INVESTIGATION ON METAL-CFRP-METAL SANDWICH JOINT USING MECHANICAL CLINCHING PROCESS

M.Tech Thesis

By

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DISCIPLINE OF MECHANICAL ENGINEERING

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A THESIS

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Rishabh Verma

DISCIPLINE OF MECHANICAL ENGINEERING

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **Investigation on Metal-CFRP-Metal Sandwich joint using Mechanical Clinching process** in the partial fulfilment of the requirements for the award of the degree of **MASTER OF TECHNOLOGY** and submitted in the **DISCIPLINE OF MECHANICAL ENGINEERING, Indian Institute of Technology Indore**, is an authentic record of my own work carried out during the time period from May 2023 to June 2024 under the supervision of Dr Ashish Rajak, Assistant professor in the department of Mechanical engineering, Indian Institute of technology Indore.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other institute.

Rishabh Verma

Signature of the student
(Rishabh Verma)04-06-2024

This is to certify that the above statement made by the candidate is correct to the best of my/our knowledge.

Date -04-06-2024

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Rishabh Verma has successfully given his M.Tech Oral Examination held on **03-06-2024**

Signature of Supervisor of M.Tech thesis
Date: 04-06-2024

Convener, DPGC
Date: 04-06-2024

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With Regards

Rishabh Verma

DEDICATION

This thesis is dedicated to all who gave continuous support during my entire project , whose unwavering support and encouragement have been my guiding light throughout this journey. Their belief in my potential has been a constant source of motivation and inspiration.

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Rishabh Verma

Abstract

Recently the automobile sector has been moving towards lightweight components for fuel saving and economic operation. The use of carbon fibre-reinforced plastic (CFRP) has increased nowadays due to its lightweight, high strength-to-weight ratio and durability. Mechanical clinching is a process of joining two or more materials by applying pressure by the tool and joint form by interlock creation. This study investigates the joining process of AA 1050-CFRP-AA 1050 sheets in sandwich structure utilizing hole clinching process, joining of sandwich carbon fibre with mild steel sheets using clinching assisted resistance spot welding process and comparison of clinching after spot welding as well as spot welding after clinching . The mechanical strength of the joint was investigated by lap shear and peel tests followed by cross-section analysis. Numerical analysis was performed using ABAQUS software to optimize the size of hole in CFRP, to understand the flow of material in the extensible die and its comparison with experiment result.

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Chapter 1

Introduction

The clinching process is a joining technique used in manufacturing industries to join sheet metal components without need of extra materials such as filler metals or adhesives. It involves the deformation of materials through the application of force, creating a strong mechanical interlock between the sheets being joined. This process is particularly advantageous for joining materials that are difficult to weld or have surface coatings that may be damaged by many joining methods.

The clinching process is commonly used in automotive, aerospace, electronics, and appliance manufacturing industries for applications such as chassis assembly, enclosure fabrication, and component joining. With its numerous advantages and adaptability to various materials, the clinching process continues to be a preferred choice for joining sheet metal components in modern manufacturing operations.

Advantage of clinching process

1 Unlike welding, clinching does not produce any fumes, gases, or by-products, making it an environment friendly joining method.

2 Since clinching is a cold joining process, it does not introduce heat into the materials being joined, eliminating the risk of distortion or thermal damage.

3 Clinched joints typically exhibit high tensile and shear strength, providing reliable performance in various applications.

4 Clinched joints often have a good appearance with minimal visible distortion, improving the surface finish of finished products, particularly in industries where visual appeal is important.

1.1 Mechanical Clinching process

Clinching is a mechanical fastening technique performed at a rapid speed that joins thin sheets of metal by a combination of drawing and forming without any thermal effects. Clinching equipment includes a tooling set with a punch and die. With the clinching process, similar-dissimilar ductile sheet metals can be joined with a total thickness of 0.1 mm to 5mm. In recent years, the importance of mechanical joining techniques based on cold forming has been recognized due to its low cost and ease of automation.

1.2 Resistance spot welding process

Electric resistance spot welding is an important process in the industry. In electric resistance spot welding, the overlapping work piece is positioned between the electrodes, then the heat is obtained by passing a large electrical current for a short period of time. Automobile -body assembly needs 7000 to 12000 spots of welding according to the size of a car, so the spot welding is an important process in automobile bodies. Each spot welding is not performed on the same condition because of the alignment of sheets and electrodes as well as the surface condition. For that reason, a spot-welding process needs the optimum process condition that can afford allowance in parametric values for good quality of welding.

1.3 Research objectives.

The primary objective of this M. Tech thesis is to conduct in depth investigative analysis on joining of sandwich metal-CFRP-metal using mechanical clinching process this research aims to

- Joining of dissimilar material sheets for the multi-material design of automotive components.
- To join sheets with different ductility (such as AA 1050, Mild steel with CFRP).
- To perform numerical analysis in ABAQUS software to understand the flow of material in the die and its comparison with the experiment results.
- Optimizing predrilled hole diameter of CFRP sheet and clinching pressure for the proper joint.
- To join Mild steel- CFRP- Mild steel with pre-deformed sheet using resistance spot welding process.
- Mechanical strength evaluation using lap shear and peel test.
- To analyse effect of clinching after resistance spot welding and vice versa

1.4 Scope of the study

To achieve research objectives 2D simulation of clinching process will be done in Abaqus software and its comparison with experiment results, samples for shear and peel test will be prepared to check its strength for joining by clinching as well as resistance spot welding process.

Digital and optical microscopy will be conducted to compare cross-section of the samples by experiments and simulation as well as to observe fusion of welding by varying welding time.

1.5 Organization of the Thesis

This thesis is organized into several chapters to systematically present the research findings and analyses. Chapter 2 provides an extensive literature review, discussing the fundamental concepts of Clinching and resistance spot welding, and previous studies related to this research area. Chapter 3 outlines the research methodology, including the experimental setup, materials, and testing procedures.

Chapter 4 presents the Numerical analysis or 2D simulation of mechanical clinching process, Chapter 5 presents the results and analysis of the investigation, including the testing and microstructural characteristics of the samples. Finally, Chapter 6 concludes the thesis with a summary of the research outcomes and proposes future research directions in this field.

In conclusion, this M. Tech thesis aims to contribute valuable insights into the joining of sandwich metal and carbon fibre. The findings of this study will not only advance the knowledge in multi material as well as light weight structure but also hold practical significance for various engineering applications.

Chapter 2

Fundamental Concept and Literature review

2.1 Background

The clinching process has been used for centuries in various ways. Historically, blacksmiths and metalworkers used techniques like clinching to join metal parts. However, modern industrial clinching processes have evolved significantly and are now highly engineered and precise. It is difficult to connect light weight alloy, composite materials, and dissimilar sheets. Therefore, it is very necessary to study the new sheet connection technology. Riveting joint appearance is not very good, the use of rivet can lead to corrosion, not easy to connect brittle materials that will break it, the need for large riveting force. Clinching is a new technology of thin sheets connection. It does not require any additional components[1]. It only needs plastic deformation under pressure to form a interlock, which provides strength to the joint.

2.2 The Process of Clinching

Generally clinching process contains five basic steps

a) **Initial pressing-** In this step for proper alignment of tool initial pressing is required

b) **Initial forming-** In this step punch move downward and material deform elastically.

c) **Plastic forming-**The punch is moved downward continuously, because of which the sheet undergoes plastic deformation. The upper part forms a certain profile, which prevents the downward flow of the material. Movement of tool in the last should be controlled to get desired final bottom thickness.

d) **Holding pressure-**In this stage, the punch is kept in its position for some time to prevent the sheet elastic recovery or spring back.

e) **Backing-** In the last stage, the punch is moved backword.

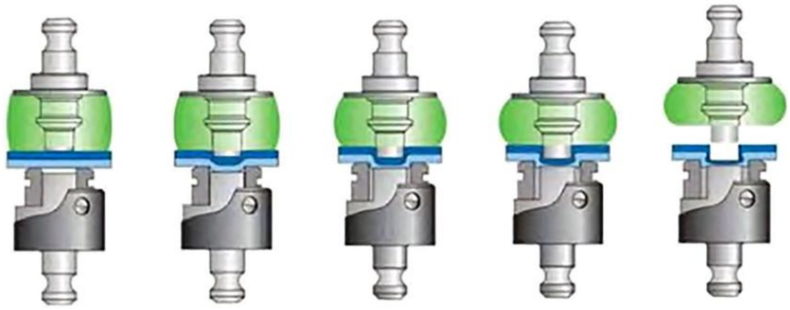


Figure 1 Process of clinching [1]

2.3 Hole clinching

The hole clinching process involves creating a hole in a material and simultaneously forming a mechanical interlock around the hole to join two or more materials together. This method is particularly useful for joining materials like metal sheets, including aluminium, steel, carbon fibre composites (CFRP). In hole clinching tool is coming and deforming upper sheet through the hole to the lower sheet with in the shape of die.

