methodology section of the experimentation reviews in detail the procedure that is undertaken in order to perform the experiment. The procedure involves several steps that are necessary to be performed prior to the actual experiment starting phase. These kinds of procedures include the surface preparation, cleaning of the sample surfaces, sandwich preparation and polishing of the surfaces to observe the sample with Optical microscope and SEM etc.

To review the methodology in detail, let us start from the beginning.

3.2.1 Surface preparation and removal of oxide layer

Initially aluminum alloy and steel are cut into in to small pieces by the help of automatic cutting machine equipped with an alumina blade. The small pieces are then cleaned properly by an abrasive paper. The abrasive paper differ in according with the grain size e.g., P320 have coarse grains compared to P4000. Sandpaper grit is a measurement of the size of abrasive materials on the sandpaper. The greater the grit number, the finer the abrasive, and the smoother the surface finish[42]. Coarser abrasives with lower grit numbers scrape off things considerably faster. The grit is measured in the figure 31 using the CAMI (Coated Abrasives Manufacturing Institute) and FEPA (Federation of European Producers of Abrasives) standards, with the latter being prefixed by a "P." Micro and macro are the two basic subdivisions, with many more gradations in between.

Grade	Description	CAMI	FEPA	Diameter	Used for
Ultra Fine	Most delicate abrasives	800 or 1000	P1500, P2000 or P2500	8.4-12.6 micrometers	Final sanding and polishing thick finishes
Super Fine	Slightly wipes away patches/small inconsistencies but not strong enough for removal	400, 500 or 600	P800, P1000 or P1200	15.3 to 23.0 micrometers	Final wood finishing
Extra Fine	Slightly less fine and more abrasive than Super Fine	360 or 320	P400, P500 or P600	25.8 to 36.0 micrometers	Initiative methods for wood polishing
Very Fine	The least fine of the micro abrasives	240	P240, P280, P320 or P360	40.5 to 58.5 micrometers	Sanding finishes between consecutive coats and drywall and wood

Grade	Description	CAMI	FEPA	Diameter	Used for
Very Fine	A coarser material than Very Fine under the micro abrasives	150, 180 or 220	P150, P180 or P220	190 to 265 micrometers	Sanding on bare wood
Fine	Cannot remove varnish or paint on wood	100 or 120	P100 or P120	115 to 162 micrometers	Preparing wood for finishing, cleaning plaster and removing water stains on wood
Medium	Medium to coarse surface texture after sanding	80	P60 or P80	190 to 265 micrometers	Sanding bare wood to prepare it for removing varnish and final finishing
Coarse	Has the ability to remove material rapidly	40, 50 or 60	P40 or P50	336 to 425 micrometers	Wiping away a layer of debris or finish with minimal effort
Extra Coarse	Quickens the removal of most materials rapidly	24, 30 or 36	P12, P16, P30 or P36	530 to 1815 micrometers	Initial efforts in hardwood floor sanding

Figure 31Grit Size of Abrasive paper, left side micro grit and right size macro grit[43]

As we know the fact that formation of oxides is common in the brazing phenomenon and oxides are not good for joining. So, this procedure helps us in removing the oxide layer from the sample pieces. The following image 32 depicts the sample after they are cleaned with the abrasive paper.

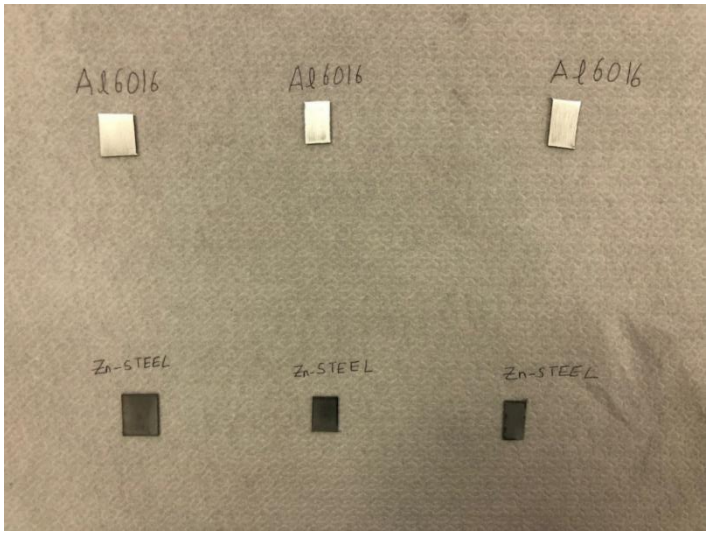


Figure 32 samples after preparation with abrasive paper

The grades of abrasive paper are important in the aspect that it defines the smoothness of the surface achieved. The abrasive paper grade like the P320 defines the diameter of grits of the sandpaper. The grit is sized by a gauge number, in which low numbers signify a larger, coarse grit. Just to provide an example, the 24 to 50 grit sand paper is very coarse and rough while a 1000 grit sand paper will be extremely fine with very small fine abrasive particles. You'll need coarse sandpaper with a 40- to 60-grit rating for hard sanding and stripping, and 80- to 120-grit sandpaper for smoothing surfaces and eliminating tiny flaws. Use a fine sandpaper with a grit of 360 to 600 to finish surfaces smoothly. The following figure 32 represents the P320 abrasive paper. For our experiments in order to remove the oxide layers we always use P320 abrasive paper.

Figure 33: The P320 abrasive paper

3.2.2 Ultrasonic bath cleaning for undesired particles

After the samples are prepared by removing the oxide layers using P320 abrasive paper now it's time to clean the samples for the removal of undesired particles and contaminants for brazing. This can be done by putting the samples into beaker and put ethanol solution in the beaker until the sample completely covered by the ethanol. Then breaker is covered by Aluminium foil and put into ultrasonic bath for 5 minutes at room temperature. Ultrasonic cleaning washes the surface of submerged objects with high-frequency sound waves conveyed through liquid. The cavitation of solution molecules is caused by high-frequency sound waves, generally 40 kHz, agitating the liquid solution of water or solvent. Metals, glass, rubber, ceramics, and some hard polymers are among the materials that may be cleaned by ultrasonic cleaning[44]. Ultrasonic cleaning is very effective in removing pollutants stuck to complicated goods with blind holes, fissures, and recesses. Dust, grime, oil, grease, pigments, flux agents, fingerprints, and polishing compound are examples of pollutants eliminated by ultrasonic cleaning. The figure 34 shows the sample dipped in the ethanol solution.

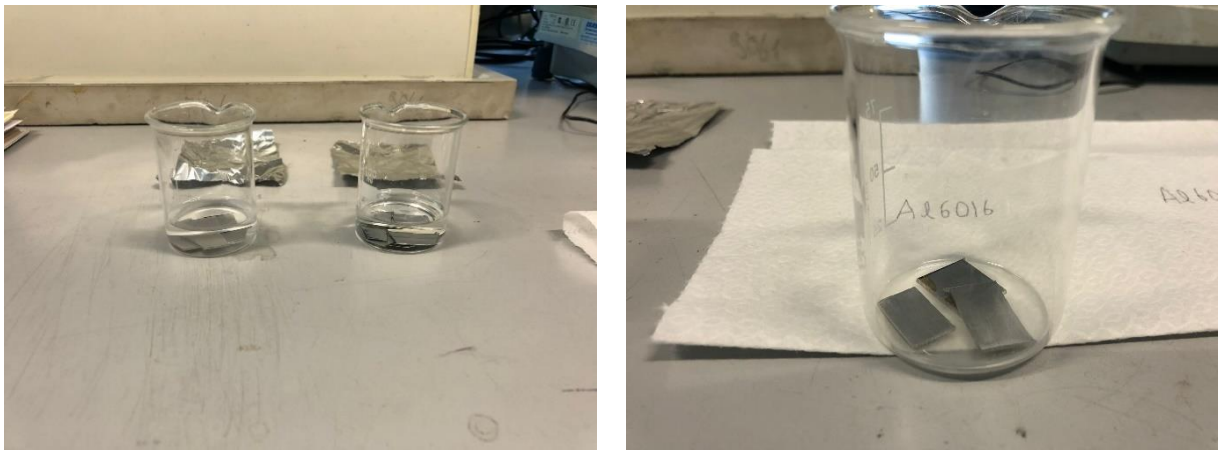


Figure 34: (a) samples dipped in ethanol solution (b) Aluminum Alloy cleaned in ethanol solution

The figure shows the ultrasonic cleaner used for all the experiments conducted in this thesis.

Figure 35 Ultrasonic cleaner for cleaning the sample

Once the sample are washed in the ultrasonic washer it was removed from the washer and the ethanol is disposed in the specific container. As the samples are dipped in the ethanol it is advisable to dry the sample against any liquid particles. Because if the samples are wet or any fluid particle trapped inside or on the surface this would affect the joining process in brazing. So, highly compressed air is used to dry the sample. In figure 36 (a) we can see the air gun of compressed gas used for drying the samples and in (b) the samples after drying with compressed air. Once the samples are dried using compressed air now, they are ready for brazing in the furnace.

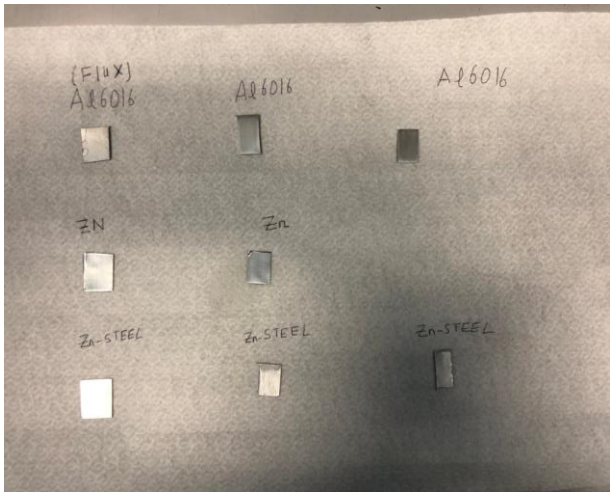


Figure 36: (a) Air gun for compressed air, (b) Samples after cleaning with ethanol and dried with compressed air

All the experiments performed in this thesis are identical till this step. All experimental work include cleaning against oxide layer, ultrasonic cleaning and drying with compressed air. The difference arises after this point. First, we will explain general methodology and then we will discuss specific experiments.

3.2.3 Furnace Brazing

In this topic we will discuss the most important part of brazing and also one of the important parts of this thesis. Once the samples are cleaned and dried now it's time to put them in the furnace. But before we have to identify the sandwich arrangement in which we have to set the samples and then insert in the furnace. Sandwich is basically the arrangement of the samples in specific order keeping in mind all the factors related to brazing e.g., wetting of Aluminium. From literature and by performing different experiments we found the in-sandwich arrangement is recommended to put Aluminium on the bottom followed by brazing filler and Zn- coated steel. On the contrary, if Zn-coated steel is put on the bottom and Aluminium on the top the Aluminium, after melting doesn't spread properly and failed to join with Steel. For experimental purposes in this thesis, we mostly used the sandwich arrangement as Aluminium on the bottom followed by brazing filler, Zinc in our case, and Zn-coated steel on top. In Figure 37 we see a sandwich arrangement in which on the very bottom we have iron support on which we put graphite layer. Graphite layer is used in order to favour the detachment of the sample and iron piece after brazing process. On the graphite layer our main sandwich is placed again covered from top by graphite layer. Load is applied by putting iron piece on the top in order to give better joining.

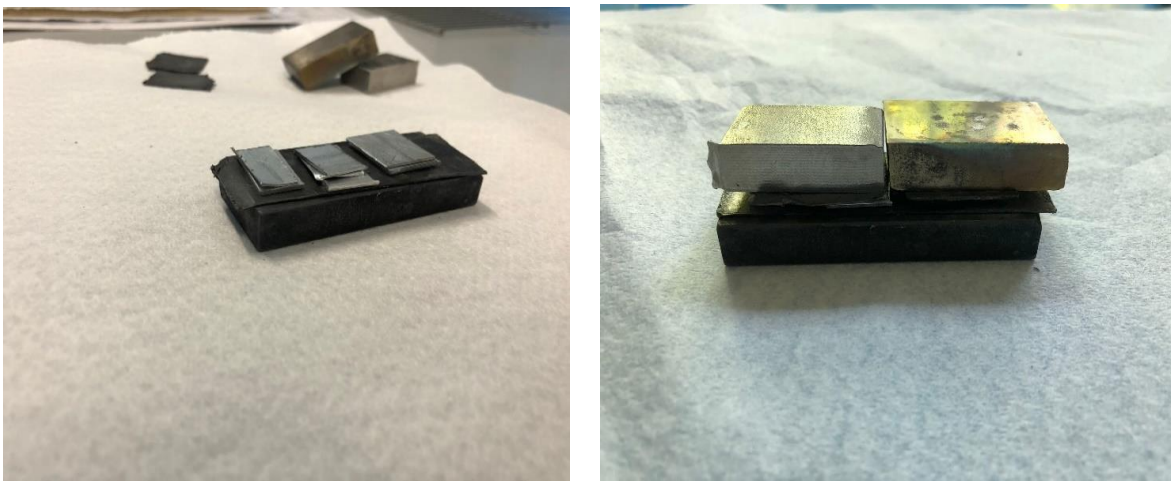


Figure 37 (a) Sandwich of Al, Zn, Zn-steel (b) final sample to put in furnace

Once, the sandwich preparation is done now it's time to start the main process of brazing joining. The sandwich is carefully inserted in the centre of the furnace. The furnace used for this thesis is tubular furnace (Carbolite, Hope Valley, UK). During the brazing process Argon gas is fed in the furnace to prevent high temperature oxidation phenomenon[41]. Also, titanium sponge is fed in the furnace to capture eventual oxygen. Finally, the thermal and time conditions are set for brazing and furnace is turned on to perform brazing. Figure 38 depicts the furnace used for brazing.

Figure 38:Tubular furnace for brazing

Once the brazing has been performed, the tubular furnace is opened, and the sample is subjected to room temperature air before it is taken out of the furnace. Afterwards, the sample is then extracted from the furnace. The following figure 39 shows the sample after it has been extracted from the furnace.

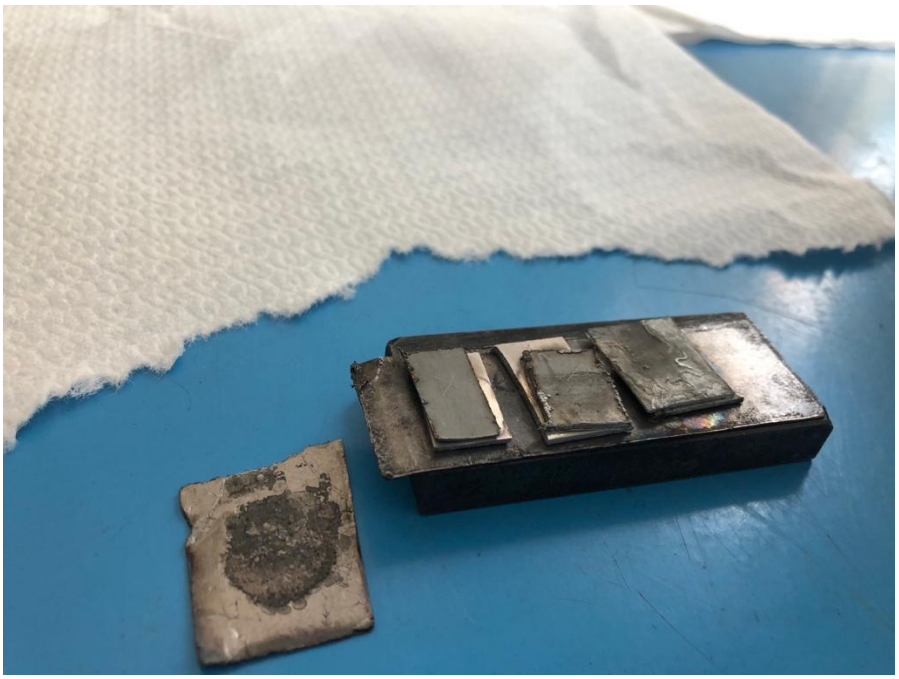


Figure 39: Sample after it has been taken out of the furnace

3.2.4 Resin and Mounting

After the samples are taken out from the furnace, the samples are then mounted in resin. The procedure involves the placement of the sample in a plastic die as shown in the figure 40 below.

Figure 40: Samples before they are put in plastic cups

To further explain, the samples were taped to the bottom lid of the plastic housing containers to keep them steady while the liquid mixture was poured into the containers. The liquid mixture is made up of Technovit 4071 powder and solution (cold mounted resin). The powder to the solution ratio in the liquid solution is 2:1. The following figure 41 shows the samples being placed inside the plastic dies.

Figure 41: Samples after being placed inside the plastic cups

It is quite difficult to remove the gloss coated sample from the plastic containers once the liquid mixture has hardened after 8-10 hours. To avoid this problem, a little amount of liquid soap was sprayed to the plastic containers' surfaces that come into touch with the liquid combination. It will be easy to remove the gloss coated samples from the plastic containers in this instance.

The following figure 42 shows the picture after the resin has been poured in the plastic cups for 8-10 hours. The resin gets hard when it’s dried for 8-10 hours.

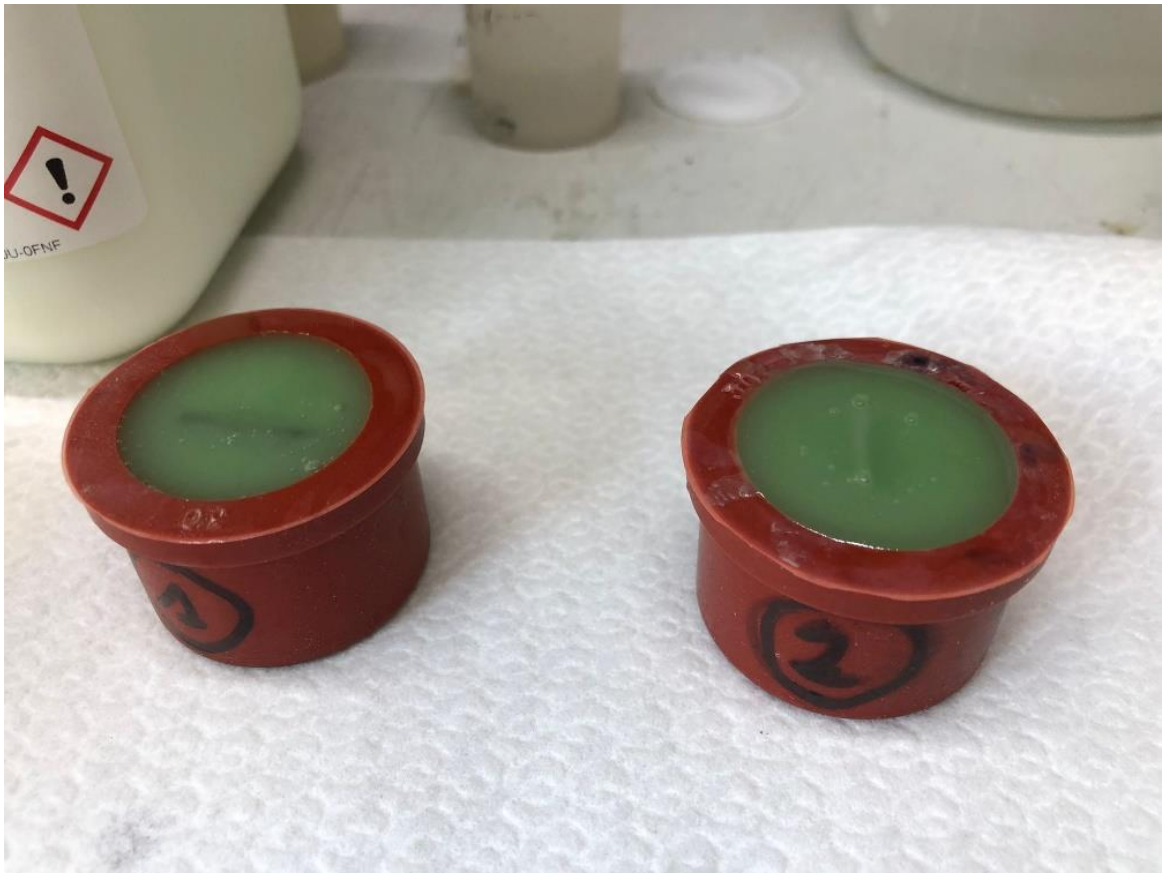


Figure 42: Samples after they are inside the resin

After hardening and obtaining solid parts, the samples were gently removed from the plastic housing containers with great care, and they were ready for the next operation, polishing, with the goal of obtaining bright surfaces free of scratches and oxide layers (aluminium and its alloys are easily oxidised in the air), in order to analyse the joint using an optical microscope, EDS, and SEM.

But before the polishing operation is to start, we first cut each of the sample into two parts from the middle in a transverse manner and the sample metallographically prepared to analyse the section under optical microscope and scanning electron microscope. The following figure 43 shows the machine cutter, and the sample after cutting before the polishing operation is started.

Figure 43: (a) TR80 EVOLUTION Abrasive Cutter (b) Sample after being transversely cut

3.2.5 Polishing Operation

Polishing is the final step in creating smooth, shining surfaces while also removing oxide layers from the samples. Abrasive papers with various surface roughness numbers are used. Because aluminium and its alloys are soft, polishing them precisely is extremely difficult and time-consuming. As we're joining aluminum and its alloys to zinc coated steel and both of them have different hardness, so it is difficult to obtain the same polishing results for both of the dissimilar metals.

To initialize the procedure, the polishing of the sample was done by P80 polishing paper, which is the coarsest polishing paper. The procedure involves the usage of extremely fine abrasive papers aswell. The abrasive paper is gradually changed from P80, P120, P240, P320, P2500 up to P4000.

When the number of abrasive paper increases, the roughness of the surface decreases. It is also possible to utilise diamond pastes on specific cloths for the final polishing in order to obtain a mirror polished surface. The final step is the mirror polishing of the sample by using

1µm diamond liquid. Even though, we are using an extremely small size of the diamond liquid, we know that diamond is the hardest material, it can cause scratching on the sample if the diamond particles sticks together. To make sure that there is no scratching of the sample due to diamond paste accumulation, we use a lubricant that makes sure that the sample is well protected.

Polishing is done with water supply due to the fact that polishing is an operation that some particles emerge to the air and should be removed also, it helps for cooling the sample during polishing. Another important point during polishing is keeping the sample fixed position on the abrasive plate in order to have flat surfaces. It is not practical to use the force on the sample against to plate, it might cause not having flat surfaces and it is big problem during micro hardness test, optical microscopy and so on. It is always preferable to have flat surfaces instead of forcing the sample against the abrasive blade. This is also for the sake of the next procedures.

The machine used for polishing, can be seen in figure 43. The water supply is turned on, the abrasive blade moves, which then polishes the resin mounted sample.

Figure 44: Polishing Machine used in experimentation

When the samples have been polished, it is important not to touch the polished surfaces. Because Al is a soft material, it is quite simple to lose all of the brightness and smoothness of the surface with only a light touch. Now further observations and analysis can be performed with the help of the samples obtained to brazed study the brazed joint obtained. The samples are now metallographically prepared to analyse further the cross section using the optical microscope and to investigate the brazing alloy/substrate interface.

3.2.6 Optical Microscopy

The optical microscope was used to obtain photographs at the micro-scale with different magnitudes for each sample after there were no more scratches on the samples' surfaces and they were bright enough.

The optical microscopy procedure started off with a magnification of 20x and reached up till 500x. At 20x, which is considered as a low magnification factor, we can obtain a generic image of the overall sample while at greater magnifications, we can analyse separate portions of our sample and further study it.

Lenses, eyepieces, light source, and camera are the main components of an optical microscope.

Light from an incandescent source is directed into a condenser lens beneath the stage, through the specimen, via an objective lens, and to the eye through a second magnifying lens, the ocular or eyepiece. Through a hole in the stage, the condenser focuses light on the specimen. The light is exhibited to the eye after passing through the specimen with an apparent field that is substantially greater than the region lit [45].

Optical microscopy can reach magnification up to 1000x because the wavelength of visible light is at about 10^{-1} µm. Optical microscopy is useful to investigate continuity of the joint and reaction zones at the interface. However no chemical analyses are possible, and they should be done by Scanning Electron Microscopy.

3.2.7 Scanning Electron Microscopy

After optical microscopy, scanning electron microscopy is performed. There are some sample preparation processes to get the samples ready for SEM. Because SEM is conducted by an electric field, an electric connection between the samples and the microscope is required. Metal clamping tools are also available to assist keep samples motionless inside the microscope. The SEM needs a complete circuit in order for the electrons to flow, so in order to complete the circuit, we placed a conduction tape on our sample as well as on the bottom of the clamp of the SEM. Following figure 50 shows the sample being placed inside the scanning electron microscope's vacuum chamber for analysis.

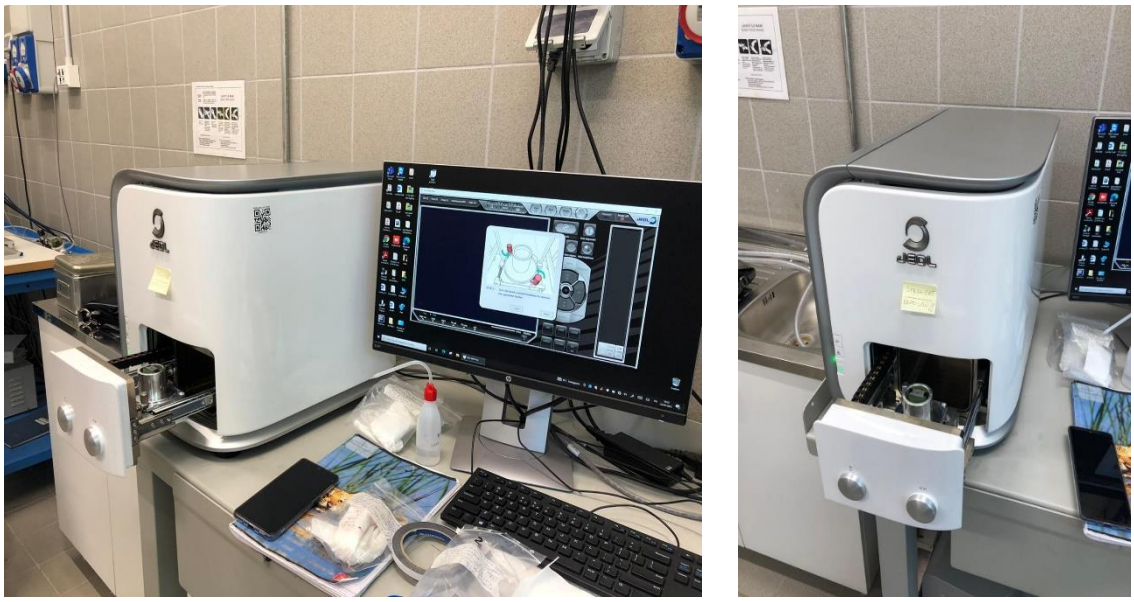


Figure 45: Sample placed inside the Vacuum Chamber

Second, having materials dry before doing SEM is always preferable than observing little water drops on the surface with SEM. To avoid this, samples dried using compressed air. The samples were placed inside the specimen chamber, which was then vacuumed.

