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Evaluation of new spot variant approach for joining of dissimilar materials

Master's thesis which has been submitted as thesis for
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Abstract of master's thesis

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Abstract

Lightweight structures are typically applied in structurally optimized components integrating multi-lightweight materials. One major limitation for further development and wider use of these structures is the difficulty to join the materials with significant dissimilar physical properties, especially metals to polymeric based materials. The joining of metal to polymer is one important demand from modern mechanical design that still strives to find reliable and energy efficient manufacturing solutions for this field of application. The existing solutions are not able to meet all the demands, namely regarding load-bearing structures where thicker components are needed. In this scenario, a new solution for hybrid joining of advanced lightweight engineering material, was recently invented at Aalto University, and it will be tested in the variant of spot joining. The new solution envisages the joining of thick structural components enabling multi-directional mechanical resistance.

The current work aims to evaluate a new approach for the spot variant and to understand the process better. New laboratorial conditions were developed for the implementation of the joining method. Tentative work started with some slot variant tests, but focus was put on the spot variant. The results obtained from the mechanical testing of the spot variant indicate a 50% and 85% increase in the tensile shear and cross tension tests respectively.

Keywords Lightweight materials, structural components, dissimilar materials, Polyether ether ketone (PEEK), aluminium, spot variant.

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Gnana Sambandhan Meikandaan.

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Abbreviations

MEMS	Micro-Electromechanical Systems
FSpJ	Friction Spot Joining
CFRPC	Carbon Fibre Reinforced Polymer Composite
CFRP	Carbon Fibre Reinforced Polymer
VOC	Volatile Organic Compounds
LAMP	Laser Assisted Metal and Plastic
YAG	Yttrium Aluminium Garnet
UTS	Ultimate Tensile Strength
TMAZ	Thermo-Mechanically Affected Zone
HAZ	Heat Affected Zone
NDT	Non-Destructive Testing
MIG	Metal Inert Gas
PEEK	Polyether Ether ketone
FEM	Finite Element Analysis
ABS	Acrylonitrile Butadiene Styrene
SEM	Scanning Electron Microscope
FSW	Friction Stir Welding

1. INTRODUCTION

Joining materials together is one of the most primitive manufacturing technologies going around the world now. Over time, it has developed and evolved into one of the most utilized techniques today [1]. It is a critical part of many revolutionary technologies such as a Wheatstone resistance bridge to Micro-Electromechanical Systems (MEMS). By definition, joining is the act or process of putting or bringing things together to make them continuous or to form a unit. In the fabrication sense, it is the process of attaching one component, structural element, detail or part to create an assembly, where the assembly of component parts or elements is required to perform some function or combination of functions that are needed or desired and that cannot be achieved by a single component or element alone [1].

For most of the structures, it is ideal to have no joints or less number of joints. However, joining is most often preferred for one of the following reasons.

- Functionality
- Manufacturability
- Cost
- Aesthetics

The urge to join different materials resulting in unique combinations has given rise to multiple types of materials which were unknown before [2] [3]. The need to produce lightweight structures with very less environmental impact is one of the driving forces of research in many fields today. According to the report “Lightweight Materials Market by Type (Composites, Metals, Plastics), Application (Automotive, Aviation, Marine, Wind Energy) – Global Trends & Forecast to 2019”, the market value for lightweight materials will grow from an estimated $88.5 billion in 2014 to $133.1 billion by 2019 at a Compound Annual Growth Rate (CAGR) of 8.5%. Another report titled “Global Lightweight Materials Market-Analysis & Forecast (2017-2023) (Focus on Metals, Composites, Plastics; Applications in Automotive, Aerospace & Defence and Wind Energy)”, predicts that the market value for lightweight materials will reach $242.78 billion by 2023 at a CAGR of 7% between 2017 and 2023. The Asia-Pacific market is especially projected to be a hot bed for such technologies. Though lightweight materials and polymers have been in use for quite a while in structural applications, a combination of these materials have not been fully explored. The main reason for this lack of research is the fact that these materials have contrasting properties and are difficult to join. It is under these circumstances that the current research obtains significance. The work presented here presents a method of joining dissimilar materials which is largely different from any existing work at the moment. When implemented, the process has vast potential in multiple facets such as automotive, aerospace, railways, marine and wind energy generation.

Organization of the thesis:

The thesis report has been neatly arranged into chapters and sub-chapters for easy understanding of the work flow behind the process. Each chapter has a small introduction about what the particular chapter is about and includes pictures and tables wherever needed.

2. THEORETICAL BACKGROUND

This chapter aims to provide a solid theoretical background for better understanding of the proposed process. The chapter starts from the very basics of joining processes before explaining in detail about the relevant processes. It also contains an outline of the various research doe in the field.

2.1. Various Joining Techniques

Most of the joining techniques are based on one of the following options [4].

- Mechanical
- Chemical
- Physical

Common joining techniques include

- Mechanical joining
- Adhesive bonding
- Welding
- Soldering
- Brazing

2.1.1. Mechanical Joining

It is one of the oldest methods used by humankind to join various components together [1]. It involves the attachment of components in an assembly or elements in a structure through the use of either an integral feature of the components or through the use of a supplemental device called a fastener, resulting in integral mechanical attachment or mechanical fastening respectively. Mechanical joining may manifest into two categories namely

- Mechanical fastening (Uses fasteners)
- Integral mechanical attachment (Uses an integral feature of the component)

In both these cases, the loads are transferred from one component to the other only by means of the mechanical forces arising from the interlocking or interference of two or more components [5]. The joining appears to occur between the different geometric shapes of the components at the macroscopic level but it occurs between the peaks and valleys on the interacting surfaces at the microscopic level. No atomic, ionic or molecular bonding happens between the associated components. It is due to this reason that this method can be used to join dissimilar materials. On the contrary, if there is an atomic or ionic bonding, it usually indicates the presence of a problem at the specific point (e.g. galvanic corrosion) [6].

Mechanical fasteners are supplemental devices that are used to create macroscopic interlocking between or among abutting or mating joint elements, with the fastener interfacing with each joint element to transfer the load from one element to the other in either shear or tension [1]. It is possible for the fastener to allow relative motion between the parts since the forces involved are purely mechanical. Tension type fasteners are intended to prevent any separation of joint elements and, because of the clamping force they are required to apply to function properly, do not allow for any kind of motion between the elements. Shear type fasteners are intended to hold the joint in some directions but will allow some relative motion in some degrees of freedom. Tension type fasteners carry loads parallel to their axes while shear type fasteners carry loads perpendicular to their axes. The fasteners can also be classified as follows.

- Threaded fasteners
- Unthreaded fasteners

Threaded fasteners are designed primarily to develop clamping forces or preload through the use of threads while unthreaded fasteners are designed to resist shear through a bearing with a pinning action. They can also be classified into metallic and non-metallic fasteners [7].

Integral attachments are geometric features that are physical portions of the parts or structural elements comprising an assembly or structure. These features may occur naturally in the structure as a part of its natural geometry or maybe designed into the structure as a detail to accomplish the joining process. The characteristics of these features include

- They are integral components and not supplemental like a fastener
- They do not add to the part count of a component
- They are explicitly selected or designed to facilitate assembly with lower forces and simpler motions than what is required for a fastener
- They facilitate the automated assembly of parts
- They add little to no weight to the component

Table 1 shows the various mechanical fasteners and integral mechanic attachments.

Table 1 Mechanical fasteners and integral attachments

Mechanical Fastening	**Threaded Fasteners** • Bolts and threaded studs • Screws • Nuts and lock nuts • Tapping • Screw and washer assemblies
	Unthreaded Fasteners • Upset rivet • Self-setting rivets • Two-piece rivets • Nails, Tacks, Pegs • Pins • Washers
	Other Fasteners • Staples • Stitches and sutures • Knots, wraps

	• Magnetic fasteners • Couplings • Clutches
Integral Mechanical Attachments	**Rigid Integral Interlocks** • Dovetails and grooves • Mortise and tenons • Wedges • Shoulders
	Elastic Integral Interlocks • Snap-fit features • Thermal shrink fits • Interference press fits
	Plastic Integral Interlocks • Crimps • Hems • Press fits

Stress concentration, slippage and excessive deflection are some of the most common failures associated with mechanical joining. Some cases may be affected by the nature of the material in use. Though this method does not really depend on the material used, it does have some effect in some cases. For example, fibre reinforced joints exhibit lower joint efficiency when these are used [8].

Advantages of Mechanical Fasteners

- Allows intentional disassembly without damaging the parts involved
- Allows some degree of motion in certain directions
- Does not change the microstructure or composition of the components involved
- Allows joining of dissimilar materials together
- Does not involve any special preparation of joints
- Relatively low cost
- Efficient joints

Disadvantages of Mechanical Fasteners

- Accidental disassembly can occur sometimes
- Stress concentrations are introduced at the point of fastening
- They allow fluid leakage if not used without sealants or gaskets
- Fasteners add weight to the component

2.1.2. Adhesive bonding

Adhesive bonding is the process of joining materials with the aid of a substance, acting as a chemical agent, capable of holding those materials together by surface attachment forces [1].

An adhesively bonded joint is usually formed by means of adherends, adhesives, primers and the adhesive interphase region [9]. Figure 1 shows the same.

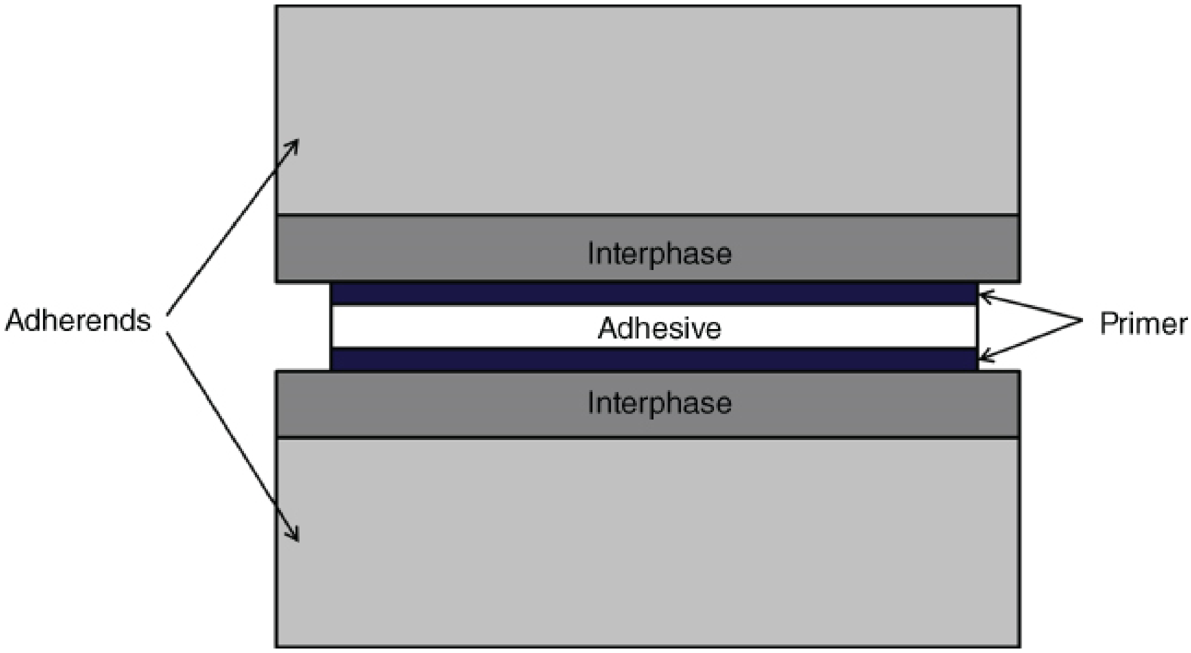

Figure 1 Components of an adhesive joint [9]

The substrate represents the material to be bonded. After the bonding has taken place, it is referred to as the adherend. The region between the adhesive and the adherend is known as the interphase region. The properties and the quality of an adhesively bonded joint depend on the nature of the interpose region. The forces that enable the surface attachment are chemical in origin but it can also be mechanical or electrostatic. The two major types of adhesive bonding include

- Structural adhesive bonding
- Non-structural adhesive bonding

In structural adhesive bonding, the primary objective is to develop sufficient strength in the joint. The adherend or the substrate is stressed to near the point that the adherend or the adhesive fails. Such a type of failure would occur due to plastic yielding or fracture in either brittle or ductile fashion [1]. The advantage with such a joint is that a designer can make maximum use of the adherend's strength resulting in high joint efficiencies. A major field of application for such type of joints is in aircrafts [10] [11]. It is typically used for joining different materials with glass, aramids (group of polymers based on long chain synthetic polyamide in which at least 85% of the amide linkages are attached directly to two aromatic rings), graphite reinforced thermosetting and thermoplastic polymer matrix composites and various metal to metal and metal to polymer honeycomb joints. A majority of these structures are classified as flight critical structures making them highly important [12] [13] [14].

In non-structural adhesive bonding, the primary use of the adhesive is something other than for its structural strength and integrity. Typical examples include use of sealing to prevent fluid loss or intrusion, thermal insulation and vibration damping. These are typically used in automobile industries [15].

Some of the common types of adhesives are shown in Table 2 [1].

Table 2 Common adhesive types

Natural adhesives	• Animal based adhesives (Casein, Collagen, Gelatin • Plant based adhesives (Pitch, Natural rubbers, Asphalt) • Mineral based adhesives (Sodium silicate, Water glass, Mineral based sol-gels, Calcium carbonate)
Synthetic adhesives	Synthetic organic adhesives • Chemically activated adhesives (anaerobics, cyanoacrylates, epoxies) • Heat or radiation activated adhesives • Evaporation or diffusion adhesives • Thermoplastic hot-melt adhesives • Pressure sensitive adhesives • Delayed tack adhesives Synthetic inorganic adhesives • Portland cements • High alumina cements • Mortars (Gypsum) • Refractory cements • Dental cements

The principal function of adhesives is to join materials together. This is done by transmitting the stresses from one element to another in a way such that the stresses are more uniformly distributed than most other mechanical methods. For example, a mechanical fastener introduces a hole into the elements to allow joining. Without a hole, a uniformly applied load across a uniform cross section is carried uniformly by the entire joint element. But, if a hole is present, then the load will not be uniformly distributed across the cross section leading to stress concentrations. Figure 2 shows the same.

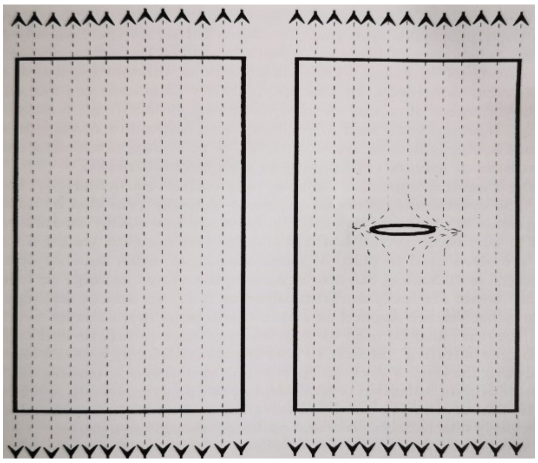

Figure 2 Stress concentration in the presence of a hole [1]

The adhesives, when used properly, fill the entire joint and creates binding forces over the entire area of the joint rather than at discrete points like a mechanical fastener. Irrespective of the adhesive mechanism, a larger adhesive area results in lower stress development. This allows the adhesives to carry considerable loads even though their inherent load carrying ability per unit area is lower than most fasteners, attachments and welds. Another important property exhibited by certain adhesives is their viscoelastic strain behaviour. Polymer based adhesives, the most commonly used type, exhibits this property. When an instantaneous load is applied or released, the material exhibits an instantaneous strain response followed by a time dependent strain response. The degree and rate of the time dependent strain response vary with the structure and stress-strain behaviour of the particular polymer. This softens the load which was applied and results in the development of more uniform stress levels.

There are four theories to explain the process of adhesion bonding phenomenon. They are

- Electrostatic theory of adhesion
- Diffusion theory of adhesion
- Mechanical theory of adhesion
- Adsorption theory of adhesion

The electrostatic theory attributes the adhesion between the adherend and the adhesive to the development of electrostatic forces of attraction between the two surfaces. These forces can rise from the transfer of charge between the two due to the relative difference in the electronegativity between the two materials [1]. The diffusion theory states that when two materials are at least partially soluble in one another, they can form a solution at their interface. Atom exchange occurs through diffusion. The diffusion can either be solid state diffusion or a faster diffusion. The mechanical theory states that for an adhesive to function properly, it must penetrate the microscopic asperities such as peaks, valleys, open pores and crevices on the surface of the adherends to display and trapped air in the interface [1]. Adhesion in such a scenario is believed to be the mechanical interlocking between the adhesive and the adherend. A typical example of such a mechanism is cement. The adsorption theory attributes the adhesion to the molecular contact and the secondary bonding that occur between the adhesive and the adherend. This process of establishing contact between the adhesive and the adherend is known as wetting. It is the process by which a liquid spontaneously adheres to and spreads over the surface of a solid [16]. The degree of wetting is controlled by the balance between the surface energy or the surface tension of the liquid-solid interface and the liquid—vapour/ solid-vapour interfaces. A completely wetted surface is when the liquid adheres and spreads to form an infinitely thin film with a wetting angle of 0 degrees. A non-wetted surface is when the angle of wetting reaches 180 degrees. For proper wetting to occur, it should have a surface energy lower than the adherend. Figure 3 shows the same.

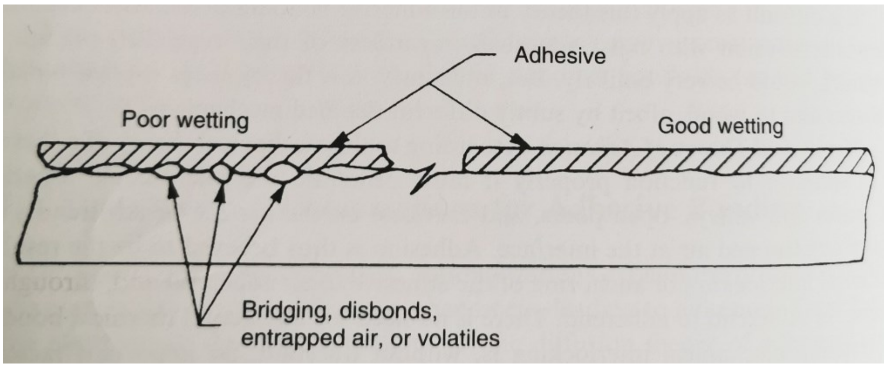

Figure 3 Effect of wetting on adhesion [1]

An adhesive joint should have good environmental resistance. This in turn is dependent on the nature of the bond which formed during the bonding process [17]. A lot of research has gone into the analyses of the adhesive bonding joints. Chang et al. presents a comparison between the stresses acting on the adhesive bonding joints and welded joints [18]. A lot of research has also gone into the joint design, analysis and failure of such joints [19] [20].