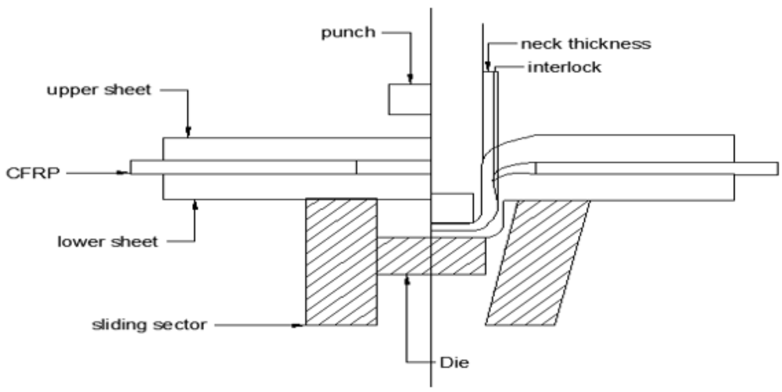


Figure 2 Hole clinching setup

2.4 Parameters of clinching [2]

a) Interlock- The interlock means the portion of material that is deformed and mechanically interlocked during the clinching process. When two or more materials are joined by clinching, the punch displaces material around the hole, creating S shape on the backside of the joint. This mechanically locks the materials together, providing a strong and reliable joint. The size and quality of the interlock are crucial factors in determining the strength and integrity of the clinched joint.

b) Neck thickness- The neck thickness, also known as the flange thickness, is the thickness of the material that remains after the hole is punched and the interlock is formed. It refers to the section of material that connects the formed interlock to the rest of the material. The neck thickness is an important parameter as it affects the overall strength and stability of the clinched joint. A thicker neck typically results in a stronger joint, but it may also require more force to form during the clinching process.

c) Final bottom thickness- The final bottom thickness in a clinching machine refers to the thickness of the joined materials after the clinching process is completed. Clinching is a method of joining sheet materials without additional fasteners such as rivets or screws. It typically involves deforming the materials to form a mechanical interlock between them.

2.5 Types of die used in clinching [1]-

a) Extensible die- Extensible die shown in figure 3 (a) has sliding sectors so when tool deform sheet these sectors move, and movement of those sectors helps in creation of interlock which is providing strength to the joint.

b) Fixed die- A fixed die shown in figure 3(b) refers to a die that maintains a constant shape and size throughout the clinching process. Unlike an extensible die, a fixed die does not have the ability to adjust its dimensions.

c) Flat die- A flat die is shown in figure 3(c) refers to the die have surface flat and no protrusion on the joined sheet was observed. Flat clinching is a type of clinching process to produce one-side planar joints.

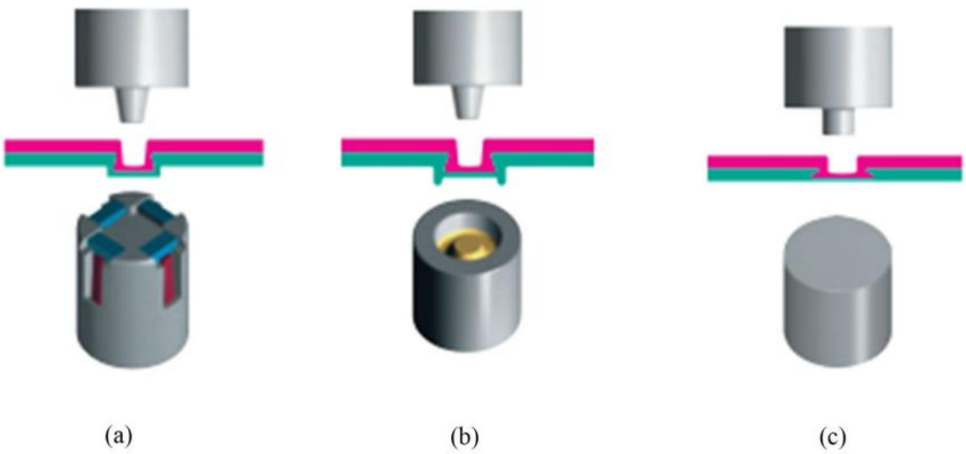


Figure 3 Types of die in clinching a) Extensible die b)Fixed die c) Flat die [1]

2.6 Types of tools used in clinching [3]

a) Round tool- A round punch tool in a clinching machine would be a part of the machine's tooling system used to create the necessary deformation in the materials being joined. The round punch would likely have a circular shape to improve the joining process, and it would be designed to apply pressure evenly to the materials being joined.

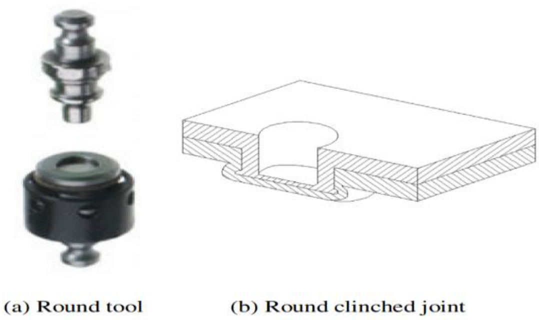


Figure 4 a) Round tool b) Round clinch joint.[3]

b) Square tool- Square punch tools are used in clinching machines to create joints with specific geometries and mechanical properties depending on the requirements of the application. These joints are often strong, reliable, and aesthetically pleasing, making them suitable for various industries such as automotive, aerospace, electronics, and appliance manufacturing.

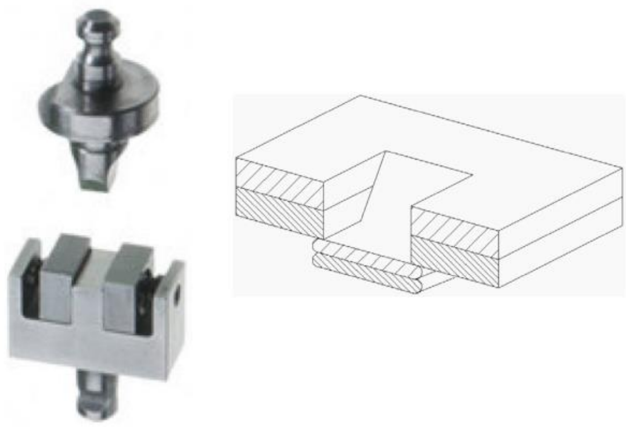


Figure 5 a) Square tool b) Square clinched joint [3]

2.7 Types of failure in Clinching

a) Neck failure- In clinching neck failure typically refers to a failure occurring in the neck area of a clinched joint, neck failure occurs due to insufficient material thickness, To prevent neck failure in clinching, it's essential to consider factors such as material selection, joint design, tooling configuration, process parameters like pressure.

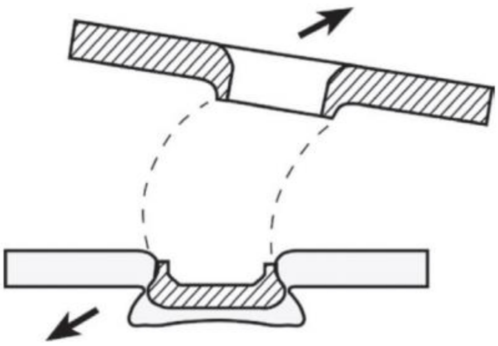


Figure 6 Neck failure of clinch joint [3]

b) Button failure- Button failure in clinching typically refers to a specific type of failure mode that can occur during the clinching process, particularly when joining materials using protrusion-style clinching joints.

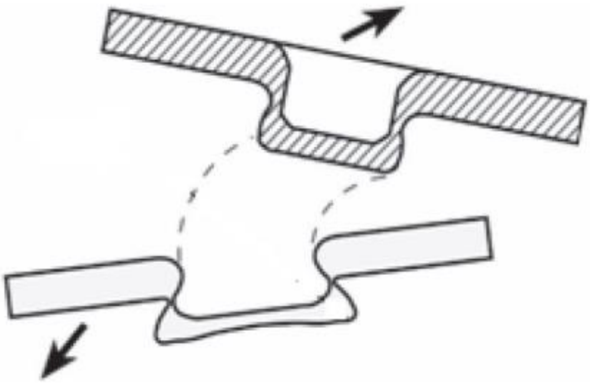


Figure 7 Button failure [3]

2.8 -Joining of Carbon fibre with Aluminium alloy using Clinching

Chan-Joo Lee et.al [4] investigated joining of CFRP with AA 6061 using hole clinching for the successful multi material design of automobile components. Lightweight material is now a days requirement to reduce emissions and there are many methods available for joining dissimilar materials like riveting, bolting, adhesive bonding, friction stir welding however there are some limitations are associated with these processes hole clinching can be one of the methods to join CFRP with AA 6061 in which tool deform upper sheet through the pre-drilled hole .