Adjustment control panels and varied magnitudes were used to produce micro-scale pictures with greater resolution and magnitude than optical microscopy, based on the desired magnitudes and desirable spots on the surface that required to be analysed. Scanning

electron microscopes function on the same principles as optical microscopes, except instead of light, they employ electrons and an electrical field.

An electron beam is focussed into a tiny probe and raster over the surface of a material in scanning electron microscopy (SEM). As the electrons penetrate the surface, they have many interactions with the sample that result in the emission of electrons or photons. The form of the sample is the most direct outcome of observation in the scanning electron microscope. The beam diameter determines the resolution [46]. The pieces of the SEM and their configuration are depicted in Figure 46. Figure 47 depicts a more complete working diagram.

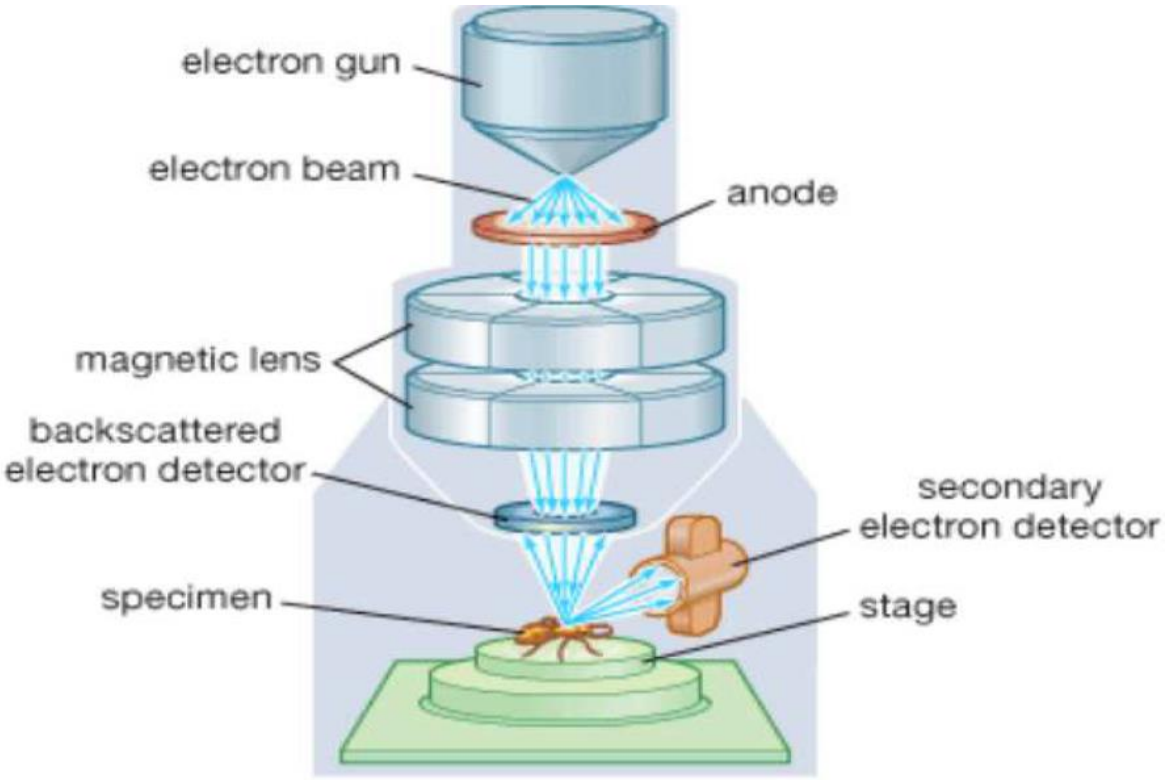


Figure 46: Basic Configuration of SEM[46]

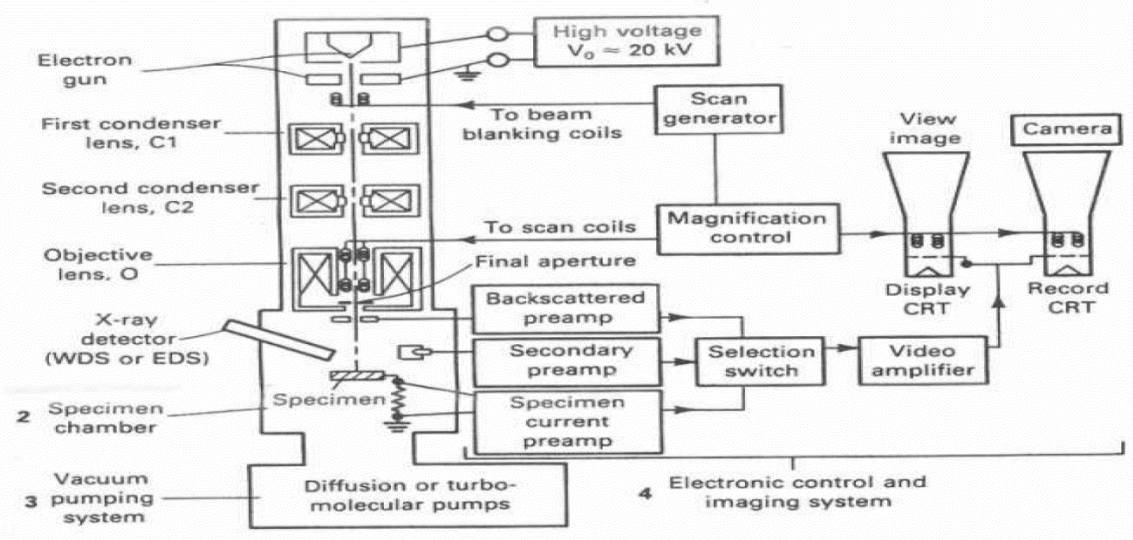


Figure 47: Detailed Working Diagram of SEM[46]

3.2.8 Energy Dispersive Spectrometry (EDS)

Because it incorporates an X-ray spectrometer, the Jeol machine can do EDS and SEM analysis simultaneously. It is feasible to do element mapping, point analysis, and area analysis simultaneously after obtaining electron images with SEM. Both of these tasks were combined in a single instrument.

When the necessary electron picture for a point or a region is produced, a chemical analysis may be performed to view all of the specific elements and their relative proportions at the designated spot. As illustrated in Figure 48, the required spectrum point was picked on the electron picture, and the chemical analysis revealed the specific components.

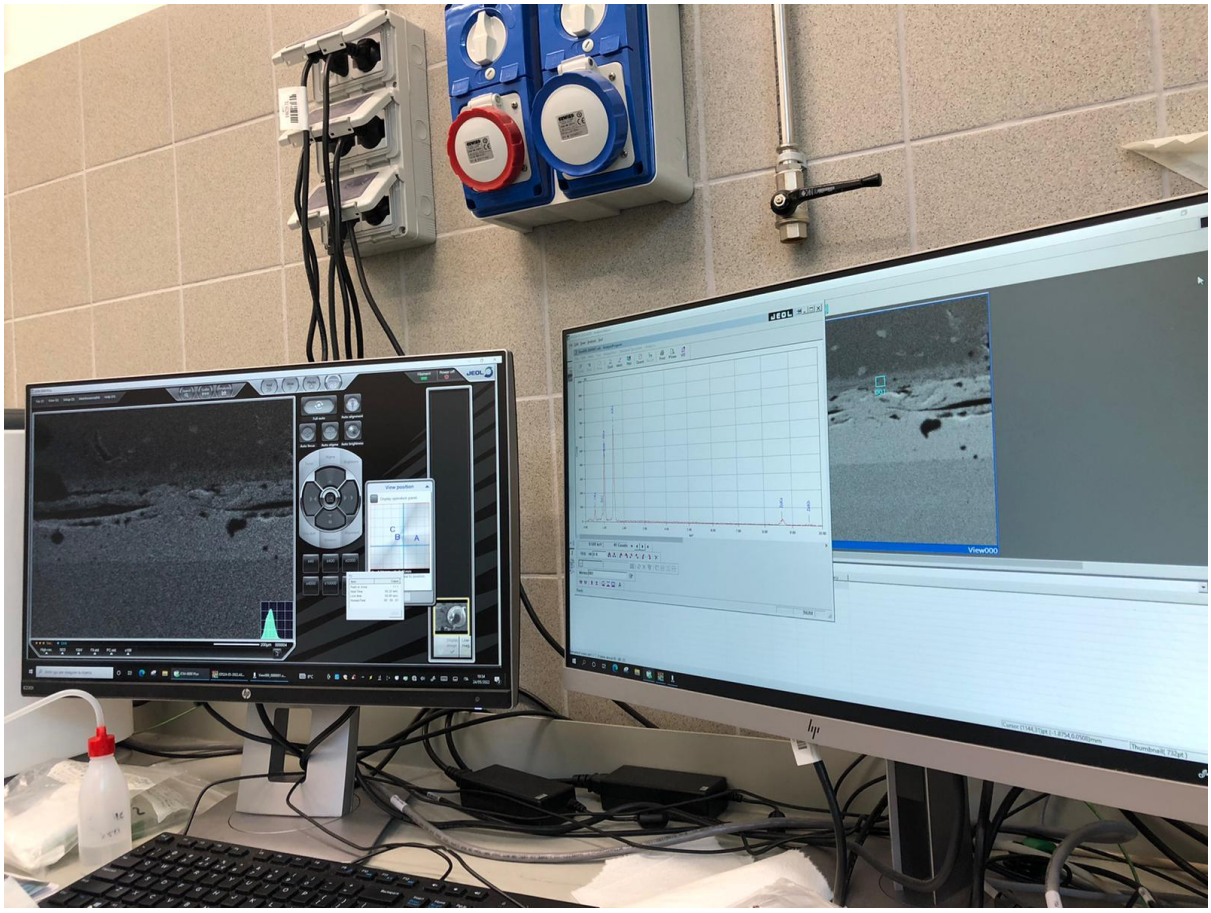


Figure 48: Computer Screen for SEM and EDS analysis

To get a localised chemical analysis, EDS uses the X-ray spectra generated by a solid sample attacked with a focussed stream of electrons. In principle, any elements from atomic number 4 (Be) to 92 (U) may be identified, albeit not all devices are capable of detecting 'light' elements (Z 10). Because of the simplicity of X-ray spectra, qualitative analysis entails identifying the lines in the spectrum, which is quite simple. Measure line intensities for each element in the sample and for the same elements in calibration standards of known composition in quantitative analysis (determination of the concentrations of the elements present) [47].

Element distribution pictures or ‘maps' can be created by scanning the beam in a television-like raster and showing the intensity of a selected Xray line. In addition, depending on the mode selected, pictures created by electrons gathered from the sample indicate surface topography or mean atomic number variations [47].

The absorption of an individual Xray photon by the detector causes the ejection of a photoelectron, which gives up its energy to the production of electron hole pairs, which is how X-ray spectrum measurement is done. An applied bias sweeps the electron-hole pairs away, forming a charge pulse [48]. A preamplifier converts the charge pulse to a voltage pulse. A linear amplifier (pulse processor) amplifies and "shapes" the signal before passing it to a multi-channel analyzer, where the data is presented as a histogram of intensity versus voltage[48].

The crucial thing to remember here is that the voltage pulse generated is proportional to the energy of the entering X-ray photon[48]. Figure 49 depicts the flow chart for X-ray spectrum measurement. When the X-ray photon's energy is high, the voltage pulse peak is also high.

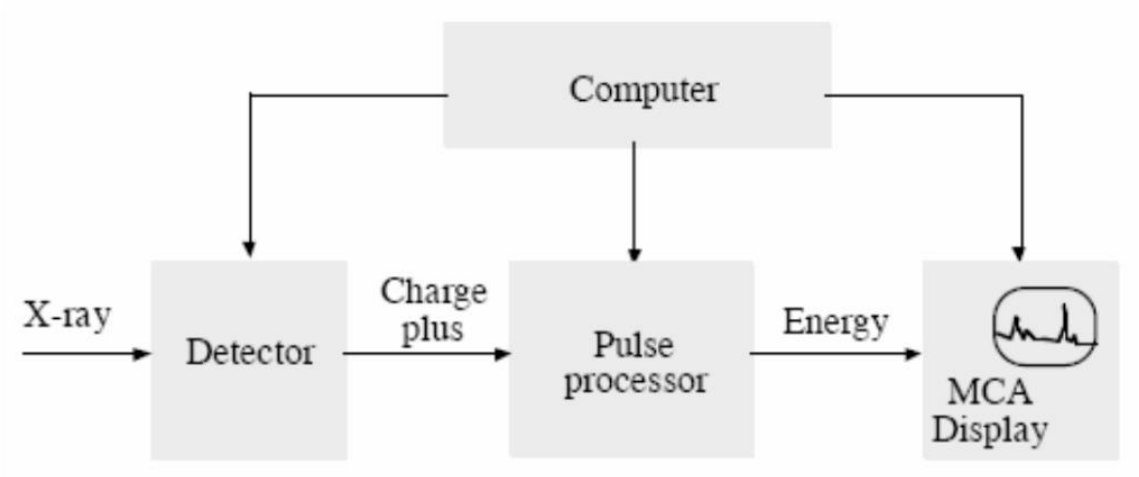


Figure 49: X-Ray Spectral Measurement[48]

EDS reveals the different compositions of the elements in the sample. EDS has been employed for the investigation of the reaction layer of the joints.

3.2.9 Experimental details for this thesis

In the topic we will specifically discuss the details of brazing joining used for this thesis. The initial surface treatment to remove oxide layer with abrasive paper followed by cleaning with ethanol solution in ultrasonic cleaner is identical for all the performed experiments. The main difference is in

the brazing conditions, time, and temperature, for joining. We performed several experiments with different brazing condition, the details is given below.

3.2.9.1 Al6016 and Al-foam / Zn-Steel

Brazing joining of Zn coated steel and Aluminium Al6016 is performed using pure zinc as filler materials. Several attempts for brazing are performed at different conditions to find the optimal conditions.

- First try to join Zn-steel and Al6010 was done by pure Zinc as filler material. Zn-coated steel was in the bottom followed by Zn and on the top, we have Al6016. In the furnace we set 500°C temperature but the actual temperature in the center of furnace is 480°C, dwell time is 5 minutes. The temperature increase by 10°C per minute until it reaches 480°C at which is remain constant for 5 minutes and it decrease to 25°C by 10°C per minute. The resistance is turned on in all the time of reaction. To avoid oxidation argon gas is constantly fed in the furnace.
- The second try is made with all the same conditions as above, the only difference is that this time instead of Zn coated steel we put Al6016 on bottom in the sandwich arrangement.
- Al6016, Zn-Steel, and pure zinc as filler is also brazed but this time, we used aluminium flux. The brazing was accomplished by using a flux comprising cesium fluoroaluminate (FLUX-AL6, Stella Welding, Albizzate (VA), Italy). Flux is only applied to the surface of Al6016 which is exposed to the Zinc filler. Aluminium flux help to avoid the oxide formation during the brazing process. As, oxides are hard phase, so it is advisable to avoid oxides formation. The brazing temperature is 500°C set on furnace but real felt temperature is 480°C. Ramp is 10°C per minute both for increase and decrease. The dwell time is set as 7 minutes.
- Aluminum foams have a large number of applications in the automobile sector, which has been fascinated by metal foams since they were originally invented. There are additional potential uses in shipbuilding, aircraft, and civil engineering[49]. So, this time we use Al foam instead of Al6016. In the sandwich arrangement the Al-foam is

placed in the center covered by zinc from top and bottom. Zinc is covered by Zn-coated stell from above and below. Furnace conditions are set as 480°C inside the furnace for 7 minutes as dwell time. Temperature increase 10°C per minute until it reach 480°C and decrease by 10°C till 25°C. Before we put the sample in the furnace we performed etching of Al-foam with nitric acid and washed with ethanol solution in ultrasonic cleaner.

3.2.9.2 Al5182 / Zn coated steel

Different attempts to join Al5182 and Zn coated steels are performed using Zama as filler for brazing. The Zama which we used is sent by casting industry and it is the one which is left over after machining. So, this Zama don't have planar geometry, the surface is not regular. The details of these experiments are discussed below.

- First of all, we try to braze Al5182 with Zinc coated steel with brazing filler as Zama. The Zama which we used is sent by casting industry and it is the one which is left over after machining. So, this Zama don't have planar geometry, the surface is not regular. Sandwich arraignment is like always Aluminium on bottom followed by filler metal in our case Zama and on the top, we have Zn-steel. The brazing temperature is 540°C set on furnace but actual temperature inside furnace is 520°C. Dwell time and ramp is in minutes. The temp increase by 10°C until it reach 520°C, remain constant for 5 minutes and decrease by 10°C until 25°C. While we were doing resin and mounting the sample detached because the joining was not very good.
- Second try was made using 2 layers of Zama. All the things are same as of above reaction but, we changed the dwell time to 10 minutes instead of 5 minutes as in the last experiment. Also, the sample sandwich was mechanically pressed to make the Zama layers more stable when we put the sample inside the furnace. In this case sample reacted but failed to join because the 10 minutes time is considered to be more.
- Finally, we try to join Al5182 and Zn-coated steel with the one layer of Zama with the dwell time to be 7 minutes. This time we inserted two sandwiches at the same time in

furnace. The difference is that for one sample we wash Al6016, Zn coated steel and Zama chips in ethanol solution in ultrasonic cleaner and for the other sandwich we only wash Al6016 and Zn coated steel in ethanol solution in ultrasonic washer. The samples with the Zama chips washed in ethanol seemed to be joined and the other sample do not join.

Table 5 summaries the experiments done for this thesis.

Experiments	Materials	Brazing alloy	Temperature(°C)	Time(minutes)	Surface preparation
1	Al6016, Zn-Steel (Bottom)	Pure Zinc	480 (set on furnace 500)	5	P320 treated, Ethanol washing
2	Zn-Steel, Al6016 (Bottom)	Pure Zinc	480 (set on furnace 500)	5	P320 treated, Ethanol washing
3	Zn-Steel, Al6016(Bottom)	Pure Zinc	480 (set on furnace 500)	7	P320 treated, Ethanol washing, Flux applied on Al
4	Zn-Steel, Al6016(Bottom)	Pure Zinc	480 (set on furnace 500)	7	P320 treated, Ethanol washing. Without flux
5	Zn-Steel, Al6016(Bottom)	Without filler	480 (set on furnace 500)	7	P320 treated, Ethanol washing.
6	Zn-Steel, Al5182(Bottom)	Zama (2 layers)	520 (set on furnace 540	5	P320 treated, Ethanol washing.
7	Zn-Steel, Al5182(Bottom)	Zama (2 layers)	520 (set on furnace 540)	10	P320 treated, Ethanol washing, Mechanically pressed.
8	Zn-Steel, Al5182(Bottom)	Zama (1 layer)	520 (set on furnace 540)	7	P320 treated, Ethanol washing, Mechanically pressed
9	Zn-Steel, Al5182(Bottom)	Zama (1 layer)	520 (set on furnace 540)	7	P320 treated, Ethanol washing also Zama, Mechanically pressed.

10	Zn-Steel, Al-Foam(centre)	Pure Zinc	480 (set on furnace 540)	7	P320 treated, Nitric acid etching of Al-Foam, Ethanol washing, Flux applied on Al-Foam.
11	Zn-Steel, Al-Foam(centre)	Pure Zinc	480 (set on furnace 540	7	P320 treated, Nitric acid etching of Al-Foam, Ethanol washing.

Table 7: Summary of the experiments

4 Results and discussion

In this chapter, all the characterization results of optical microscopy, SEM and EDS Analysis are reported and discussed. Once the samples are polished, they are ready to be analysed at Optical microscope and scanning electron microscope (SEM). At first by use of optical microscope we analysis the cross-section of each sample at the optical microscope. We have limitations for magnification on Optical microscope. So, to analysis sample at high resolution and magnifications we use SEM. Scanning electron microscopy (SEM) in combination with energy dispersive X-ray spectroscopy (EDS or EDX) produces a clear image of the sample's tiny surface features as well as precise information on its elemental composition.

4.1 Zn-Coated Steel analysis

In this topic we will discuss the results we found for Zn-coated steel using SEM and EDS analysis. The thickness of Zinc coating on zinc coated steel is observed using SEM. Both the

cross-section and top view of Zn-stell are analysed for area and point analysis. Figure 50 shows the top view of images taken at different magnitudes using SEM.

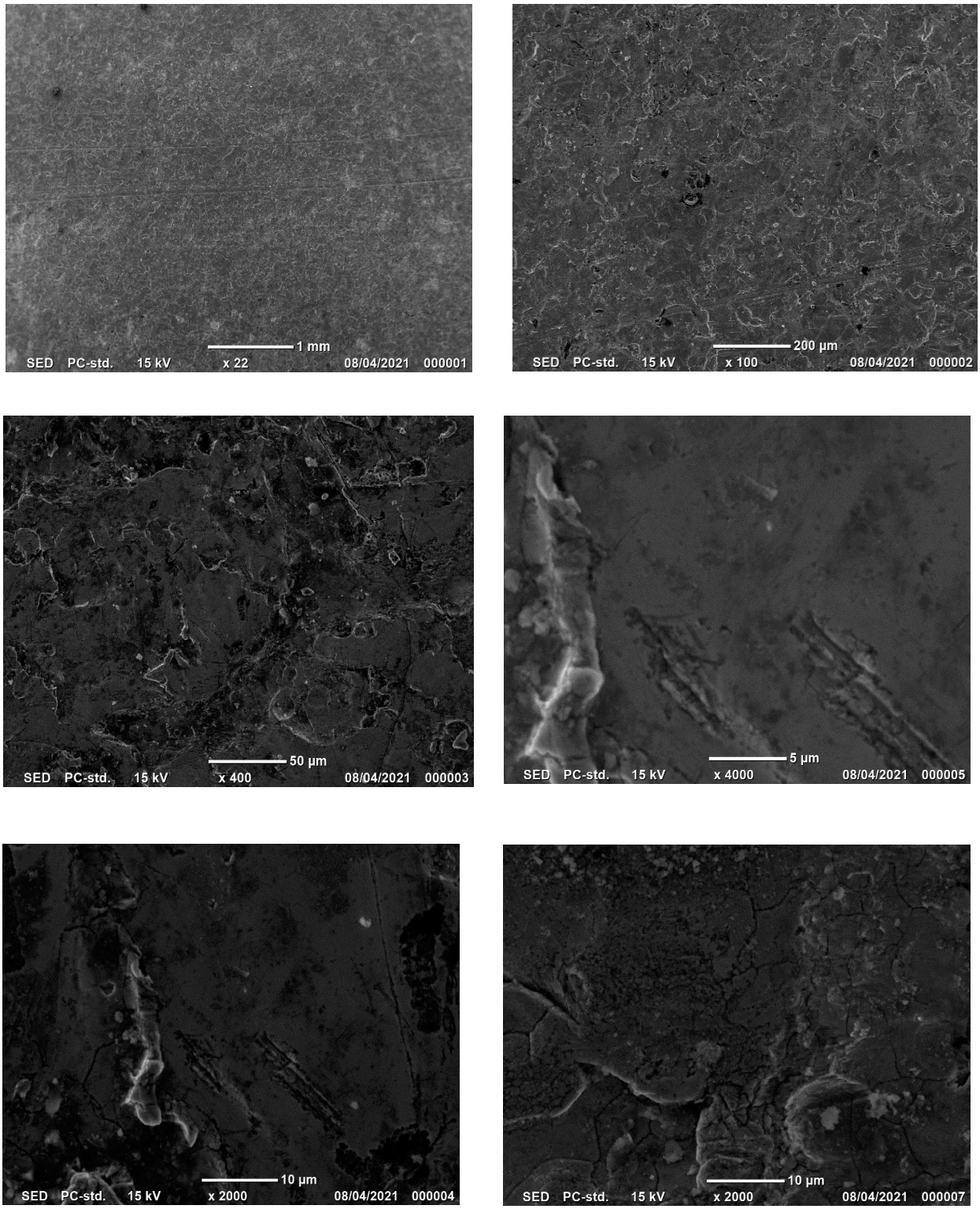


Figure 50: Top of Zn-coated steel at different magnifications using SEM

Looking at Figure 50 we can understand that the surface of the Zn-coated steel appears quite rough at the micro-scale.

To further analysis the composition of the top view of the zinc coated stell SEM and EDS analysis are performed together. By using the results obtained for composition in EDS the mean and standard deviations are calculated. The Figure 51 shows the images used for area analysis of top view of zinc coated steel at magnification of 100x.

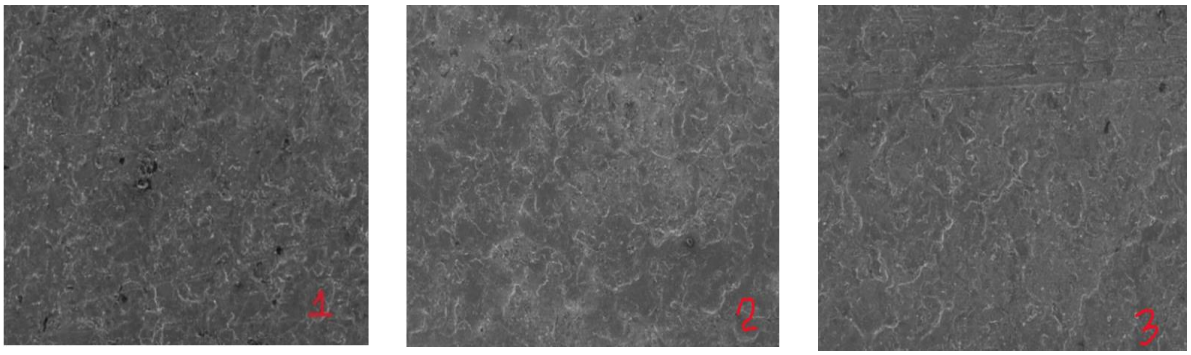


Figure 51: Images used for area analysis and calculations of mean and standard deviations

The table in Figure 52 describes the chemical compositions of Zn-coated steel form EDS analysis on the top view. The results obtained for mean shows that on overall 80% Zn is present on the steel top layer. A moderate carbon contamination, always present, can be observed together with a small amount of oxygen (attributable to contaminations and surface oxidation) and small amounts of Si, Fe and Al. Standard deviation is always lower than 1% and the coating and be considered homogeneous.