Advantages of adhesive bonding

- High load carrying capacity possible
- Minimal stress concentration due to load distribution over the bonding area
- Suitable for both thin and thick adherends
- Suitable for dissimilar materials
- Acts as a sealant and dampener
- Minimizes or prevents galvanic corrosion
- High strength to weight ratio

Disadvantages of adhesive bonding

- Sensitive to peel off
- Long curing times
- Complicated stress analysis
- Environmentally susceptible

2.1.3. Welding

In a general statement, welding can be defined as a process in which materials of the same fundamental type or class are brought together and caused to join through the formation of primary (and, occasionally, secondary) chemical bonds under the combined action of heat and pressure [21]. Metals are joined in welding through the formation of metallic bonds. Thermoplastic polymers are joined in welding through the formation of some covalent bonds within molecular chains and substantial secondary forces. The key to most welding processes is atomic level interdiffusion between the materials being joined either in the liquid, solid or mixed state.

A lot of research is being done in the joining of metals with polymers. It has been identified as a key area of research with a lot of potential [22]. Conventional welding processes are not ideal for joining dissimilar materials but a few relatively new processes such as friction welding, ultrasonic welding and laser welding have been found to be suitable for the same. An interesting development in the welding area is infrared welding [23]. The inherent difficulty in welding dissimilar materials is the nature of the bonds that are formed during the process. In metals, metallic bonds are formed across the interface between them. However, in polymers, covalent bonds are formed, provided there is sufficient heat and pressure applied. In case if there is insufficient heat and pressure, secondary van der Waal's dipole bonding occurs. In addition to these, intertwining of long chain molecules occur in thermoplastic polymers. This enhances the joint. Thermosetting polymers do not respond to heat after they have been cured. Hence, they cannot be welded. The potential for a process to join such polymers is huge and one research in particular, tries to handle the situation in a different way. Fusion bonding of cured thermoset polymers can be done by introducing an intermediate layer of thermoplastic material [24].

There are various ways to classify the numerous welding processes. Table 3 shows the classification of welding processes based on their primary energy source [1].

Table 3 Classification of welding processes based on their primary energy source

Mechanical	• Cold welding • High Pressure welding • Friction welding • Ultrasonic welding • Friction stir welding • Continuous seam welding
Chemical	• Pressure gas welding • Pressure thermit welding • Forge welding • Transient liquid phase bonding • Oxy-fuel gas welding
Electrical	• Stud arc welding • Resistance spot welding • Resistance seam welding • Flash welding • Upset welding

	• Gas Tungsten Arc welding • Plasma arc welding • Gas metal arc welding • Shielded metal arc welding • Submerged arc welding • Electroslag welding

Table shows only a few examples of each energy source and does not provide the complete set of processes as they are too wide a topic to discuss or provide in detail. To narrow down the potential processes within the scope of the project, the following processes are discussed in detail.

- Friction spot joining
- Induction welding
- Ultrasonic welding
- Laser welding

2.1.3.1. Friction spot joining

As has been stressed throughout the earlier sections of this work, multimaterial structures are gaining a lot of importance in many fields of engineering. The aeronautical field is a prime example. Large aircraft carriers such as Boeing 787 Dreamliner and Airbus A350 XWB use nearly 50 wt% of composites mixed with 50 wt% of lightweight alloys such as aluminium [25] [26]. The Friction Spot Joining (FSpJ), patented by and developed at the Helmholtz-Zentrum Geesthacht, Germany provides a good solution for joining dissimilar materials. It is a basically a variant of the Friction Spot Welding (FSpW) process. The tool for the FSpJ process consists of a three-part non-consumable tool. The parts are the clamping ring, sleeve and the pin which are mounted coaxially and can be moved independently of each other. The pin and the sleeve can move vertically and rotate independently and produce the heat due to the friction between these parts. Figure 4 shows the tool for the FSpJ process [9].

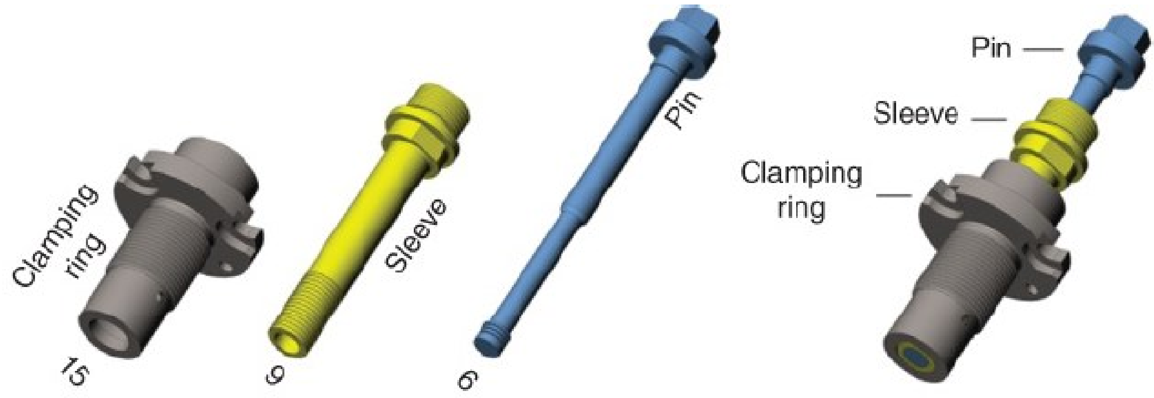

Figure 4 Tool for the FSpJ process [9]

The FSpJ process can use the same equipment as the FSpW process. Some of the notable manufacturers manufacturing this equipment include ColdWater Machine company, Harms und Wende GmbH and Kawasaki Heavy Industries [27] [28] [29].

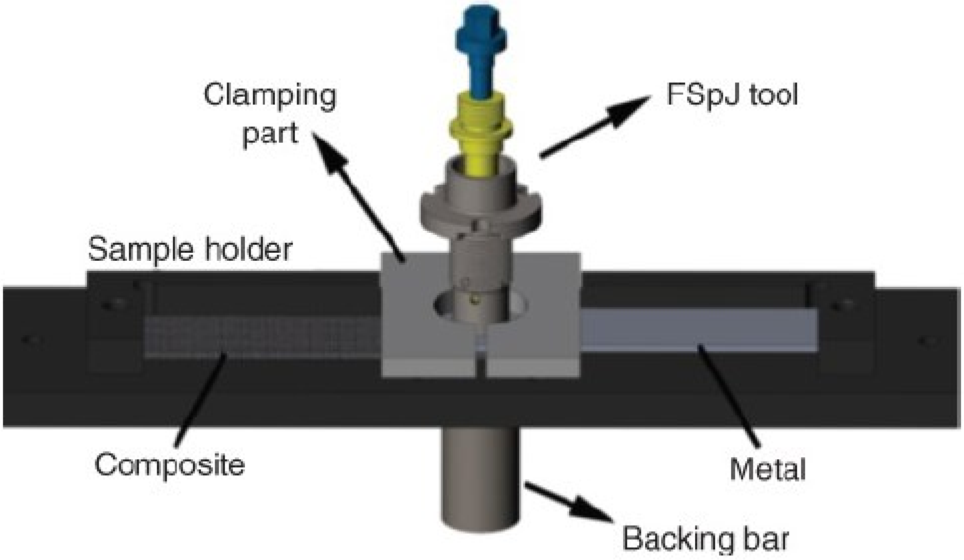

Figure 5 FSpJ setup before the process starts [9]

Figure shows the tool and material setup before the start of the joining process [9]. It can be seen that the metal and composite are placed in such a manner that they overlap each other and are clamped in that position for the entirety of the process. This prevents the material from moving during the weld operation as well as during the cooling stage after the welding. It is important to note that the metal and polymer behave differently while cooling and hence the clamping is of paramount importance. The parts are further clamped using the clamping ring and the backing bar as shown in Figure 6.

The entire FSpJ process can be divided into three main steps. The process itself can be done in two different ways namely

- Pin plunge technique
- Sleeve plunge technique

The first step of the sleeve plunge technique is when the rotating sleeve plunges into the metallic sheet at a predefine position and the pin retracts upward. Friction develops between the rotating sleeve and the metal thereby increasing the temperature locally around the tool. Even though the temperature rises, it is still below the melting point of the metal. This causes the metal to soften and it is plasticized. This plasticized metal flows into the reservoir left by the retraction of the pin. In the second step, the pin is pushed down thereby forcing the plasticized metal along with it. This metal is forced into the keyhole left in the metallic sheet created by the plunging sleeve. After this, the tool is retracted and then the joint is left to cool down. The sleeve will plunge only to the order of a few millimetres into the metal and not into the composite. Plunging into the composite will result in the destruction of the fibre structure. Figure shows the sleeve variant of the process [9].

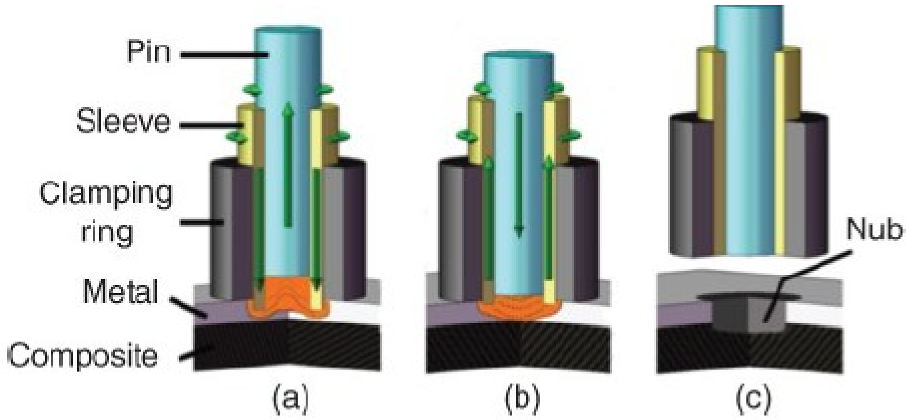

Figure 6 FSpJ process steps (a) plunging of the sleeve (b) refilling of the keyhole (c) joint consolidation [9]

In the pin plunge technique, the pin plunges into the metal rather than the sleeve. The rest of the process is similar to the sleeve plunge variant. It can be noted that the sleeve area is larger than the pin area and hence, the joint area in the sleeve area is larger too. This results in superior mechanical performance.

Figure 7 shows the top view of a FSpJ joint in a metal-composite arrangement [9].

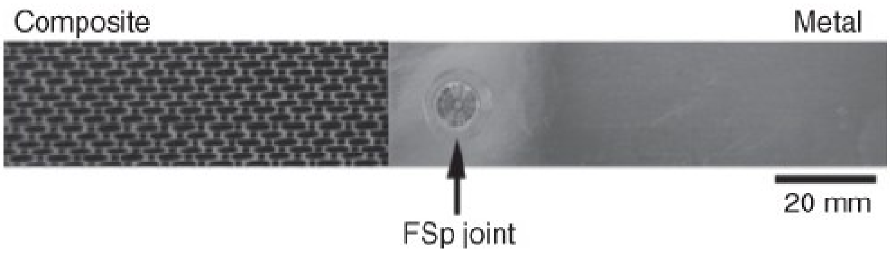

Figure 7 Top view of a FSpJ joint [9]

The key differences of the FSpJ process from the FSpW process are as follows [9]

- The plunge depth is very shallow as only the metal is affected leaving the composite untouched.
- One of the main bonding mechanism in FSpJ process is the force of adhesion from the creation of a molten layer of metal. In the FSpW process, it is atomic diffusion in the

case of metal spot welds and molecular interdiffusion in the case of thermoplastic spot welds.

- Mixing of materials do not occur in FSpJ thereby reducing the sharp interfaces.

Advantages of Friction Spot Joining

- The FSpJ process has very short cycle time in the order of 2 to 8 seconds depending on the materials used
- Weight saving
- It is environmentally safe as there are no emissions during or after the cycle
- The joints are repairable in the case of thermoplastic polymers
- The joints are recyclable

Limitations of Friction Spot Joining

- Only overlap joints can be produced with FSpJ
- The joint is physically and chemically bonded and hence the joint cannot be disassembled and reassembled
- The FSpJ joints have very low torsion and peeling strength
- With the present technological knowledge, it is difficult to join thin plates of the order of 1 mm or less

2.1.3.2. Induction Welding

Induction welding is another dissimilar joining technique for joining metals and thermoplastic polymers. The joint is achieved through the heating of the metallic component by an alternating electromagnetic field. The thermoplastic composite material should be melted or softened to establish an intimate contact between the components. The experimental setup of the process is shown in Figure 8 [9].

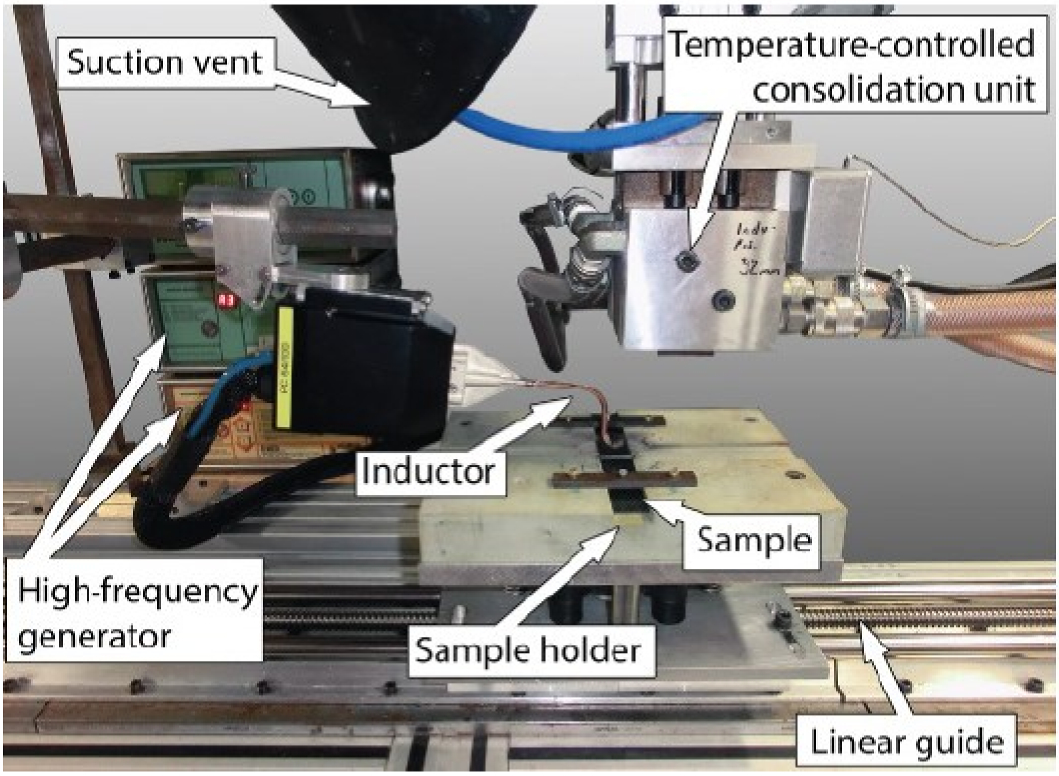

Figure 8 Induction welding process setup [9]

Figure 8 shows a discontinuous induction welding apparatus. The sample to be welded is attached to the sample holder. Generally, the metal is placed over the composite sample. An alternating magnetic field is applied in order to generate heat. This heats the metal sample first following which the sample holder is moved to the temperature controlled consolidation unit. The consolidation unit consists of a pneumatic cylinder which applies the pressure along with a temperature controlled stamp. It presses the parts together and the molten material wets the surface thereby filling all the surface asperities. The joint is now allowed to cool below the glass transition temperature of the composite material.

The basic physical phenomenon behind the process is electromagnetic induction. An alternating current generates an alternating magnetic field in a conductive material. This, in turn, induces eddy currents in the metal sample which is used for heating it up. The heat generated is due to the electrical resistance of the metal sample to the eddy current. Figure 9 shows the principle of electromagnetic induction in a sample to be welded. The sample comprises a metal and a Carbon Fibre Reinforced Polymer Composite (CFRPC).

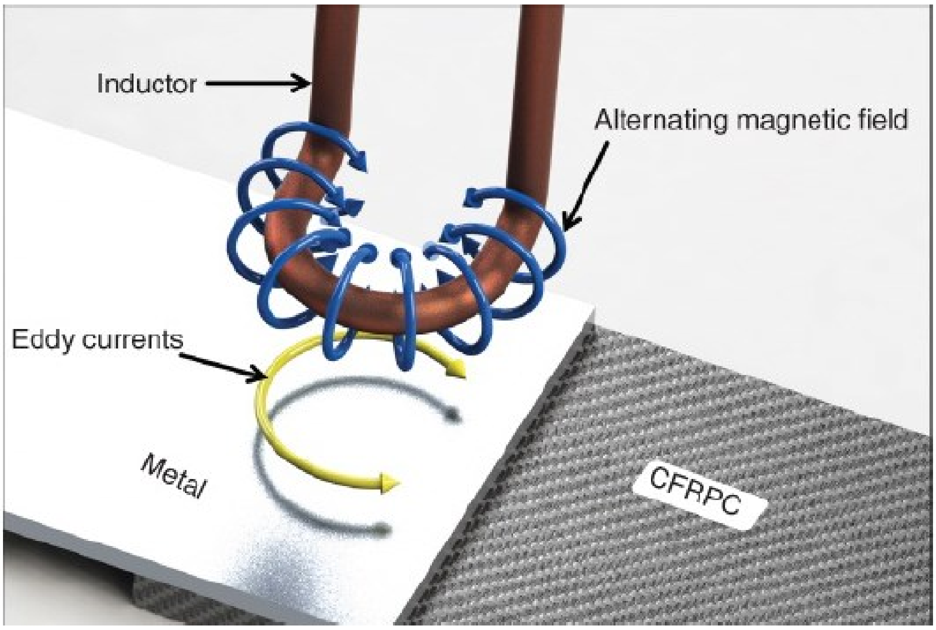

Figure 9 Electromagnetic induction in the sample [9]

Advantages of induction welding [9]

- High flexibility of the process
- Process is nearly independent of the sample size
- Accessibility is not an issue as the heating occurs from only one direction
- Reduces stress concentrations
- Low investment costs when compared to other processes such as vibration welding

The main limitation or disadvantage of the process is the process time. The process time can vary anywhere between a few seconds to minutes. Processes such as ultrasonic welding are faster than this [9].

2.1.3.3. Ultrasonic welding

The ultrasonic welding or joining is a novel technology which combines the use of ultrasonic energy to join surfaces produced by metal injection molding [30]. The metal injection molding process used for this process is known as MIMStruct manufacturing. It is based on the basic metal injection molding process and was developed and patented by the Helmholtz-Zentrum Geesthacht [31].

The MIMStruct manufacturing allows the production of surface structured metallic parts with excellent dimensional tolerance, surface finish and has high reproducibility. It uses a polymer powder feedstock to injection mold a metallic part followed by a sintering process. A binder based on a wax-polymer combination is used during the process.