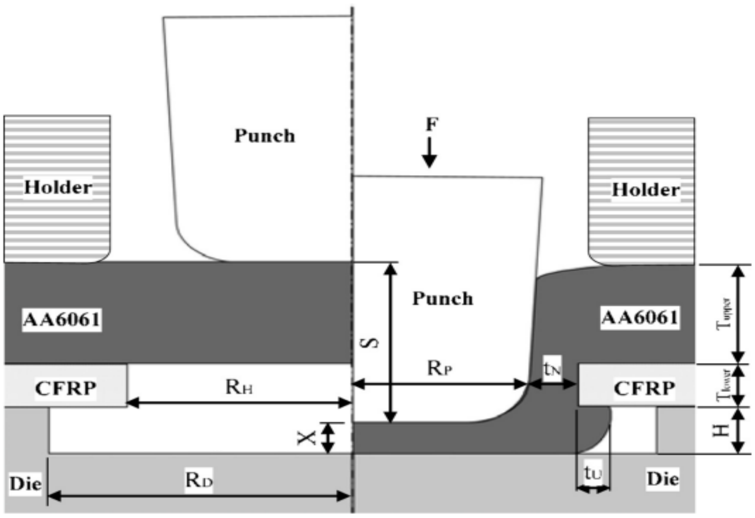


Figure 8 Schematic diagram of hole clinching [4]

$F_s = k_f * A_s = k_f * \pi \ (2R_P * t_N + t_N^{\ 2}\ ) \ldots\ldots\ldots (1)$

k_f is the shear fracture stress of the material

t_N= neck thickness

A_s is a fractured area of the upper sheet neck under shear load

$R_H = R_P + t_N \ldots\ldots\ldots\ldots.(2)$

R_H = Radius of punch

R_P = Radius of hole

So for a particular strength of the joint which is needed value of neck thickness can be find out from equation 1 and radius of hole can be find out from equation 2.

Pai-Chen Lin et al.[5] investigated effects of processing parameters on preheated (heat-assisted) clinching process to join aluminium alloy 5052-H32 (AA5052) and thermoplastic carbon-fibre-reinforced-plastic (TP-CFRP) sheets for cross-tension (CT) specimens.

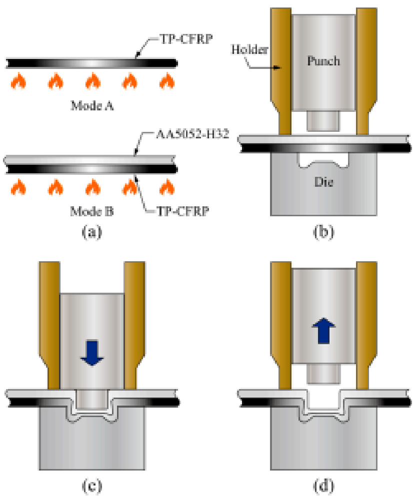


Figure 9 Heat assisted clinching a) Preheating, b) clamping, c) punching, d) retracting [5]

Preheating was done to make CFRP soft and ductile so that it will deform easily clamping was needed to make it perfectly aligned than punching make it deform with in the shape of die for the creation of interlock.

Yang Liu et al.[6] investigate distortion or tearing in carbon fibre reinforced polymers (CFRP) in joints with aluminium alloy and CFRP a damage model was developed to understand damage in the CFRP, hole diameter in the CFRP was optimized to get desired interlock and neck thickness, large hole diameter results low interlock value and large neck thickness.

2.9 The process of Resistance spot welding

Resistance spot welding is a process used to join two or more metal sheets together at specific points. It involves applying pressure and passing an electric current for short period of time[7] through the sheets, which generates heat due to resistance.

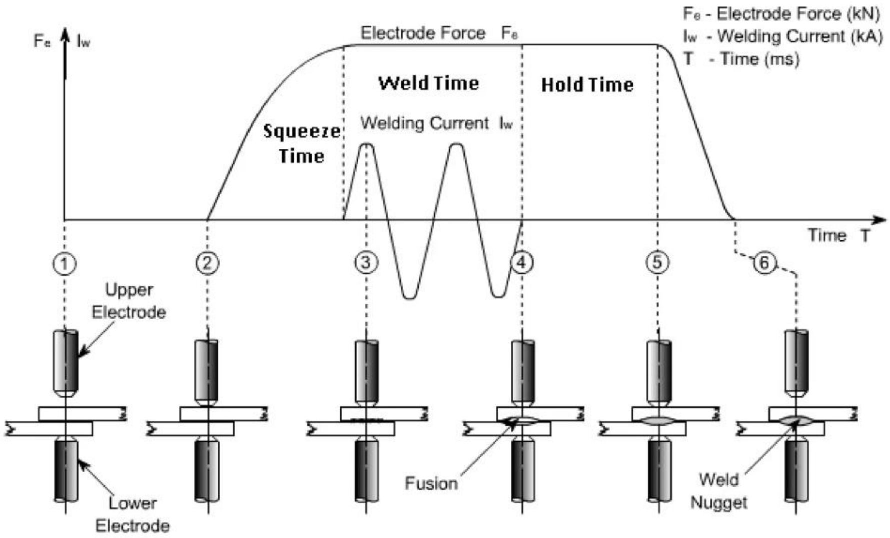


Figure 10 Process of Resistance spot welding [8].

Squeeze time- This is the initial step of the welding process where the electrodes come and apply pressure to the workpieces being welded. The squeeze time ensures proper alignment and contact between the electrodes and the workpieces before the welding current is applied. It is the time when electrode touches the workpiece till the first application of current.

Weld time- Once the electrodes have applied pressure and the workpieces are properly aligned, the weld time begins. During this time, a high electrical current for this short period of time is passed through the workpieces, generating heat at the contact points between them. This heat causes the materials to soften and fusion and form the weld nugget. Too large weld time may cause defects.

Hold time-After the weld time is completed, hold time begins. This time allows the molten material to solidify and cool while still pressure applied from the electrodes. The hold time is crucial for ensuring the integrity and strength of the weld joint.

Off time- At this time current is off and electrode retraces to its initial position.

2.9.1 Defects in Resistance spot welding

a) **Expulsion-** In resistance spot welding, expulsion is ejection of molten metal from the weld area during the welding process. It is considered a defect because it can reduce quality of the weld. Expulsion can occur due to various reasons such as high welding current, insufficient electrode force.

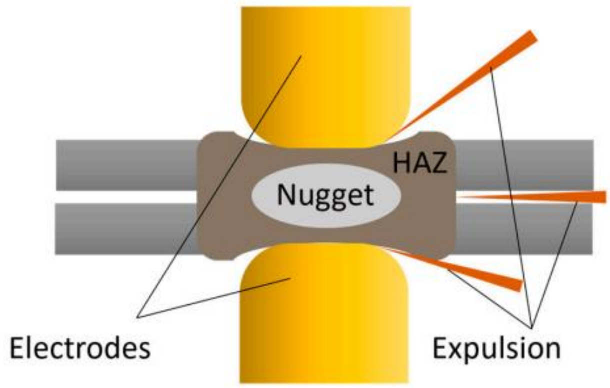


Figure 11 Schematic of Expulsion defect [9]

b) **Shrinkage void-** Shrinkage voids, also known as shrinkage cavities, are another type of defect that can occur in resistance spot welding. These voids appear as small depressions on the surface of the welded joint and can compromise the strength and reduce the quality of weld. Several factors can contribute to the formation of shrinkage voids such as insufficient welding pressure, less material thickness.

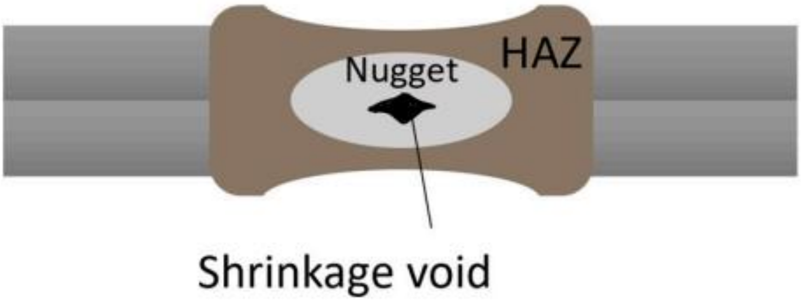


Figure 12 Schematic of Shrinkage void [9]

c) **Cracking-** Cracking mainly occurs due to non-homogeneous deformation. Different stress occurs at different points in weld regions and results in cracking. Liquid metal embrittlement is a phenomenon that can occur in resistance spot welding and usually under the action of tensile stresses.

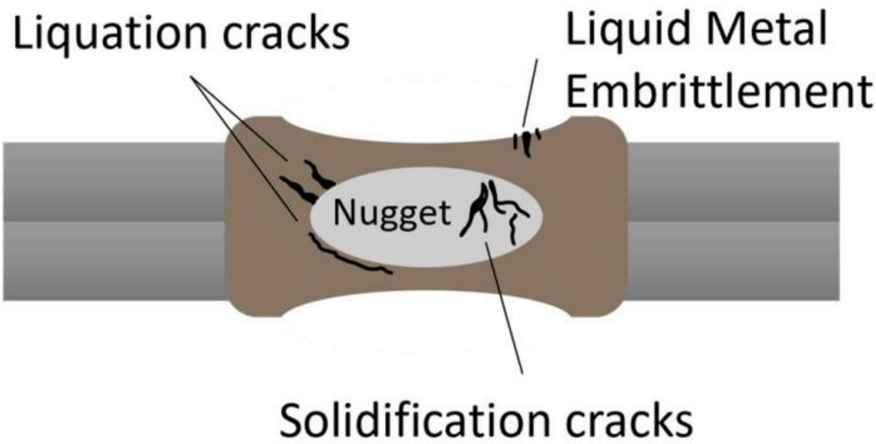


Figure 13 Schematic of Cracks during RSW process [9]

2.10 Joining of CFRP with Aluminium Alloy sheet using Resistance spot welding.

Sendong Ren et al.[10] investigated joining of Al 5052 and CFRP produced by coaxial one-side resistance spot welding as shown in figure 14. The N-C=O covalent bond between silane coupling agent and CFRP is the primary joining mechanism of Al5052/CFRP COS- RSW joints.