Elements	% area 1	% area 2	% area 3	%wt mean	St. dev %
C	8.91	9.65	10.13	9.56	0.50
O	6.49	7.76	6.84	7.03	0.53
Al	1.67	1.64	1.31	1.54	0.16
Si	0.36	0.34	0.18	0.29	0.08
Fe	1.73	1.91	1.00	1.54	0.39
Zn	80.84	78.70	80.54	80.02	0.94

Figure 52:Area analysis of Zn-coated steel and calculation of mean and standard deviations

We perform point analysis on 2 specific parts of the Zn-Steel top surface at magnification of 2000x to know in-depth the composition. The results are shown in the figure below (Figure 53).

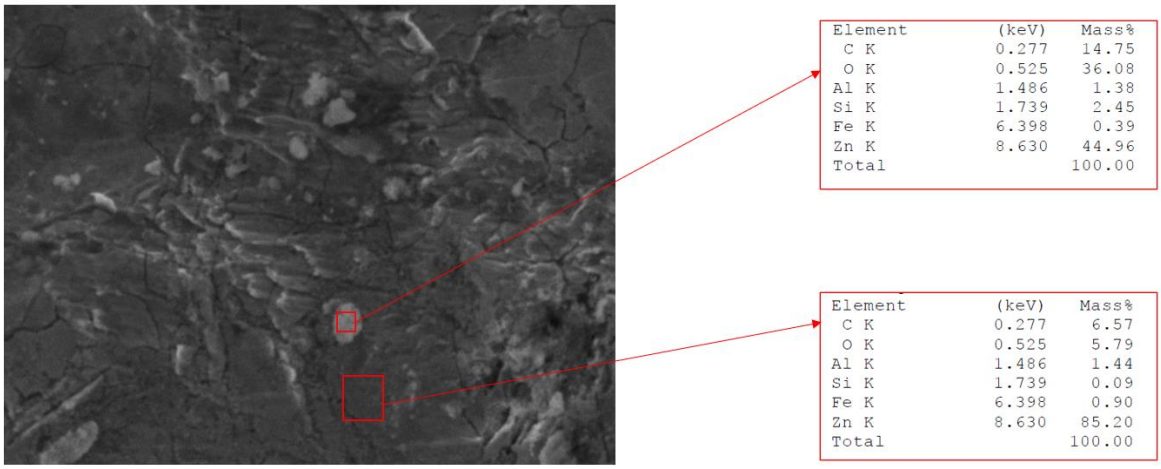


Figure 53:Point analysis of the Zn-steel top surface at magnifications of 2000x

The analysis reported in Figure 53 highlight the presence of few oxidized particles on a homogeneous coating constituted mainly by zinc and poorly oxidized.

4.2 Zn-coated steel cross-sectional analysis

The cross section of Zinc coated steel is analysed using SEM and EDS. The thickness of the Zinc coating on Steel is also measured at different points.

The figure below shows the images taken by SEM of Zinc coated steel section at different magnifications.

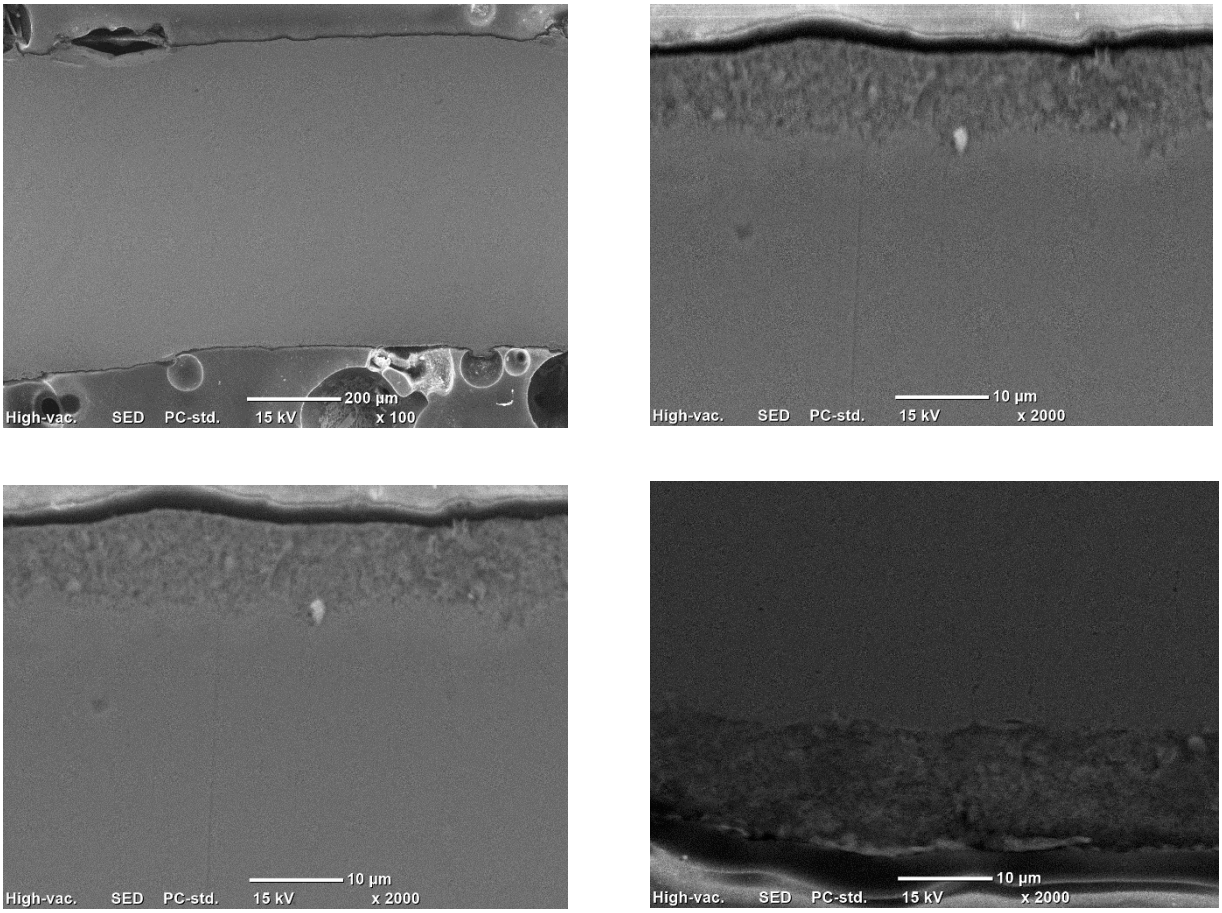


Figure 54: Cross-sectional images taken by SEM on different magnitude (100x 2000x)

Now we will analysis the cross-section of Zn-steel on different points in order to have a greater understanding of composition of elements in some specific points. Point analysis using EDS is given in the figure below. From the results of figures below it can be seen that a good amount of zinc is present on the surface of steel which favours the reactions in brazing. The percentage of Zinc varies all over the surface of steel.

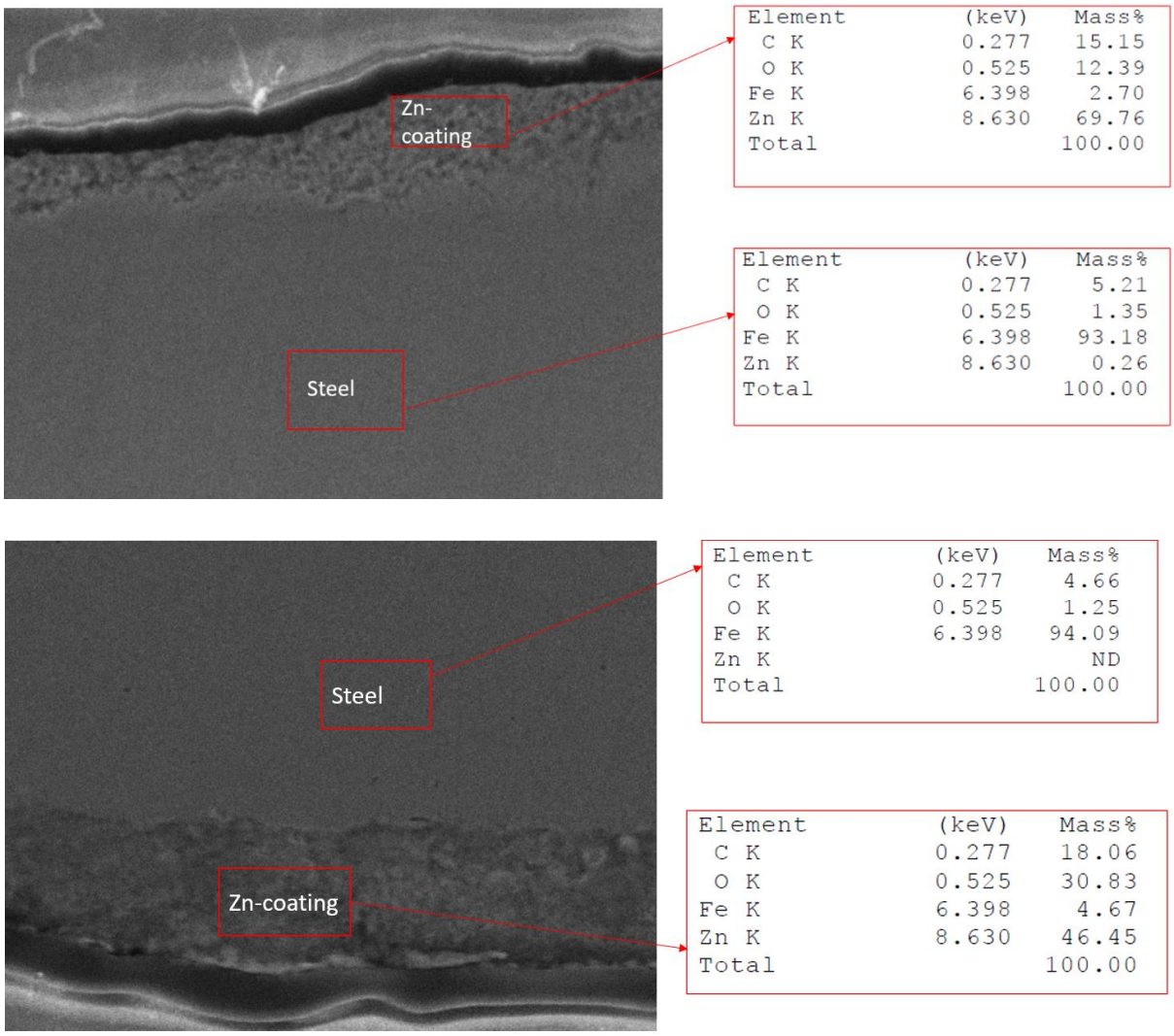
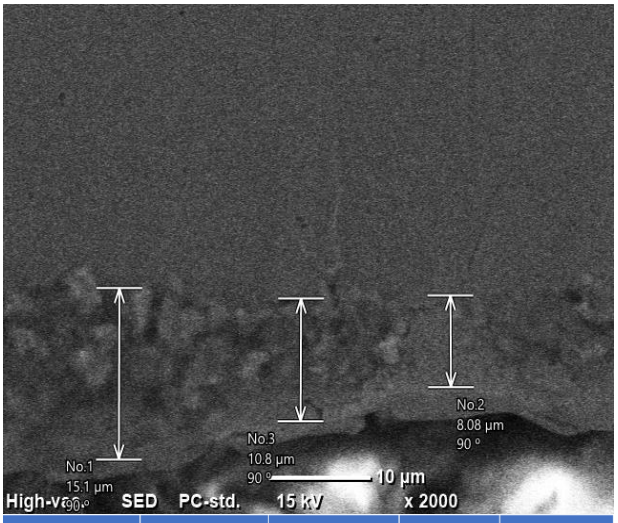
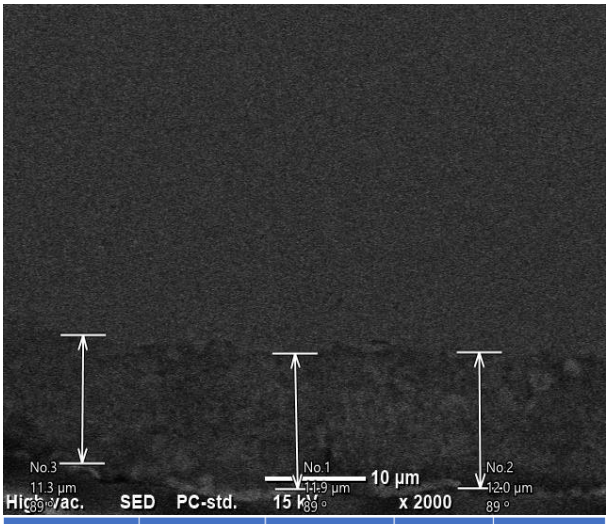


Figure 55:EDS point analysis of Zn-Coated steel section on 2 different points

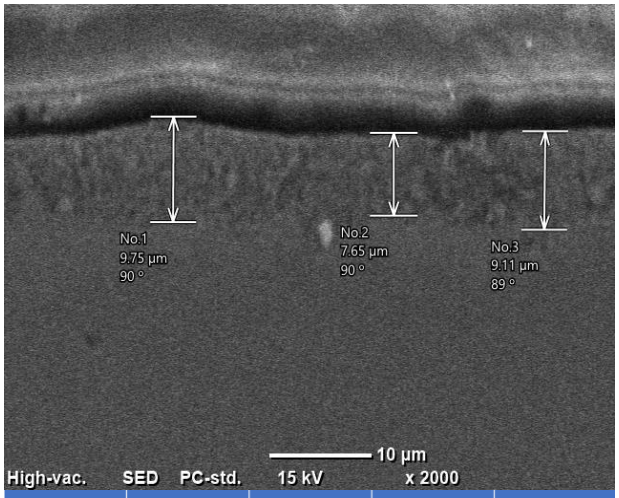
Finally, we observed the width of Zn-coating in the cross-section of Zinc coated steel at different points by SEM. Images take by SEM for width of Zn coating are in figures below. The figure 56 indicates that the thickness of the Zinc coating has different value for different points in sample. But the average value is considered to be 10 µm. But the result for Standard deviations shows that the Zinc layer is not uniformly distributed on the whole surface rather it differs point to point in sample. These observations can be useful for further analysis.



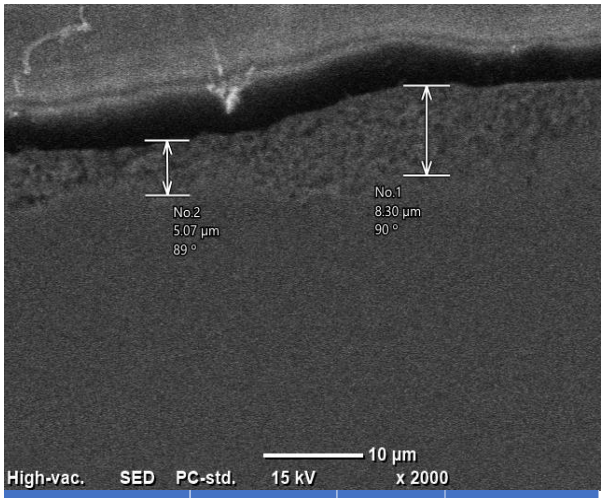
Length 1(µm)	Length 2(µm)	Length 3(µm)	Mean	St. dev
15.1	10.8	8.08	11.32	2.88



Length 1(µm)	Length 2(µm)	Length 3(µm)	Mean	St. dev
11.3	11.9	12.0	11.73	0.30



Length 1 (µm)	Length 2 (µm)	Length 3 (µm)	Mean	St. dev
9.75	7.65	9.11	8.83	0.88



Length 1(µm)	Length 2(µm)	Mean	St. dev
5.07	8.30	6.685	1.61

Figure 56: Width of Zn coating in Zinc coated steel

4.3 Joining of Al6016 and Zinc coated still using Zinc filler

In this topic we will discuss the results obtained using optical microscope, SEM and EDS analysis. In order to get better joining different experiments are performed in different conditions. Also, for some sample we use flux to avoid the formation of oxides during brazing.

4.3.1 Al6016/Zn-steel on bottom/ pure zinc

Materials used for this experiment are Al616, Zn coated steel and pure zinc. All of the specimens' surfaces were activated by removing oxide with abrasive paper grinding (320 grit) and cleaning with ultrasonic washing in ethanol (5mins). In the sandwich we have steel on the bottom. Figure below shows the sample before and after cleaning.

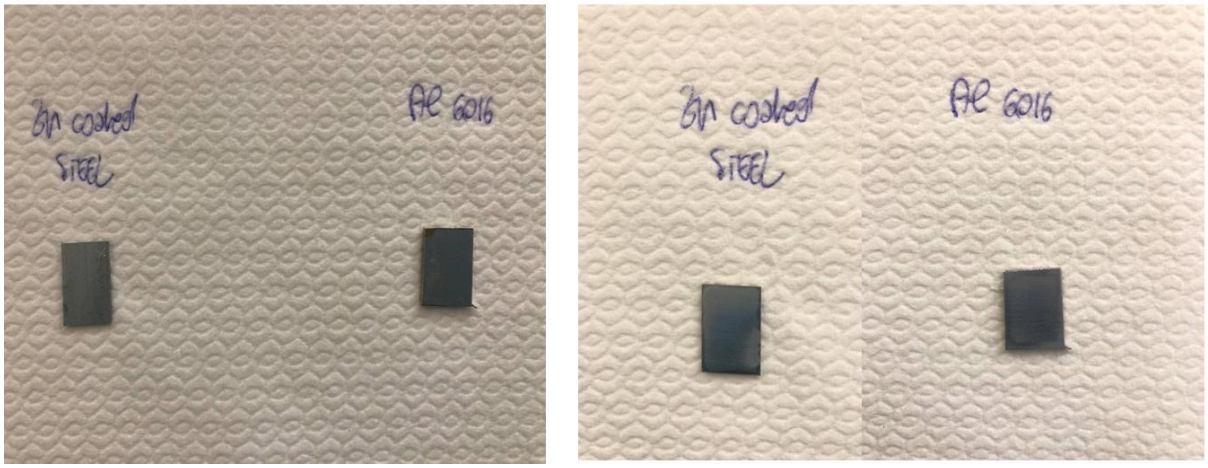


Figure 57(a left) samples in original form (b right) samples after P320 treatment and ultrasonic cleaning

The samples are placed inside the furnace at 480°C for 5 minutes. Ramp is 10°C per minutes. Once the brazing process is finished the sample are extracted from tubular furnace and resin mounted for future analysis on optical microscope, SEM and EDS analysis. The sample reacted during process but failed to join so we only perform Optical microscopy to analysis the reaction layer. The images taken from optical microscope are shown below. Images in figure 58 shows that Aluminium Al6016 poorly reacted with Zinc.

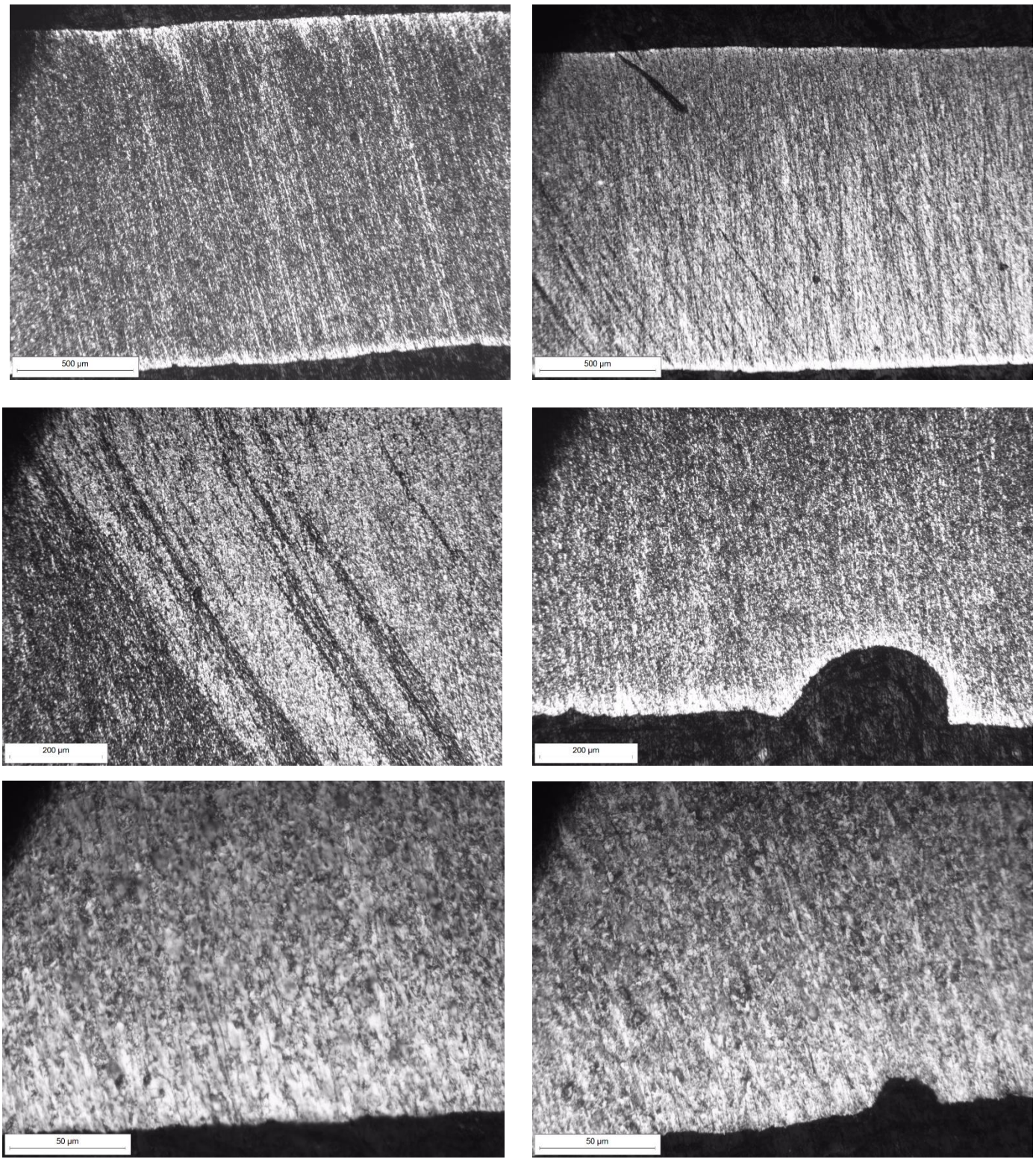


Figure 58: Images of Al6016 taken by optical microscope at different magnitudes

The images in the figure 59 are for Zinc coated steel and Zn filler. By observing the images at different magnitudes, we come to know that the reaction occurred between Zn-Steel and Zn.

But the joining was not strong. We have cavities and cracks in the reaction zone. Also, formation of second phase can be seen.

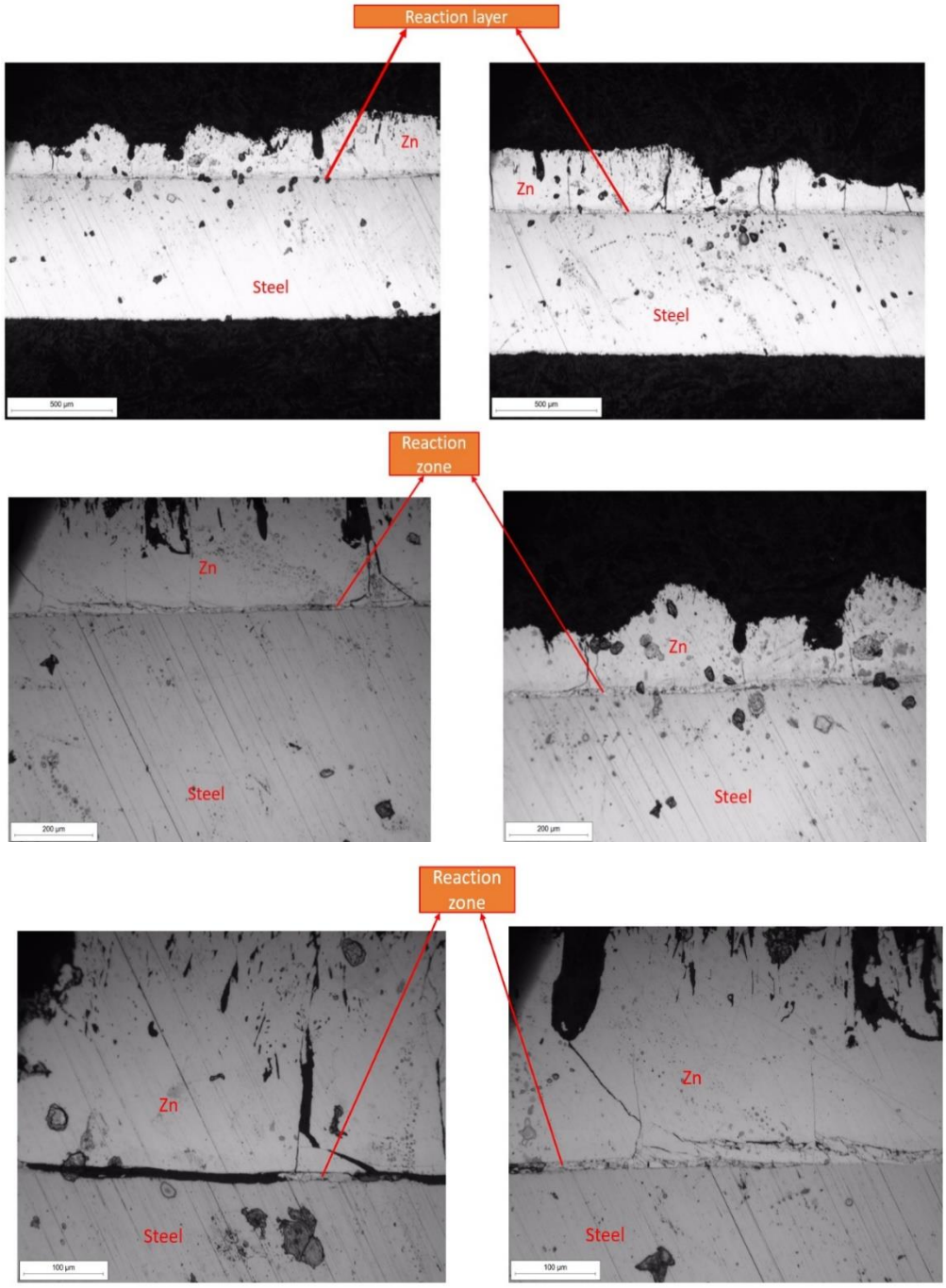


Figure 59: Optical microscope images of the transverse section of the samples of Zn-steel and Zn at different magnifications

At higher magnifications even with Optical microscope some continuous joining between Zn-coated steel and Zn can be observed. The dark spots seen in Figure 59 are polishing defects. We can say that the joining on average is not very continues.