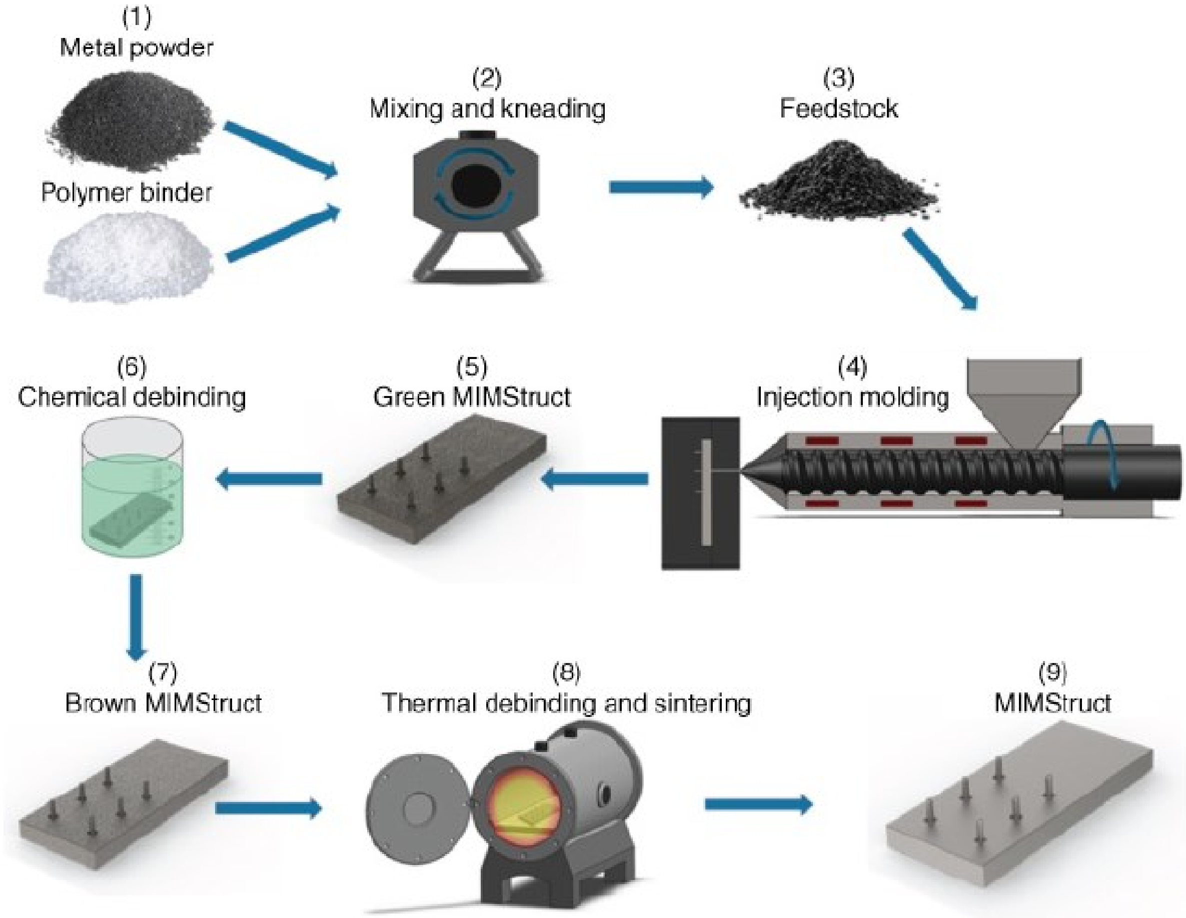

Figure 10 MIMStruct manufacturing process [9]

Figure 10 shows a typical MIMStruct manufacturing process and its steps [9]. The polymer binder is mixed and kneaded with the metallic powder to obtain the feedstock. The binder acts as a medium for shaping and holding the metal particles together and adjusts the viscosity of the feedstock. The negative mold has a negative oversized shape of the desired part in order to accommodate the part shrinkage during the sintering process. The injection molded part is termed as green MIMStruct and is introduced to chemical and thermal debinding after that. The chemical debinding process intends to remove all the non-polar molecules from the binder as they cause pseudo elasticity of the feedstock. The part resulting from this stage is termed as brown MIMStruct and has a microporous structure. This part is now subjected to thermal binding in a controlled, inert atmosphere. This removes all the remaining polymer binder from the part and is then subjected to sintering under high vacuum atmosphere and high temperature.

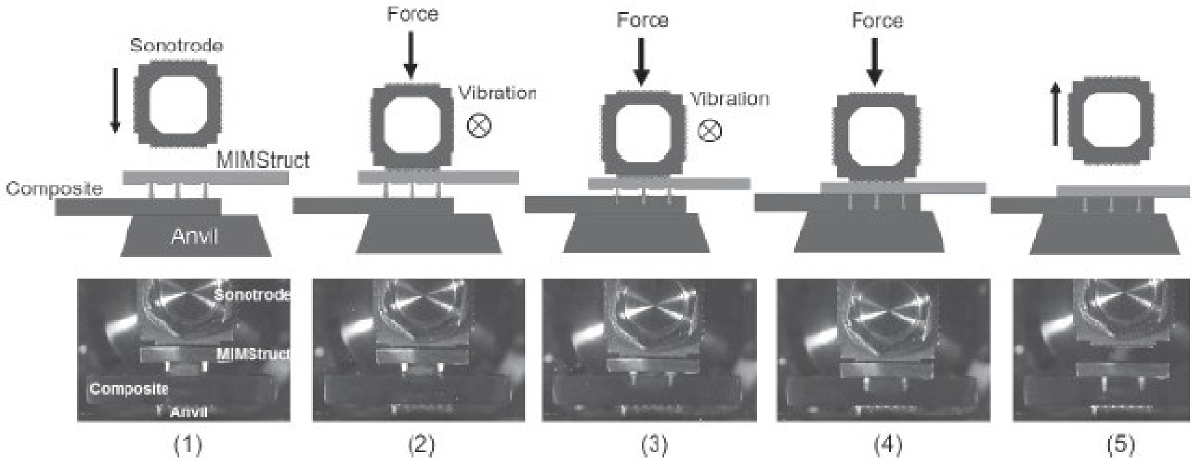

Figure 11 Stages in the ultrasonic joining process [9]

Figure 11 shows the various stages in the ultrasonic joining process [9]. In the first step, the parts to be joined are fixed between an anvil and a sonotrode. In the Figure, it can be seen that the metal part from the MIMStruct process has pin like protrusions. The parts are placed such that these protrusions are in contact with the composite surface. In the second step, the sonotrode touches the upper end of the MIMStruct part and applies a static pressure perpendicular to the contact surface. In the third step, the sonotrode starts to vibrate back and forth parallel to the contact surface. It vibrates with a high frequency in the order of 20-40 kHz and with amplitudes varying between a few micrometres up to 52 micrometres. This motion causes the pin like protrusions to produce heat due to friction and increases the temperature locally at the interface between the pin and the composite surface.

The pressure and vibration of the sonotrode are kept constant during the joining process. This along with friction softens the polymeric material. After the polymer has softened, the pins are inserted. This will cause a certain amount of the polymer to be expelled out. The expelled material will consolidate at the joint interface. When the MIMStruct material is fully placed over the surface of the polymer, the expelled polymer material will wet the base of the MIMStruct material. Adhesion takes place as a result of this. The resulting joint is due to a combination of mechanical interlocking and adhesion forces. The shape of the pins can be varied in order to increase the mechanical performance of the joint.

The process can be done in two different ways namely parallel mode and perpendicular mode. Parallel vibration of the sonotrode allows higher power to be generated and delivered to the joining area. For a conventional ultrasonic welding of aluminium to Carbon Fibre Reinforced Polymer (CFRP), parallel oscillation allows direct contact between the load bearing fibres and the metal to be created without excessively damaging the carbon fibres [32]. On the contrary, if the metallic surface is to be shielded from the marks resulting from contact with the joining tool, then perpendicular vibrations of the sonotrode is preferred. In this case, the sonotrode vibration is applied on the polymer surface rather than the metal. The ultrasonic energy which is applied to the polymer is transformed into thermal energy by the internal friction in the polymer [33]. Figure 12 shows the two different vibrations [9].

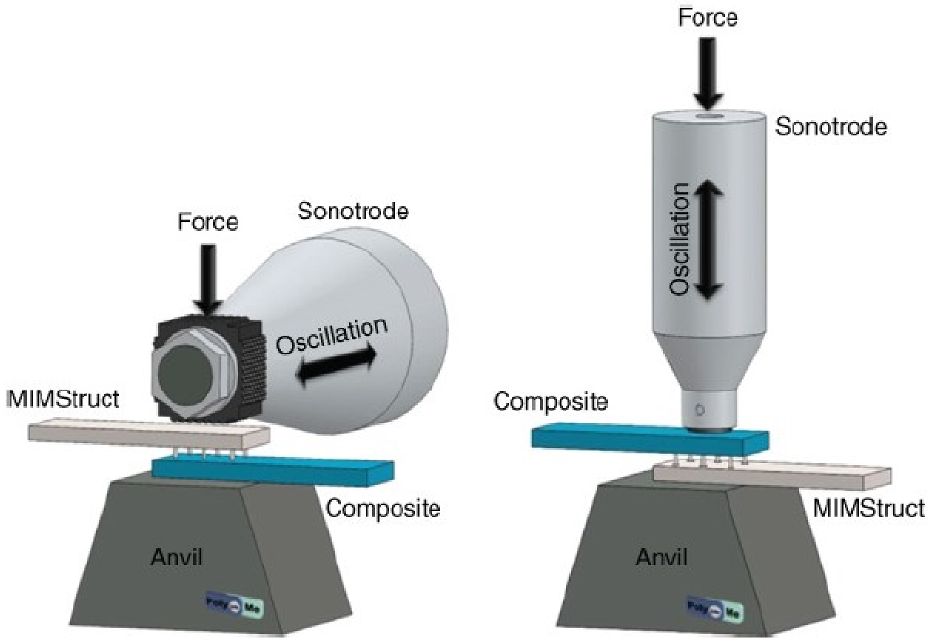

Figure 12 Parallel and perpendicular vibrations of the sonotrode [9]

The main advantage of ultrasonic welding is the precise control of heat generation. The heat generated is mostly localized in the region surrounding the pin and hence the area affected by the heat is vastly localized. The joining is clean without any spatter, sparks or fumes and hence is safe. The process is energy efficient and environment friendly and is safe for the operator. No solvents, adhesives or adhesive materials are used. The pins also serve to distribute the stresses when a load is applied thereby improving the damage tolerance of the hybrid structure.

The process is only suitable for overlapping joints and that is a major limitation. Direct application to thermoset based composites is not possible as an additional thermoplastic or adhesive layer may be needed to achieve joining. This takes away one of the main advantages of the process itself. Local disassembly of the joint is not possible without damaging it and hence inspections are difficult to perform.

2.1.3.4. Laser Welding

The joining of metals and thermoplastic polymers are done generally with adhesives and mechanical fasteners. Though these are the most sought after form of joining, there have been several issues regarding their use. For adhesives, the primary concern is its impact on the environment [34]. One major limitation is the emission of Volatile Organic Compounds (VOC) [35]. The Laser Assisted Metal and Plastic (LAMP) joining technology aims to eliminate such limitations [36] [37] [38]. It is a simple procedure in which a laser beam is directly irradiated on lapped sheets of a metal and a thermoplastic [39] [40] [41].

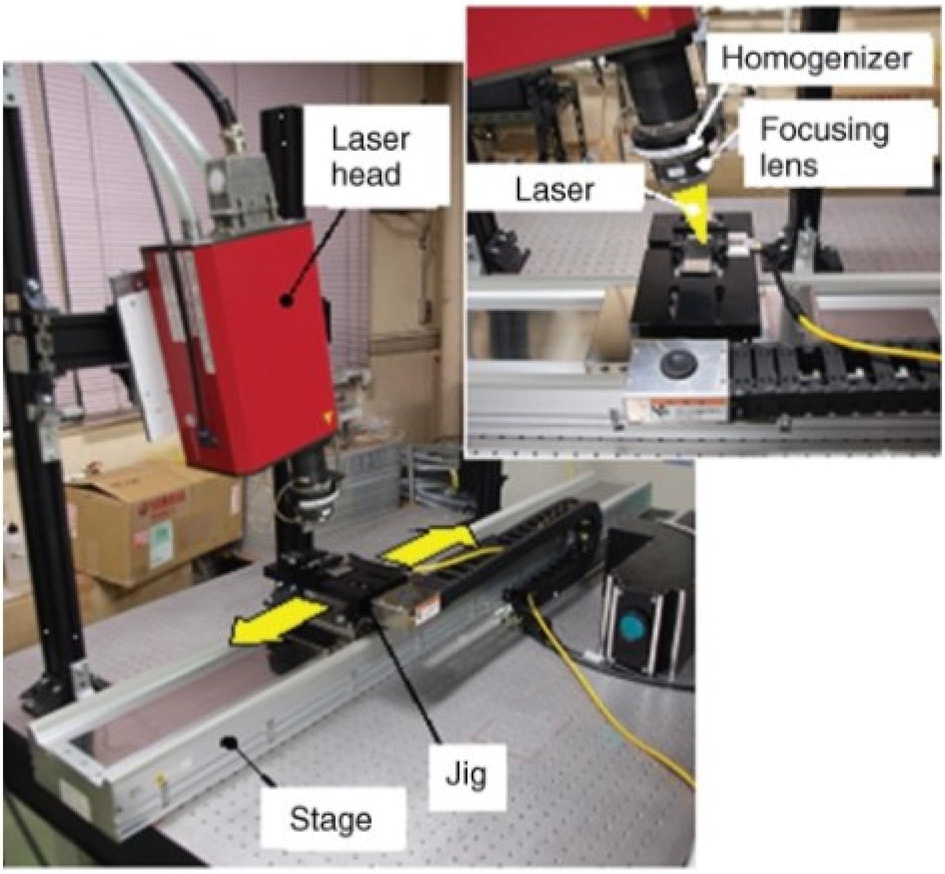

Figure 13 Laser welding setup [9]

Figure 13 shows a laser welding setup [9]. The most common sources of laser which are used for this process include Yttrium Aluminium Garnet (YAG), fibre and disc laser and diode laser. These can be used either in the continuous or pulsed wave mode. The focussing optic focusses the laser beam on the desired area. An inert shielding gas is used during the process. The focussed beam melts the particular area. The beams are generally focussed over the thermoplastic polymer surface. The polymer starts to melt and bubbles start to form in the molten material. Polymers with more than 70% laser transparency can be directly irradiated with the laser beam. Other heat sources can be used if the metal is to be exposed to the beam.

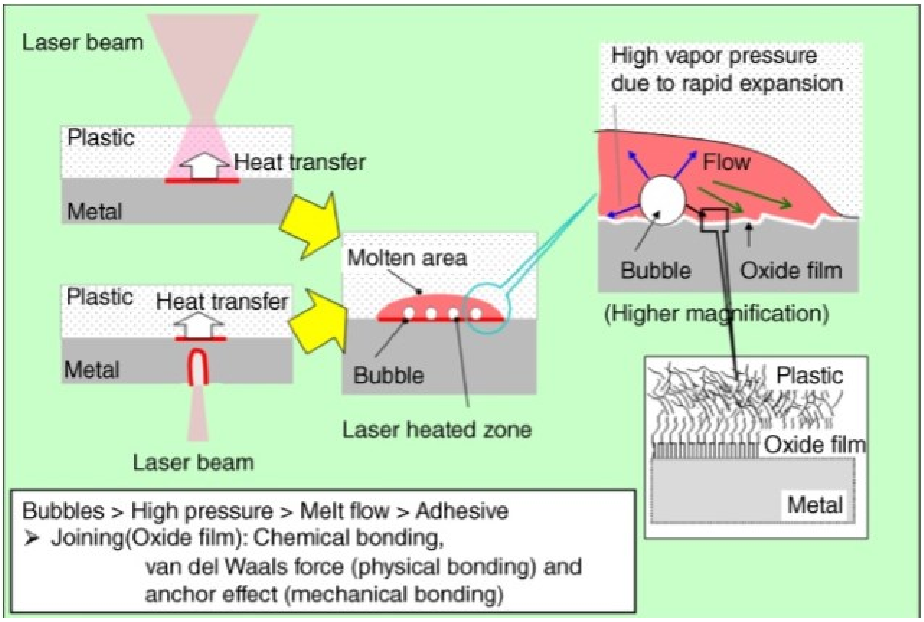

Figure 14 Mechanism of laser welding [9]

Figure 14 shows the mechanism of laser welding [9]. When a laser beam is exposed to the surface of the plastic, the polymer material gets melted and bubbles start to form as a result of the expansion of air and/or partial decomposition of the polymer. The molten material is thus forced to flow on the metal surface thereby filling its asperities. The joint is formed by mechanical bonding and van der Waals forces. A tight interface between the metal and the polymer is required during the process. If there is an air gap at the joint interface, these gases, primarily oxygen and nitrogen get accumulated inside the joint interface, leading to weaker joints. This is compounded by the release of hydrocarbons from the polymer when it melts.

Advantages of laser welding

- Short processing times and higher productivity
- Can be automated
- Reduced VOC emission
- Long term stability of the joint
- No surface preparation required
- High tensile shear strength of the joint
- No increase in weight

Limitations of laser welding

- Suitable only for thermoplastic polymers
- Tight interface between the metal and the polymer is required during the joining process

Apart from the processes mentioned above, there are other joining techniques which are suitable for joining metals and polymers. The most relevant and important one among them is injection overmolding.

2.1.4. Injection Overmolding

Polymer-metal hybrid structures are gaining importance in many fields and automotive industry is one of the most prominent among them. The main aim of such structures is to combine various requirements of several adjacent components into a single component or subassembly through system level application in order to deliver a customer specific solution or function [42] [43] [44] [45]. The combination of multiple components results in greater system level benefits than using them as standalone units [46] [47] [48] [49] [50]. The advantages of polymer-metal hybrid structures are as follows [9].

- reduction of the number of components
- production of integrated components ready to assemble
- weight reduction compared to the traditional all-metal solutions
- additional design and styling freedom
- production of in-mold features such as brackets, bosses, and attachment points
- safety improvement due to lowered centre of gravity of the vehicle (automobile industry)
- major increase in the bending strength of stamped metal sections
- improved damping in the acoustic range

The first well known case of polymer-metal hybrid structures is the front end of the Audi A6 [51]. The component was produced through injection overmolding a sheet-metal stamping with a cross-rib shaped structure made of an elastomer modified polyamide. Some common areas of application of this technology include instrument panel, bumper cross beams, door modules and tailgates in automobiles. Newer technologies are developed as an alternate to the classical overmolding techniques [52]. The four major categories of polymer-metal hybrid technologies include

- Injection overmolding
- Metal overmolding combined with secondary joining
- Technologies involving adhesive bonding
- Direct-adhesion technologies

The basic injection overmolding process consists of four steps. In the first step, sheet-metal blanks are stamped to obtain the desired shape of the metal inserts. This is followed by punching of flared through holes in the metal inserts. The inserts are then placed in the injection molding die. The final step is the overmolding of metal inserts with a cross ribbed integrated polymeric material. The process yields a tight interlocking and a superior combination of properties of the component materials (metal and polymer). It is achieved through

- Formation of rivets from the molten nylon that penetrate the insert through holes
- Overmolding of U-shaped inset flanges

Figure 15 represents a solid model of the simplified polymer-metal hybrid component (consisting of an overmolded cross-ribbed nylon structure and a U-shaped metal stamping) produced by injection overmolding [9].