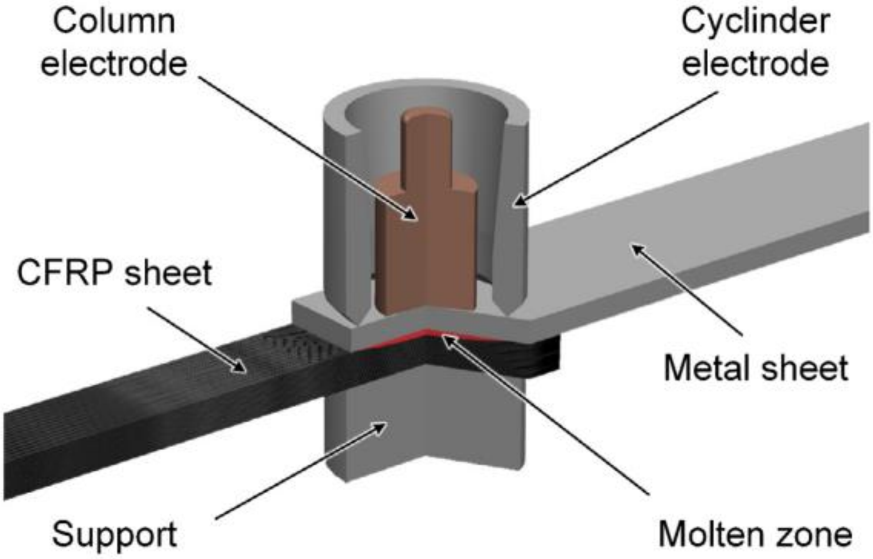


Figure 14 Schematic of the coaxial one-side resistance spot welding process.[10]

2.11 Joining of Aluminium Alloy and Mild Steel Sheet

Joining of aluminium and mild steel is challenging due to their differing properties, including melting points and deformability. Both materials are used in automobile industries so there is need to join them, resistance spot welding is one of method to join mid steel but it is difficult to join Aluminium because of its high thermal conductivity and low melting point. Y. Abe et al.[11] investigated joining of aluminium and mild steel by mechanical clinching and solve the problem of different melting temperatures for the aluminium alloy and steel sheets by cold forming.

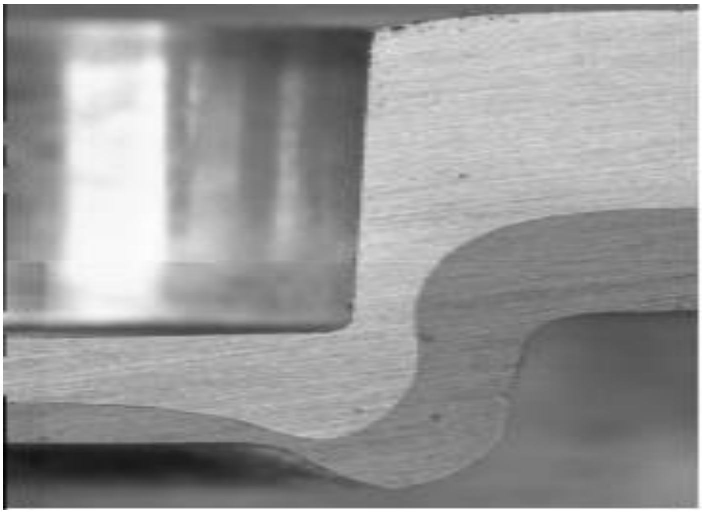


Figure 15 Joining of Aluminium and mild steel sheet using clinching [11]

Daxin Ren et al.[12] investigated joining of galvanized mild steel sheet to 5083 Al alloy using novel clinch-resistance spot welding process and compares normal resistance spot welding with clinch resistance spot welding process.

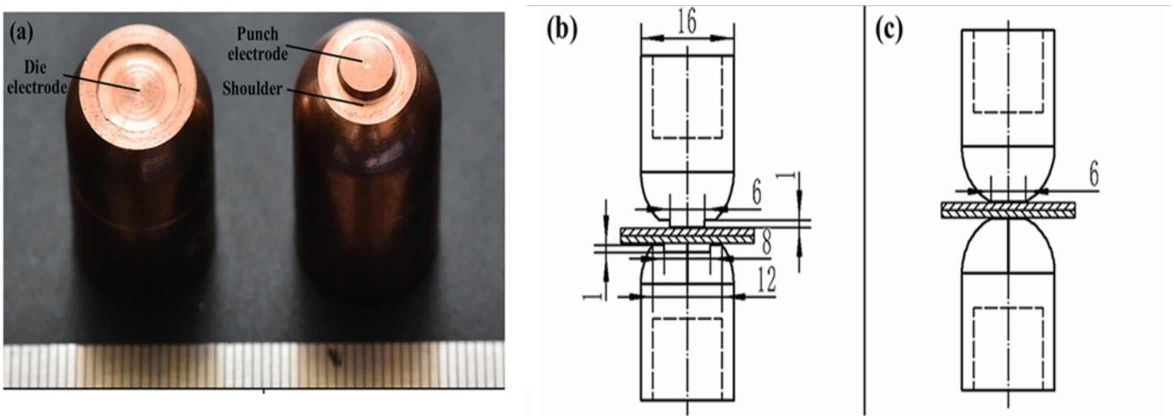


Figure 16 a) Clinch resistance electrode, b) Schematic of Clinch resistance spot welding, c) Schematic of Normal resistance spot welding process [12]

With the use of clinch resistance spot welding a cup section was observed which results in 3D connections of bonding surfaces and which is providing strength to the joint.

2.12 Other processes available to join CFRP with metal.

Dong-Jun Kwon et al.[13] investigated joining of CFRP and steel sheet with riveting and bolting and analyse effect of adhesive in clearance it was observed that with the use of adhesive distribute the load more evenly across the joint interface and increased joint strength.

Zhang Dawei et al.[14] investigated various process to join hybrid CFRP and metal joint like adhesive bonding, mechanical fastening, joining by Z pin, Ultrasonic welding it was observed that joining by adhesive bonding and mechanical fastening is sensitive to the environment and unnecessary increases weight of the component joining by plastic deformation is better approach which is not increasing weight .

2.13 Simulation study of Clinching

L. Kaðèák et al [15] investigated FE analysis of Clinching with fixed die by joining three sheets. The simulation of the joining process was done using the ANSYS Mechanical 1software in 2D axisymmetric terms.

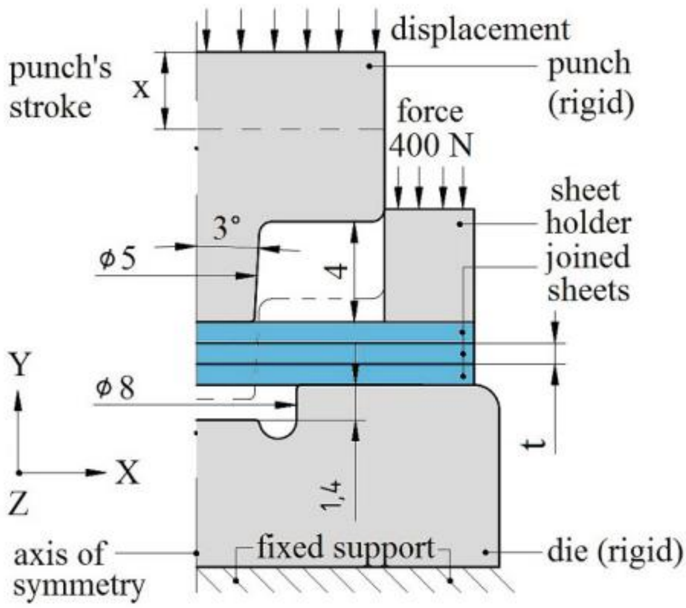


Figure 17 FEA model [15]

to reduce simulation time punch, die and sheet holder is taken as rigid body and was taken as deformable body the simulation study was performed using static implicit condition for better convergence fine mesh size was considered all boundary conditions are shown in fig 17

2.14 Conclusion from literature survey

Clinching offers advantages in terms of simplicity, cost-effectiveness, and applicability to a wide range of material thicknesses. On the other hand, resistance spot welding show more joint strength and integrity, particularly suitable for applications demanding high mechanical load bearing capacity. The practical implications of these findings are significant for industries using lightweight and durable joints, such as automotive and aerospace sectors.

Joining CFRP with metal is found to be difficult by many processes like riveting, adhesive bonding, welding. Hole clinching or joining by plastic deformation can be one of the methods to join CFRP with Aluminum Alloy but it is difficult to join high strength sheets and CFRP with clinching so use of resistance spot welding helps to join Mild steel sheet with CFRP.