4.3.2 Al6016 on bottom/Zn-steel / pure zinc

To verify our observation that the Al6016 failed to join because of its presence on top of sample and, during brazing it melts but unable to float in a way to join to Zn and Zn-Steel. We conducted the same reaction with all the same procedure but with Al6016 in the bottom of the sandwich. We found that this technique works, and our sample joined. So, we perform optical microscopy, SEM and EDS analysis on this new sample to better understand brazing phenomenon and joint formation.

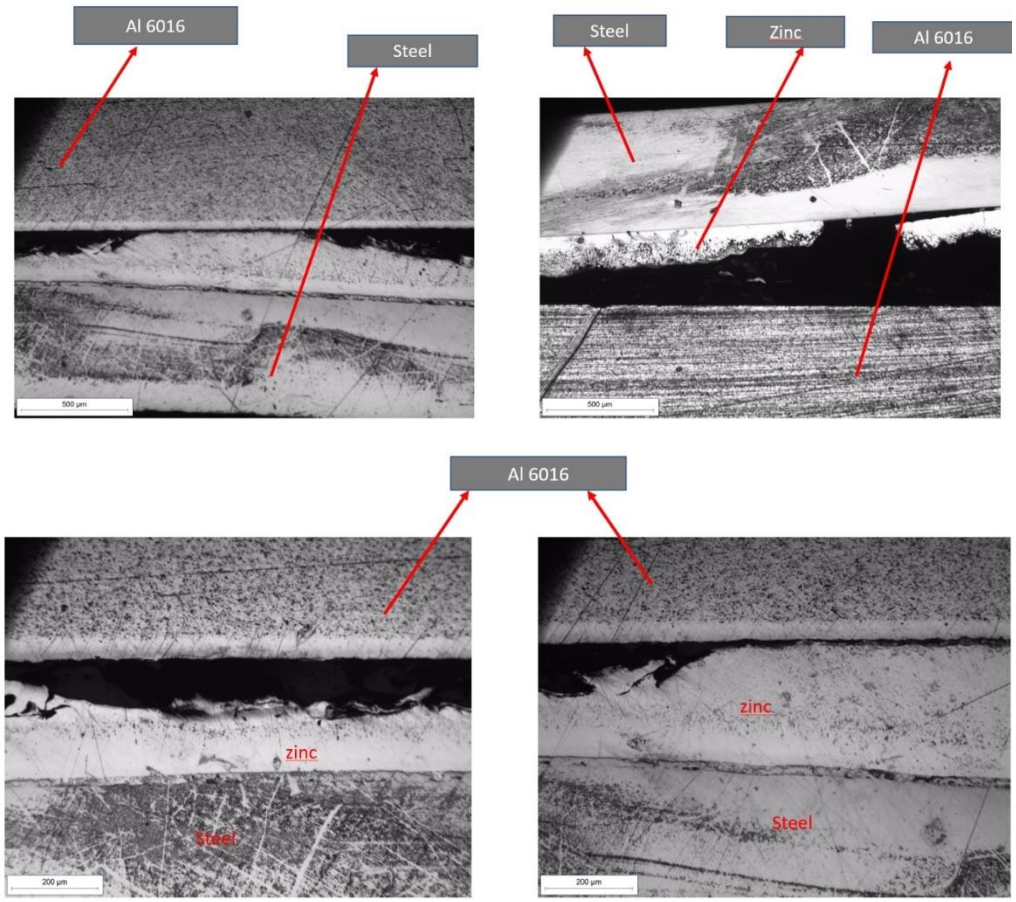


Figure 60: Optical microscope images of the transverse section of the samples of Zn-steel, Al6016 and Zn at different magnifications

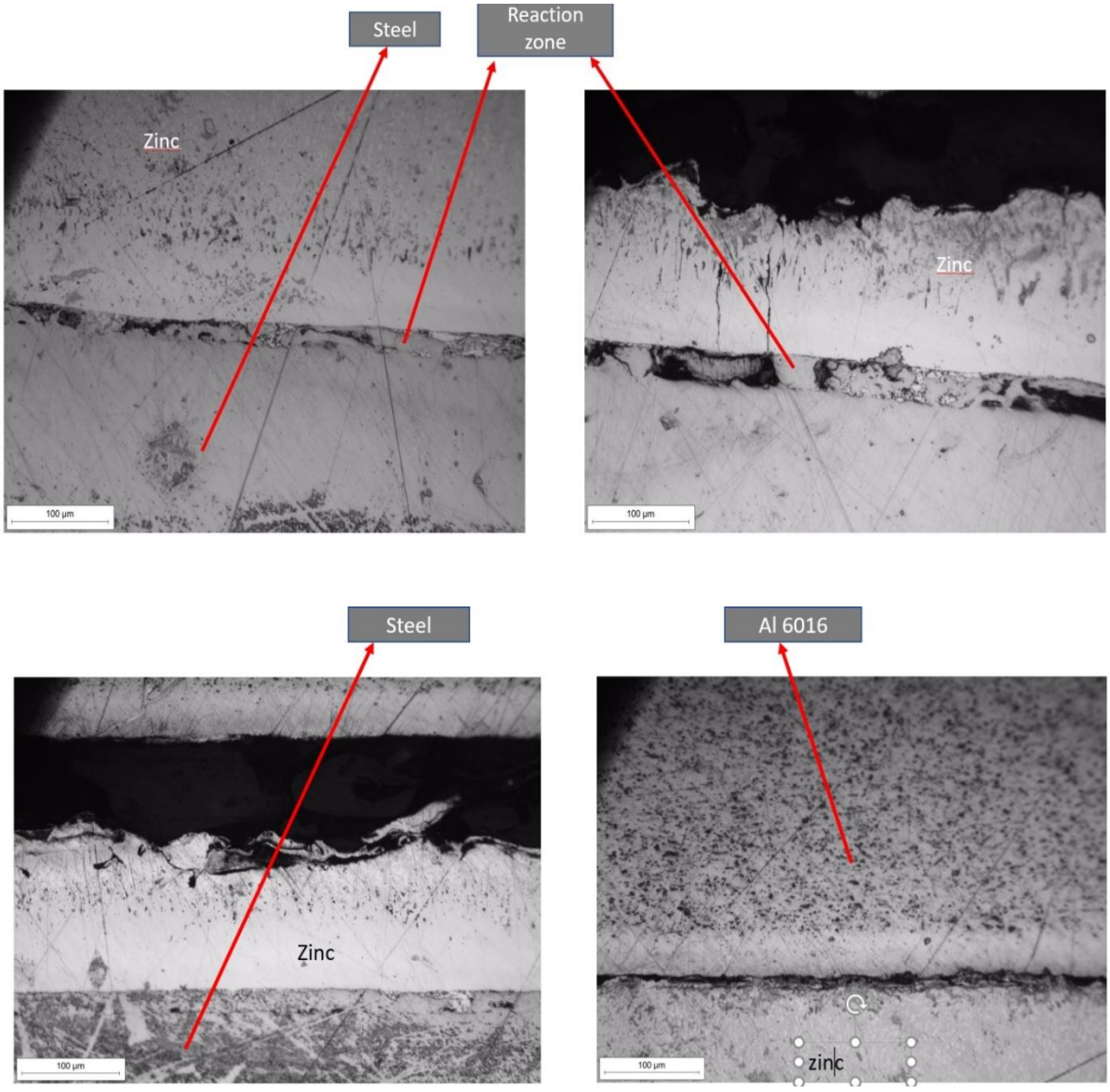


Figure 61:Optical microscope images of the transverse section of the samples of Zn-steel, Al6016 and Zn at higher magnifications

By observing the microscopic image, we have a basic idea that the overall joining of sample is not good. But, in some parts of Zn-coated steel and Zinc we have continuous joining. In case of Al6016 and Zn the reaction occurred but we don't see any appreciated joining. To analysis future and to get the idea of chemical composition we do SEM and EDS analysis. To get better results we did our final attempt to join Al6016 and Zinc coated steel. This time we took three samples of Al6016 and Zn-steel. Figure 62 (a) shows the samples after treating with P320 abrasive paper and (b) shows the sample after cleaning in ultrasonic bath.

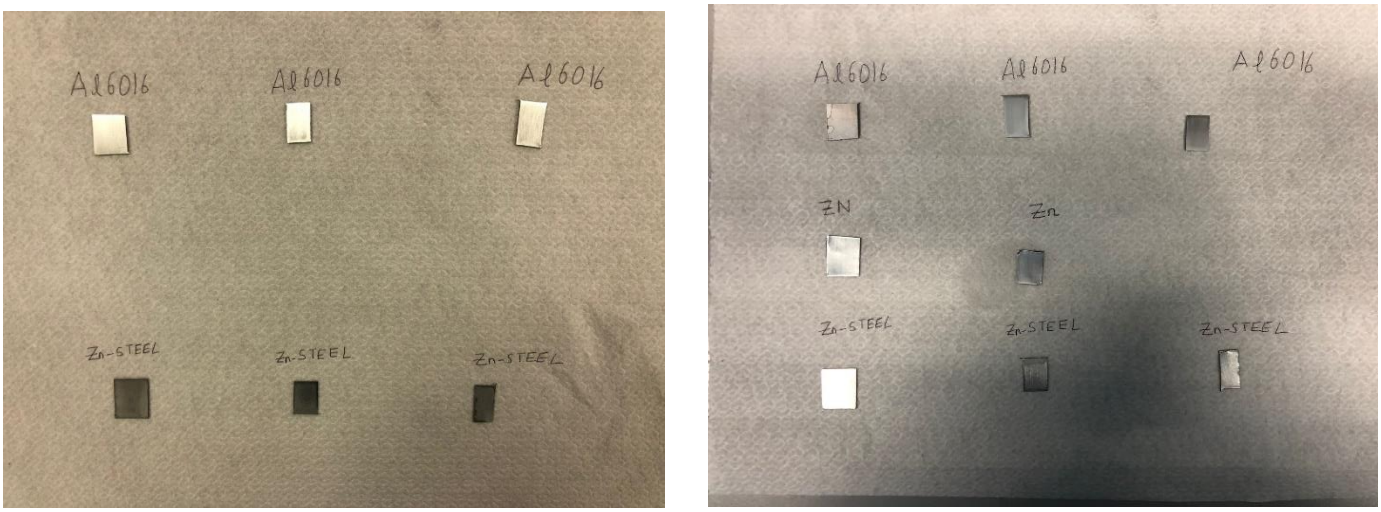


Figure 62: (a left) samples after treated with P320 abrasive paper (b right) samples after cleaning in ultrasonic bath

But we perform some slight changes for the brazing. All three samples are put in the furnace at the same time. The changes made for the experiments are discussed below:

- In the first sample we use flux comprising cesium fluoroaluminate (FLUX-AL6, Stella Welding, Albizzate (VA), Italy). The flux is only applied on the aluminum side exposed to Zn filler.
- In the second sample no flux is applied on the Aluminium.
- The sample only consists of Zn-coated steel and Al6016. Zn filler is missing in the sample.

The brazing conditions for furnace are 480°C (500°C set) with dwell time of 7 minutes and ramp is also 10°C per minutes in argon atmosphere. In figure 63 (a) we can see the sandwich arrangement for this reaction (b left) the samples after taking out of the furnace. The sample with flux was joined the other two samples failed to join. The sample without flux was not joined properly so in the process of resin and mounting it detached. The unjoin sample of Zn-Steel and Al6016 is not prepared for optical microscope observation.

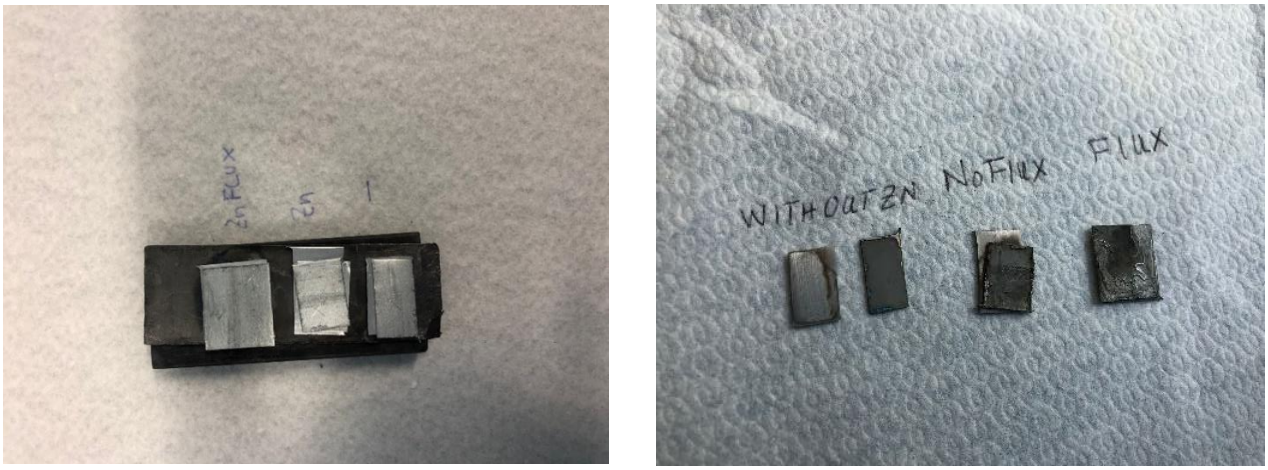


Figure 63 (left) samples for brazing (b) samples after brazing

To study the joining interface, bond morphology and joining between samples we took images from optical microscope. The results of optical microscope are shown below.

4.3.2.1 Al6016 without flux (bottom)/Zn-steel / pure zinc

Images in figure 64 are captured by optical microscope. By looking at the pictures we understand that the joining with zinc and steel is better than joining of Al6016 and zinc. This phenomenon can be attributed to the oxidation of the aluminium surface which can obstacle reaction and joining, as previously observed by the research group in the study of the reactions of Al6016 alloy with Zn based alloys and in the joining with Al-foams [41][50].

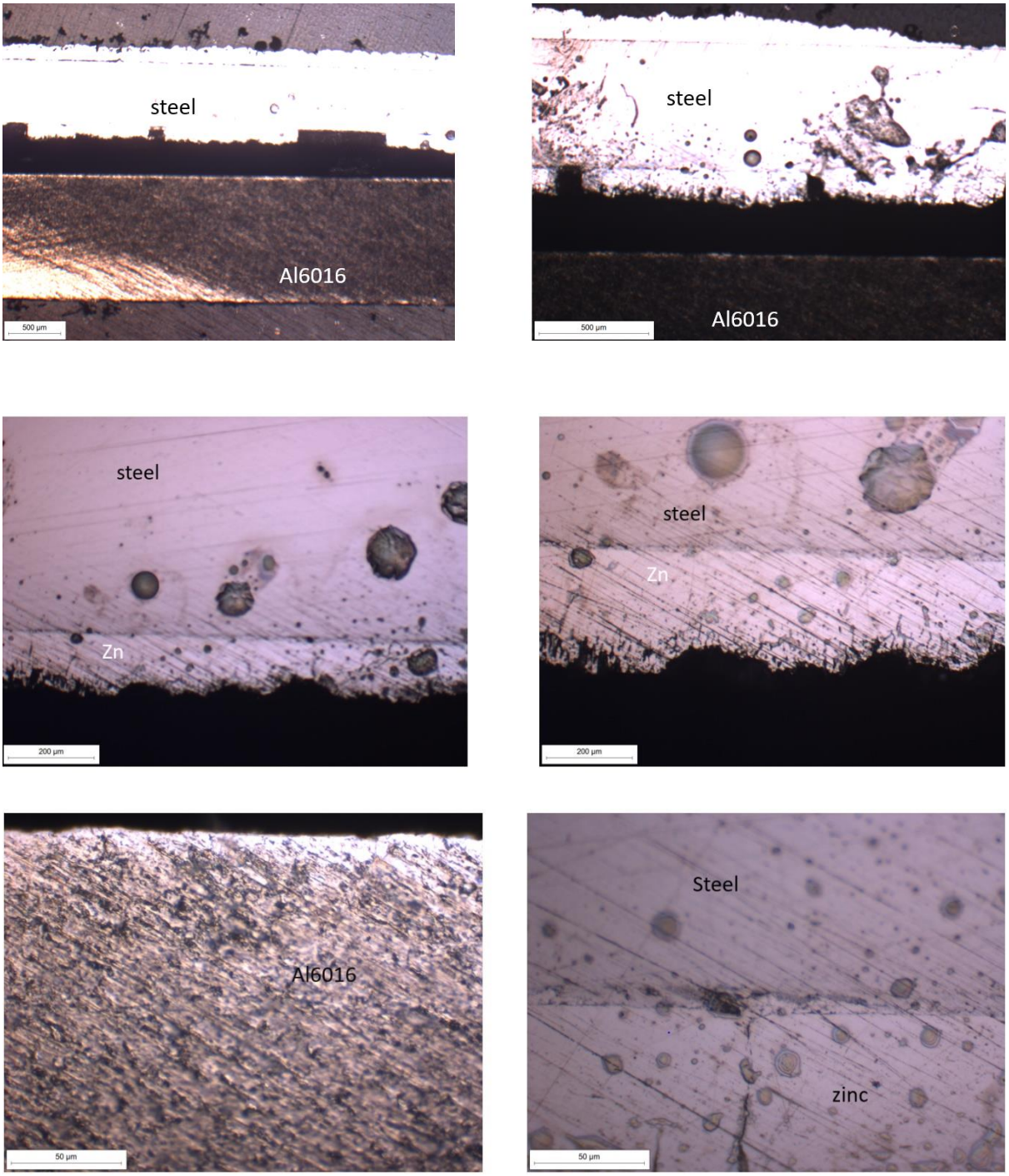


Figure 64: Optical microscope images of the transverse section of the samples of Zn-steel, Al6016 (no flux) and Zn at different magnifications

4.3.2.2 Al6016 on bottom with flux applied /Zn-steel / pure zinc

We analyse the sample of Al6016 with flux applied and Zn-coated steel on optical microscopy and some interesting results are found. Figure below shows images take by optical microscope for different magnifications.

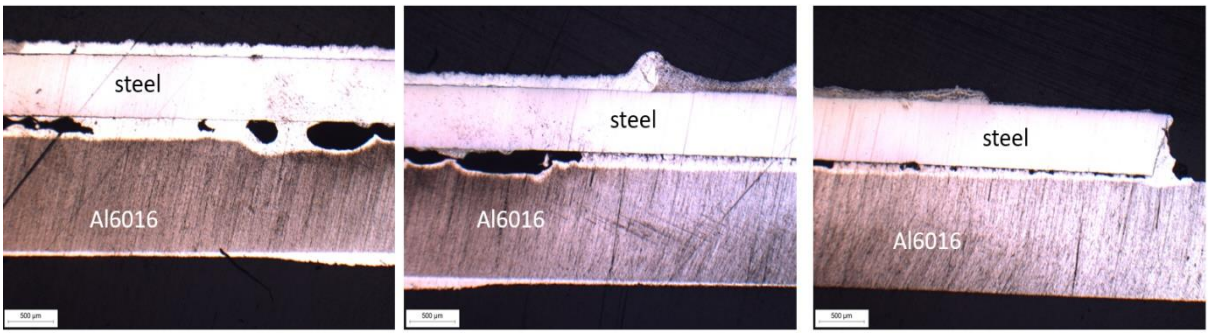


Figure 65: Optical microscope images of the transverse section of the samples of Zn-steel, Al6016 (flux) and Zn at 20x magnification

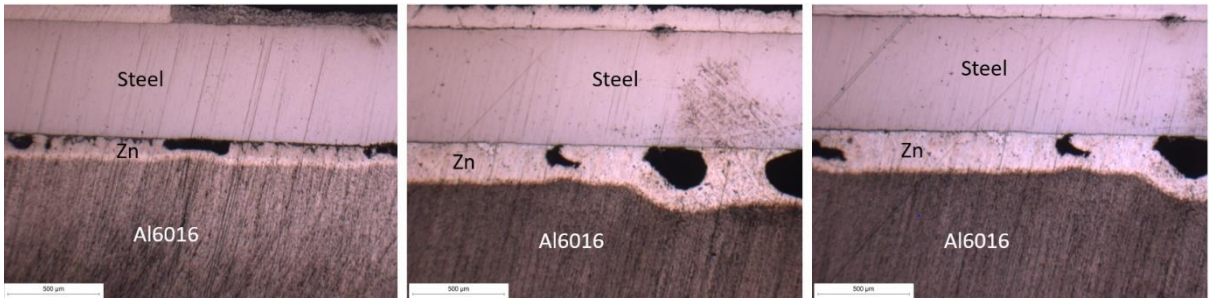


Figure 66: Optical microscope images of the transverse section of the samples of Zn-steel, Al6016 (flux) and Zn at 50x magnification

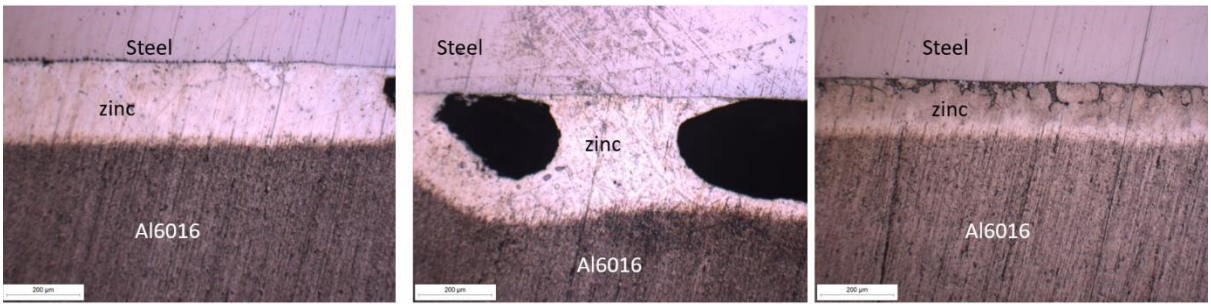


Figure 67:Optical microscope images of the transverse section of the samples of Zn-steel, Al6016 (flux) and Zn at 100x magnification

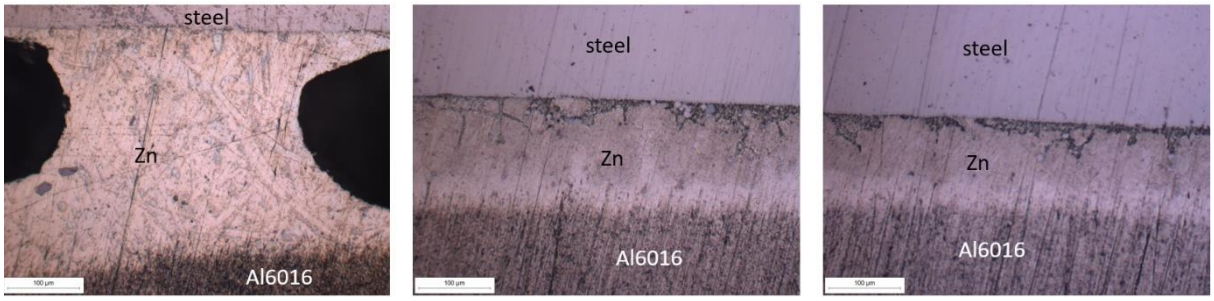


Figure 68: Optical microscope images of the transverse section of the samples of Zn-steel, Al6016 (flux) and Zn at 200x magnification

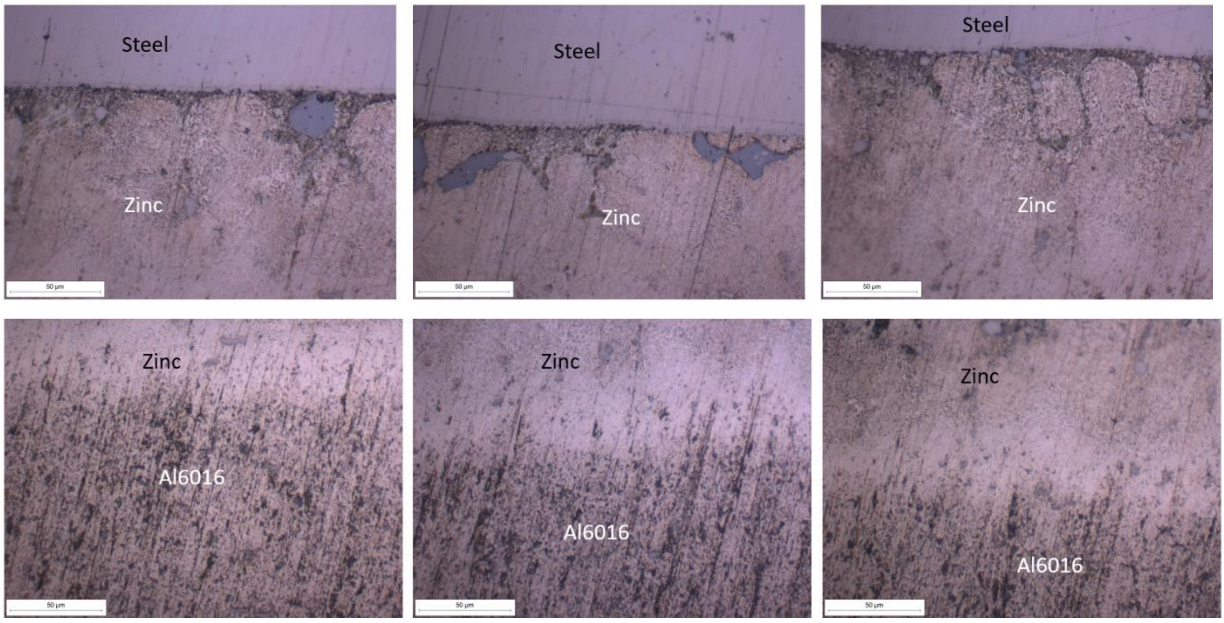


Figure 69:Optical microscope images of the transverse section of the samples of Zn-steel, Al6016 (flux) and Zn at 400x magnification

To better observe the sample, we use SEM. SEM gives images with higher magnifications.