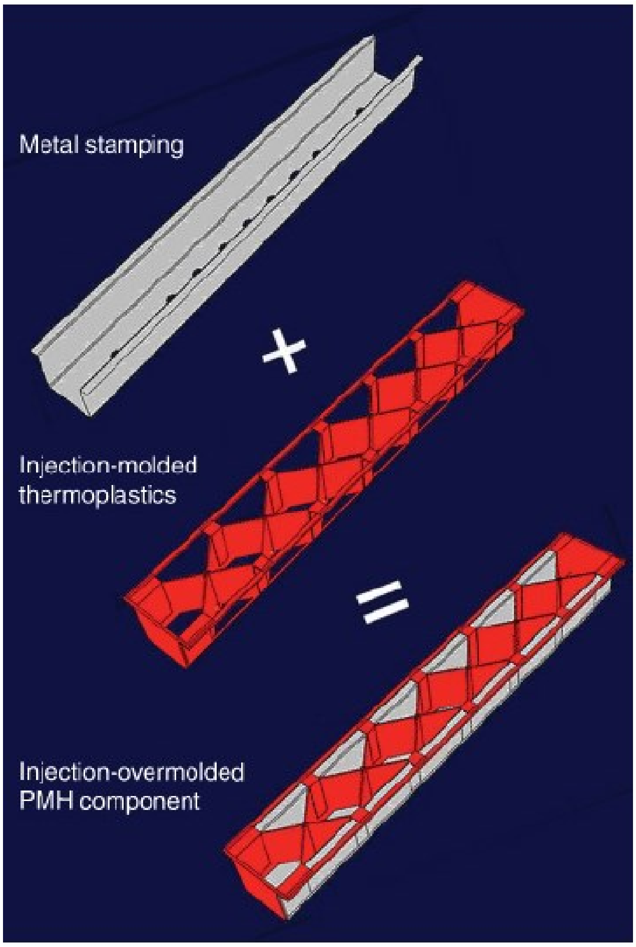

Figure 15 An example of an injection overmolded component [9]

The structural performance of a polymer-metal hybrid component depends greatly on the extent of load transfer through the polymer/metal interfaces. This, in turn, is controlled by the mechanism and strength of the joint. The injection overmolded joints rely on the shrink fit phenomenon. Interference fit is a type of fastening which is achieved by friction between two parts after they are pushed together [53]. Shrink fit is a technique in which an interference fit is achieved by a relative size change after assembly. The performance of injection overmolded joints also rely on the formation of mechanical interlocks promoted by the presence of special undercut geometric features within the metal component [9].

The advantages of injection overmolding include tight interlocking of the joints and low weight. Higher setup and processing times and expensive equipment are the major limitations of the process.

2.2. State of the art research

The upcoming paragraphs represent a small amount of the research being done related to the current work. The proposed work is based on friction joining processes and hence the materials discussed would be related to the same. This is done to understand the depth of research being done in the same field and the potential for the current work.

Ashish Swarnkar et al. discuss about the potential advantages of the friction welding process over other processes [54]. The paper deals with the friction welding of aluminium alloys and the effect of various parameters like tool rotational speed and feed rate on the quality of the weld. The aluminium alloy used for study is AA6061. This series of alloys have magnesium and silicon and are used for making complex shapes as they have good weldability. The welded specimens were subjected to tensile tests and intergranular corrosion tests. The tensile tests were performed without any heat treatment. The resulting welds were smooth and uniform with a fine equiaxial grain structure. It was found that the welding speed has a direct effect on the tensile strength of the joint when the tool rotation rate and the tool geometry are kept constant.

Mohammed. M. Hasan et al. discuss about a simplified clamping system for the basic friction stir welding of aluminium alloys [55]. The effect of having a good clamping system is demonstrated and the concerning deformities in the weld have been discussed. The work pieces tend to move apart from each other during the welding process. This creates a gap between the work pieces even after the weld and leads to imperfect joints. It was found that proper backing plates are also required in addition to the clamping setup. The backing plates also serve to improve the quality of the joint and aids in proper mixing of materials. Cooling was not of utmost importance for the welding of aluminium alloys and will play a role when welding materials such as steel and titanium. The materials used here are AA7075 and AA6061 aluminium series. These materials were chosen as they are widely used in automotive, aircraft, aerospace and marine industries. The welding speed and tool rotation speed were varied while other parameters were kept constant. Taguchi method was used to create multiple experimental setups using these parameters. In order to prevent the work pieces from lifting up during the welding process, bolts and nuts were used to clamp it down. Figure 16 shows the entire clamping and backing bar setup [55].

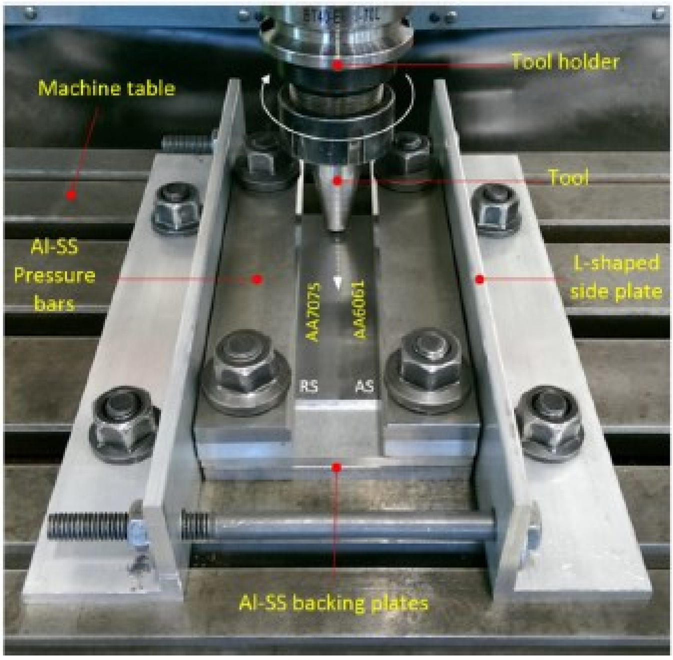

Figure 16 The clamping and backing bar setup [55]

Standard dimensions were used for the work pieces throughout the trial. The study was limited to the research of butt joints only. The welded joints were subjected to tensile tests and microscopic analysis. The Ultimate Tensile Strength (UTS) of the specimens were found out and the microscopic analysis of the Heat Affected Zone (HAZ) and Thermo-Mechanically Affected Zone (TMAZ) were done. The results show a maximum UTS of about 82% with respect to the UTS of the AA6061 alloy. The welds were also defect free and had a good surface finish without any gaps in the final weld.

Vidya Joshi et al. discuss about the optimization of friction stir welding parameters for aluminium alloys [56]. Welding parameters such as tool rotation speed and traverse speed affect the quality of the weld in a direct manner and have to be controlled. Improper parameters cause flash generation due to excess heat, cavities, grooves and inclusions. These reduce the quality of the weld and should be avoided. The material chosen for the study is AA5083 aluminium sample. The work pieces are butt-welded using friction stir welding. A standard tool with a tapered, threaded pin was used. The resulting welds were inspected using two planar Non-Destructive Testing (NDT) methods namely Radiography and Immersion Ultrasonic testing. A, B and C scans are done in the Immersion Ultrasonic Testing. The ultrasonic testing methods were found to be more efficient in detecting defects than radiography. It was also found that an increase in traverse speed causes insufficient heat generation and causes defects such as cavities.

Anganan K et al. discuss about the mechanical properties of a Metal Inert Gas (MIG) welded and Friction stir welded AA6082-T6 aluminium alloy [57]. The paper demonstrates the advantages of friction stir welding over the conventional welding techniques. The friction stir welding causes a very localised amount of heat generation and does not affect the surrounding material. Such a joint has three distinct zones, which are of interest namely the nugget, the Thermo-Mechanically Affected Zone (TMAZ) and the Heat Affected Zone (HAZ). The nugget represents the portion where the probe has passed through. TMAZ represents the zone immediately adjacent to the nugget. The area that is affected by the heat but does not experience any mechanical shearing is known as the HAZ. In order to reduce the amount of flash generation when the pin of the tool initially touches the surface of the material, a hole smaller than the diameter of the pin is drilled on the material before the welding starts. The MIG welding was done using AA4145 as filler material and argon as shielding gas. Only butt welds were considered for the comparison in the study. Tensile tests and Vickers hardness tests were done to compare the welds from both processes. It was found that the friction stir welded joints had considerable increase in their tensile strength over the MIG welded joints. The friction stir welded joint also had a narrower HAZ than the MIG variant.

Nuno Mendes et al. put forward a robotic friction stir welding variant aided by hybrid force or motion control [58]. The anthropomorphic robots have some important advantages over other equipment such as high flexibility, larger workspace, faster setup times and automation through diverse programming. A major hurdle affecting the widespread use of robots in such welding processes is the high forces involved. The relationship between the plunge depth and the corresponding axial force is highly important. High forces cause stiffness in the robot, which in turn, affects the ability of the robot to weld. This can be overcome by introducing force and motion control. The study focuses primarily on the welding of Acrylonitrile Butadiene Styrene (ABS). The main manipulator used is an anthropomorphic robot with six degrees of freedom and the tool used was developed based on existing research. The main aim of the study was to design a tool that will support the axial forces generated during the process. The tool should also move in harmony with the robot wrist, transmit the power properly and measure the forces generated by the welding process. Figure 17 shows the robotic friction stir welding manipulator setup [58].

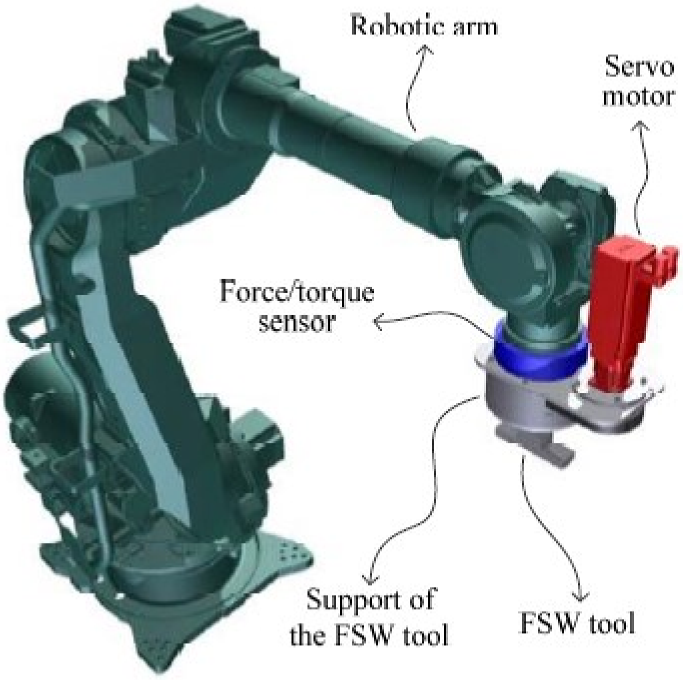

Figure 17 Robotic Friction stir welding setup [58]

The robotic system was designed and then analysed using Finite Element Analysis (FEM). The test results show that the welds were of acceptable quality. When the tests were conducted without any motion or force control, the forces were not enough to achieve a good weld. The same setup can be applied to different materials by adjusting the parameters according to the material used.

Yongxian Huang et al. discuss about the joining of aluminium and polymer using friction stir lap welding [59]. The study reports a successful lap joint between AA6061-T6 aluminium alloy and Polyether Ether ketone (PEEK) by friction stir lap welding. The tool consisted of a tapered thread pin with triple facets. A pin without threads was not ideal for pushing the aluminium material into the polymer. The mechanism of joint formation was attributed to mechanical interlocking.

Figure 18 Friction Stir lap welding tool used for joining aluminium and PEEK [59]

Figure 18 shows the tool used for joining aluminium and PEEK [59]. The PEEK material used was 7 mm thick while the aluminium alloy was 2.5 mm thick. The aluminium alloy was placed over the PEEK material for the welding. The tool rotation speed was kept constant while the traverse speed was varied. As the tool plunged into the material, it pushed the aluminium into the polymer forming an aluminium anchor. This anchor is responsible for the mechanical interlocking. The welded specimens were subjected to microstructural analysis with an optical microscope and a Scanning Electron Microscope (SEM). They were also subjected to shear tensile tests and Vickers hardness tests. The results show that the triple facet tapered pin was instrumental in mechanical interlocking and aided the formation of the aluminium anchor. Decrease in heat input reduces the size of the anchor and it reduces the interface gap width between the polymer and aluminium. These factors greatly reduce the load bearing capacity of the joint.

Rupinder Singh et al. discus about the friction welding of dissimilar materials with powder metal reinforcement [60]. The welding of dissimilar thermoplastics such as Acrylonitrile Butadiene Styrene (ABS) with Nylon6 has been found to be promising as the joint strength obtained is not sufficiently strong. This is due to the difference in their properties such as melt flow index and glass transition temperature. This can be overcome by the introduction of metal powder reinforcements. Melt flow index is a measure of the ease of flow of the melt of a thermoplastic polymer. The work pieces for this study were circular in shape and were friction welded using a centre lathe. A successful weld was obtained when the ABS was reinforced with Fe powder by 10% weight. The addition of Fe powder to ABS may have changed the melt flow index of the material making it similar to that of Nylon6. Further studies revealed that a 40% reinforcement of both ABS and Nylon6 with Fe powder, both the materials attained similar melt flow indexes. The joints obtained were subjected to tensile strength tests and Shore D hardness tests. The porosity of the material at the joint was also tested. The most efficient parameters for the production of a good joint were found.

Yongxian Huang et al. discuss about the friction stir welding of polymers and polymer matrix composites [61]. The paper puts forward the various advantages of the friction welding polymers. The paper also explains in detail about the various parameters that influence the quality of the joint. Figure 19 shows the same [61].

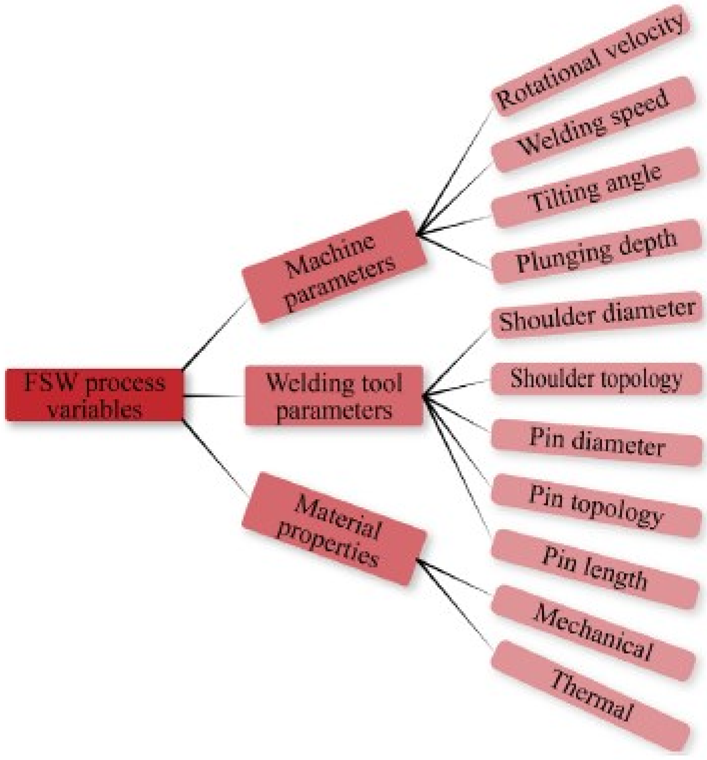

Figure 19 Parameters affecting the Friction Stir Welding (FSW) process [61]

The process yields good welds with optimal parameters. The major issues regarding the process include poor joint quality due to low thermal conductivity of the polymer materials, low crystallinity of the material, creation of voids in the retreating side of the tool movement and the lack of root penetration.

Yongxian Huang et al. discuss about the friction spot welding of carbon fibre reinforced polyetherimide laminate [62]. The feasibility and fracture mechanism of the joint was carried out in the study. The material used in the study was a polyetherimide laminate sheet reinforced with 45% of 5-harness satin weave carbon fibres. Optimal parameters for an efficient joint for the material in concern was found out. The results concluded that the major cause of the joining mechanism was the macromolecular interdiffusion and intermixing of carbon fibres at the interface between the upper and lower sheets. Increasing the rotational speed was instrumental in increasing the intermixing of the fibres and improved the tensile shear strength of the joint. The fracture stresses were found to be comparable with a joint obtained using ultrasonic welding. The lack of joining zone present just outside the thermo-mechanically affected zone is the main source of crack formation and propagation resulting in joint failure. The fractured surface showed signs of brittle fracture in the thermo-mechanically affected zone and ductile fracture in the sleeve-stirring zone.

3. Through Hole Extrusion Welding (THEW) process

Chapter 2 discussed about the various joining processes available for joining metal to a polymer. Each had its own share of advantages and limitations. However, there are some stark limitations in these processes that may need addressing in the near future. Under such circumstances, a new process which can overcome the limitations of the existing methods is a potential game changer. The proposed process has two variants namely THEW spot variant and THEW slot variant. Both of them will be explained in detail in the upcoming sub-chapters.

3.1. THEW spot variant

The Through Hole Extrusion Welding (THEW) spot variant is a novel process that is under development. As stated earlier, the current work is an extension of an already existing work. The previous work was done as a proof of concept and brought to light the basics of the process [63]. The process involves three materials namely aluminium, stainless steel or titanium and a polymer. The reasoning for choosing these materials will be explained in a separate chapter later in the report. The stainless steel or titanium plate will act as the extrusion plate. The extrusion plate will have a circular hole of a specific diameter through which material flow will be directed. The process setup consists of aluminium on the top followed by the extrusion plate and the polymer at the bottom. A non-consumable, rotating probe will plunge into the aluminium thereby stirring it. The aluminium attains viscoplasticity and is pushed through the extrusion plate inside the polymer. The aluminium forms a hook shaped profile inside the polymer thereby forming a joint. The probe tip plunges through the aluminium and a few millimetres into the polymer. At no point should the probe come into contact with the extrusion plate. The plunging point is chosen at an offset from the centre of the circular hole in the extrusion plate. The direction of offset can be varied in any given direction. Usually, the offset is given in the x-axis. Figure 20 shows the same.

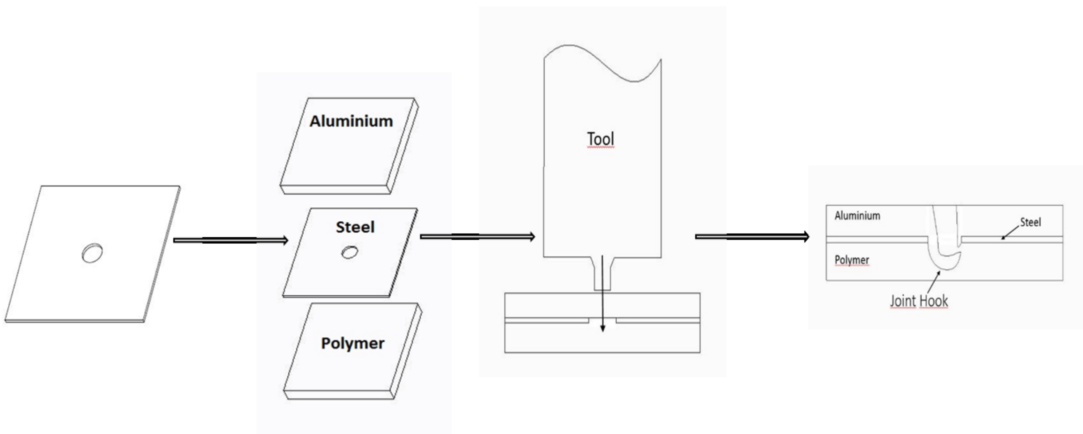

Figure 20 THEW spot variant

3.1.1. THEW spot variant stepwise procedure

The following points show the stepwise procedure for the spot variant of the THEW process.