Chapter 3

Research methodology.

3.1 Experiment procedure

In the clinching process, metal sheets are joined through a cold-forming process by deforming and interlocking the sheets through a combination of axial force and die geometry without the need for additional fasteners. The machine arrangement is shown in Figure. Predrilled hole CFRP sheet is in between two AA 1050 sheets tool is deforming upper sheet through this hole to the lower sheet within the shape of die. Experiment was performed by drilling hole of 6mm in CFRP because interlock creation was more in 6mm which was optimized by simulation. Input parameter of clinching was taken as pressure equal to 2 bar which was optimized conducting number of experiments. Fig 18 shows A Clinch tool of diameter 4.6 mm and an extensible die of outer diameter 15.95 mm.

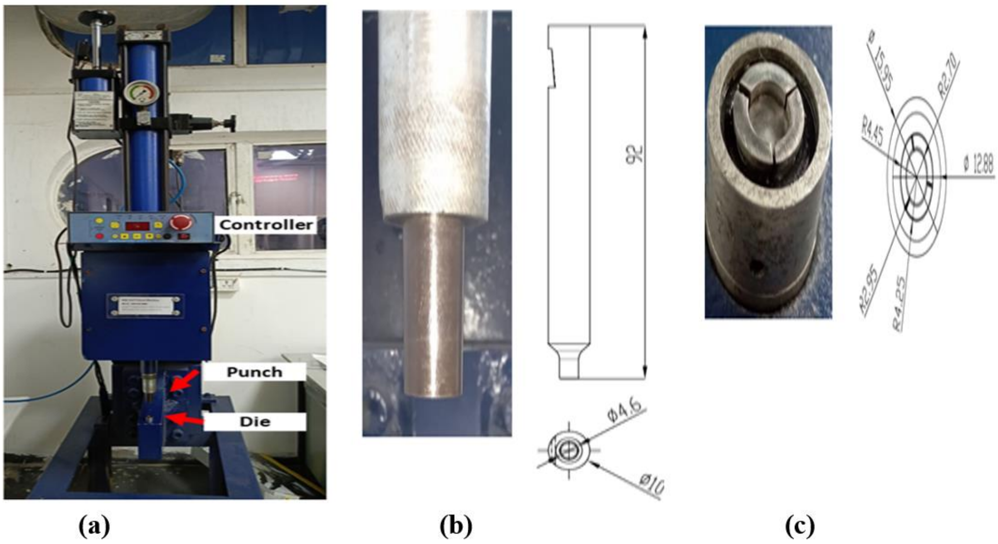


Figure 18 (a) Mechanical Clinching machine (b) Clinching tool (c) Extensible die.

In resistance spot welding, two sheets are sandwiched between the upper and lower electrodes. The pressure is applied while a high current at low voltage is passed to generate heat at the sheet interface to make a joint. The sandwiched joint among mild steel-CFRP-mild steel sheets was performed using a resistance spot welding process. For joining, a CFRP sheet with a pre-drilled hole is placed between two mild steel sheets. There is a need to pre-deform upper mild steel sheets so that upper and lower mild steel sheets remain in contact with each other. The amount of pre-deformation of the upper mild steel sheet was kept equal to the thickness of the CFRP sheet. The pre-deformation of the upper mild steel sheet was performed using a clinching machine with the punch and die. Upper sheet deformation by the clinching machine results in proper and more controlled deformation because the amount of deformation depends on the clinching pressure applied.

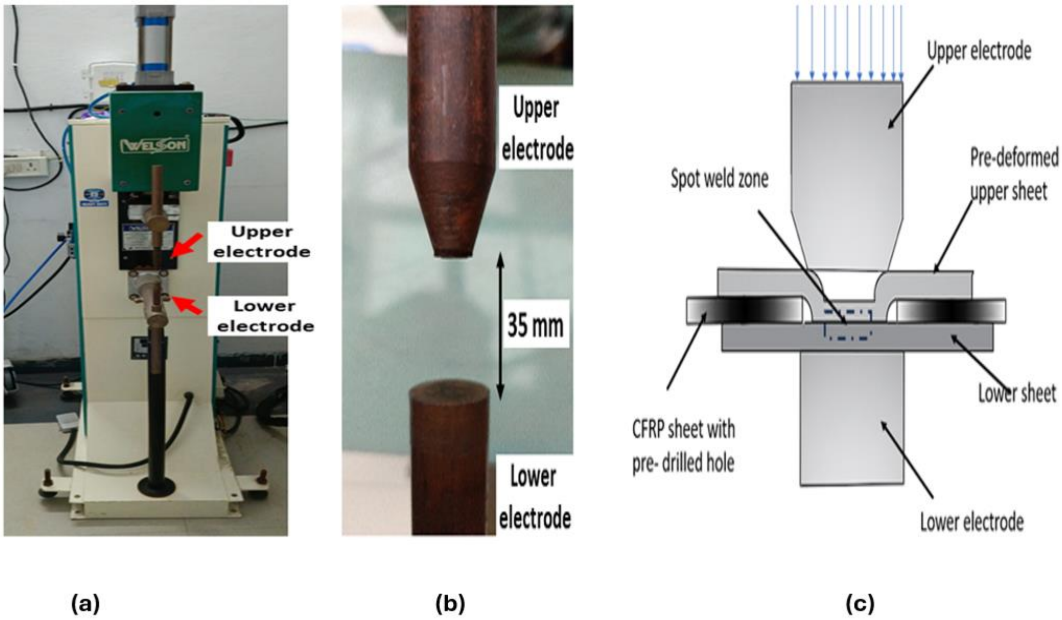


Figure 19 (a) Resistance spot welding machine (b) Spot welding electrodes (c) Schematic of joining Sandwich CFRP with MS using Resistance spot welding

A 4 bar of pressure was applied to pre-deform the upper mild steel sheet which was optimised using the hit and trial method.

The dimensions of the samples are 62×30 mm with an overlapping distance of 30 mm used for the shear test. These tests were performed with a speed of 1 mm/min on the Universal Testing Machine (UTM), and shear test results were analysed to find the type of failure. The image of pre deformed upper sheet is shown in Figure 20

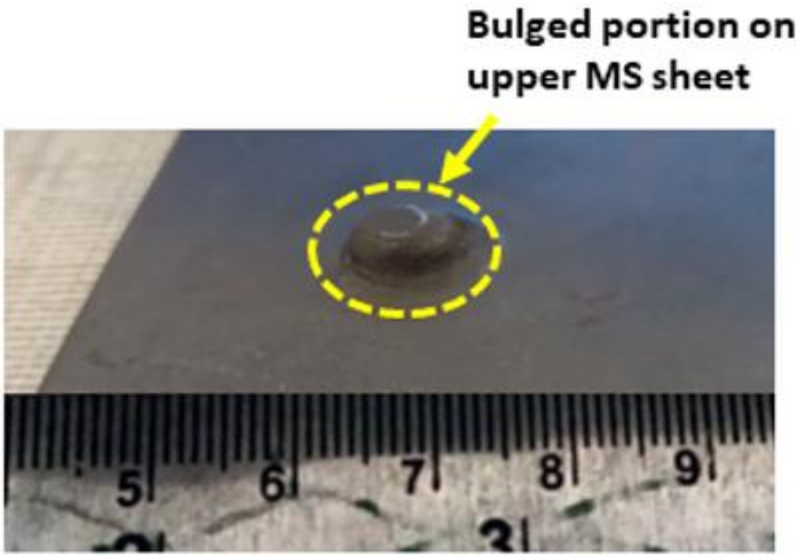


Figure 20 Pre deformed upper Mild steel sheet using Clinching machine.

Resistance spot welding was used to join the sheets, upper electrodes of diameter 6.5 mm and lower electrodes of diameter 16.5 mm were used with squeeze time of 0.4s, weld time of 0.25s and hold time of 0.1s and pressure of 4 bar maintained during the experiment which was optimized by conducting several experiments as shown in table 2. After optimizing the squeeze and hold time for the experiment, The effect of weld time has been studied, below 0.25 seconds poor joint strength was observed by visual inspection, and above 0.25 seconds expulsion and overheating of mild steel was observed.

Table 1 Process parameters to CFRP with MS by Resistance spot welding.