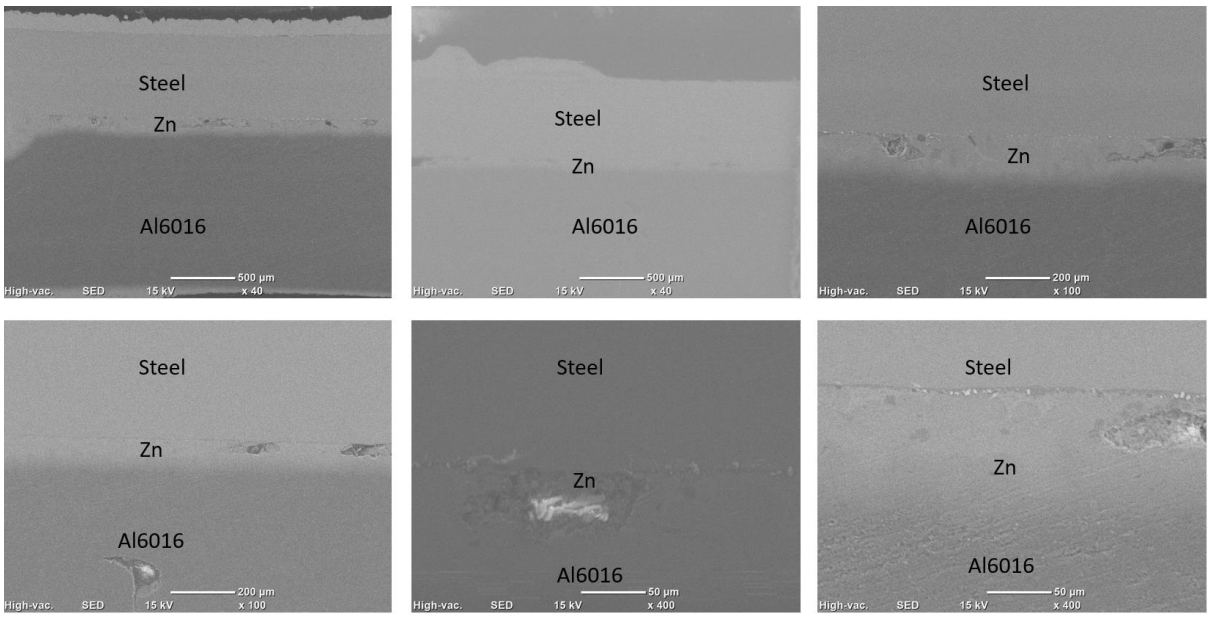


Figure 70: SEM images for Al6016(flux), Zn-coated Steel and Zn at 40x, 100x, 200x, 400x

To better understand the joining interface and reaction zone point analysis at different point in the sample is performed by SEM and EDS. EDS gives the details of the chemical compositions at selected points.

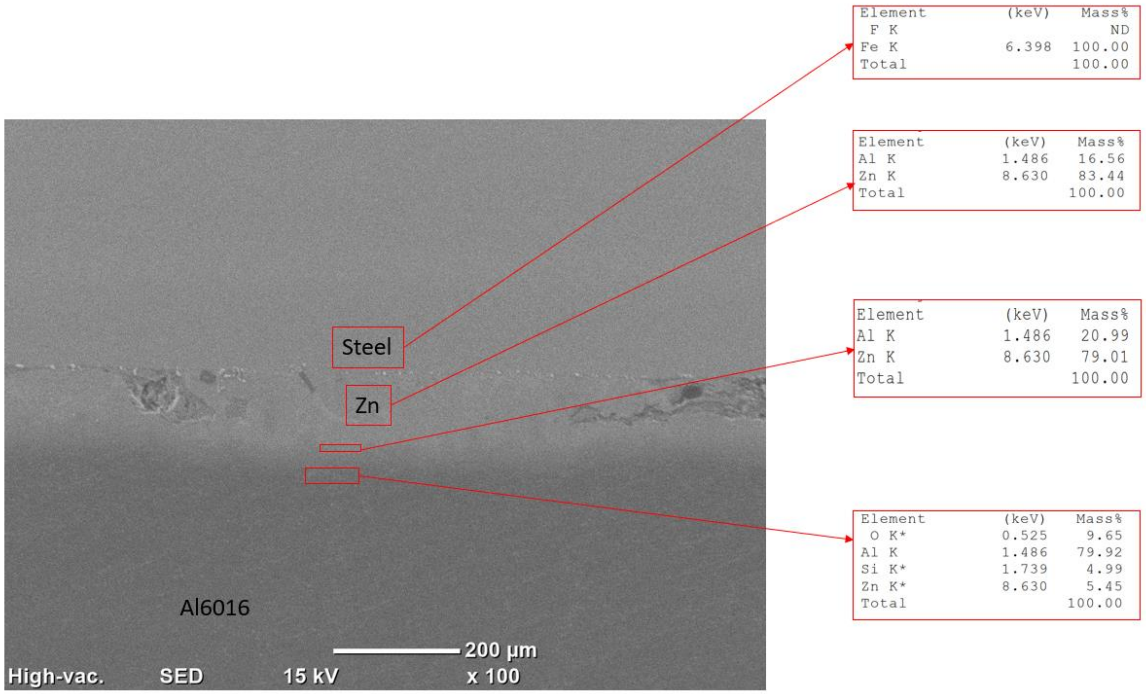


Figure 71: Point analysis using SEM and EDS of Al6016(flux), Zn-steel and Zn at 100x magnification

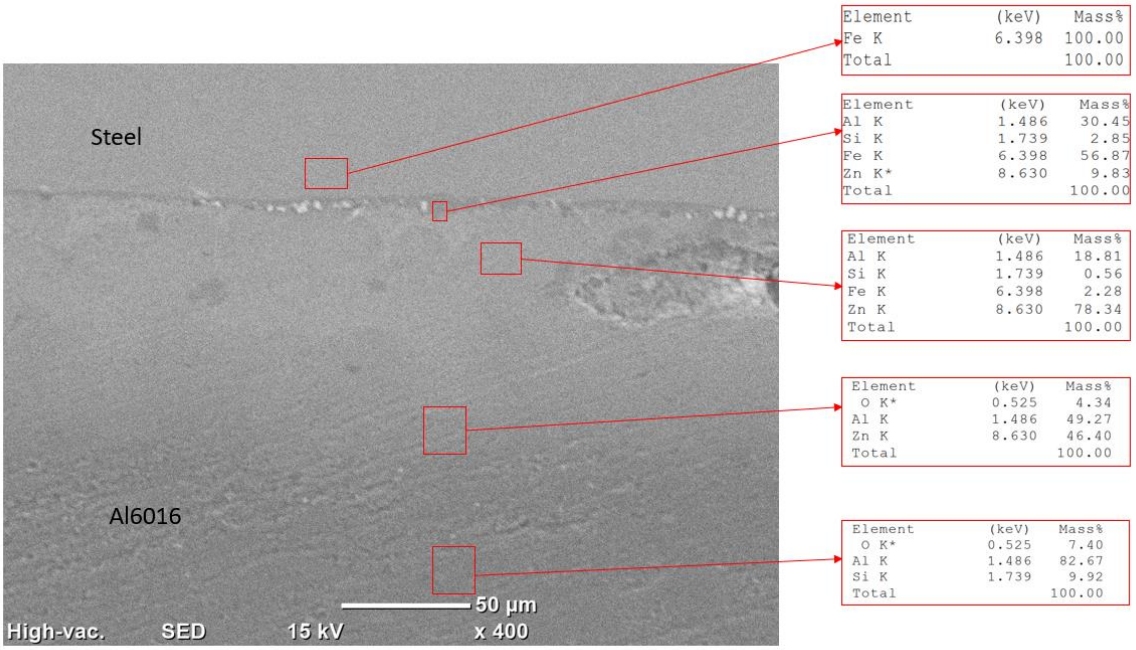


Figure 72: SEM and EDS analysis of Al6016(flux), Zn-steel, Zn at 400x magnification

Optical and SEM images evidence the continuity of the joint. EDS analysis show the reaction between zinc filler and aluminium with the diffusion of aluminium in the zinc layer up to the interface with the steel side.

4.4 Joining of Al5182 and Zinc coated still using Zama filler

Aluminum alloy Al5182 belongs to the 5000 series of aluminum alloys which are known for their good corrosion resistance. They are mainly used in buildings and automotive sector. So, we try to braze join the Al5182 with Zn-coated steel. The filler used this time is Zama which is an alloy of Zinc. We perform different experiments the details of which are discussed below.

4.4.1 Al5182/Zinc coated steel braze with Zama @5 minutes

The first try was made with Al5182 and Zn-coated steel with 2 layers of Zama. Al5182 and Zn coated steel are washed with ethanol solution for 5 minutes in ultrasonic bath. The conditions for furnace are 540°C set but real temperature inside furnace is 520°C, dwell time is 5 minutes, and the ramp is 10°C per minutes. Al5182 is placed on the bottom covered by Zama and on the top, we have Zn-Steel. After brazing the sample seemed to be joined but later in the process of resin mounting the sample detached. By the detachment of the sample, we can understand that the joining is not strong. We perform metallography with optical microscope to see the details of the reaction zone.

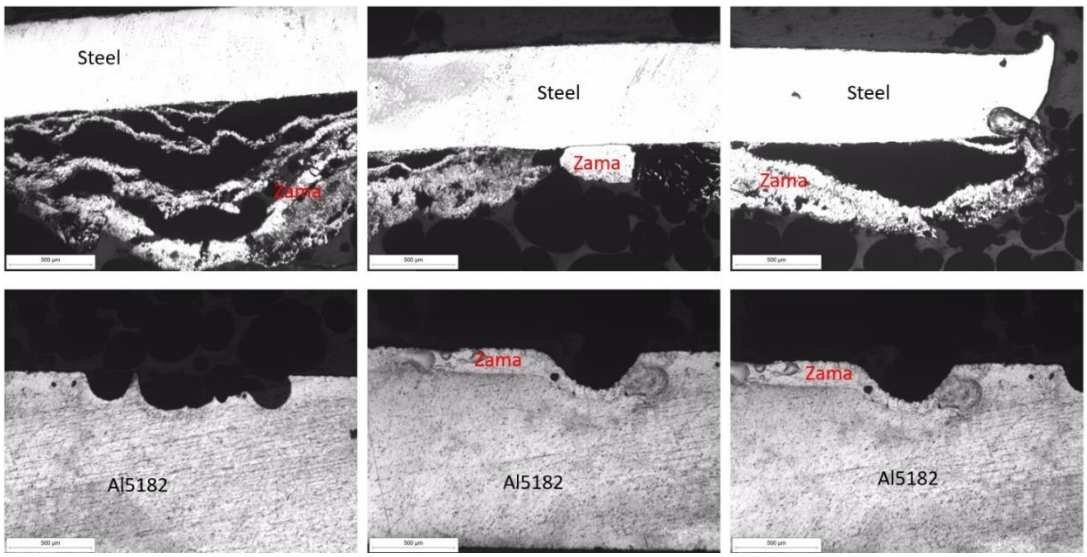


Figure 73: Optical microscope images of the transverse section of the samples of Zn-steel, Al5182, Zama at 20x magnification

Optical images evidence that reaction occurred both on the steel and on the aluminium sides, but the ZAMA layer resulted not continuous to guarantee a good joint. This discontinuity can be associated with the irregular surface of the ZAMA chips and to the presence of two layers which resulted in poor contact between the brazing material and the surfaces to be joined.

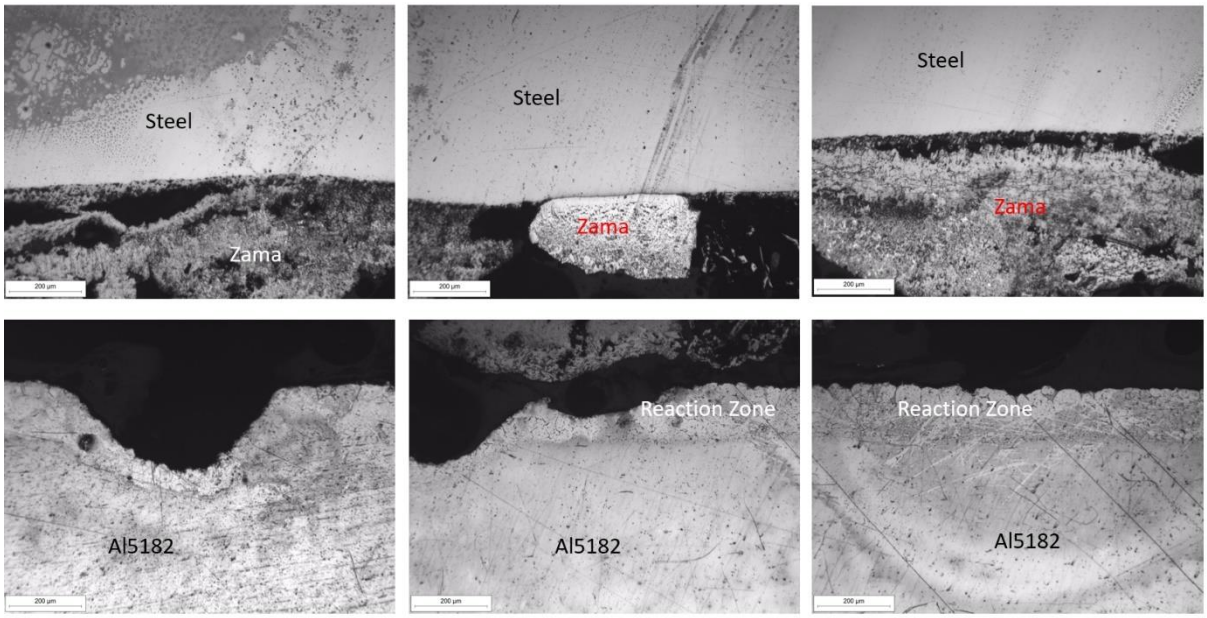


Figure 74: Optical microscope images of the transverse section of the samples of Zn-steel, Al5182, Zama at 50x magnification

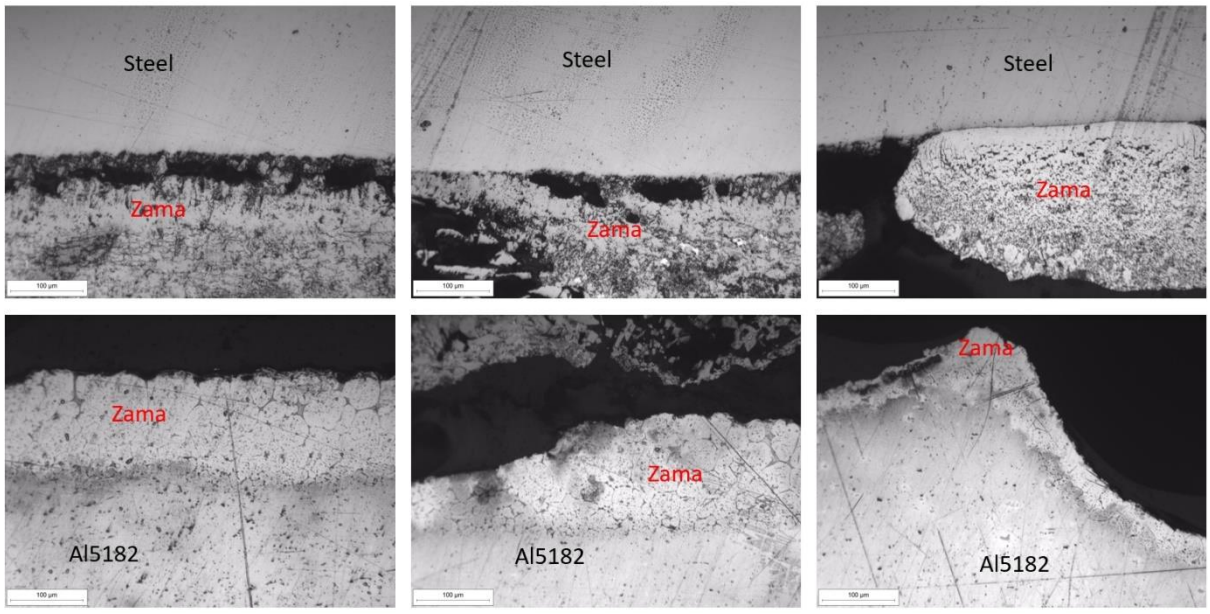


Figure 75: Optical microscope images of the transverse section of the samples of Zn-steel, Al5182, Zama at 100x magnification

To have a better understanding of the composition of the reacted sample we did the SEM and EDS analysis.

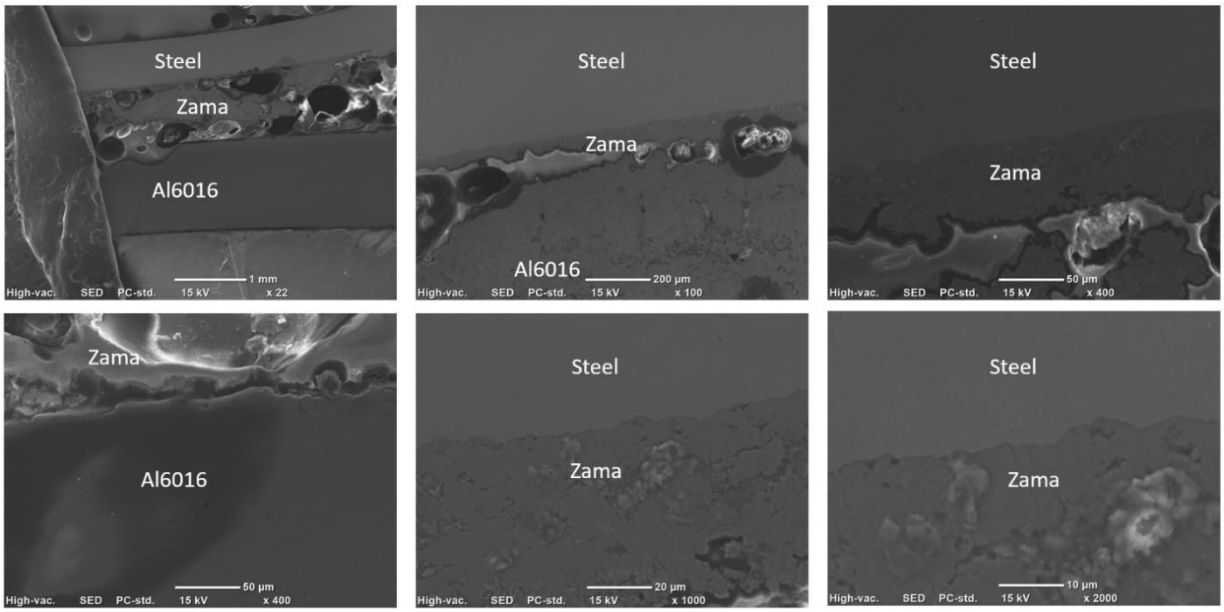


Figure 76: SEM images for Al5182, Zn- Steel, Zama at 22x, 100x, 400x, 1000x, 2000x magnification

The details of chemical composition of the Al5182, Zn-Steel and Zama can be found by the EDS analysis. The reaction is confirmed by the presence of Al, Zn and Fe in the reaction layer.

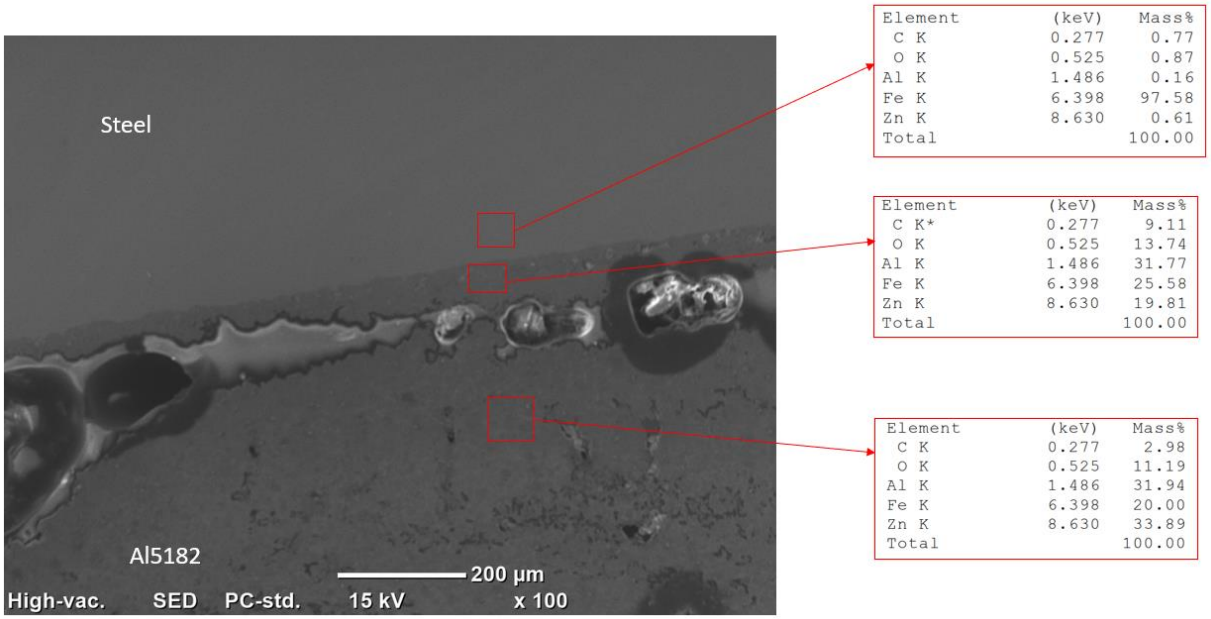


Figure 77: EDS analysis of Al5182, Zn-steel and Zama

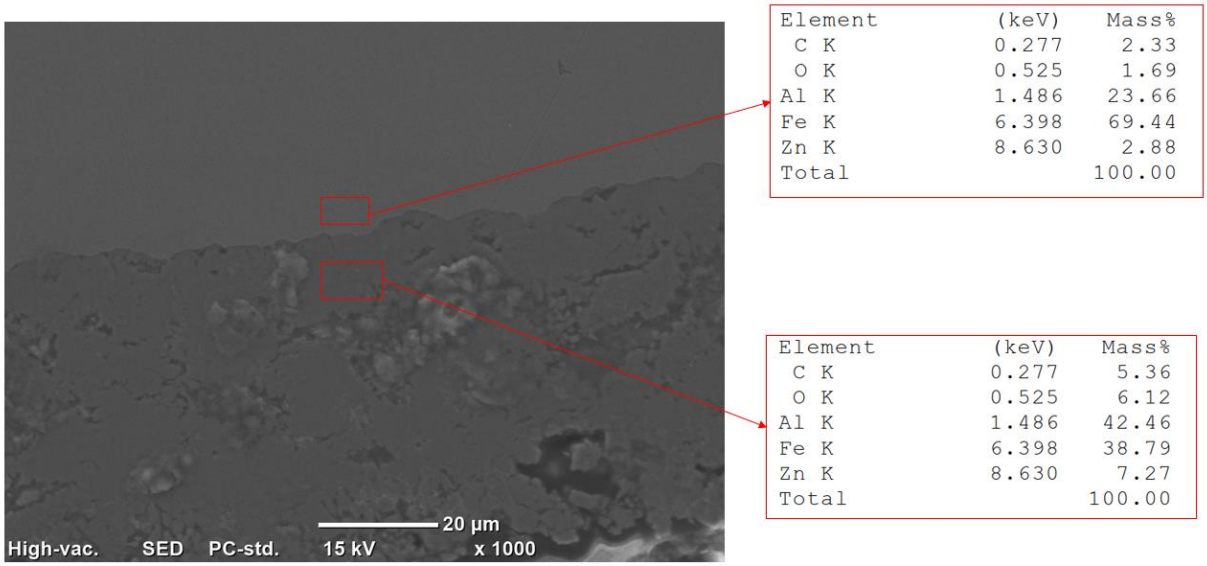
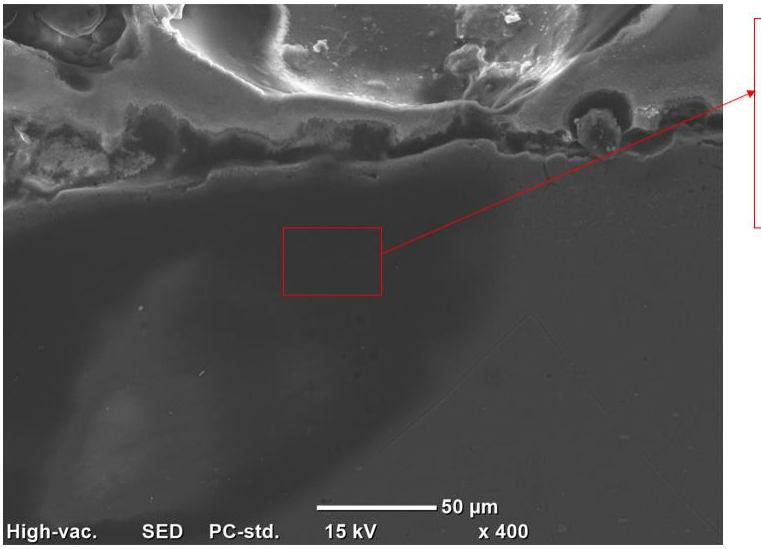


Figure 78 : EDS analysis of Al5182, Zn-steel and Zama



Element	(keV)	Mass%
C K	0.277	52.60
O K	0.525	28.38
Al K	1.486	14.81
Fe K	6.398	0.15
Zn K	8.630	4.05
Total		100.00

Figure 79: EDS analysis of Al5182, Zn-steel and Zama

4.4.2 Al5182/Zinc coated steel braze with Zama @7 and 10 minutes

We performed another experiment with all the same conditions the only changes are the dwell time i.e., 10 minutes. Al5182 and Zn-steel failed to join so we decided to change the brazing conditions. In figure 80 we can see the unjointed sample of Al5182 and Zn coated steel. The fact that samples failed to join is considered to be the large dwell time.

Figure 80: Unjoin sample of Al5182, Steel and Zama for 10 minutes dwell time

So, this time we put two samples at the same time in the furnace. The details of the experiments are discussed below:

- In the first sample the Al5182, Zn- Steel and Zama all are washed with ethanol in ultrasonic cleaner for 5 minutes.
- Al5182 and Zn-steel are just washed in ethanol solution in ultrasonic cleaner for 5 minutes. Zama chips are not washed with ultrasonic cleaner.
- The dwell time for both of the above discussed sample is 7 minutes with ramp of 10°C per minute. The temperature of the furnace is set at 540°C but the real felt temperature is 520°C.

The samples in which also the Zama chips are washed in ethanol are joined but the other one failed to join, this can be attributed to the presence of contaminations on the ZAMA chips, due probably to the production process, which can hamper the reaction with the metallic substrates to be joined. Figure 81 shows both joined and not joined samples before and after brazing. So, we perform Optical microscope analysis for the joined sample.