- The first step is to prepare the materials (aluminium, extrusion plate and polymer) according to the required dimensions.
- The polymer is at the bottom while the extrusion plate with the hole is placed over the polymer.
- The position of the hole along with a certain offset is taken note in the friction stir welding machine. This position will serve as the point where the probe tip plunges into the aluminium.
- After the reference position is taken down, the aluminium is placed over the extrusion plate carefully without disturbing it and clamped tightly in place. Any change will displace the reference position.
- The materials are welded using the friction stir welding machine.

3.2. THEW slot variant

The slot variant of the THEW process is an improvement over the spot variant. The process is typically the same as the spot variant in all aspects except for the difference in the extrusion plate and the inclination of the welding machine. Instead of a circular hole, the extrusion plate will have a slot over a certain length. The welding machine head was fixed at an inclination of 2.5°. This aids the closure of the weld as the tool traverses the slot. The aluminium will be pushed through the slot into the polymer by means of a non-consuming, rotating probe. The process parameters will be explained in the upcoming chapters. Figure 21 shows the process.

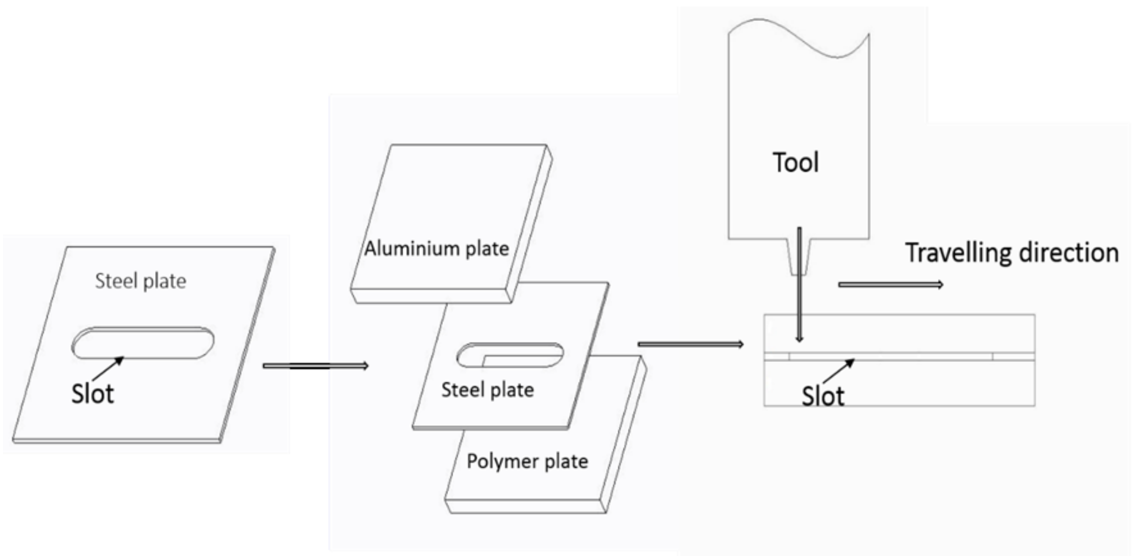

Figure 21 THEW slot variant

3.2.1. THEW slot variant stepwise procedure

The following points show the stepwise procedure for the slot variant of the THEW process.

- The first step is to prepare the materials (aluminium, extrusion plate and polymer) according to the required dimensions.

- The polymer is at the bottom while the extrusion plate with the slot is placed over the polymer.
- The position of the slot along with a certain offset is taken note in the friction stir welding machine. This position will serve as the point where the probe tip plunges into the aluminium.
- After the reference position is taken down, the aluminium is placed over the extrusion plate carefully without disturbing it and clamped tightly in place. Any change will displace the reference position.
- The materials are welded using the friction stir welding machine.

3.3. Comparison of various processes

All the joining processes stated in the previous chapters had its own advantages and limitations. In this scenario, it would be better to emphasize the necessity of a new process for joining metals and polymers together. A comparative representation would be the best way to put forward this. The joints obtained from the THEW process offers multi-directional constraints and can be used for both thermoplastic and thermoset polymers. The joint is airtight too. Some of the common criteria used to compare joining processes include

- Equipment cost
- Easy joint design
- Setup time
- Processing time
- Weight
- Environmental impact
- Microstructural effect
- Multi-directional load resistance
- Mechanical resistance per joint
- Multiple joining mechanisms
- Thickness of the components

The parameters reflect the most important features expected out of a process for joining dissimilar materials. With these parameters as reference, a strategy canvas was created. All the processes were graded on an arbitrary scale of 1 to 10. 1 represents a poor performance for the process for a specific parameter while 10 represents the best for a specific parameter. For example, if adhesive bonding has been graded 1 for processing time, it means the processing time for the process is very high. These grades are relative and subjective and hence are not accurate. It is used for the sake of comparison only.

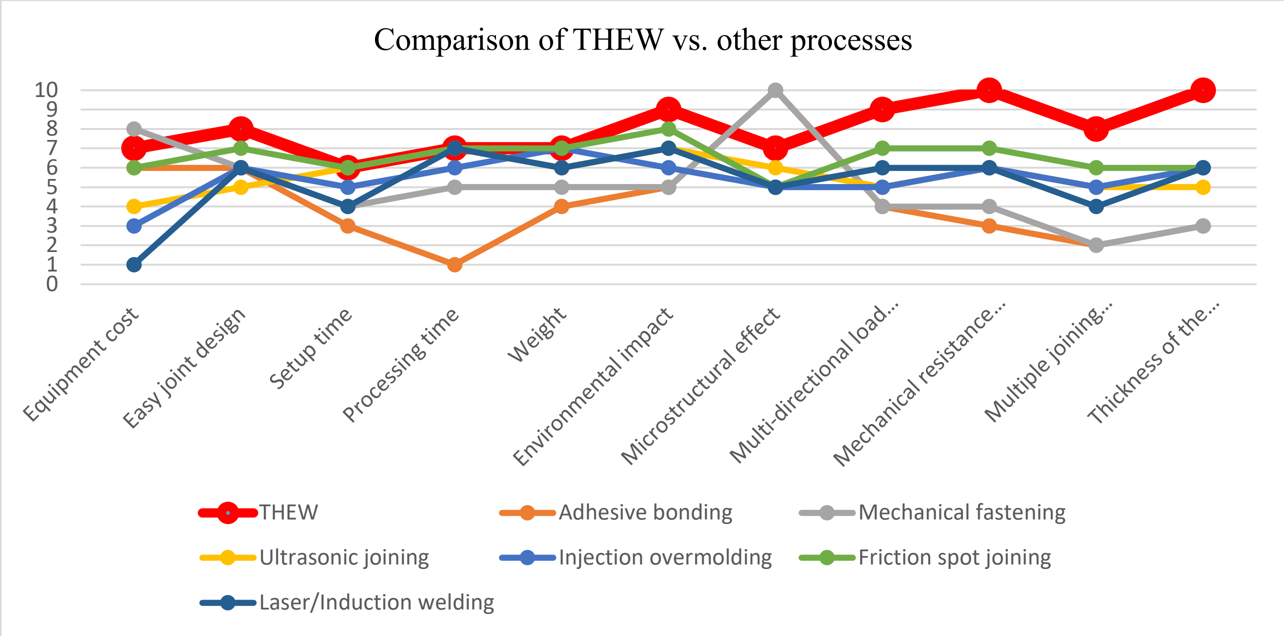

Figure 22 Comparison of THEW vs. other processes

Figure 22 shows the comparison graph between THEW and other processes. It can be seen that the THEW process is on par with the other processes in many of the areas and ahead of them in key areas such as environmental impact, mechanical resistance per joint, multiple joining mechanisms and thickness of the components.

4. MATERIALS AND EQUIPMENT

4.1. Materials Used

The materials used for the current study include aluminium alloy AA5754-H111, Stainless steel grade 316, Titanium grade 5 and Polyethylene Ether ketone (PEEK). The stainless steel and titanium serve as the extrusion plates during the process. Each of these materials and the reason for choosing them will be explained in the following sub-chapters.

4.1.1. Aluminium alloy AA5754-H111

Aluminium alloys are one of the most widely used materials in engineering and structural applications. Some of the key characteristics of aluminium when compared with steel (a common engineering material) include [64]

- The key difference in the melting point of the metal and its oxide is a huge factor. Most oxides of iron have a melting point very similar to that of the metal itself. On the contrary, the melting point of aluminium oxide is 2060 °C, which is 1400 °C more than that of aluminium.
- The oxide layer is highly durable and self-healing. Hence, these alloys have excellent corrosion resistance.
- The coefficient of thermal expansion is twice that of steel.
- The specific heat of aluminium of aluminium is twice that of steel.
- The electrical conductivity of aluminium is six times that of steel.
- It does not change colour with increase in temperature unlike steel.
- It is non-magnetic in nature.
- The modulus of elasticity of aluminium is three times that of steel.
- Aluminium does not change its crystal structure on heating and cooling unlike steel.

Keeping in mind the extensive potential of aluminium across industries, an alloy of aluminium was chosen as one of the base materials for the project. After consideration, the alloy AA5754-H111 was chosen for the study. The chosen material belongs to a group of alloys in the wrought aluminium/magnesium family. The International Alloy Designation System is the most widely accepted naming system for wrought alloys. Wrought alloys are generally designated with four numbers. The first digit represents the main alloying material; the second represents the variations of the initial alloy while the third and fourth represent the individual alloy variations. The numbers themselves are insignificant but they are unique. These numbers can be followed by specific alphabets such as F, O, H, W and T [65]. These alphabets are based on the temper designation system for aluminium alloys. 'F' stands for fabricated, 'O' stands for annealed, 'H' stands for strain-hardened, 'W' stands for solution heat treated and 'T' stands for thermally treated to produce stable tempers other than 'F', 'O' and 'H'. These alphabets may further be followed by numbers ('H' will always be followed by two or three digits after it). The aluminium alloy chosen has a composition as shown in Table 4 [66].

Table 4 Composition of AA5754-H111 alloy

Element	% present
Magnesium	2.60 - 3.60
Manganese + Chromium	0.10 – 0.60
Manganese	0.0 – 0.50
Silicon	0.0 – 0.40
Iron	0.0 – 0.40
Chromium	0.0 – 0.30
Zinc	0.0 – 0.20
Titanium	0.0 – 0.15
Copper	0.0 – 0.10
Others (each)	0.0 – 0.05
Aluminium	Balance

H111 represents some work hardening imparted by shaping processes but less than what is required for H11 temper. This is the most common form of tempering. The alloy is usually supplied in the form of sheets, plates or patterned sheets. The properties of the H111 tempered material are shown below in Table 5.

Table 5 Properties of AA5754-H111 alloy

Property	Value
Density	2.66 g/cm^3
Melting point	600 °C
Thermal expansion	24 x10^{-6} /K
Modulus of Elasticity	68 GPa
Thermal Conductivity	147 W/m.K
Electrical Resistivity	0.049 x10^{-6} Ω .m
Proof Stress	60 Min MPa
Tensile Strength	160 - 200 MPa
Elongation A50 mm	12 Min %
Hardness Brinell	44 HB

The weldability of AA5754-H111 alloy are shown in Table 6.

Table 6 Weldability of AA5754-H111 alloy

Welding type	Weldability
Gas	Excellent
Arc	Excellent
Resistance	Excellent
Brazability	Poor

The cold workability is very good while the machinability of the material is average. The material was chosen for its extensive use in aerospace, shipbuilding and automotive industries [67]. These industries are potential candidates of use for the current study.

4.1.2. Stainless steel AISI 316

When chromium is added to steels, it progressively increases the corrosion resistance of the material. This is because of the formation of a thin protective layer of chromium oxide, which is highly non-reactive. Any steel that has at least 12% of chromium is considered stainless steel [68]. Grade 316 represent austenitic steels with nickel and molybdenum. The addition of nickel is to preserve the austenitic structure of the material. Grade 316 steels are used in applications requiring corrosion resistance superior to grade 304 steels such as exhaust manifolds, furnace parts, heat exchangers and marine environments. They provide superior corrosion resistance in chloride environments than their 304 counterparts [69]. They also show impressive resistance to acetic, formic, phosphoric and tartaric acids. The composition of AISI 316 stainless steel is shown in Table 7 [70].

Table 7 Composition of AISI 316 stainless steel

Composition	Wt %
Carbon	0.08 max.
Manganese	2.00 max.
Phosphorus	0.045 max.
Sulphur	0.030 max.
Silicon	0.75 max.
Chromium	16.0 - 18.0
Nickel	10.0 – 14.0
Molybdenum	2.0 – 3.0
Nitrogen	0.10 max.
Iron	balance

The typical properties of AISI 316 stainless steel are shown in Table 8 [71].

Table 8 Properties of stainless steel AISI 316

Properties	Range
Young's Modulus	205 GPa
Yield Strength (elastic limit)	310 MPa
Tensile Strength	515 MPa
Elongation	50 %strain
Compressive Strength	310 MPa
Flexural Strength	310 MPa
Shear Modulus	82 GPa
Hardness-Vickers	220 HV
Density	8,07e3 kg/m^3
Melting Point	1400°C
Thermal Conductivity	13 W/m.°C
Specific Heat Capacity	490 J/kg.°C
Thermal Expansion Coefficient	15 µstrain/°C

The weldability of the material is very good and it has a low thermal conductivity. The low thermal conductivity is highly important as it shields the polymer from the high temperatures attained during the welding process. The heat generated on the aluminium side of the setup should not be transferred easily to the polymer, as it will melt the material due to the difference in their melting temperatures.

4.1.3. Titanium

Titanium is the seventh most abundant material in the Earth's crust and is present in its oxide form. However, the process of separating the material from its oxide is highly difficult. Nowadays, it is one of the most sought after materials used worldwide. Titanium alloys have excellent tensile strength, toughness, corrosion resistance and can withstand high temperatures. They are also lightweight in nature. The alloys of titanium can be classified broadly into four categories as follows [72].

- Alpha alloys: contains neutral alloying elements such as tin and/or alpha stabilisers aluminium or oxygen only; not heat treatable.
- Near-alpha alloys: contains a small amount of ductile beta phase stabilisers such as molybdenum, silicon or vanadium.
- Alpha and beta alloys: metastable; contains combination of alpha and beta stabilisers and can be heat-treated.
- Beta and near beta alloys: metastable; contains sufficient beta stabilisers to maintain beta phase when quenched; can be solution treated and aged to improve strength.

The ASTM International provides certain guidelines on the treatment of the titanium alloys, which are represented by a certain grade. The grade that has been used for the current study is grade 5. It is also known as Ti6Al4V, Ti-6Al-4V or Ti 6-4 and is the most commonly used titanium alloy. It is known as the 'workhorse alloy' of the titanium industry because of its extensive use. The chemical composition of grade 5 titanium alloy is shown in Table 9 [73].

Table 9 Composition of grade 5 titanium alloy

Composition	**Wt %**
Aluminium	6
Vanadium	4
Iron	0.25 max.
Oxygen	0.2 max.
Titanium	balance

The alloy is significantly stronger than commercially pure titanium but it has the same stiffness and thermal properties. On the contrary, its thermal conductivity is only 60% lower than that of commercially pure titanium. It has excellent strength, corrosion resistance, weldability and fabricability. It is also heat treatable. The common properties of the grade 5 alloy are shown in Table 10 [73].

Table 10 Properties of grade 5 titanium alloy

Properties	**Range**
Brinell Hardness	334
Rockwell Hardness	36
Vickers Hardness	349
Ultimate Tensile Strength	950 Mpa

Yield Tensile Strength	880 Mpa
Modulus of Elasticity	113.8 GPa
Compressive Yield Strength	970 Mpa
Poisson's ratio	0.342
Fatigue strength	510 Mpa
Shear modulus	44 GPa
Thermal conductivity	6.7 W/m-K
Melting point	1604 – 1660 °C

Since the titanium alloy can withstand high temperatures, it is of considerable importance to the current study. Hence, it was chosen as a material for the extrusion plate.

4.1.4. Polyether ether ketone

Polyether ether ketone (PEEK) is a colourless, organic thermoplastic polymer in the polyaryletherketone family. It was first introduced in the 1980's by Victrex PLC. It is one of the most sought after materials used in engineering applications nowadays. It is synthesized by the step growth polymerization by the dialkylation of bisphenolate salts. Step-growth polymerization refers to a type of polymerization mechanism in which bi-functional or multifunctional monomers react to form dimers, then trimers, longer oligomers and eventually long chain polymers [74]. Typically, it is produced by the reaction of 4,4'-difluorobenzophenone with the disodium salt of hydroquinone in the presence of diphenyl sulphone at around 300 °C [75]. The chemical structure of PEEK is shown in Figure 23 [76].

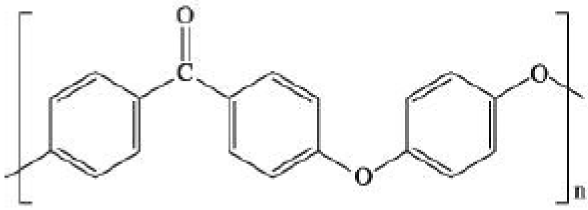

Figure 23 Chemical structure of PEEK [76]

PEEK is a semi crystalline thermoplastic material and has excellent mechanical and chemical resistance even at high temperatures. The composition of PEEK can vary depending on the ratio of the ether groups to the ketone groups. Unfilled PEEK, which does not have any other material mixed with it, has excellent resistance to high temperatures and is strong. It can also resist most acids and has excellent processability. The properties of PEEK (natural or unfilled; PEEK 450G) is shown in Table 11 [77].

Table 11 Properties of PEEK

Property	**Condition**	**Method**	**Range**
Density	23 ºC	ISO 1183	1.3 g/cm^3
Friction Coefficient			0.35
Rockwell Hardness	23 ºC	ASTM D785	99
Tensile Elongation	23 ºC	ISO 527	45%

Tensile Modulus	23 ºC	ISO 527	3.7 GPa
Bending Modulus	23 ºC	ISO 178	4.1 GPa
Melting Point		ISO 3146	343 ºC
Glass Transition Temperature	Initial temperature	ISO 3146	143 ºC
Distortion Temperature	1.8Mpa	ISO 75A-f	152 ºC
Pyro-conductivity	23 ºC	ASTM C177	0.29 W/mºC
Dielectric Strength	2.5mm thickness	IEC 60243-1	16 KV/mm

The excellent properties of PEEK coupled with its extensive engineering applications made it a good choice for the current study. Though the previous work focussed on some additional materials, the current work focusses only on the materials mentioned above.