Pressure (bar)	Squeeze time (s)	Weld time (s)	Hold time (s)
4	0.4	0.25	0.1

Table 2 Properties of AA 1050,CFRP ,Mild steel sheet [4], [16]

Material	Density (g/cm^3)	Elastic modulus (Gpa)	Yield strength (Mpa)	Poisson's ratio
AA 1050	2.71	71	105-145	0.33
Mild steel	7.8	206	248	0.303
CFRP	1.81	31.2	318.0	

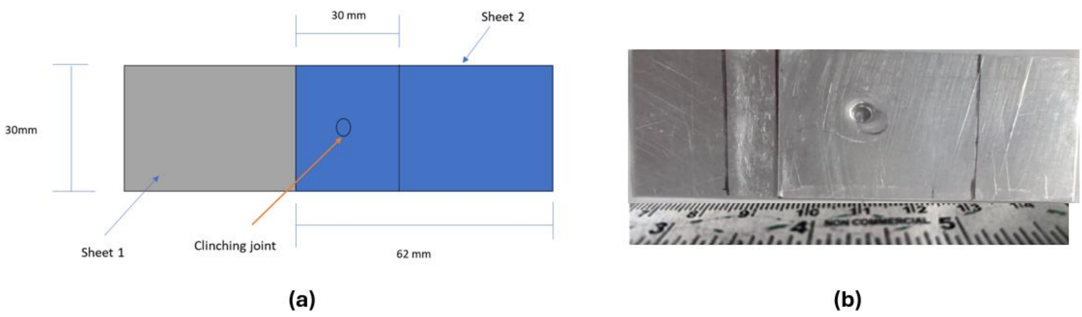


Figure 21 a) Schematic of joining two AA 1050 sheet by clinching b)Sample for shear test

Figure 21 a shows schematic diagram of joining two AA 1050 sheet by cinching machine with optimized pressure of 2 bar

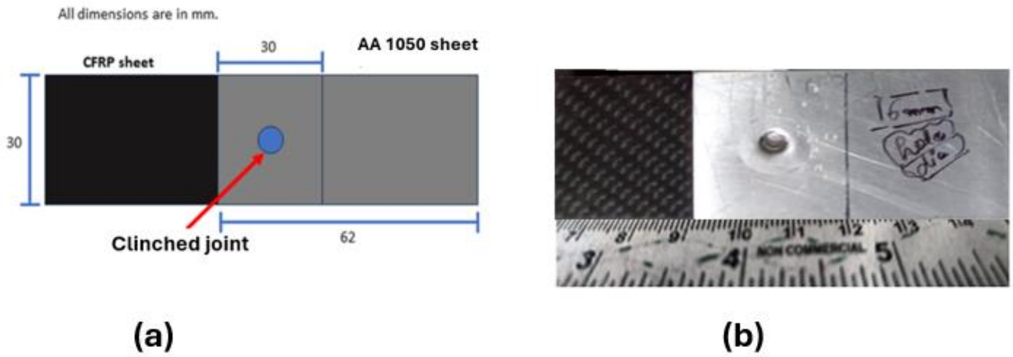


Figure 22 a) Schematic diagram of CFRP sheet of thickness 0.5mm with AA 1050 join by mechanical clinching b) Sample for shear test

Fig 22 a shows schematic diagram of sample with CFRP sheet of 0.5mm thickness with AA 1050 sheet of thickness 1.3mm join by clinching and b shows sample for shear test.

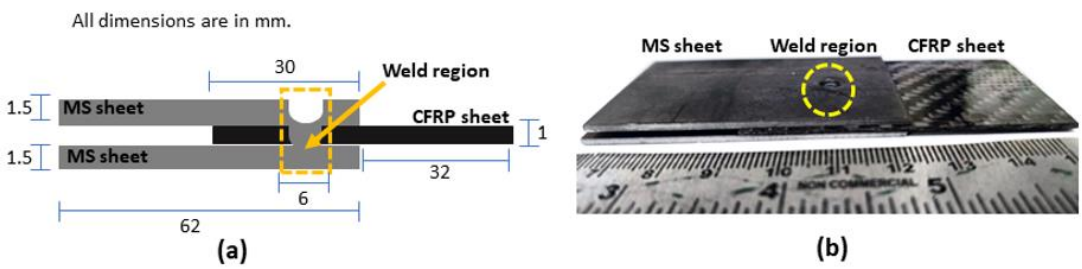
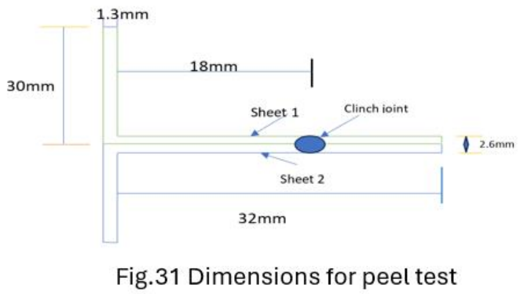
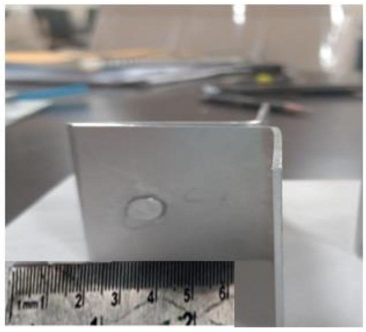


Figure 23 a) Schematic diagram of Sandwich CFRP 1mm with mild steel join by Resistance spot welding b) Sample for shear test

Figure 23 a shows CFRP sheet of thickness 1mm in between two mild steel sheet of thickness 1.5mm with upper MS sheet pre-deformed by clinching and joining by resistance spot welding.



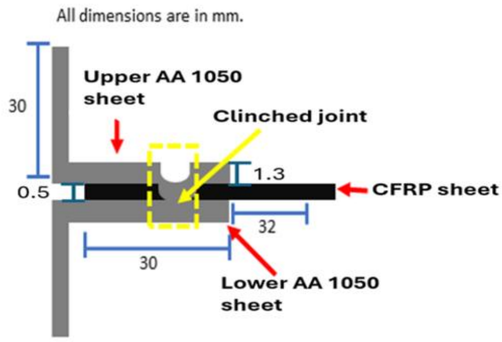
(a)



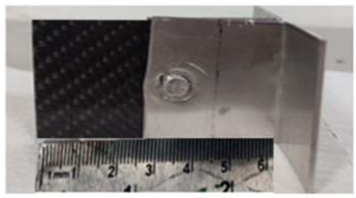
(b)

Figure 24 a) Schematic of joining two AA 1050 sheet by mechanical clinching b) sample for peel test

Figure 24 a shows schematic of peel test for two AA 1050 sheet join by mechanical clinching



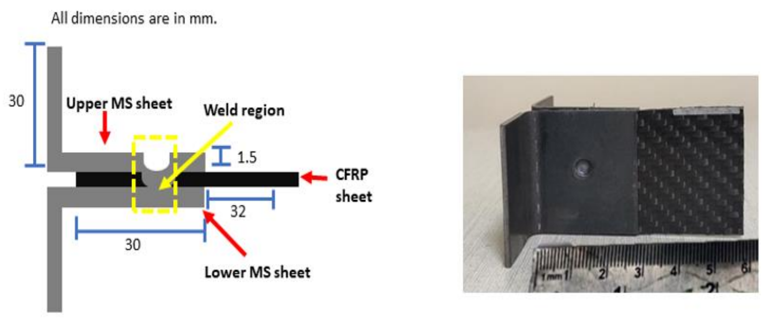
(a)



(b)

Figure 25 a) Schematic of CFRP sheet of thickness 0.5mm with AA 1050 sheet of thickness 1.3mm join by mechanical clinching b) Sample for peel test.

Fig 25 a shows sandwich CFRP sheet of thickness 0.5mm with AA 1050 sheet of thickness 1.3mm join by mechanical clinching and b shows sample for peel test



(a) (b)

Figure 26 a)Schematic diagram of CFRP of 1mm thickness with Mild steel sheet of 1.5mm thickness join by Resistance spot welding.

Figure 26 a show a schematic diagram of sandwich CFRP 1mm thickness with MS sheet of thickness 1.5mm join by resistance spot welding b sample for peel test.

3.2 Mechanical testing and characterization instruments

1) Shearing machine

Shearing machines provide precise and clean cuts on sheet metal, ensuring accuracy in dimensions and shapes. This precision is important for research because there is need of tight tolerances.

Figure 27 Shearing machine used to cut the sample to proper dimension

2) Lathe machine- The primary function of a lathe machine is turning, facing .drilling which involves rotating a workpiece against a cutting tool to remove material and create cylindrical shapes. This process is widely used in manufacturing cylindrical components such as shafts, rods, and bushings.

Figure 28 Lathe machine used to make electrode of Resistance Spot welding.

3) Digital microscope- Digital microscopes are essential tools in material science for studying the microstructure, composition, and properties of materials. They can help in the analysis of metals, polymers, ceramics, and other materials at the micro, macro, and nano scales, contributing to the development of new materials and technologies.

Figure 29 Digital microscope use to take image of cross-section

4) Optical Microscope-Optical microscopes, also known as light microscopes, are versatile instruments used in various scientific, industrial, and educational settings. They utilize visible light and optical lenses to magnify and resolve microscopic details of specimens.

Figure 30 Optical microscope used to analyse grain structure

5) Micro hardness tester-A micro hardness tester is an instrument used to measure the hardness of materials, particularly those that are very small or thin. Hardness is a measure of a material's resistance to deformation, and it's an important characteristic in materials science and engineering.

Figure 31 Micro hardness tester

6) Polishing machine - Polishing machine was used to increase surface finish, good surface finish is required to analyse grain structure a number of paper of different grit size used to increase surface finish.

Figure 32 Polishing machine.

7) UTM machine- A Universal Testing Machine (UTM) is a versatile instrument used to perform a wide range of mechanical tests on materials. Shear test and peel test was performed on UTM machine of Capacity 10 kN.