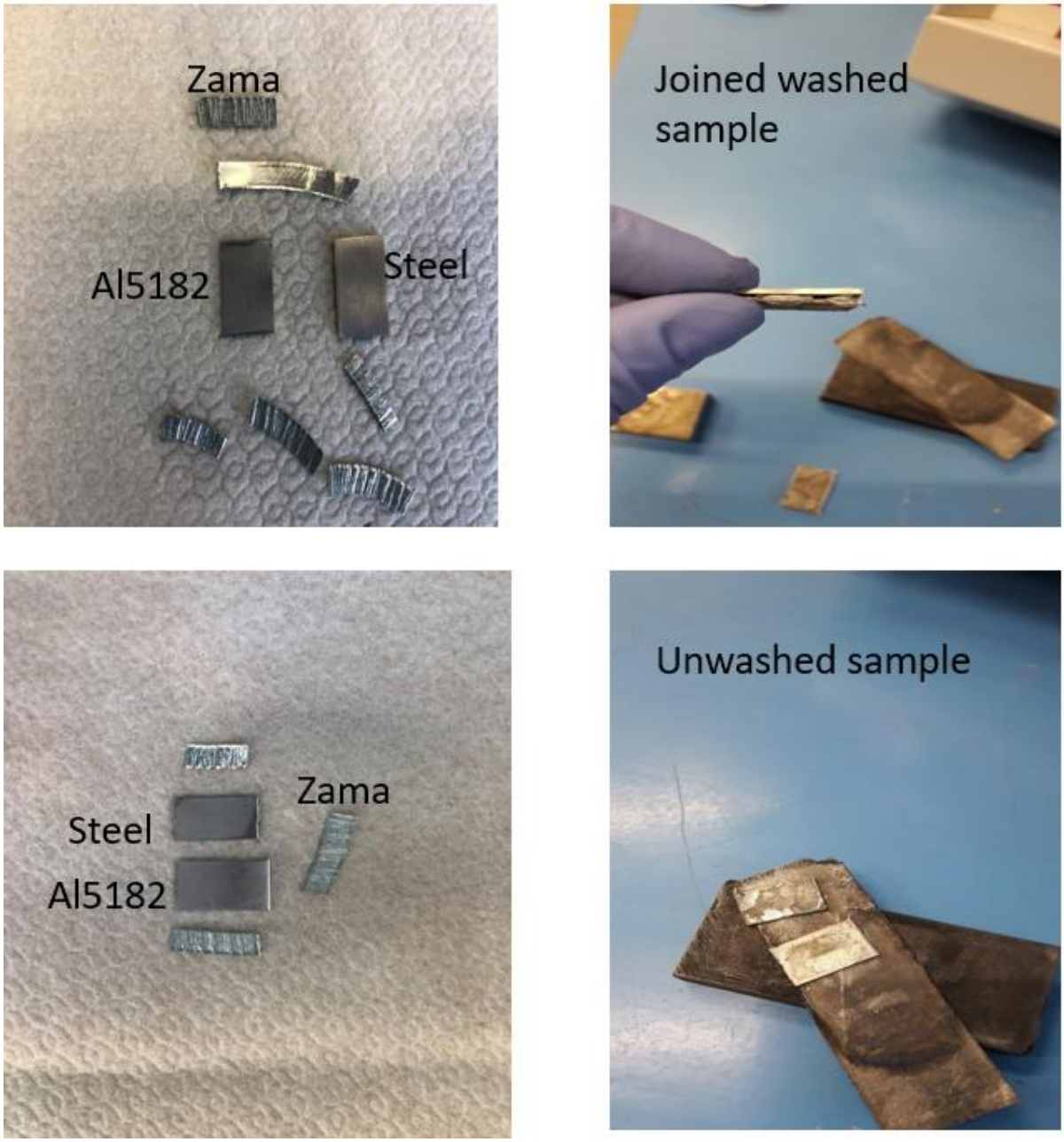


Figure 81: Al5182, Zn-steel and Zama before and after brazing for 7 minutes

So, we perform Optical microscope analysis for the joined sample. The images take by optical microscope are shown in the figure below.

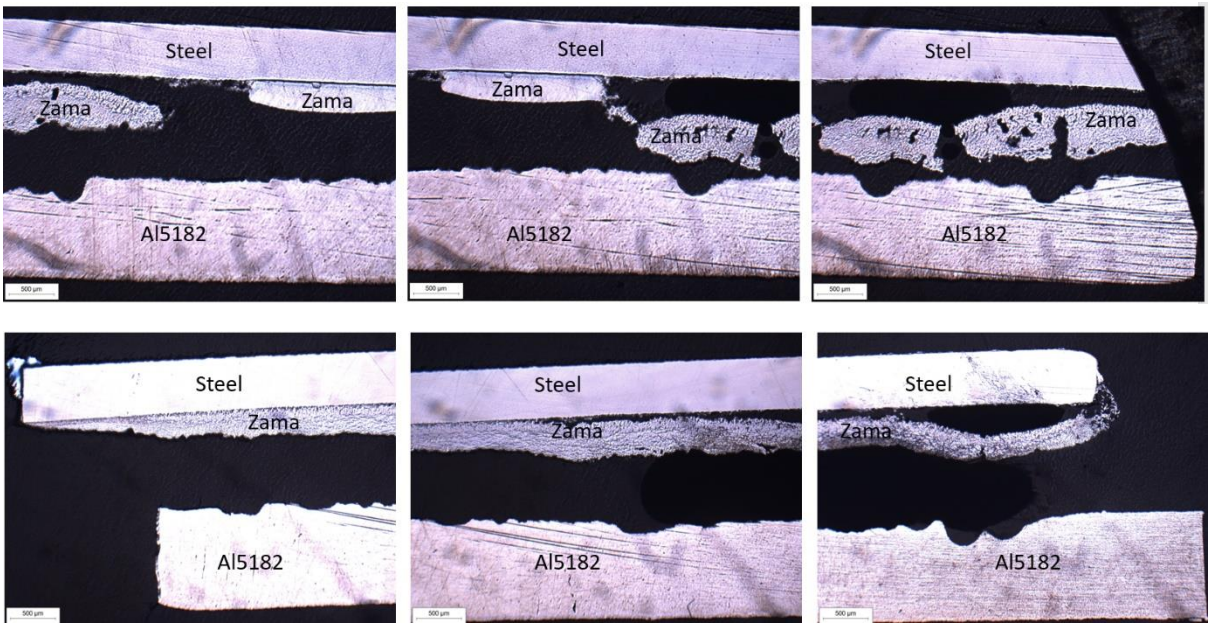


Figure 82: Optical microscope images of the transverse section of the samples of Zn-steel, Al5182, Zama at 20x magnification

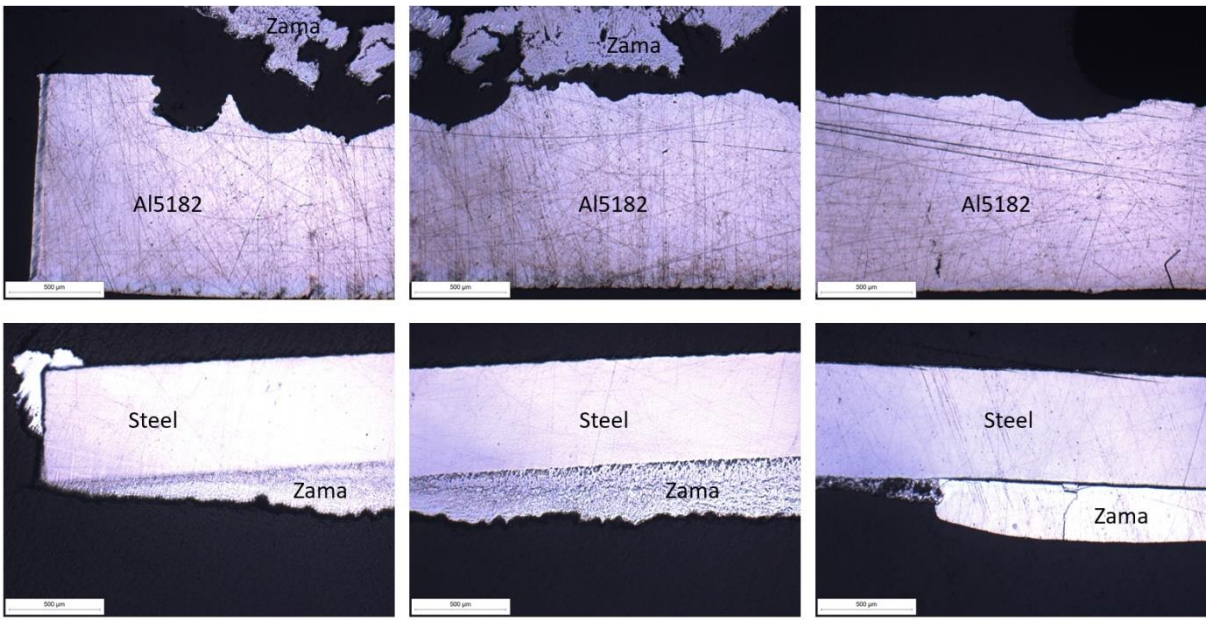


Figure 83: Optical microscope images of the transverse section of the samples of Zn-steel, Al5182, Zama at 50x magnification

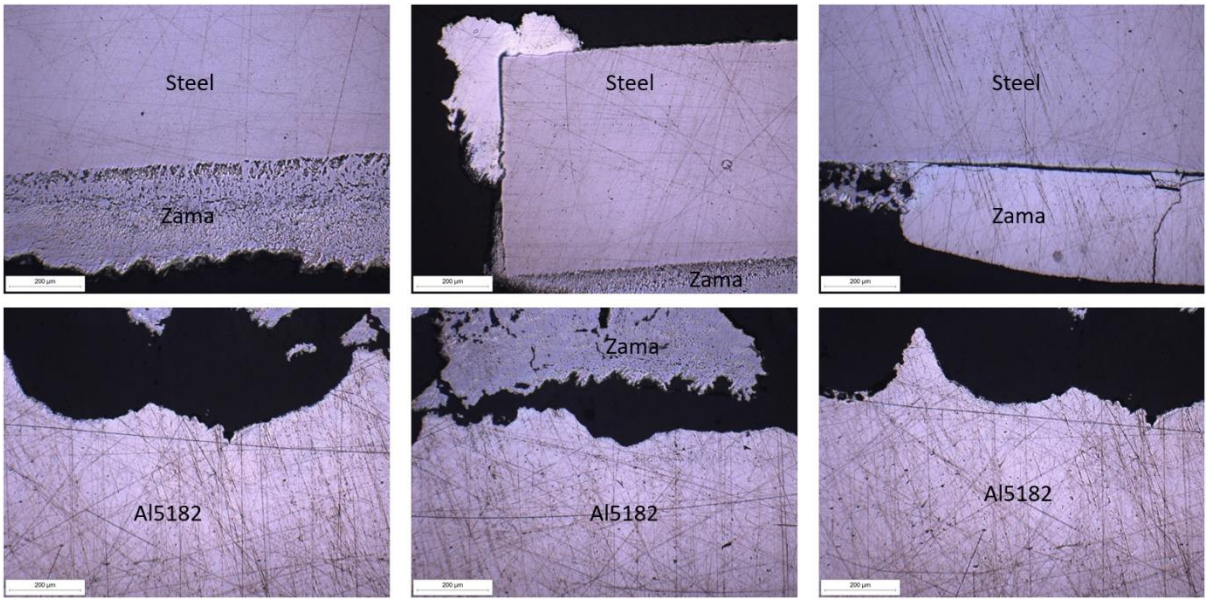


Figure 85: Optical microscope images of the transverse section of the samples of Zn-steel, Al5182, Zama at 100x magnification

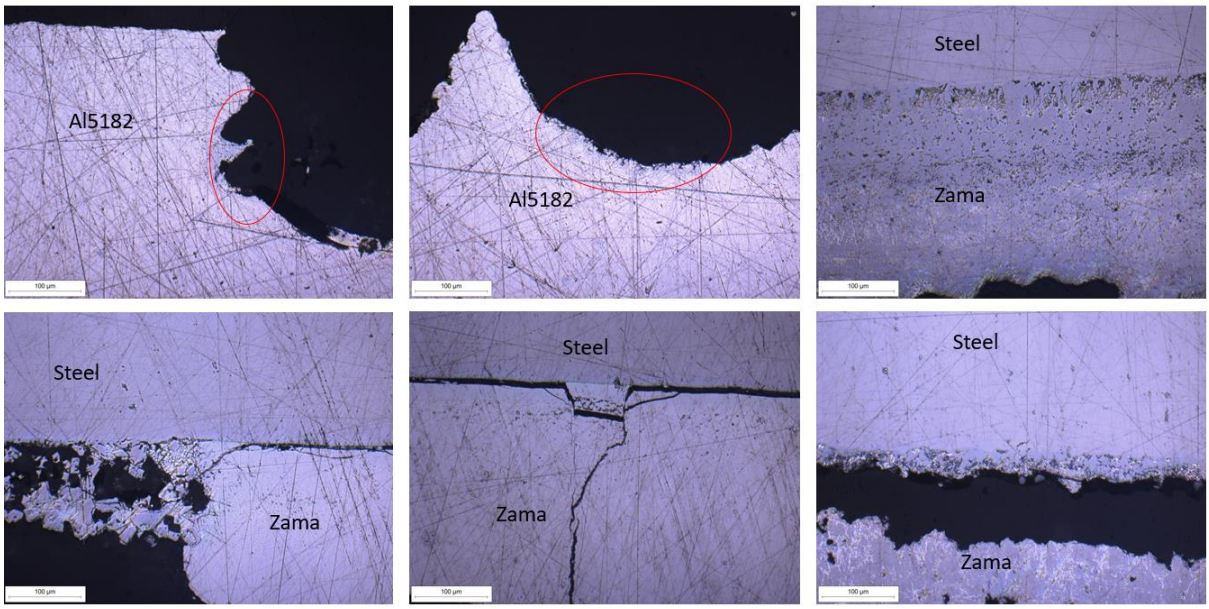


Figure 84: Optical microscope images of the transverse section of the samples of Zn-steel, Al5182, Zama at 200x magnification

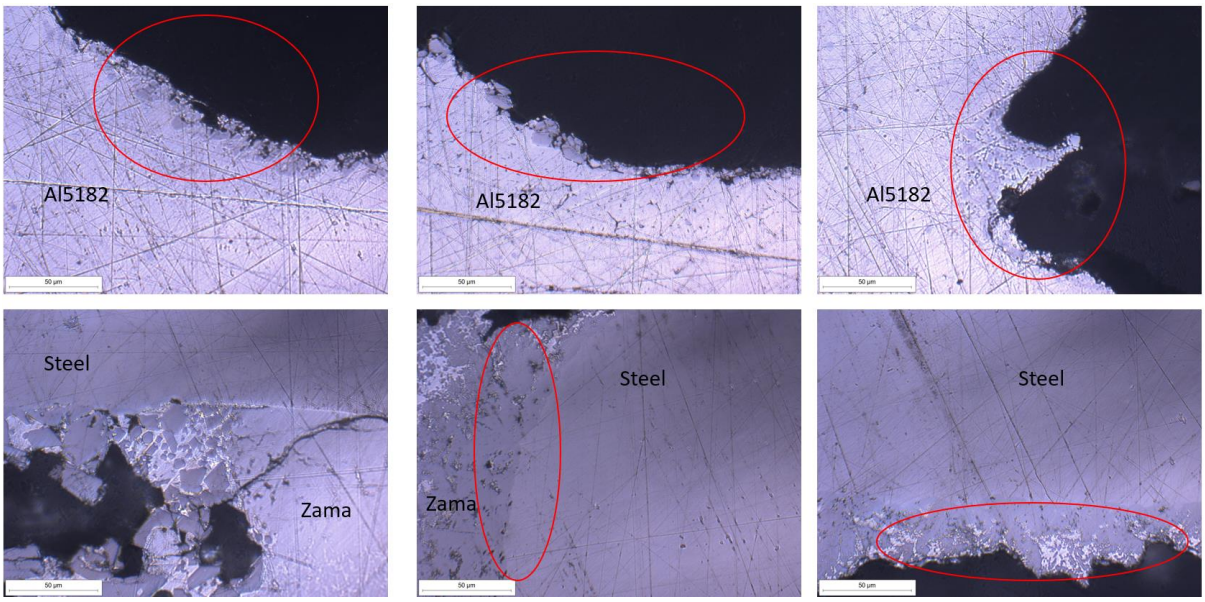


Figure 86: Optical microscope images of the transverse section of the samples of Zn-steel, Al5182, Zama at 500x magnification

The ZAMA-Zn-coated steel interface appears continuous in various points, evidencing an affective reaction during brazing. A reaction layer is clearly visible also on the aluminium side, however the bonding with the ZAMA and the Zn-coated steel is not continuous.

4.5 Al-Foam Joined to Zn-coated steel with Zinc as filler metal

For weight-sensitive applications, aluminum metal foam materials, which may be manufactured into a range of useful shapes, provide considerable performance advantages. Metal foams have good stiffness-to-weight and strength-to-weight ratios, which means they may save weight. They can also absorb a lot of energy during compressive deformation, which helps with crash energy management [42]. So, we decided to braze join the two most important materials for automotive industry that is Al-foam and Zn-Steel with zinc as brazing filler. Nitric acid etching of Al-foam was done in order to dissolve the aluminum oxide surface layer and to favour the joining process. Two samples are placed inside the furnace at same time. The details are discussed below:

- In the first sample cesium fluoroaluminate containing flux is applied on the surface of Al-foam exposed to zinc.
- No flux is applied on the second sample
- Sandwich for the furnace is prepared by placing the Al-foam in the centre and covered by Zn. On the top Steel covers the Zinc.
- The temperature for furnace is 480°C (500°C set) with the dwell time of 7 minutes. Ramp is in minutes and temperature increase and decrease by 10°C per minute.

Both the samples are joined and there optical, SEM and EDS analysis are discussed below.

4.5.1 Al-Foam (with flux) joining with Zn-Steel / Zn

For the basic analysis of the joining, sample is observed under optical microscope.

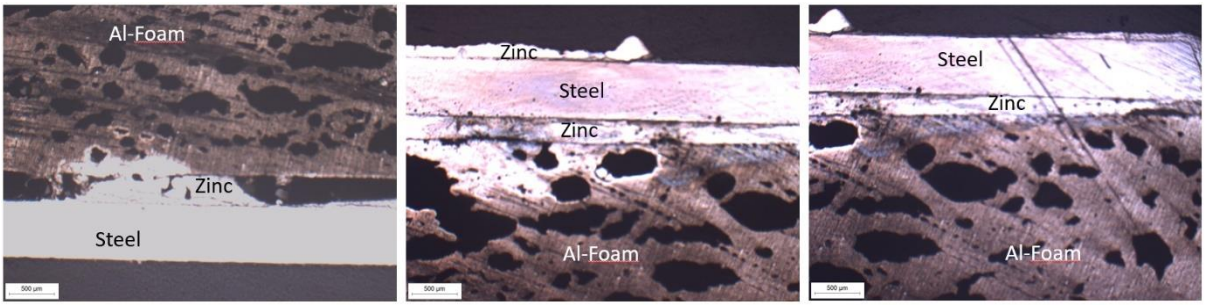


Figure 87: Optical microscope images of the transverse section of the samples of Zn-steel, Al-Foam, Zinc at 20x magnification

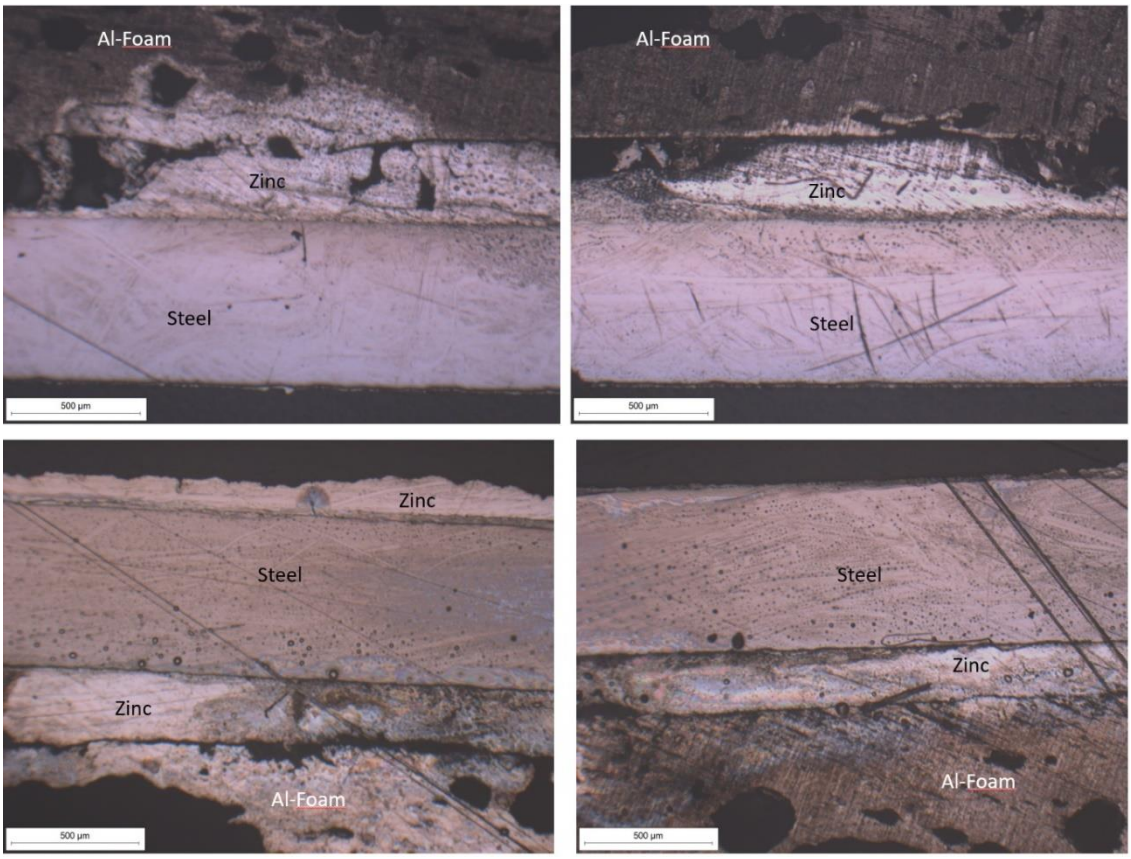


Figure 88: Optical microscope images of the transverse section of the samples of Zn-steel, Al-Foam, Zinc at 50x magnification

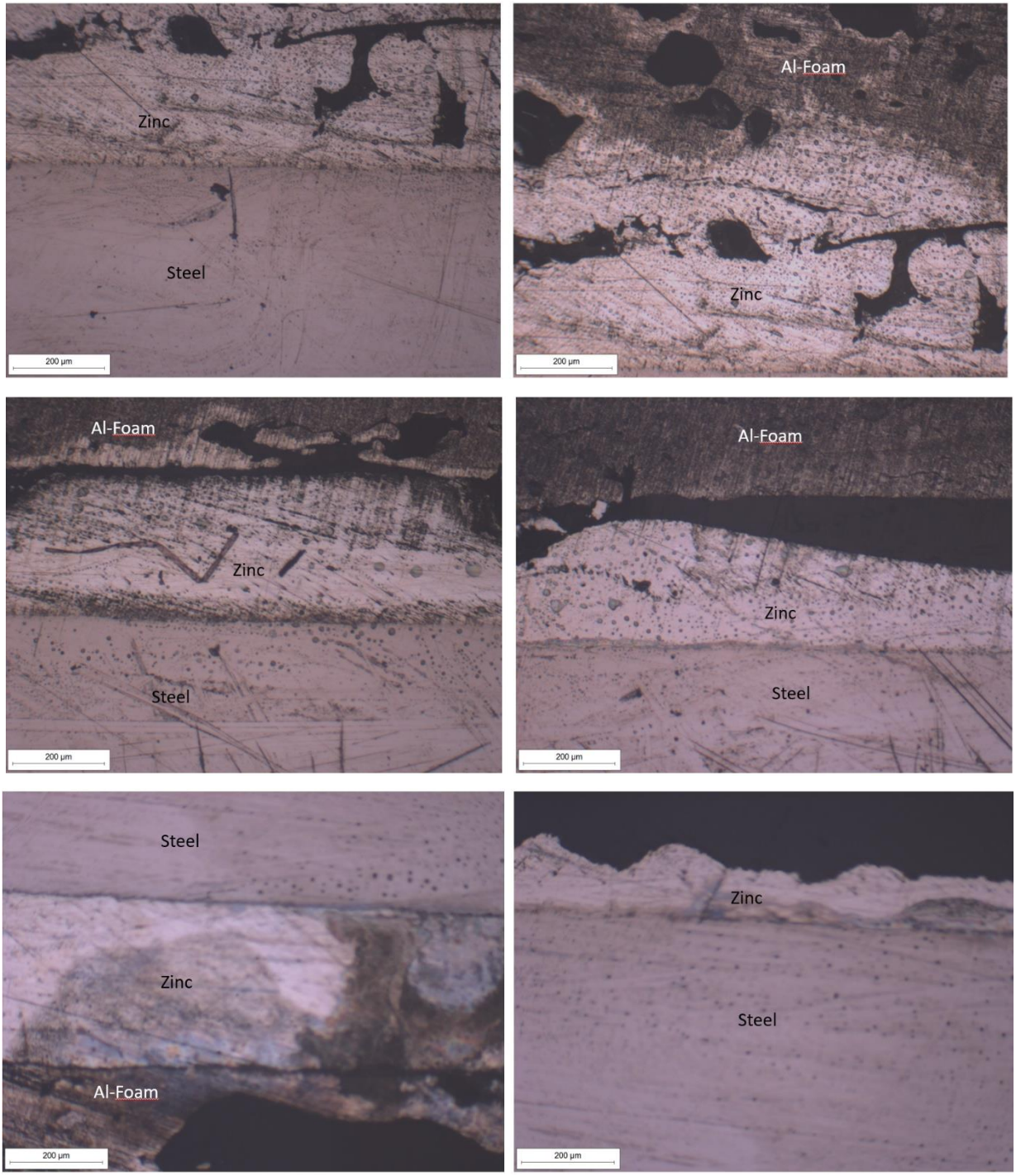


Figure 89: Optical microscope images of the transverse section of the samples of Zn-steel, Al-Foam, Zinc at 100x magnification