4.2. Equipment used

The main equipment used for the processes were the friction stir welding machine and the milling machine. The friction stir welding machine was used to do all the welds while the milling machine was used to machine the slots and holes in the extrusion plates. The milling machine was also used to machine the materials to the required dimensions if and when required.

4.2.1. Friction stir welding machine

The friction stir welding machine used was the ESAB LEGIO FSW 5UT. It is a custom-made machine developed by the Swedish manufacturer ESAB. The machine is based on the LEGIO platform that was developed to provide a standardized and modular approach to the friction stir welding process [78]. The platform offers a rigid framework for high performance during high load conditions with a wide range of welding head travel. The welding head travel is actuated by means of a ball-screw system. The welding head itself is hydraulically actuated thereby generating high forces. The contact forces are accurately controlled using Programmable Logic Controllers (PLC), which provide a closed loop feedback. The spindle is driven by an AC-motor and liquid cooling is provided for the spindle and the tool. The cooling reduces wear on the components. The z-axis control of the machine has force control and position control. Users can interact with the machine through a 15” touch screen HMI interface.

The modular system makes it possible to use different welding systems according to the requirements. The machine is available in seven different sizes while each of them can be configured in five basic designs. The size and design of the machine used was 5UT. The UT model is ideal for the production of small workpieces as it comes with a table over which fixtures can be easily integrated. The specifications of the ESAB LEGIO FSW 5UT machine are as follows [78].

- Maximum Torque: 200 Nm
- Maximum Rotational Speed: 3000 rpm

- Maximum Forging force: 100 kN
- Maximum welding travel speed: 4 m/min
- Work Envelope Dimensions: 2000*400*300 mm (XX,YY,ZZ)
- Welding control(Z-Axis):
    - Force
    - Position
    - Speed
- Welding Angle: 0 degrees to 5 degrees
- Monitoring parameters
    - Spindle speed and Torque
    - Position, Speed and Force in XX, YY and ZZ axes

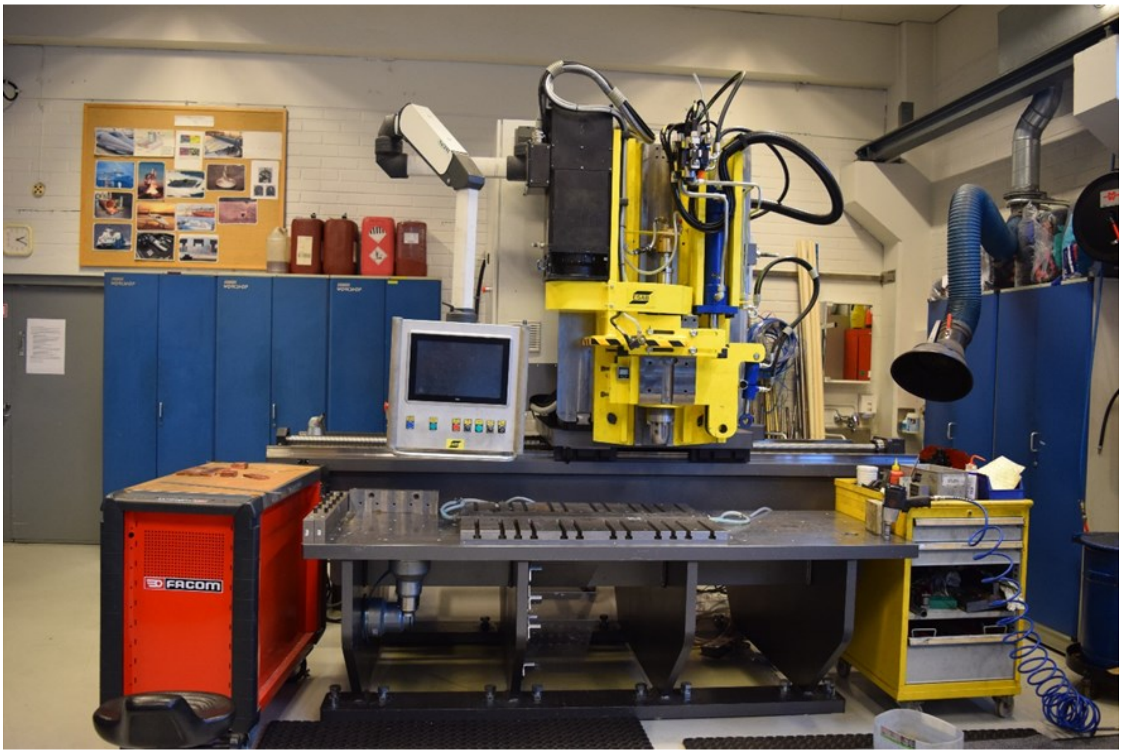

Figure 24 ESAB LEGIO FSW 5UT machine

Figure 24 shows the ESAB LEGIO FSW 5UT machine which was used for welding.

The other important machine that was used during the current work was the universal milling machine. The milling machine was used to drill and mill the holes and the cylindrical slots in the extrusion plates. The machine can be integrated with different types of chucks as per the requirement. A normal work holding chuck was used for holding drills and mills but larger drill sizes required the use of Morse taper chucks. The machine is versatile enough to fix these different types and was of great use in the work. Other machines that were used include the horizontal saw and the cylindrical grinding wheel. These two were used to cut the workpieces after the weld for inspection of the joint. Figure 25 shows the milling machine used.

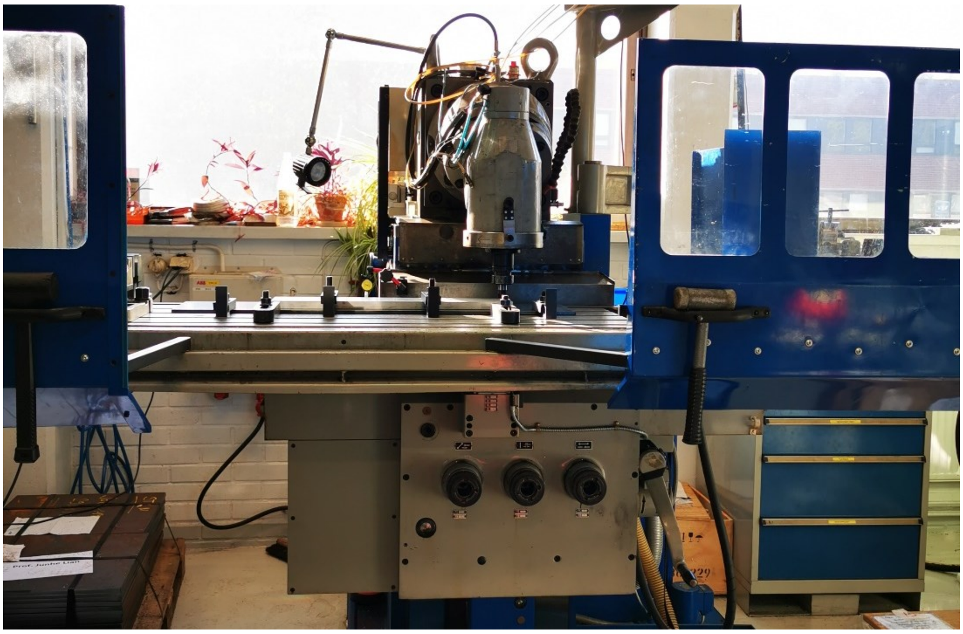

Figure 25 Milling machine

Apart from the above stated equipment, a few other were used for testing the welded workpieces. The welds were subjected to tensile shear and cross tension tests.

4.2.2. MTS Landmark 810 Material Testing System

The MTS Landmark 810 material testing system was used for both tensile shear and cross-tension tests. Figure 26 shows the same. The machine is available at the Engineering Materials laboratory of the School of Engineering in Aalto University. It is a versatile, multipurpose and high-performance machine with servo-hydraulic testing capabilities. It can be used for both static and dynamic materials and components testing. Different jigs and clamps were used to hold the workpieces on the machine. The important features of the MTS 810 are listed as follows [79].

- **Force range:** 25 kN - 500 kN
- **Materials that can be tested:** plastics, elastomers, aluminium, composites, steel, and superalloys
- **Specimen size compatibility:** subsidized, standard, medium and large.
- Facility to conduct tensile tests, cross tension tests, torsion tests and the shear tests with suitable jigs, fixtures, and clamps

Figure 26 MTS Landmark 810 Material Testing Machine

5. Process development

Before starting work on the project, the initial idea was to understand the shortcomings of the previous work and lay out a project plan for further development. The previous thesis work was reviewed thoroughly and the following process plan shown in Figure 27 was charted out.

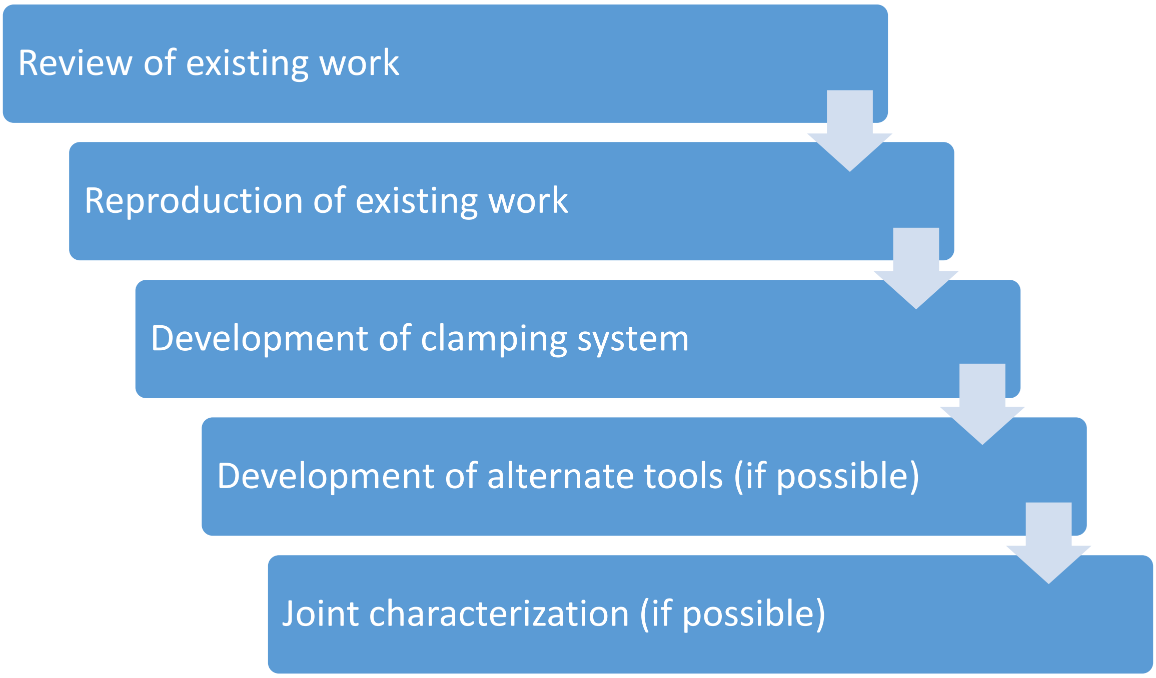

Figure 27 Initial process plan

The work is focussed on developing a novel process and hence the process plan was more open and flexible to any changes which can happen during the work.

5.1. Reproduction of existing work

The first step in the current work was to reproduce the results from the previous study. After examination of the work, the process steps were understood and the optimized parameters suggested were chosen. Based on the results put forward, it was understood that the slot variant of the THEW process was more robust in terms of mechanical performance. It was decided that the current work would benefit more from focussing on the slot variant.

The tools, clamping and the parameters chosen for the slot variant in the existing work were chosen [63]. The tool used was developed specifically for the process. It is a modular tool and has three separate parts namely the tool body, shoulder and probe. The modular design makes it easy to integrate different probes with the same tool body and shoulder. It also makes it possible to vary the length of the probe tip. The tool assembly model is shown in Figure 28 [63].

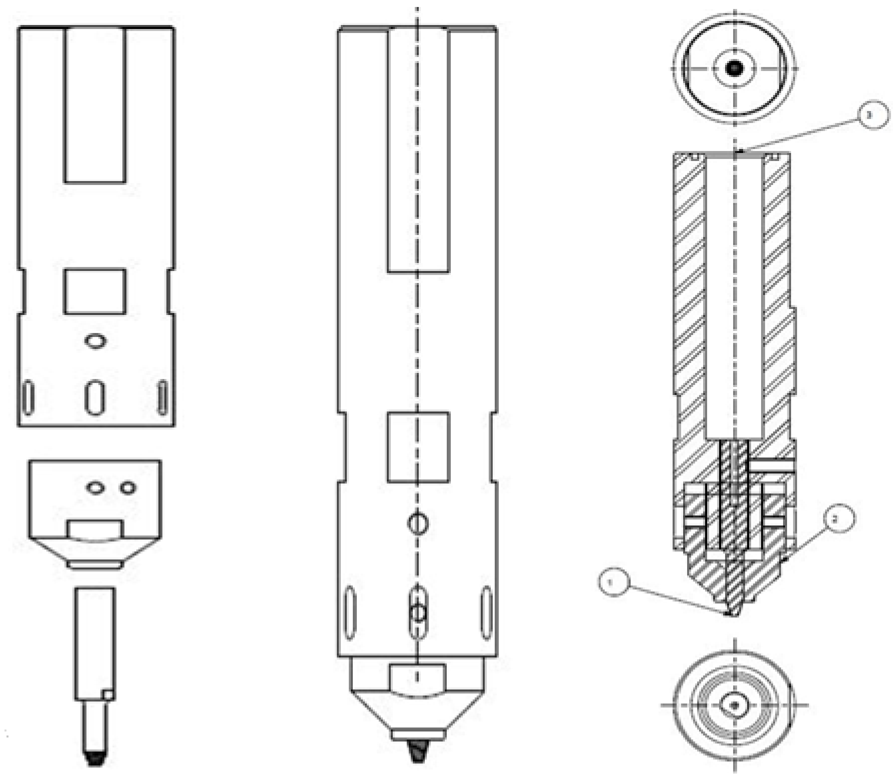

Figure 28 Figure Tool assembly
Exploded view (left); Assembly (centre); Section view (right) [63]

The probe is understood to be an integral part of the welding process. It is responsible for the shear deformation of the material and for the deposition of the viscoplastic material into the polymer. A plain cylindrical probe would lead to lesser deposition of the visco-plastic material while a conical probe resulted in the loss of material while plunging. The hybrid probes were designed by combining both the conical and cylindrical profile of the existing probes thereby achieving better material deposition and lesser flash generation. There were eight different probes to choose from- four sets of conical and four sets of hybrid probes. Each probe was unique. The hybrid probes were made with both cylindrical and conical contours and were chosen as they offered the best possible results among the lot. Figure 29 shows the hybrid probe chosen for the welding [63].

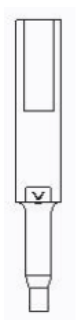

Figure 29 Hybrid probe [63]

5.1.1. Material geometry

The materials that were to be used for welding were machined to the specific dimensions required. The aluminium was cut and machined to pieces of 150*50*6 mm each. The only difference between the size of aluminium and the other materials used were the thickness. The PEEK material was 10 mm thick while the stainless steel plate was 1 mm thick. The length and width of all the three materials are the same. The specified dimensions were suggested in the previous work. The stainless steel plate was drilled and milled to produce a cylindrical through slot of size 30*8 mm. The operational parameters used for the test are shown in Table 12 [63]. Table 13 shows the dimensions of the materials that were used.

Table 12 Optimized parameters for the slot variant

Parameters	Range
Rotational speed	900 rpm
Probe length	10 mm
Weld position	-9.7 mm
Welding speed	175 mm/min
Tool plunge	0.2 mm/s
Reference force	8 kN
Control	position
Dwell time	1 sec (at plunging point)
Offset length in Y Direction	1mm (from the center)
Weld Length	22 – 24 mm
Dimensions of the slot in the stainless steel plate	8 mm dia.*26 mm length

Table 13 Dimensions of the materials

Material	Dimensions in mm
Aluminium	150*50*6
PEEK	150*50*10
Stainless steel/Titanium	150*50*1

Figure 30 shows the slots that were machined in the stainless steel plates.

Figure 30 Slots in the stainless steel plate

The stainless steel plates were 1 mm thick and hence could not be milled separately. Instead, a stack of plates was held together and a sacrificial material (usually aluminium) of the same thickness as the stack was placed over it and clamped together. This was done to make sure the stack does not lift up or move during drilling and milling. The aluminium on top also made sure there was as little air gap as possible between the stainless steel plates. The presence of air gaps would cause the plates to move. Another piece of aluminium was placed below the stack as a base. This ensured that a through slot could be created. The same procedure applies for titanium plates too.

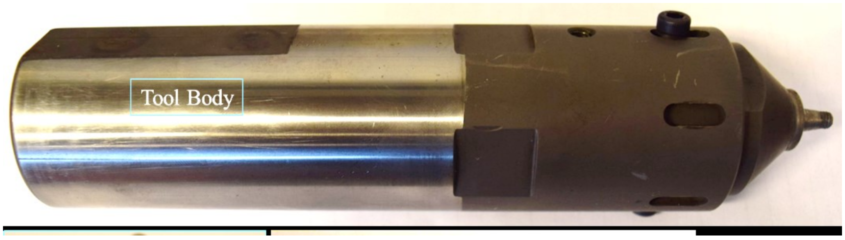

Figure 31 Tool assembly used

Figure 31 shows the tool assembly used for the welding process. The tool is fit into the friction stir welding machine. O-rings are used to seal any coolant in the machine from flowing out through the tool. The screws used in the tool assembly are covered with Teflon tapes to provide additional leak protection. These tapes will be changed frequently. The clamping arrangement used is shown in Figure 32 [63].

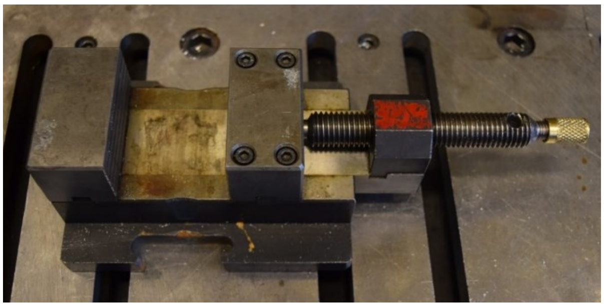

Figure 32 Clamp used

The clamp used for the process is a table vice which was integrated into the table of the friction stir welding machine. The vice was clamped to the table using separate clamps. Figure 33 shows the cooling tube setup [63].

Figure 33 Cooling tube setup

The cooling tube setup consists of three copper bars that have through holes drilled through them. Plastic tubes were connected on both sides of the bars through connector pins. The tubes were all connected to a water source on the other end. The longer of the bars were placed on top of the aluminium pieces while the smaller bar was placed below the polymer and served as a base.

5.1.2. Procedure and results

The setup and welding procedure are explained in the following steps.