Figure 33 UTM machine of capacity 10kN was used for shear and peel test

Chapter 4

FE analysis of clinching

FEA can be used to observe the tool and die shape based on the result of the simulation geometry of tool and die can be changed which is directly affecting interlock and neck thickness of the joint. There is great influence of punch corner radius and die shape in whole clinching process. This shows the finite element analysis and provide simulation procedure of the mechanical clinching joining process in terms of the FEA model, meshing, material model, boundary conditions, interactions. The simulation of the joining process was carried out using the Abaqus in 2D . The initial setup of the tools and joined materials that compose the geometrical model is shown in Fig. Both upper and lower AA 1050 sheets are of thickness 1.3mm and thickness of CFRP sheet is 0. 5mm.Downward velocity of tool was taken as 37.5mm/sec and simulation step time were taken as 1sec.

The geometrical model that constitutes the input model for the simulation consists of three rigid bodies (tool, die and sheet holder) and three deformable bodies (AA1050 and CFRP sheets), the time of simulation can be minimized by considering them as rigid bodies.

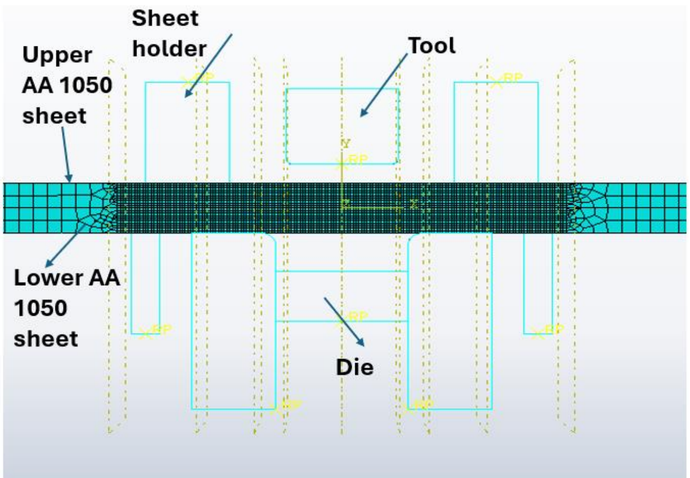


Figure 34 FEA setup of clinching of two AA 1050 sheet

Boundary condition for sheet holder was taken as fix, velocity was given to tool in downward direction and for sliding sectors displacement was restricted only rotation was permitted. The mesh sensitivity analysis has shown that AA 1050 sheet having the thickness of 1.25 mm can be meshed by 0.3 mm elements and those parts coming in contact or where analysis is required meshed by 0.1 mm to reduce simulation time.

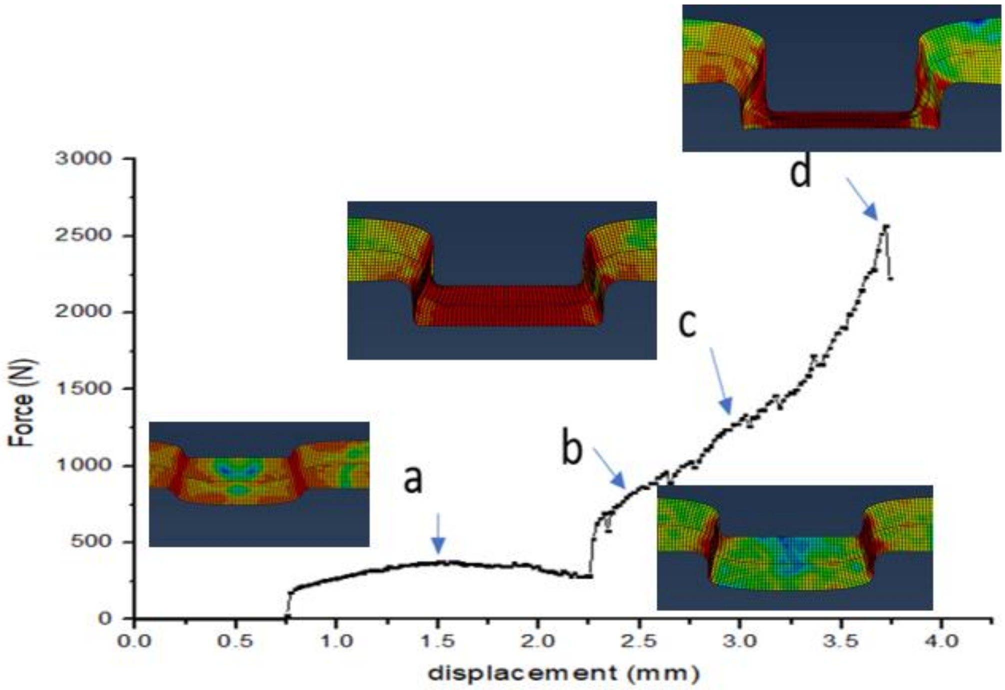


Figure 35 Force vs displacement curve

Figure 35 shows force vs displacement curve of reference point on the tool

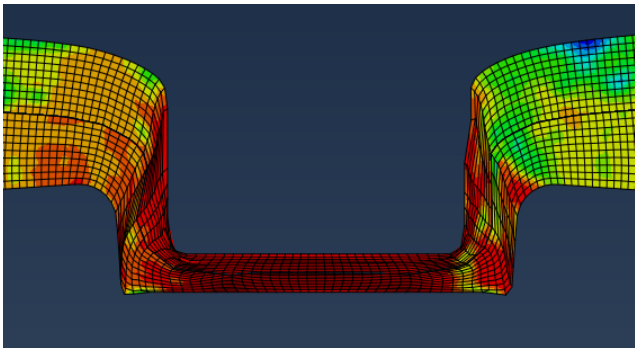


Figure 36 Cross-section of two AA 1050 sheets by simulation.

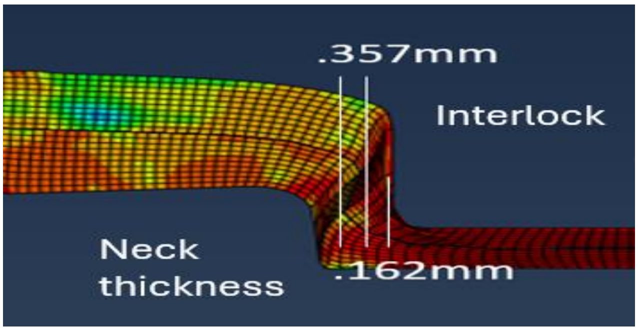


Figure 37 Interlock and final thickness value of two AA 1050 sheets by simulation

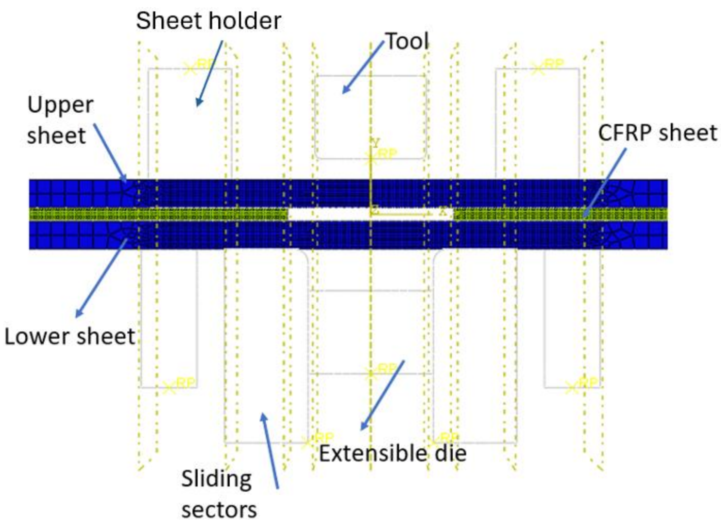


Figure 38 FEA setup of joining of sandwich CFRP with AA 1050

Optimization of hole diameter in CFRP is done by simulation by hole of 4.5mm, 5mm and 6mm. In 4.5mm hole there was no interlock creation, value of interlock was more in 6mm than in 5mm and in large hole more than 6mm equal interlock was observed and loose joint was observed.

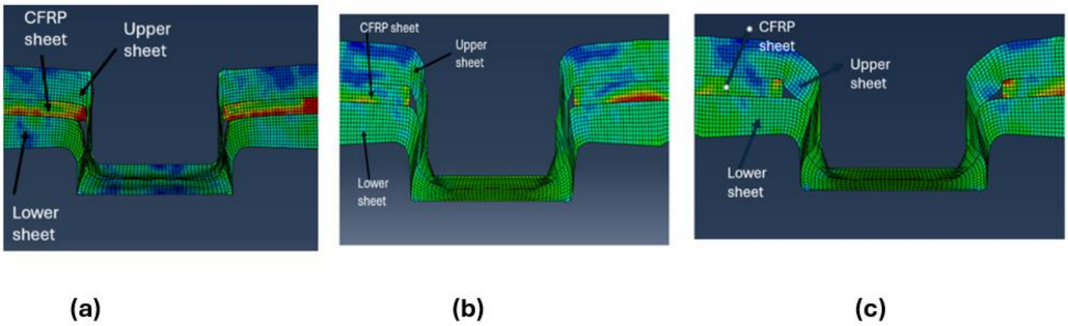


Figure 39 Simulation cross-section of CFRP drilled hole a) 4.5mm b) 5mm c) 6mm

more interlock value means more strength as well as there should not be loose connection between CFRP and aluminium sheet at 6 mm drilled when tool was deforming upper sheet through this hole to the lower sheet there was less influence of CFRP sheet which helps in creation of more interlock Fig 40 shows the comparison between interlock and neck thickness values in hole of 5mm and 6mm ,interlock and neck thickness value for 6mm are 0.226mm and 0.219mm respectively and for 5mm interlock and neck thickness are 0.196mm and 0.236 mm respectively.