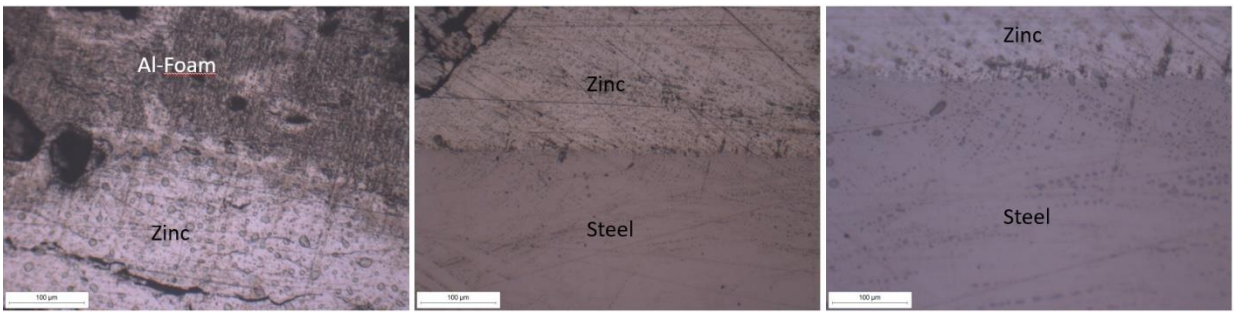


Figure 90: Optical microscope images of the transverse section of the samples of Zn-steel, Al-Foam, Zinc at 200x magnification

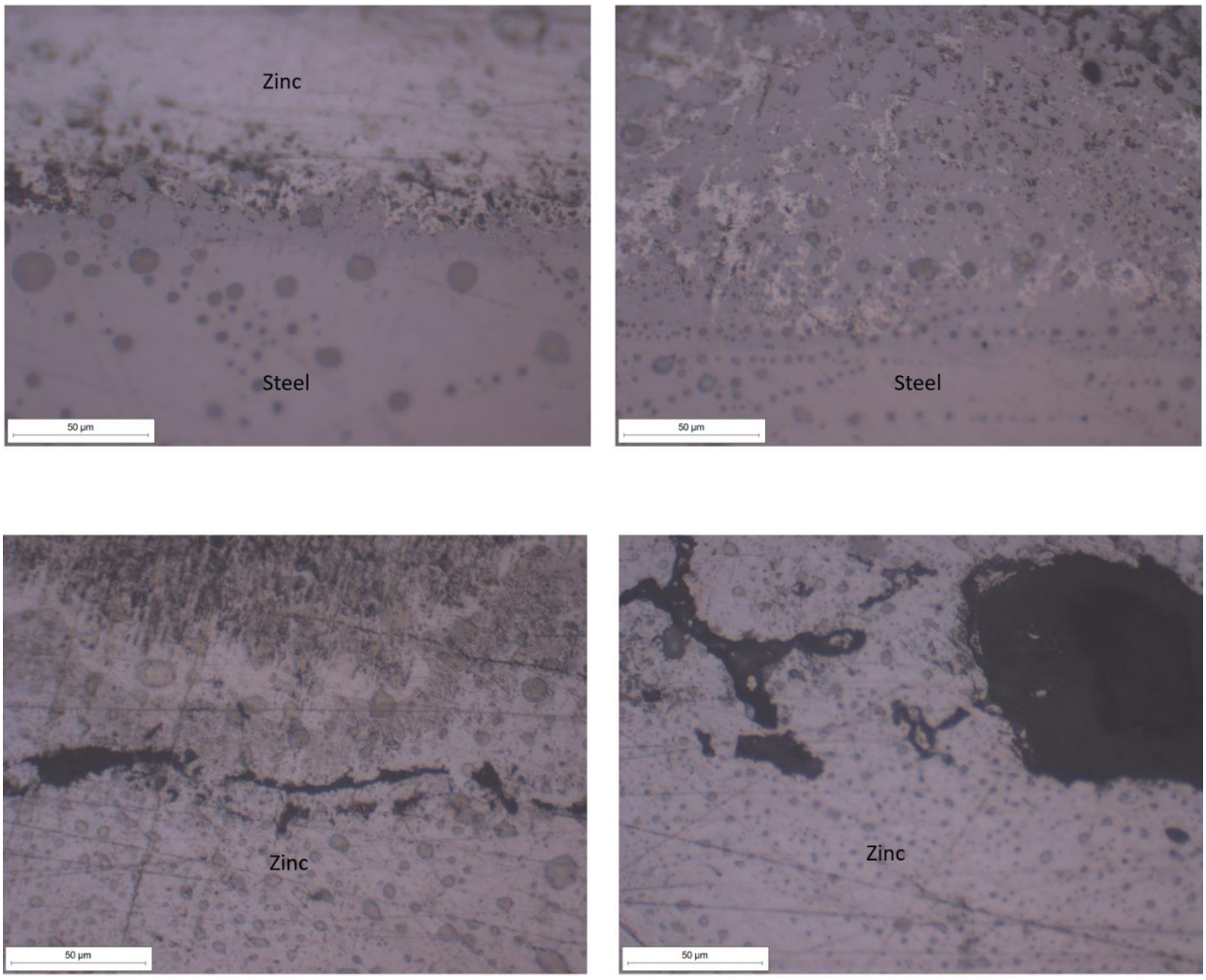


Figure 91: Optical microscope images of the transverse section of the samples of Zn-steel, Al-Foam, Zinc at 500x magnification

The interface is continuous on both sides (aluminium foam and Zn-coated steel) in many points.

The Zn layer is partially melted and removed in some zones of the top surface of the Zn-coated steel sheet. This phenomenon is due to the temperature reached during brazing and it is useful in the joining zone, in order to allow reactions between the brazing material (zinc) and the surfaces to be joined, however it should be taken into account because can alter the properties of the outer surfaces of the steel sheet.

Sample is future observed under Scanning Electron microscope to get images at higher magnifications.

SEM images confirm the continuity of the interface and evidence the dendritic morphology of the Zn brazing material due to melting and solidification during the brazing process.

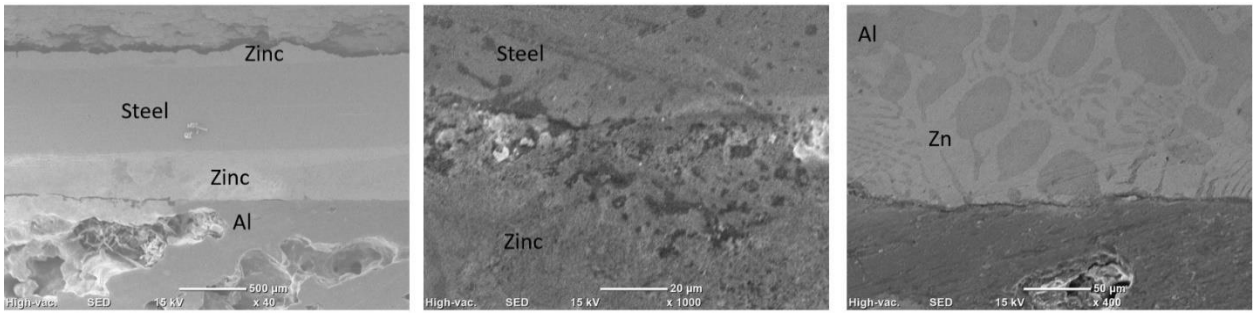


Figure 92: Images taken by SEM at 40x, 1000x and 400x

EDS analysis shows the composition in different places of the sample. In Figure 94 the diffusion of Zn in the reaction layer on the surface of the AL-foam is clearly visible.

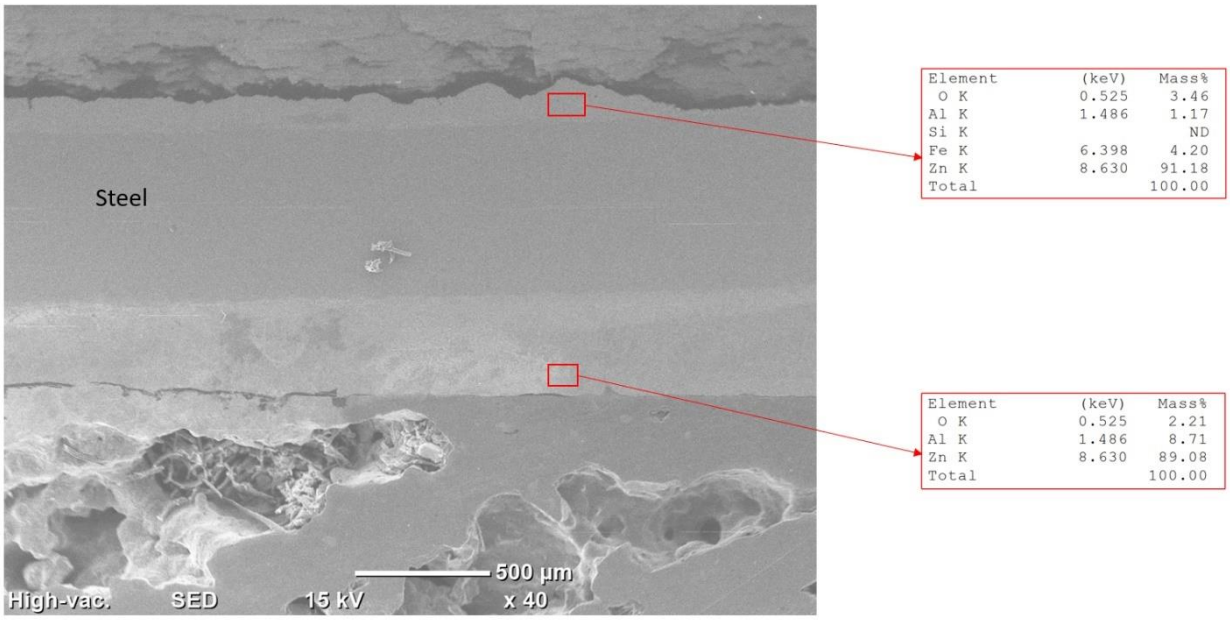


Figure 93: EDS analysis of Al-foam (FLUX), Zn-Steel and Zn at 40x magnification

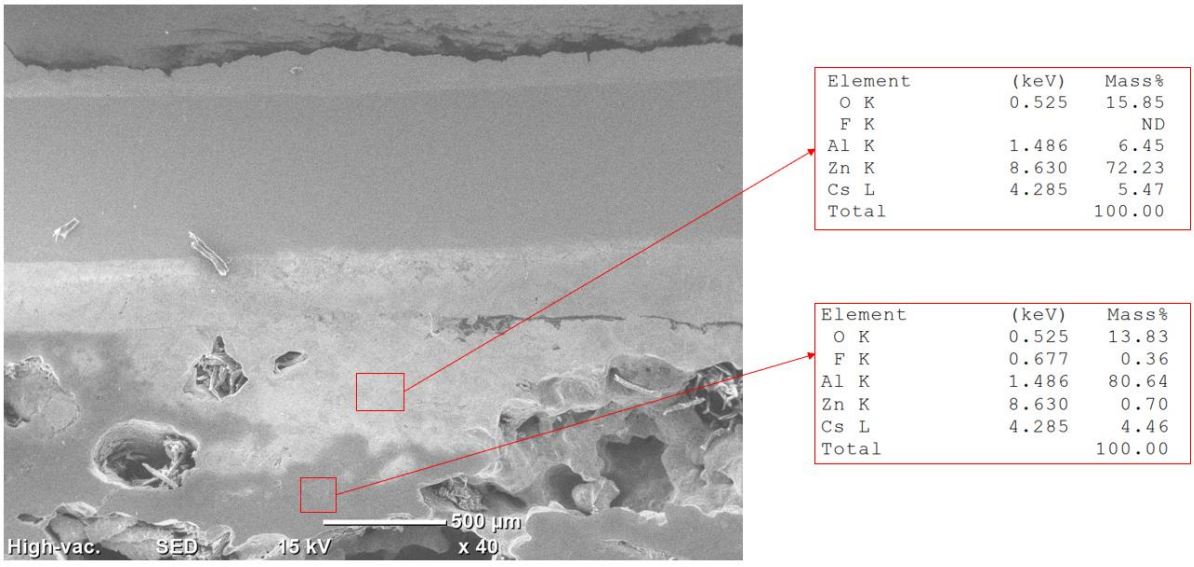


Figure 94: EDS analysis of Al-foam (FLUX), Zn-Steel and Zn at 40x magnification

Figure 95 shows the presence of a Zn rich phase (dendritic light grey structure) and a Zn-Al phase (interdendritic dark grey structure). At the interface the diffusion of Zn on the surface of the Al-foam is visible.

Moreover, residues of flux on the Al-foam surface are detected (presence of Cs and F).

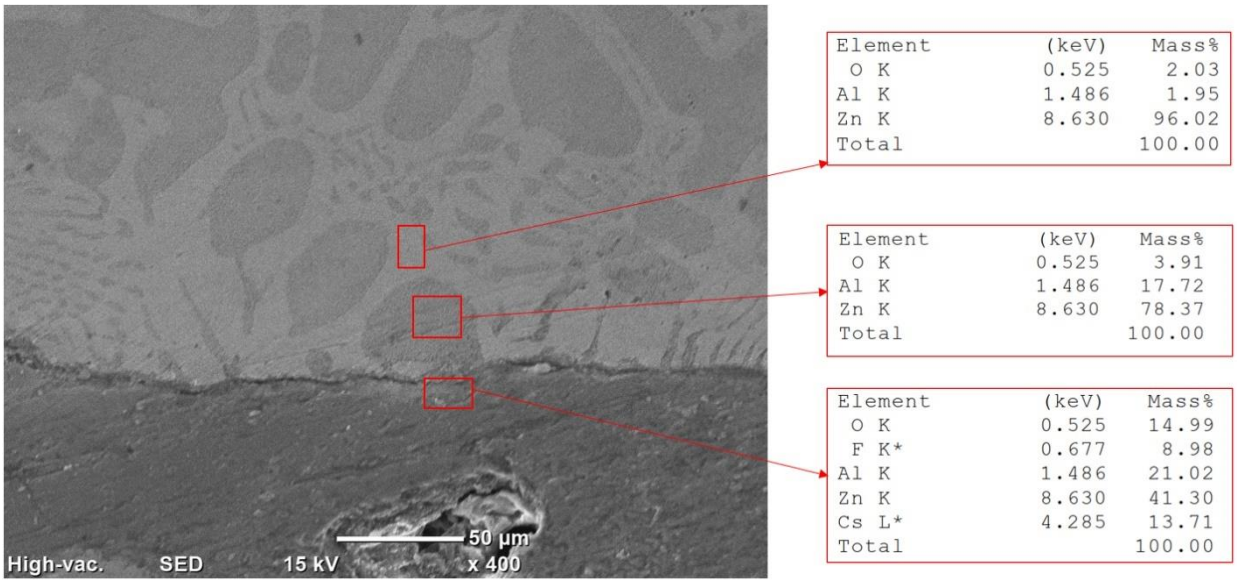


Figure 95: EDS analysis of Al-foam (FLUX), Zn-Steel and Zn at 400x magnification

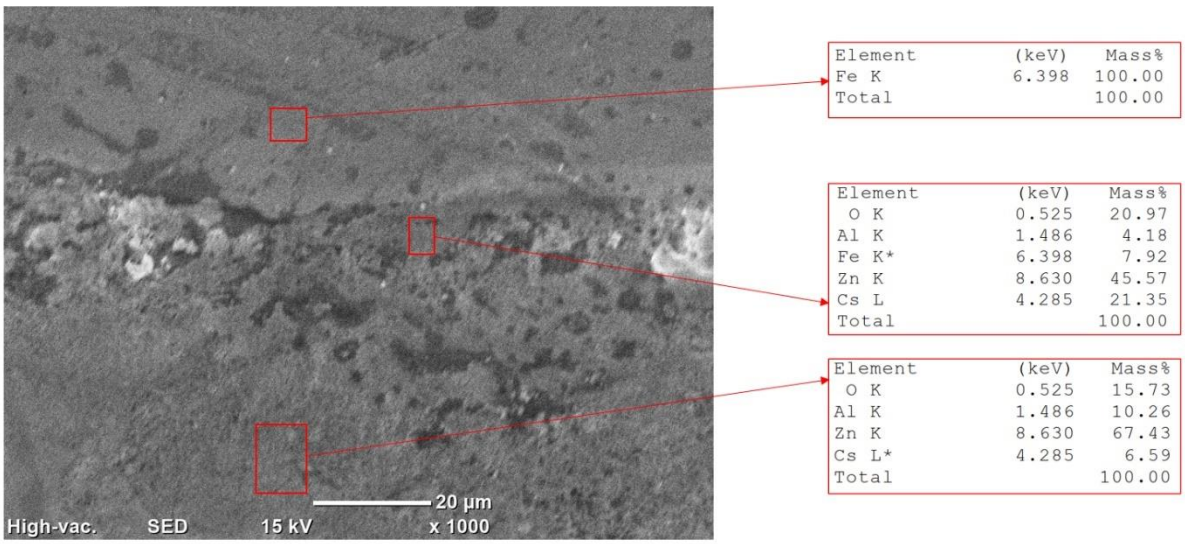


Figure 96: EDS analysis of Al-foam (FLUX), Zn-Steel and Zn at 1000x magnification

4.5.2 Al-Foam (without flux) joining with Zn-Steel / Zn

For the basic analysis of the joining, sample is observed under optical microscope.

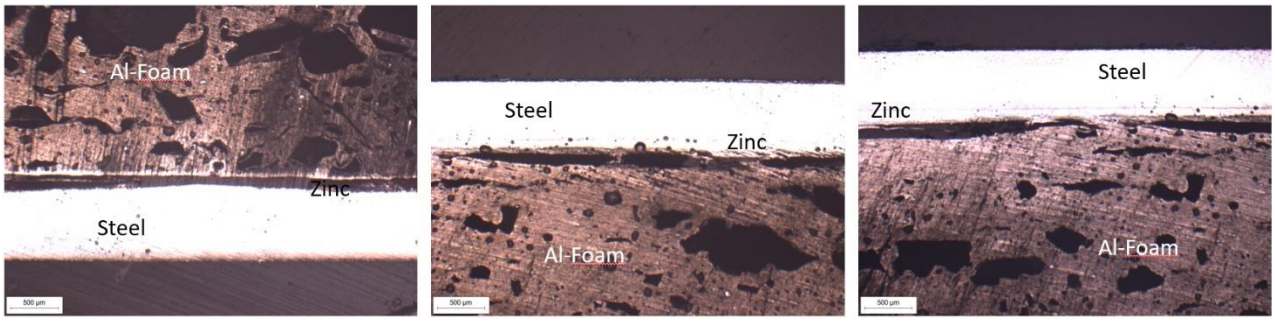


Figure 97: Optical microscope images of the transverse section of the samples of Zn-steel, Al-Foam, Zinc at 20x magnification

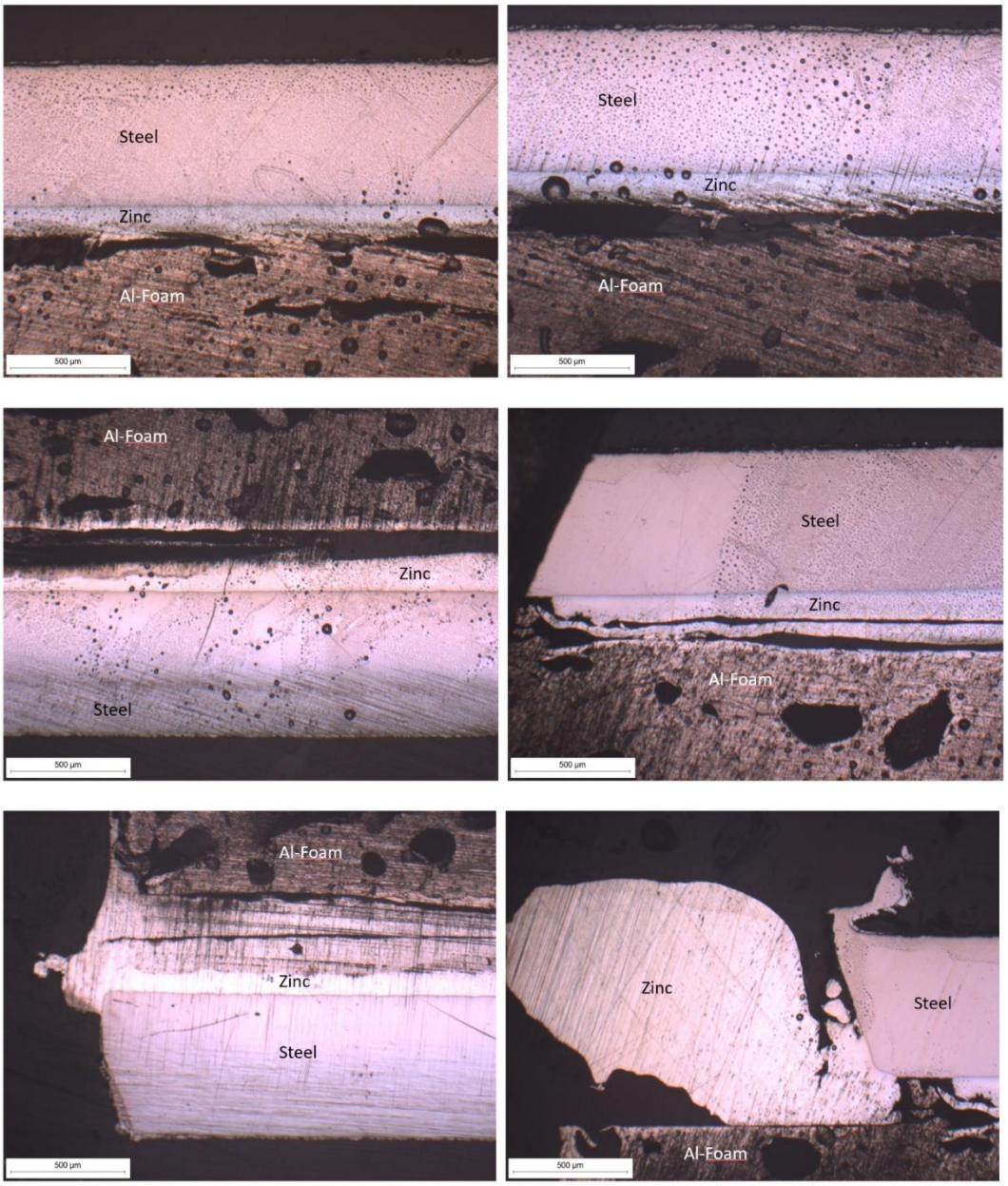


Figure 98: Optical microscope images of the transverse section of the samples of Zn-steel, Al-Foam, Zinc at 50x magnification

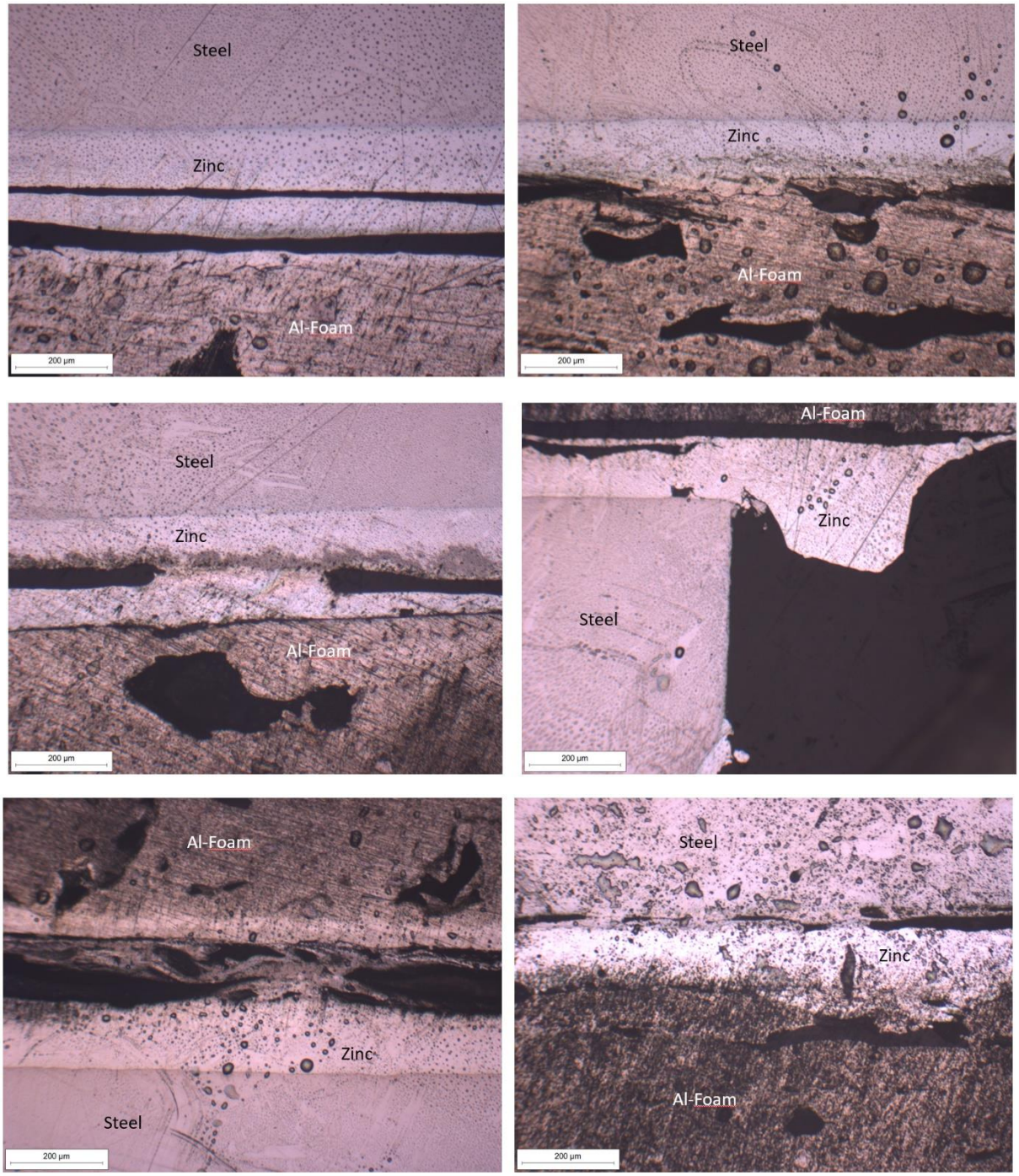


Figure 99: Optical microscope images of the transverse section of the samples of Zn-steel, Al-Foam, Zinc at 100x magnification

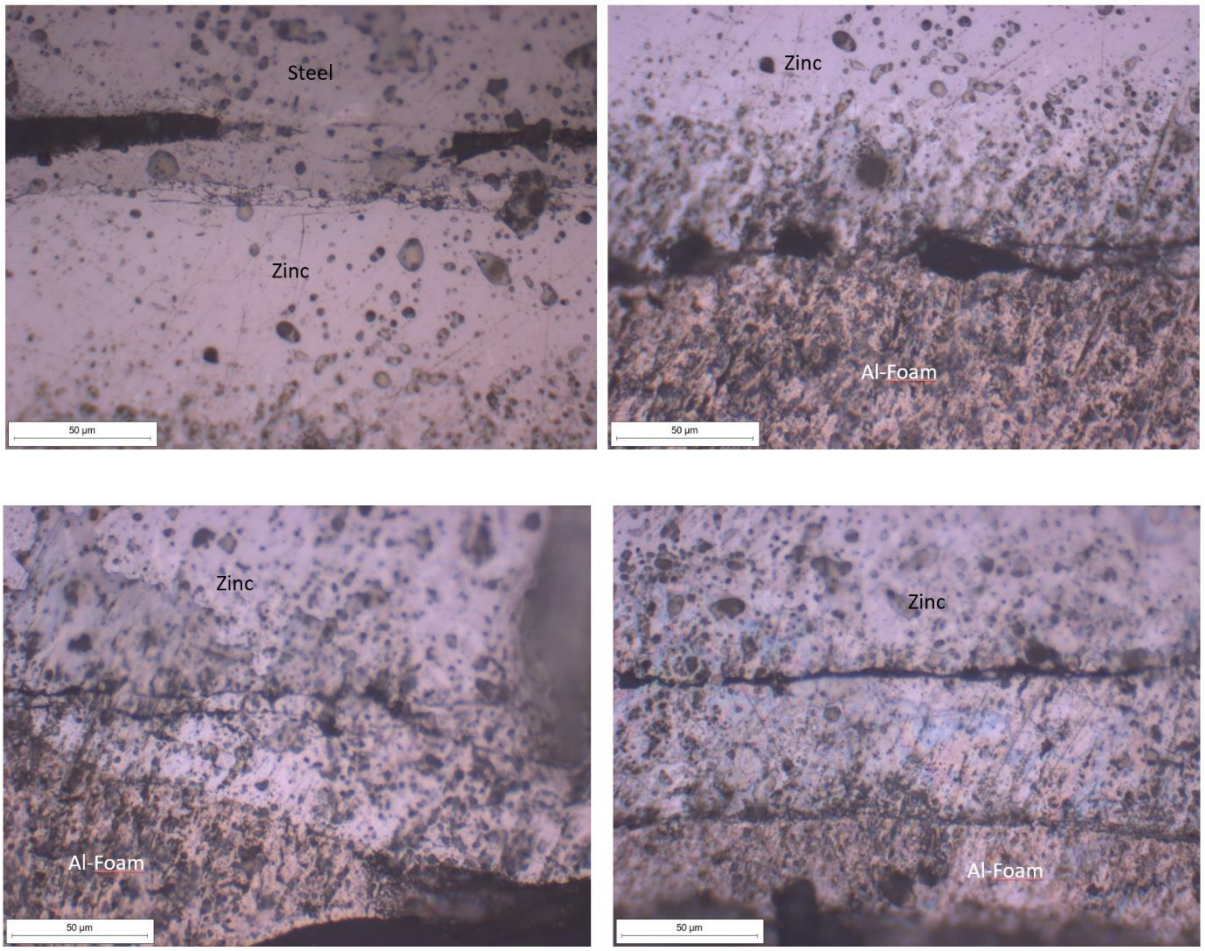


Figure 100: Optical microscope images of the transverse section of the samples of Zn-steel, Al-Foam, Zinc at 200x magnification

The interface is continuous on both sides (Al-foam and Zn-coated steel) in many points.