- The assembled tool is fixed into the friction stir welding machine.
- The table vice is fixed on the table using clamps.
- The smaller copper bar is placed in between the jaws of the vice.
- The PEEK material is placed over the copper bar. The stainless steel plate is placed over the polymer.
- The jaws of the vice are tightened just enough that the steel plate and the polymer are held tight.
- The tool is brought down and positioned at an offset from the centre of the slot. The offset is usually taken in the y-axis of the machine.
- After positioning, the current location of the probe tip is noted down in the user interface.
- After the position has been input and loaded into the machine memory, the tool is moved up.
- The aluminium is now placed carefully over the stainless steel plate without disturbing the position of the steel plate and the vice is tightened.
- The two remaining copper bars are placed over the jaws of the vice, pressing over the aluminium material.
- The tool is again brought down so that the probe tip touches the surface of the aluminium. This position is considered as the ‘zero position’ in the z-axis of the machine and entered into the machine interface. The depth of penetration will be calculated by the machine from this position and hence it is important.
- The water source is turned on and after verifying the parameters, the welding is started.

Figure 34 shows the clamping setup along with the cooling tubes before the actual welding [63].

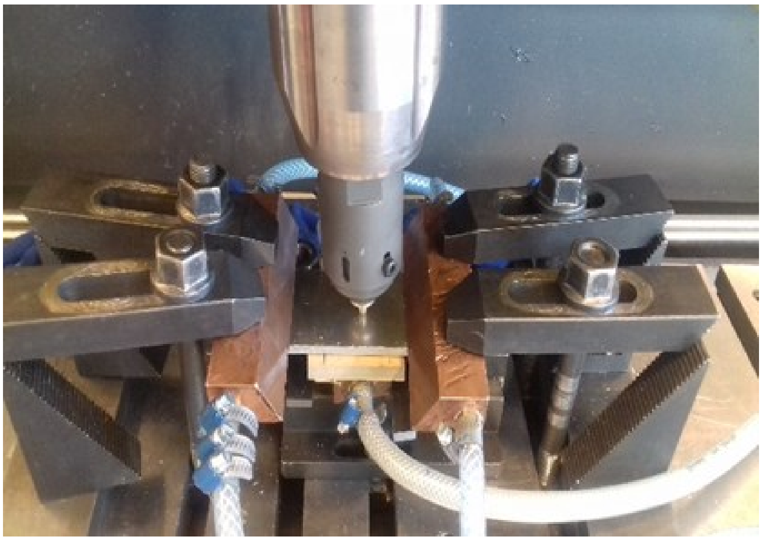

Figure 34 Clamping setup with the materials before the start of welding

There were a large number of tests done with the above stated set of parameters and clamping setup. Different results were obtained and it was very hard to reproduce good results. Figure 35 shows one such weld.

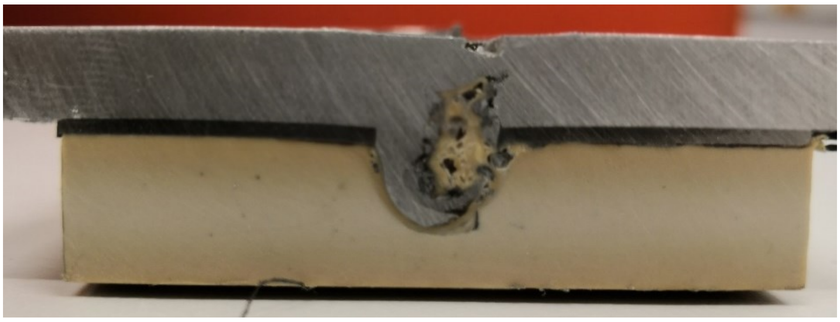

Figure 35 Cross section of joint with proper material deposition

Figure 35 shows another cross section of a joint that had better material deposition than the other cases. It can be seen that the aluminium has been pushed into the polymer leading to a joint hook. The polymer has been pushed up to fill in the gap at the joint interface. When viewed up close, it can be seen that the polymer material has some porosity that can degrade the quality of the joint.

As more workpieces were welded, it was found that the clamping setup was not ideal for the process. The table vice had limitations regarding the maximum length of the samples. There are a lot of moving parts in the workpiece and it was difficult to hold them in place. The extrusion plate should be firmly held in place between the jaws of the vice for a good weld. However, there was always some disturbance to the extrusion plate during the setup and it resulted in many failed welds. The cooling plate placed below the polymer was providing a smooth surface for the polymer to slide over and this made holding it more difficult. The vice also required that the materials were machined to the exact size with very less tolerance. A larger tolerance resulted in one of the material being either too large or too small than the others. This made the particular material free to move within the vice. The cooling plates on top of the aluminium constrained the space available for the tool to plunge. These factors led to the decision to stop using the table vice altogether and stressed the need of a different clamping setup.

5.2. Minor improvements

It was found that using the welding table of the friction stir welding machine itself was a viable option to fix the workpieces. However, to eliminate the length constraint of the table vice, the vice was rotated on its side so that longer workpieces could be held between the jaws of the vice. To solve the issue of the moving parts, a simpler solution of fastening them with a screw was considered. Figure 36 shows the same.

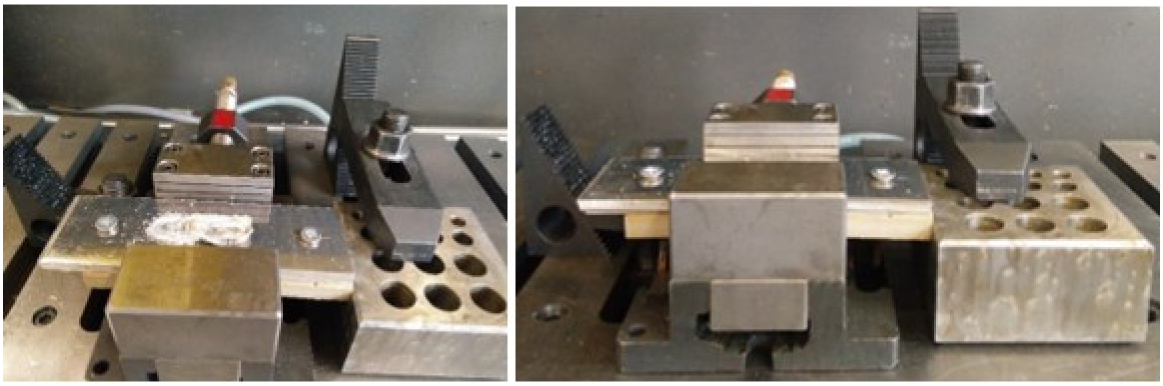

Figure 36 Workpiece fastened with screws

After the extrusion plates were milled with the slot, a hole was drilled through the aluminium, extrusion plate and the polymer material at the ends. A screw was put through the holes to make sure the materials cannot move. The setup process was modified in order to accommodate the screw. The modified setup process is as follows.

- The polymer and the extrusion plate are placed in the vice. The holes have been drilled through them already.
- The position of the slot is taken.
- The aluminium is carefully fixed and the screws are put into position through the hole thereby making sure the extrusion plate cannot move.

A block of machined steel was used as a stopper on one end of the workpiece after fixing it in the vice. The steel block was clamped to the table. This serves as a stopper and as a reference in case any of the materials move from their positions. After the welds were done, the portion containing the screws were cut off from the rest of the welded workpiece. Though it offered a solution, it had its own set of problems. The foremost issue was that of wastage of material. The material that was cut off could not be reused and it was a huge loss in terms of cost too. It also involved too much time to drill the hole for the screws and fasten the materials.

An easier and economically feasible option was considered to eliminate the movement of the extrusion plate. A 1mm deep slot was milled into the polymer surface so that the extrusion plate can fit into the slot. The embedded extrusion plate cannot move during the weld and makes it repeatable. It was decided to use this solution for all the forthcoming tests.

6. Development of clamping system

The existing clamping system had many drawbacks that were explained in the previous chapter. In order to improve the weld, a new clamping setup was developed. Solidworks modelling software was used for modelling the clamp.

6.1. Requirements of the clamping system

The requirements of a good clamping system are as follows.

- It should provide enough clamping force to clamp the required components
- It should provide a stable base over which the components can be fixed
- It should be versatile enough to hold different configurations of the workpiece
- It should make the process easy to be repeated

The above stated requirements are the most important ones to be considered when designing a clamping system and these apply well to the case under consideration here. The following sub-chapter describes the design of the clamp developed.

6.2. Design of the clamping system

Based on the requirements stated above, the clamping system was designed in Solidworks. The drawing of the system is attached in the Appendix section. Figure 37 shows the same.

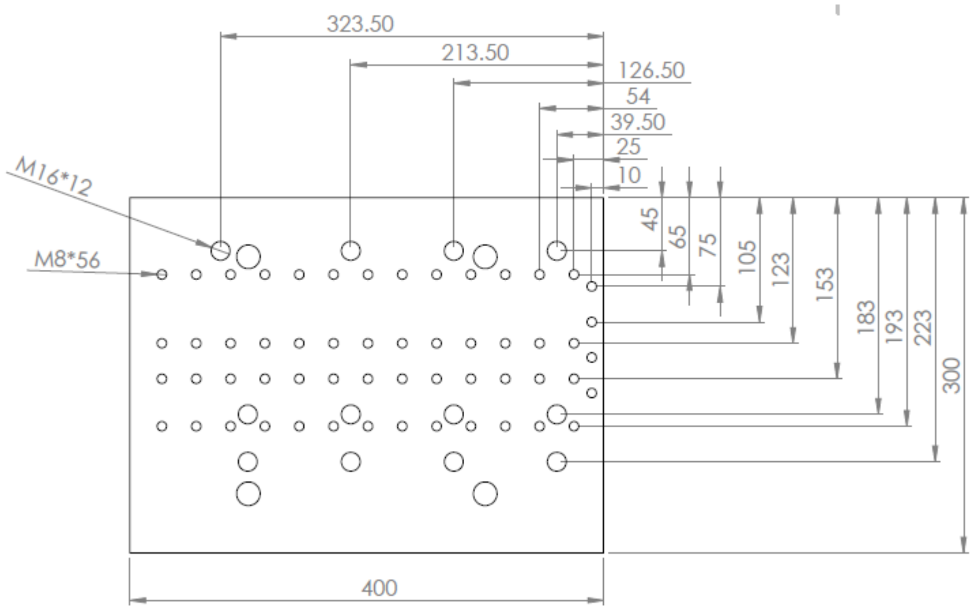

Figure 37 New clamping system

As can be seen in Figure 38, the new system is a block of material that has a series of carefully spaced holes on it. An existing block of steel was chosen for this purpose. The steel block had dimensions of 400x300x30 mm. Standard size screws can be put through all the holes. The idea is that the screws can act as stoppers and references on three directions. The block contains three different hole sizes namely M8, M16 and M20. There are totally 56 holes of M8, 12 holes of M16 and 4 holes of M20. All these are through holes that pass through the entirety of the block. The M20 holes are used to clamp the system on the table of the friction stir welding machine. The M16 holes are used to accommodate the standard holding fixtures of the machine. The smaller M8 holes are designed to hold a set of screws which will act as references and stoppers in three directions.

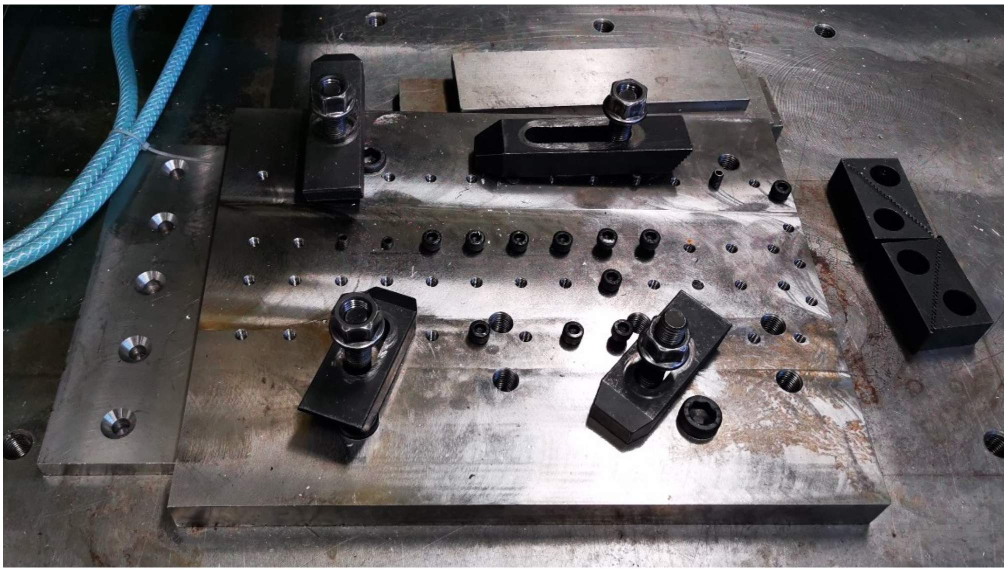

Figure 38 Clamping system with all clamps attached

Figure 38 shows the newly machined clamping system with all the screws and clamps attached before a welding process. The row of smaller bolts act as references and stoppers in 3 directions while the clamps are used to fix the workpiece firmly to the clamping table.

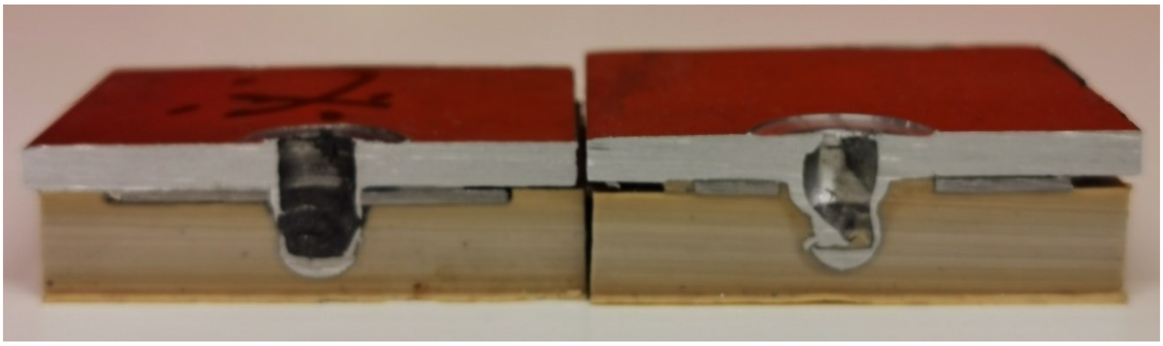

Figure 39 Welding done using the new clamping system

Figure 39 shows a weld done using the newly developed clamping system. It can be noted that the weld quality is already better than the previously obtained ones. This is due to the reason that the clamping system offers a stable base on which the workpiece is firmly clamped and has lesser space to move during the actual process itself. We can notice the extrusion plate is placed inside the slot in the polymer, thereby reducing the amount of material used too. The clamping system is also capable of providing cooling through a cooling tube that passes through the base of the table itself. The details of that can be seen in the drawing attached in the Appendix section. It should be noted that no cooling was used for the above mentioned process.

7. Stationary shoulder

There is a lot of literature which explains about the efficiency of a stationary shoulder in a friction welding process. Li et al. [80] have studied about the effects of a stationary shoulder in the friction stir welding of aluminium alloy 7075-T651. They conclude that stationary shoulder can achieve defect free aluminium joints with a homogenous distribution of constituent particles in the Heat Affected Zone (HAZ). Li et al. [81] discuss about the effect of welding parameters on microstructure and mechanical properties of AA6061-T butt welded joints using stationary shoulder friction stir welding. Their results show that they were able to obtain symmetrical and homogenous microstructures in the weld zone. They also analysed the hardness profiles of the joint at both the advancing and retreating side. The lowest hardness value of the joint reached 60% of the base material hardness [81]. Sun et al. [82] have compared the residual stress distributions in conventional and stationary shoulder high strength aluminium alloy friction stir welds. They were able to obtain a narrower weld hardness profile due to the lower power dissipation using the stationary shoulder. They were also able to find that the probe was able to heat up the material more efficiently when using a stationary shoulder. These studies show that a stationary shoulder can have major improvements in the weld quality of a friction stir weld.

7.1. Development of stationary shoulder

The stationary shoulder is used to provide a non-rotating ceiling to the workpiece when the probe plunges into the material. Instead of the shoulder rotating and causing the material to be stirred, a stationary shoulder provides a region where only the material around the probe tip is stirred. This allows for more focussed welds with improved material deposition. Figure 40 shows a weld without stationary shoulder.

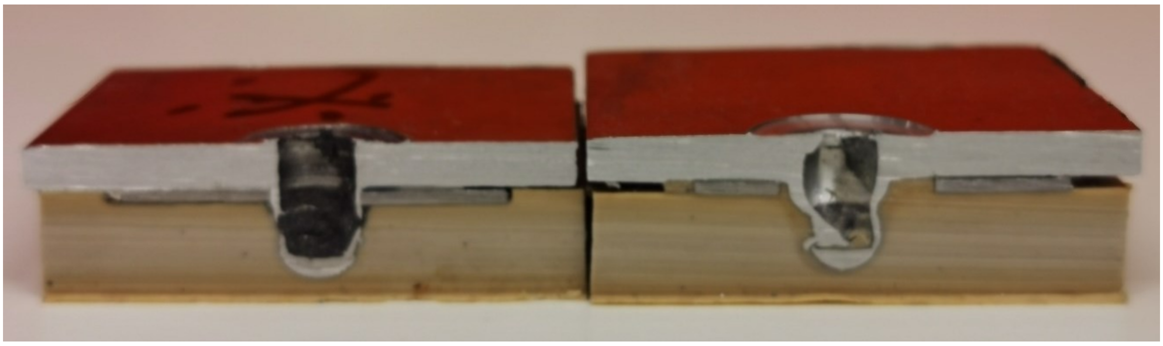

Figure 40 Welding without stationary shoulder

The stationary shoulder required for the process has to be simple enough to be used with the clamping table. Hence, it was decided against to use a stationary shoulder which was fixed to the friction welding machine. A shoulder which can be clamped over the workpieces was instead used for this purpose. The stationary shoulder used is basically a steel plate with equally spaced holes running along its length. The reason for having multiple holes is that many welds can be done in a single trial. The existing shoulder from the probe is removed leaving the tool to have only the tool body and the probe. The probe will plunge through the holes in the shoulder and into the workpieces placed below the shoulder. The probe should be sufficiently thick enough to withstand the loads on it. The hole diameter of the stationary shoulder should also be carefully chosen to give the smallest possible space between the probe and itself. A smaller diameter than acceptable would lead to the probe coming into contact with the shoulder and breaking. A larger diameter hole would result in the aluminium material being pushed up to fill this gap. During the weld, this aluminium will solidify and would oppose the rotation of the probe and ultimately breaking it. Figure 41 shows the stationary shoulder used.

Figure 41 Stationary shoulder block

The weld procedure is now as follows.

- The assembled tool is fixed into the friction stir welding machine.
- The tool is brought down and positioned at an offset from the centre of the spot. The offset is usually taken in the y-axis of the machine.
- The aluminium is now placed carefully over the extrusion plate followed by the stationary shoulder on top of the aluminium. They are clamped tight.
- The zero position is noted down and the parameters are input to the system.
- The welding process is started after verifying the parameters.

Figure 42 shows a weld obtained using the stationary shoulder. It can be noticed that the amount of aluminium that has been pushed into the polymer has increased.

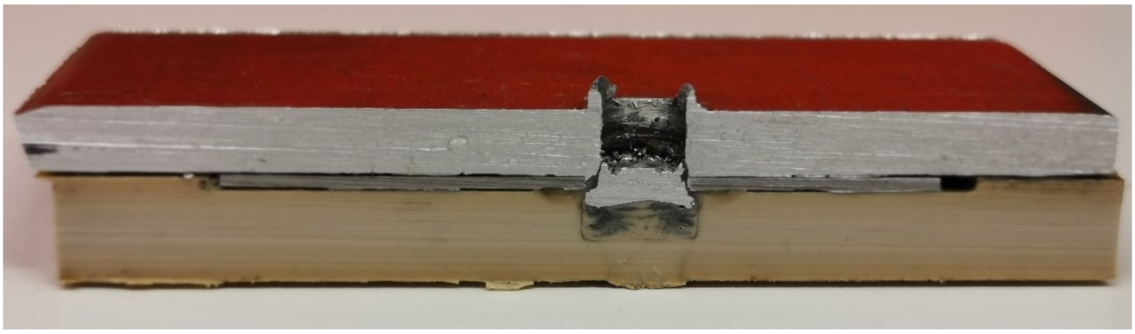

Figure 42 Weld obtained using a stationary shoulder

The depth of penetration was reduced to study the effects of a stationary shoulder in the above shown Figure 42. The tests were now repeated with the newly developed clamping system and stationary shoulder along with the set of parameters specified in Table 14.

Table 14 Parameters used

Parameters	Range
Rotational speed	900 rpm
Hole diameter in extrusion plate	10 mm
Weld position	-25 mm
Welding speed	175 mm/min
Tool plunge	0.2 mm/s
Reference force	8 kN
Control	position
Dwell time	1 sec (at plunging point)
Offset length in Y Direction	1mm (from the center)

A problem encountered while using the stationary shoulder was the cracking of polymer plate. The dwell time was changed to see the effects but the problem of cracking continued. It was observed that the tool plunging speed was higher. Hence, the dwell time was reduced to 0 seconds and the tool plunging speed was reduced to 0.1 mm/s. This prevented the polymer from cracking. Figure 43 shows a welded joint embedded in a cold mold.

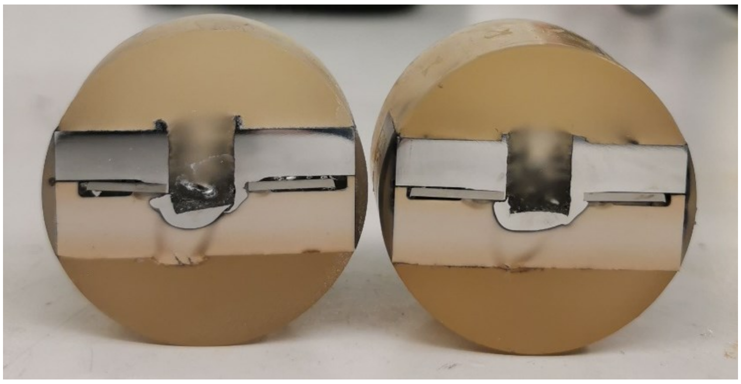

Figure 43 Welded joints embedded in molds

It can be noticed that the joint hooks have increased in thickness when compared to the joints done without a stationary shoulder. The optimised set of parameters are given in Table 15.

Table 15 Optimized set of parameters for stationary shoulder welding

Parameters	Range
Rotational speed	900 rpm
Hole diameter in extrusion plate	10 mm
Weld position	-25 mm
Welding speed	175 mm/min
Tool plunge	0.1 mm/s

Reference force	8 kN
Control	position
Dwell time	0 sec (at plunging point)
Offset length in Y Direction	1mm (from the center)

8. Mechanical testing and results

The welds obtained using the set of parameters specified in Table 15 were subjected to mechanical testing. The equipment used for the testing has been specified earlier in Chapter 4. Cross tension and tensile shear tests were done for the welded samples. All the samples had been obtained using the same set of parameters without any difference.

8.1. Tensile-shear tests

The tensile shear tests were carried out in the MTS landmark 810 material testing machine. All the tests were performed in at room temperature. The traverse speed used for the test was 1mm/min. The force-displacement plot was obtained from the computer simultaneously during the testing.

The test specimen was prepared according to the European Standard EN ISO 14273:2016 Resistance welding, Destructive testing of welds. Specimen dimensions and procedure for tensile shear testing resistance spot and embossed projection welds (ISO 14273:2016)**.** The European Standard EN ISO 14272:2016 is a Finnish national standard. Figure 44 shows the test specimen according to the standard [83].

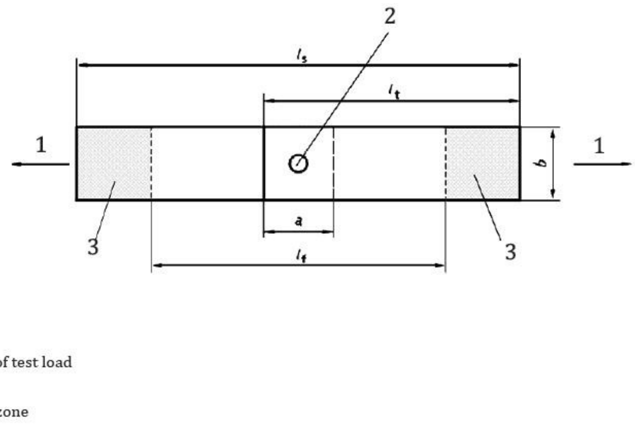

Figure 44 Schematic Diagram of Tensile Shear Test Specimen [83]

The test specimen dimension used for testing the joint strength produced by the THEW spot variant process is shown in Table 16.

Table 16 Test specimen dimensions for tensile shear test of the spot variant joint

S.No		THEW spot variant
1.	Length of Individual Test Specimen (l_t)	110 mm
2.	Free Length Between Clamps (l_f)	95 mm
3.	Specimen Length(l_s)	185 mm
4.	Specimen Width (b)	45 mm

5.	Overlap (*a*)	35 mm

Based on the above specified dimensions, the workpieces were welded and subjected to the tensile shear tests. There were a total of three samples prepared for the test and the results from the tests were collected and stored real time in the computer connected to the machine. A force vs. displacement graph was obtained from the data collected. The workpieces after the testing are shown in Figure 45. The graph is shown in Figure 46.

Figure 45 Workpieces after tensile shear testing

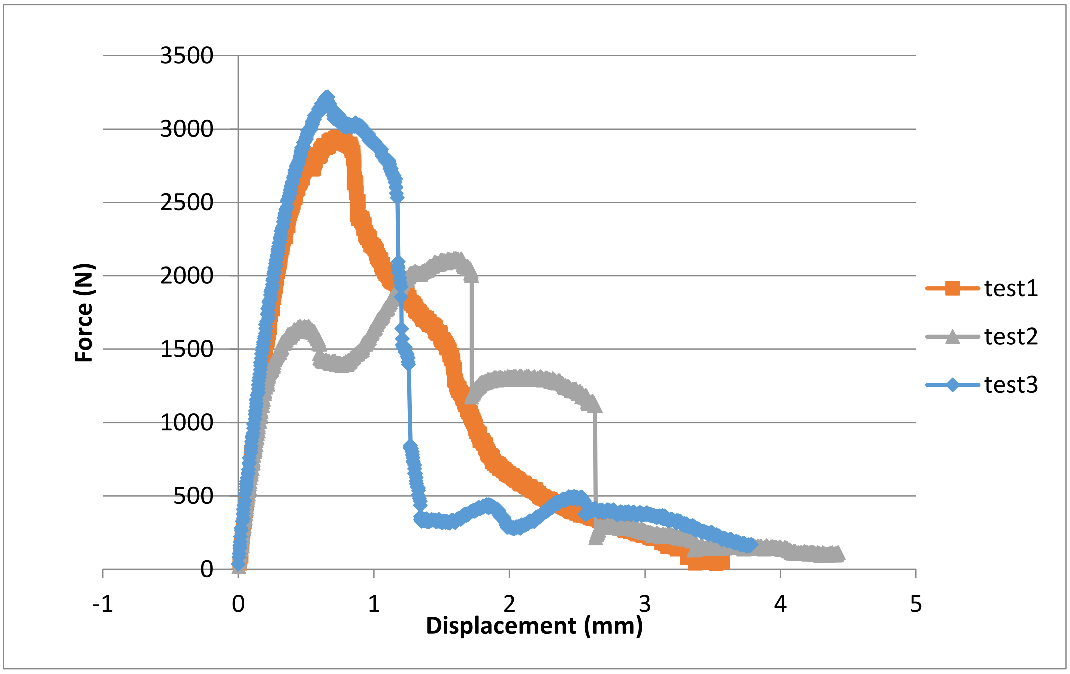

Figure 46 Force Vs. displacement for tensile shear tests

From the graph, it can be inferred that the joint had started to deform elastically initially. This is represented by the near-linear increase in load in the curve. As the joint starts to yield, the curve is no more linear as before. The yielding region is not distinct in all the three specimens. The region after this represents the plastic deformation of the joint until failure of the joint takes place ultimately. Tests 1 and 3 are nearly comparable in their curves while test 2 is different. In test 2, it can be seen that there is a slight decrease in load initially before the load increases further again. The load increases again until the joint fails by plastic deformation. The failure had taken place at the extrusion plate-PEEK interface.

The highest failure load was for test 3, which was 3218.778 N. Test 2 has the lowest failure load among the three tests. The highest failure load obtained in the previous work was 2134.6 N. This is a marked improvement in the failure load and represents a 50% improvement over the earlier results. The distinctively different regions of plastic deformation can be attributed to the deformation of the hook shaped structure at the polymer-extrusion plate interface and the reduction in the adhesive bonding between the polymer and the extrusion plate. The deformation of the hook is the primary cause of the failure as the fracture propagated until the failure of the joint happened.

8.2. Cross tension tests

The cross tension tests were carried out in the MTS landmark 810 material testing machine. All the tests were performed at laboratory room temperature. The traverse speed used for the test was 1mm/min. The test specimens were made according to the European Standard EN ISO 14272:2016 Resistance welding, Destructive testing of welds. Specimen dimensions and procedure for cross tension testing of resistance spot and embossed projection welds (ISO 14272:2016) [83]. The schematic figure of the general test specimen according to the standard is as shown in Figure 47.

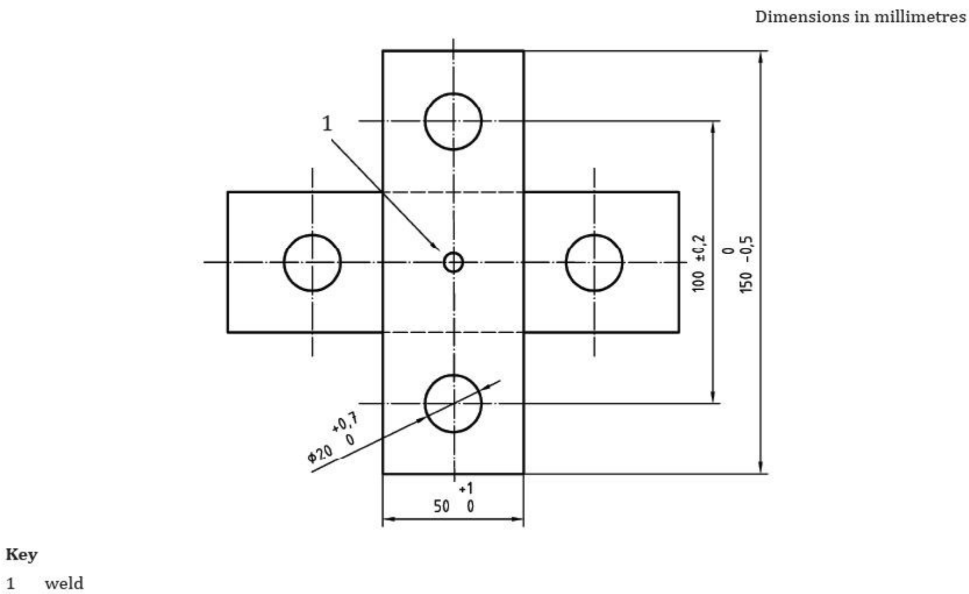

Figure 47 Schematic Diagram of Cross-Tension Test Specimen [83]

Figure 48 shows the workpieces after cross tension testing. Figure 50 shows the graph representing the force vs. displacement curves for the cross tension tests. The tests were done on three different samples which were all welded using the same parameters.

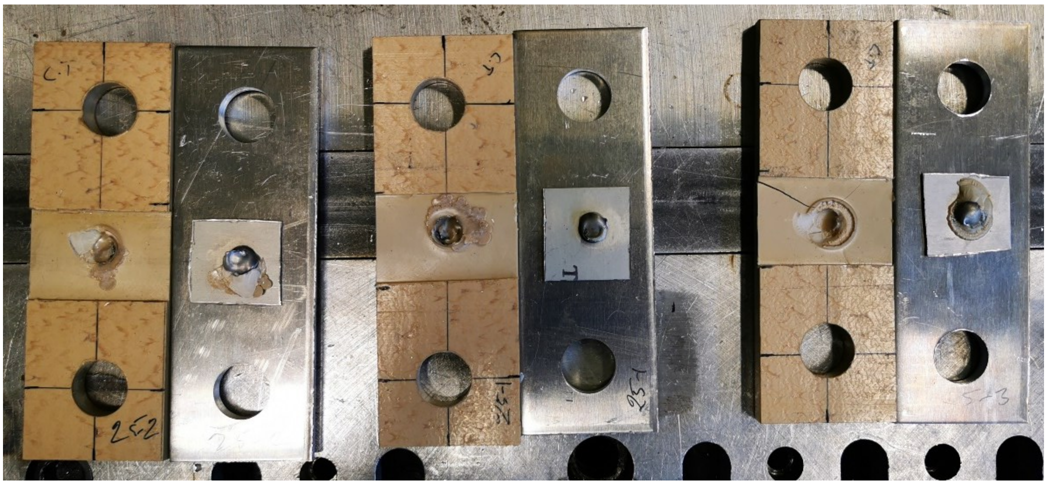

Figure 48 Workpieces after cross tension testing

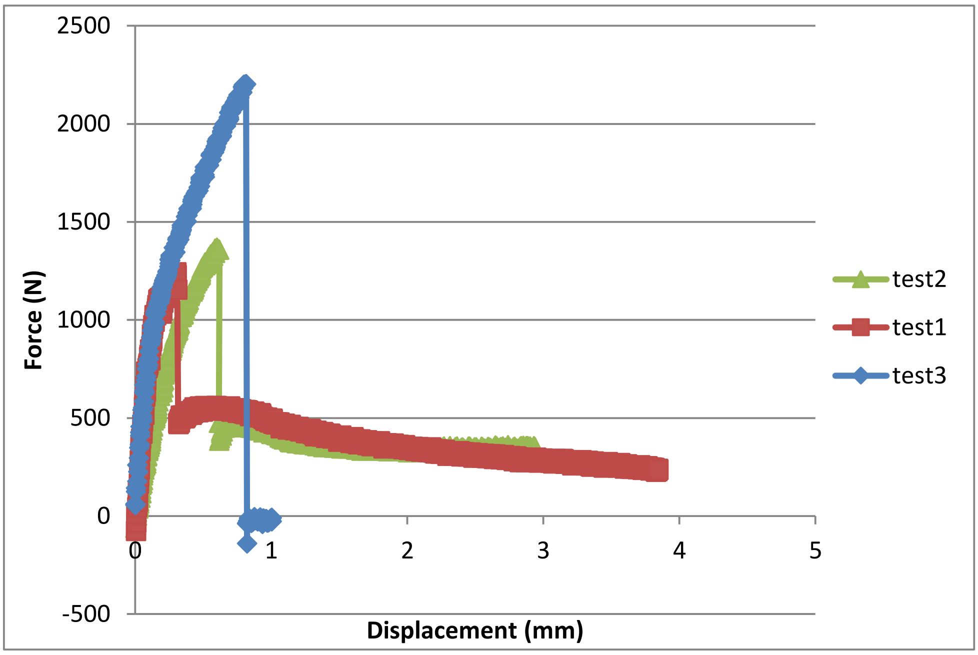

Figure 49 Force Vs. displacement curves for cross tension test samples

From Figure 49, it can be seen that the load increases linearly during the initial stages of the testing due to the elastic deformation happening during the initial stages. The deviation of the curve after this point specifies the plastic deformation of the joint. The plastic deformation continues until the failure of the joint. The plastic deformation happens due to the deformation of the hook shaped structure and the decrease in adhesive bonding between the polymer and the extrusion plate. Tests 1 and 2 are comparable in their behaviour while the test 3 is different.

The highest load failure was observed in test 3. The highest value obtained was 2201.501 N which is higher than the results obtained from the earlier work. The highest failure load obtained in the earlier work was 1189 N. The results obtained in this work show a remarkable 85% increase from the previous work.

9. Conclusion and future scope of work

9.1. Conclusion

The main objective of the work was to evaluate the spot variant of a new approach for joining dissimilar and lightweight structural materials, namely aluminium alloy to thermoplastic polymer. The main results obtained from this is summarized in this chapter.

The initial work was started with reproduction of the previous work with the slot variant and understand the basic requirements for the spot variant. The parameters proposed by the previous work were used. The shortcomings with the existing clamping system was found and the need for an improved clamping system was understood. It was also decided to focus solely on the spot variant thereafter in this work.

The new clamping system was intended to be versatile yet simple. It was designed keeping in mind that it should offer a stable base and reference of position. The other basic requirements were also considered and the finalised design was reached and then manufactured. The results from the joints manufactured, using the new clamping system, showed a marked improvement in the joint properties, such as the ultimate load under cross tension and tensile shear conditions. The components could now be fixed tight against the clamping system and a lot of various dimensions of workpieces could also be welded.

The results from the new clamping system encouraged the use of a stationary shoulder. A simple version of a stationary shoulder was implemented with proper dimensions in order to accommodate the existing probe design. Using the same parameters as before, consistent welds with improved geometry were obtained. The joint hook was visibly thick and deeper penetration was obtained. The amount of flash which came out on the surface of the aluminium was also considerably reduced. The stationary shoulder, thus, improved the overall quality of the weld. The polymer material was found to crack under high plunging speed and hence it was reduced in the final tests.

The mechanical testing of the spot variant samples was done to find out the improvement in joint functionality. The parameters with the reduced plunging speed was used for preparing these samples. Three samples were produced for both the cross tension and the tensile shear tests. The highest failure load in the cross tension tests was 2202 N while that obtained in the tensile shear tests was 3219 N. These results show an increase of 85% and 50% from the results obtained in previous work.

9.2. Future scope of work

The current work is an evaluation of the spot variant of new approach to join dissimilar materials. Based on the findings obtained from this work, it can be expanded upon in the future. A few of the important improvements and developments of interest based on this work is listed below.

- Application of the clamping system to test slot variants
- Design and development of other variants of probe

- Development of a more robust stationary shoulder
- Analysis of the weld region to understand the nature of the weld
- Easier and efficient way of producing the extrusion plates required
- Modelling of the process to understand the temperature distribution and material flow in the weld region

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Appendix

Appendix 1 Clamping system design

Appendix 1 Clamping system design