As observed for the previous sample, the Zn layer is partially melted and removed in some zones of the top surface of the Zn-coated steel sheet. This phenomenon is due to the temperature reached during brazing and it is useful in the joining zone, in order to allow reactions between the brazing material (zinc) and the surfaces to be joined, however it should be taken into account because can alter the properties of the outer surfaces of the steel sheet.

Sample is future observed under Scanning Electron microscope to get images at higher magnifications.

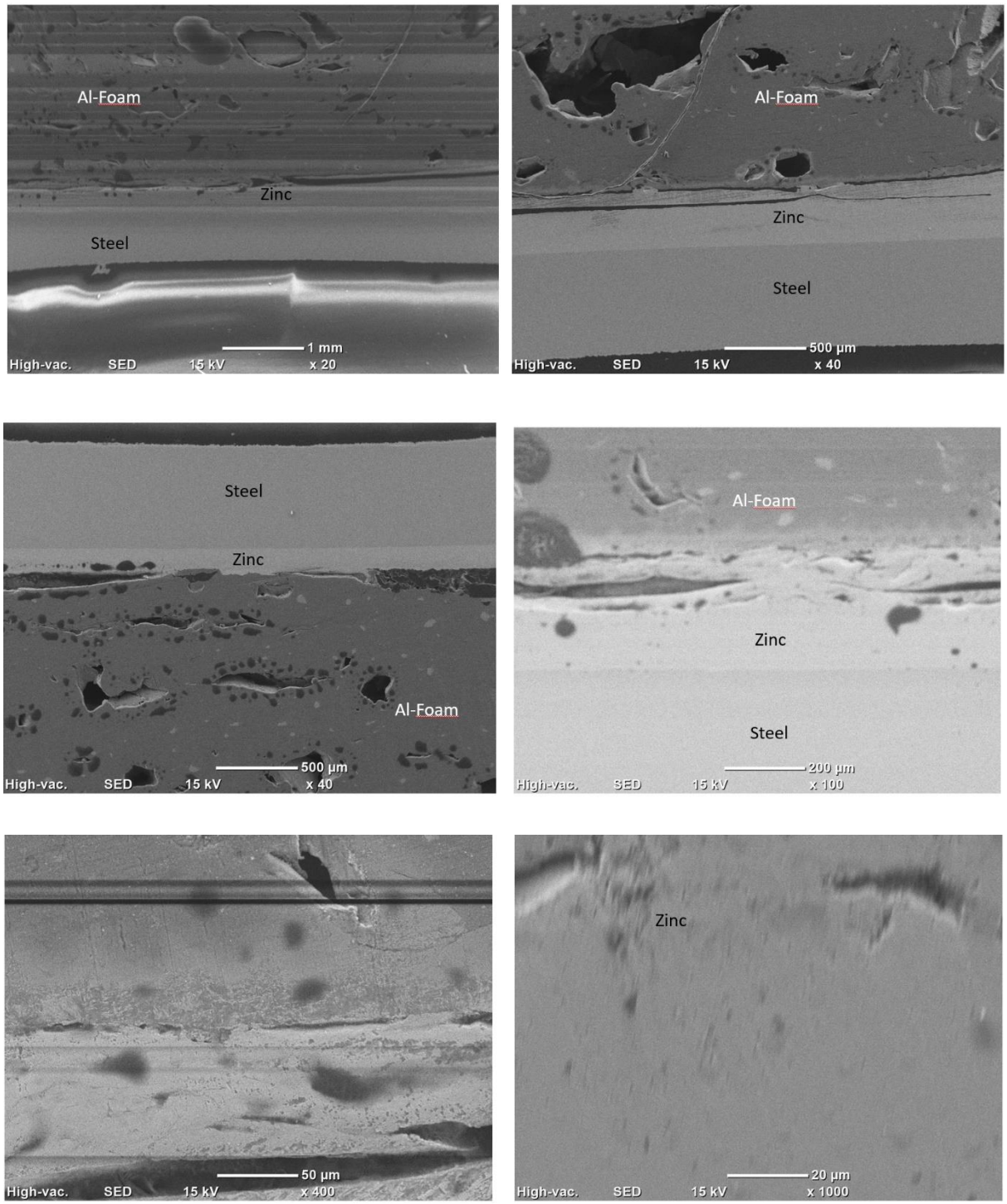


Figure 101: SEM images of the transverse section of the samples of Zn-steel, Al-Foam, Zinc at 20x, 40x, 100x, 400x, 1000x

The continuity of the joined interface is confirmed by SEM analysis.

EDS analysis shows the composition in different places of the sample. EDS analysis evidence the diffusion of Al and Fe in the joining area.

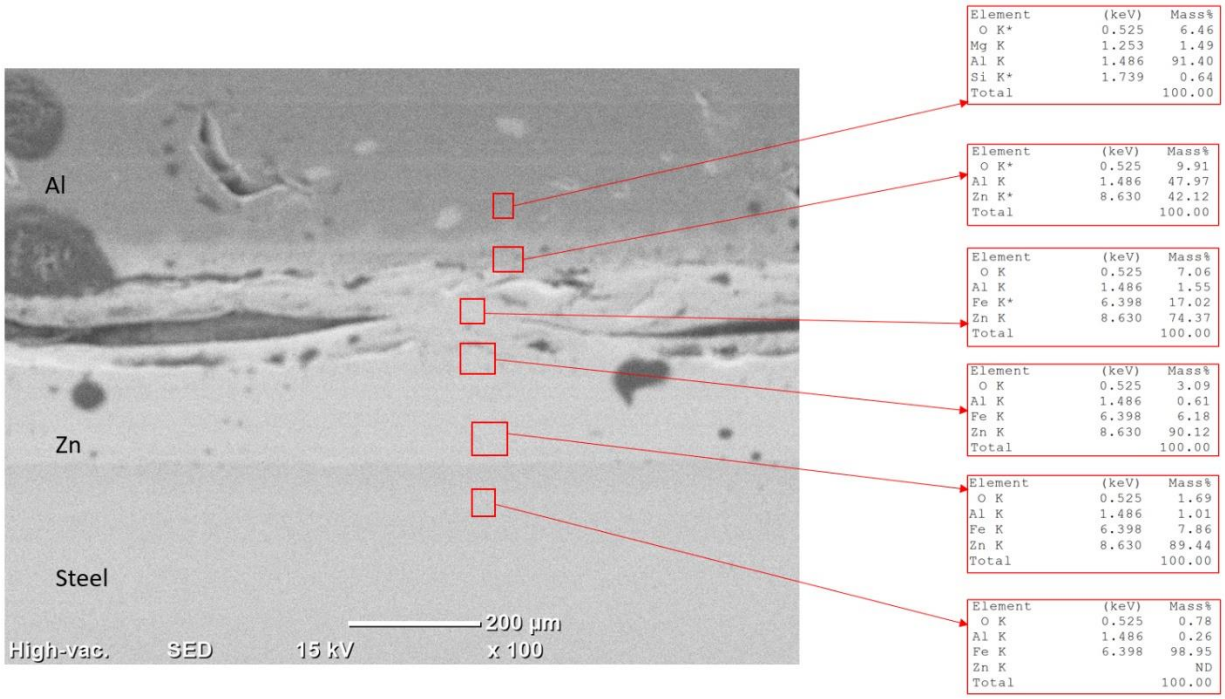


Figure 102: EDS analysis of Al-Foam, Zn-steel, and Zinc at 100x magnification

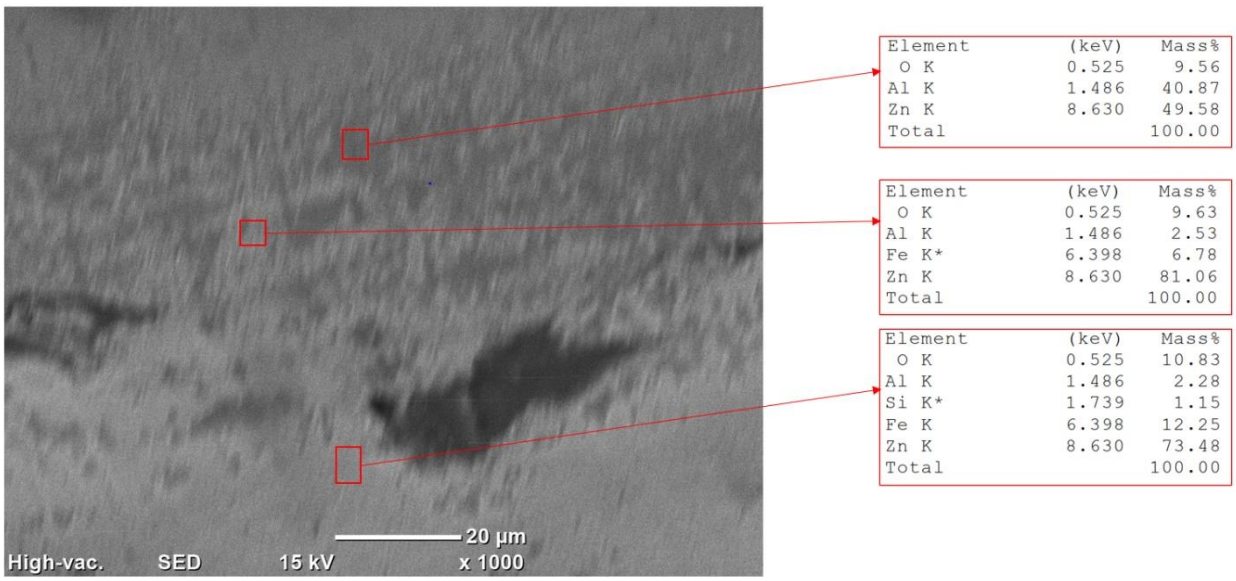


Figure 103: EDS analysis of Al-Foam, Zn-steel, and Zinc at 1000x magnification

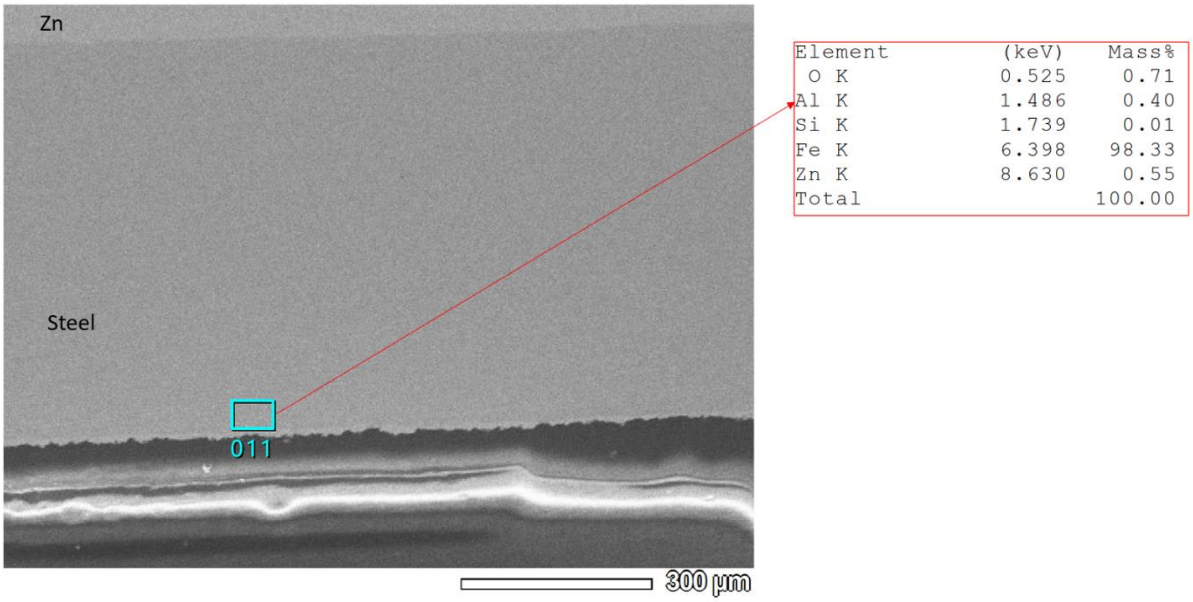
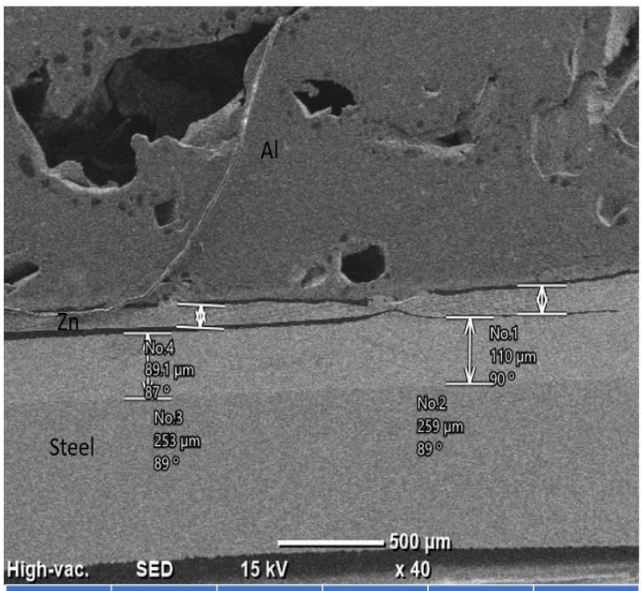


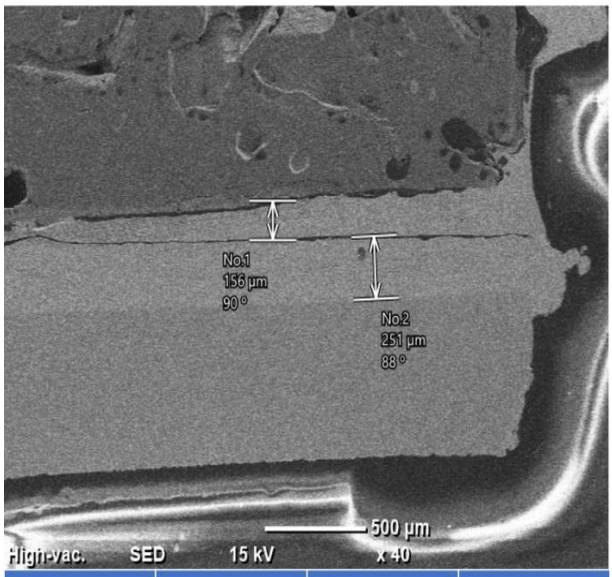
Figure 104: EDS analysis of Al-Foam, Zn-steel, and Zinc at 100x magnification

We can also calculate the thickness of Zn layer in the reaction of Al-foam and Zinc coated steel using zinc filler to have an idea how much zinc is consumed during the reaction.

It can be observed that the Zn layer on the steel plate completely reacts with the Zn filler to have a homogeneous layer that is significantly thicker (100-200 µm) than the starting Zn layer (10 µm).



Length 1 (µm)	Length 2 (µm)	Length 3 (µm)	Length 4 (µm)	Mean	St. dev
110	259	253	89.1	177.77	78.6



Length 1 (µm)	Length 2 (µm)	Mean	St. dev
156	251	203.5	47.5

Figure 105: Width of Zn layer in Al-foam and Zn-coated joining

5. Conclusion

In the research proposed in the first chapter of the thesis, we have provided an overview on some of the existing joining technologies that are already available in the market. Specifically, the thesis focuses on the joining technology of Brazing. A detailed literature review provided in the first section of the thesis to emphasize on the brazing technologies, its types and its comparison among different permanent and non-permanent joining technologies that are practiced today. The core of the discussion was the brazing joining of two dissimilar metals and alloys of aluminum and zinc coated steel. Also, zinc was an important filler material in the brazing process during our experimentation. The usage of zinc has its pros and cons. One of the most important aspects of using zinc is its compatibility with aluminum. The material provides a fine wetting surface in order for the joint to have high strength. However, zinc is an extremely volatile material and can easily outgas when heated. Also, zinc is susceptible to corrosion, produces somewhat toxic fumes, at higher temperatures, it may boil and present voids of cracks in the joint.

The Aluminium and its alloys are abundantly in use in the automotive industry and under further examination to replace steel with aluminum in the industry as per to reduce the overall weight of the produced automobile and increase the overall efficiency without compromising on strength properties of the vehicle. Al-foams have good stiffness-to-weight and strength-to-weight ratios, which means they may save weight. They can also absorb a lot of energy during compressive deformation, which helps with crash energy management.

Experimentation was performed in the labs at the Politecnico Di Torino. The experimentation consisted of brazing joining of Al6016 and Zinc coated Steel (pure Zn as filler), Al5182 and Zinc coated Steel (ZAMA as filler) and Al-foam and Zinc coated Steel (pure Zn as filler). Different oxides removing and cleaning techniques were used for the experimentation. Flux comprising of caesium fluoroaluminate was used on Al to avoid oxides formation during brazing. Metallography was performed to see the micro-structures and to analyse compositional details SEM and EDS analysis are performed.

- Top and cross-sectional analysis of steel indicated that on average 80% Zn was present on the steel top layer while after conducting the cross-sectional analysis, an average

of 10 µm thick layer was found to be present in the sample of the zinc coated steel. The surface of the Zn-coated steel appeared quite rough at the micro-scale.

- Zn-coated steel when placed on the bottom in the brazing of Zn-coated steel and Al6016 with pure zinc as filler showed poor reaction between filler and metals. Al when placed at top lack to flow in the brazing process and failed to join with Zn and Zn-coated steel.
- Al6016 (bottom) when brazed with Zn-coated steel, zinc as filler indicated that the reaction occurred, and Zinc reacted with both Al and Zn-steel. In most of points we had continuous interface between Zn and Zn-coated steel. But, in case of Al6016 and Zn the reaction occurred but we did not see any appreciated joining. This phenomenon can be attributed to the oxidation of the aluminium surface which can obstacle reaction and joining. To avoid formation of oxide Flux comprising (caesium fluoroaluminate) was applied on Al6016 and results shows the continuity of the joint and the reaction between zinc filler and aluminium with the diffusion of aluminium in the zinc layer up to the interface with the steel side.
- Al5182 (bottom) brazing with Zn-coated steel with Zama as filler confirmed the reactivity of the Zama with both Al and Zn-coated steel. The resulted Zama layer was not continuous to guarantee a good joint. This discontinuity can be associated with the irregular surface of the ZAMA chips and to the presence of two layers which resulted in poor contact between the brazing material and the surfaces to be joined. Zama chips cleaned with ethanol shows good results and seems joined but unwashed Zama chips failed to join this can be attributed to the presence of contaminations on the ZAMA chips, due probably to the production process, which can hamper the reaction with the metallic substrates to be joined.
- Al-Foam (with Flux) and Zn-coated steel reacted and formed continuous interface with pure Zinc (filler). The interface is continuous on both sides (aluminium foam and Zn-coated steel) in many points. The Zn layer is partially melted and removed in some zones of the top surface of the Zn-coated steel sheet. This phenomenon is due to the temperature reached during brazing and it is useful in the joining zone, in order to allow reactions between the brazing material (zinc) and the surfaces to be joined, however it should be taken into account because can alter the properties of the outer surfaces of the steel sheet. SEM images confirm the continuity of the interface and

evidence the dendritic morphology of the Zn brazing material due to melting and solidification during the brazing process. At the interface the diffusion of Zn on the surface of the Al-foam is visible. Moreover, residues of the flux on Al-foam surface are detected. The experiments without flux does not show significant changes but it can be observed that the Zn layer on the steel plate completely reacts with the Zn filler to have a homogeneous layer that is significantly thicker (100-200 μm) than the starting Zn layer (10 μm).

- Optimal dwell time is considered to be 7 minutes.
- Flux application was the most effective technique for increasing Al6016 and Al-foam reactivity with Zn.
- The ZAMA alloy presented significant reactivity for Al5182 without particular surface treatments, except cleaning.

These circumstances seem promising for brazing Al6016, Al-foam, and Al5182 alloys and should be investigated further.

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Appendix

A try was made to braze join Al-Foam (centre in sandwich), Zn-coated steel using Zama as filler, with flux applied to the Al-foam side. The temperature and time conditions are same as for brazing of Al5182 to Zn-Steel. Due to irregular shape and surface of Zama Chips the sample was really hard to put inside the furnace because the sandwich brakes. The sample reacted with each other but unfortunately, they failed to join. So, this experiments also confirms that the reactivity of Zama with Al is good without any specific treatment. The figure 106 shows that both Al-foam and Zn coated steel reacted with Zama.

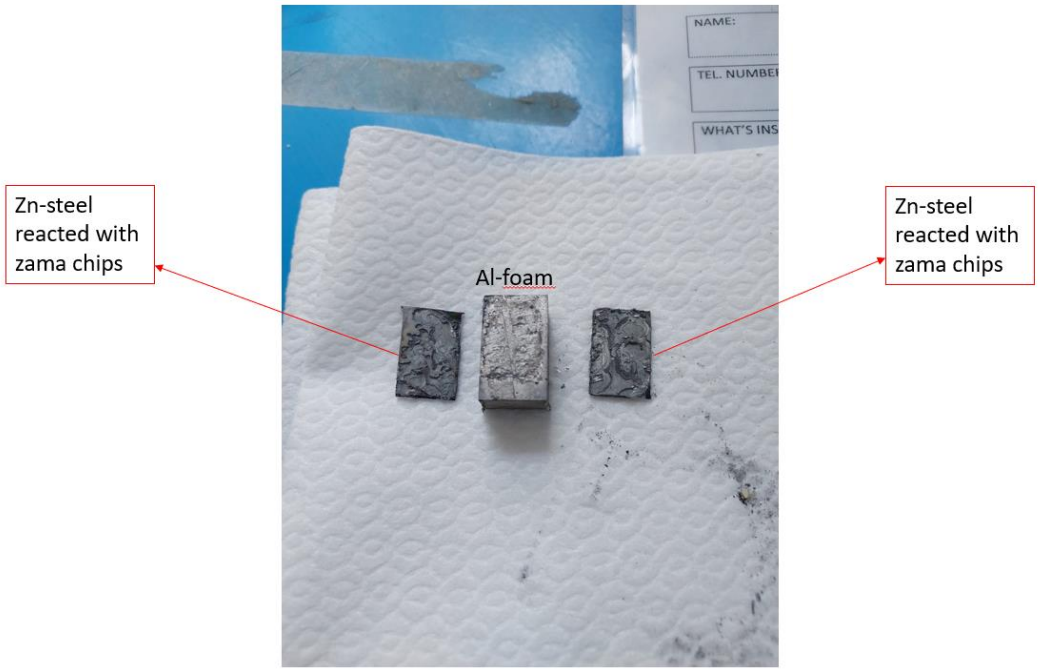

Figure 106: Brazing of Al-foam (flux) and Zn coated steel with Zama as filler

As it is already discussed that the Zama chips used for this reaction have irregular shape and because of that the contact between metals is not so stable. Even before brazing when we have to insert the sample sandwich in the furnace due to the irregular shape of the Zama chips the sandwich is not stable and the sample move form original position. This effects the joining of samples during brazing. The samples react with each other but due to lack of contact between surface of metals and filler material the joining does not happen. A mechanical load

was applied on the sandwich to get uniform contact between materials and filler material. In figure 107 we see the image of the sample on which the mechanical load is applied.

Figure 107: Mechanical load applied to make Zama chips and sandwich more flat