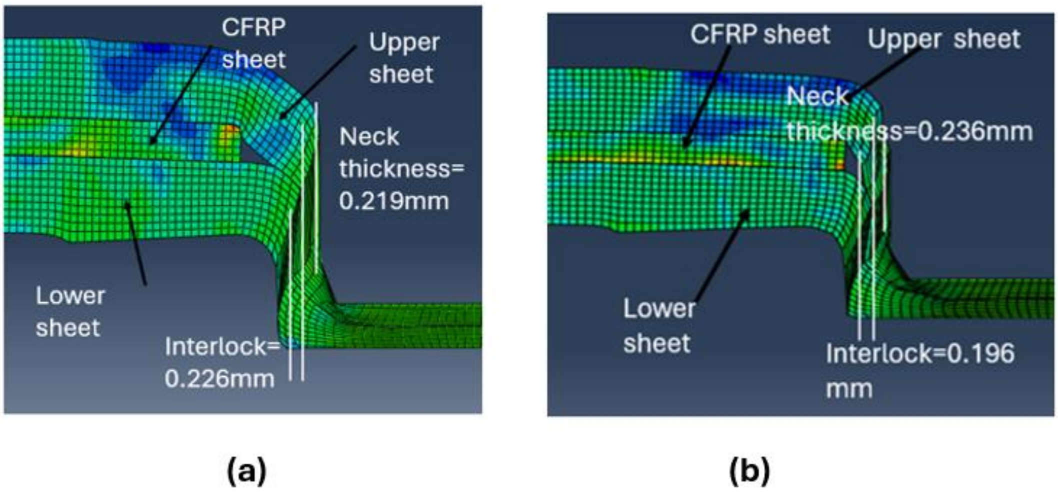


Figure 40 Comparing cross-section a) CFRP drilled hole 6mm b) CFRP drilled hole 5mm

Chapter 5

Results and discussion

5.1 Joining of two AA 1050 sheets using mechanical clinching.

Joining of two AA 1050 sheets using clinching is a highly effective mechanical bonding method, offering a durable and robust connection without the need for additional materials like adhesives or fasteners. AA 1050 aluminium alloy is famous for its excellent formability, corrosion resistance, and conductivity, making it a popular choice in various industries.

The process of clinching involves the deformation of the material around the joint area to create a strong interlock between the two sheets. Unlike traditional welding techniques, clinching does not involve melting or adding external materials, minimizing the risk of thermal distortion, or weakening of the base material.

5.1.1 Lap shear test

The Lap shear test of a joint among 1.3 mm AA 1050 prepared was performed on the Universal Testing Machine with 10 kN capacity. Where 50 mm was taken as gauge length and 22 mm was kept for the grip at both ends. The pull-out test was performed at the speed of 1 mm/min. The testing arrangement is shown in figure 41

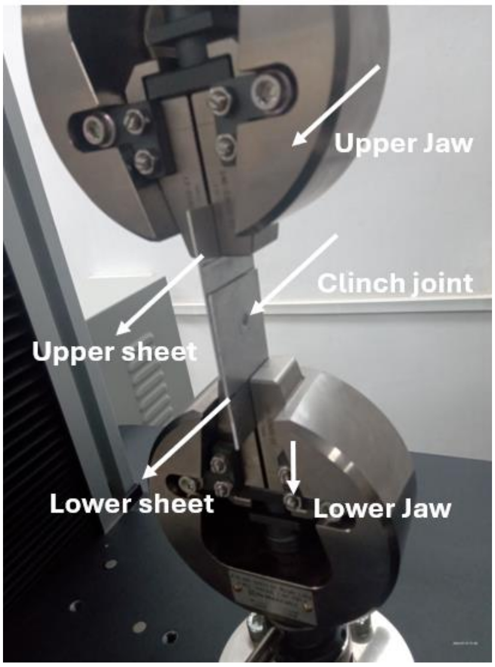


Figure 41 UTM setup of shear test of AA 1050 sheets

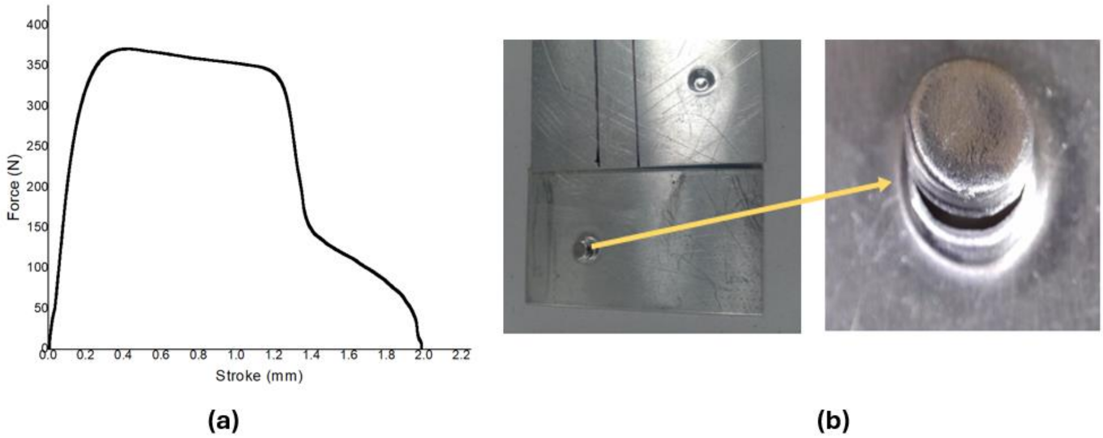


Figure 42 a) Shear test result b) Failed sample after shear test.

As it is observed from the figure 42 (a) that maximum load carried by the joint was 370 N and failure mechanism of the joint was button failure.

5.1.2 Peel test

A Peel test was performed on the samples prepared as shown in figure 43

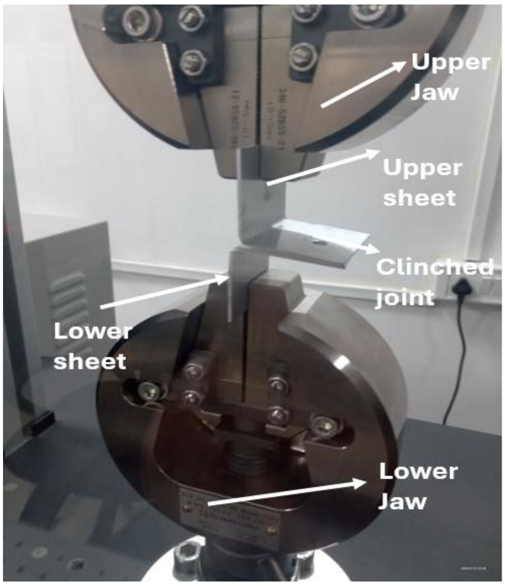
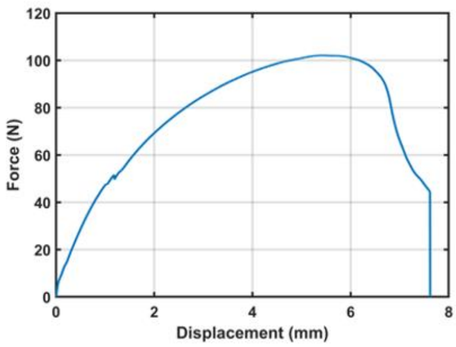


Figure 43 UTM setup of peel test of AA 1050 sheets



(a)

(b)

Figure 44 a)Peel test result b) Sample after peel test

It is observed from the figure 44 that maximum load carried by the joint was 102 N

5.2 Joining of AA 1050 with CFRP sheet of thickness 0.5mm using hole clinching.

The joining of sandwich carbon fibre with AA 1050 sheet using the hole clinching technique yielded effective results. The process effectively created strong mechanical interlock between the materials, providing a strong connection suitable for various applications. This contact is very important for achieving large load bearing capacity and enhancing the overall strength of the joint. Additionally, the clinched holes exhibited uniform deformation and interlocking features, ensuring mechanical interlocking, and enhancing the joint's stability. Mechanical testing demonstrated excellent performance of the joined specimens under various loading conditions. The joint exhibited high shear and peel strengths, which is the requirements for many structural applications.

5.2.1 Lap shear test

The Lap shear test of a sandwich joint among 1.3 mm AA 1050 and .5 mm CFRP sheets prepared was performed on the Universal Testing Machine with 10 kN capacity. Where 50 mm was taken as gauge length and 22 mm was kept for the grip at both ends. The pull-out test was performed at the speed of 1 mm/min. The schematic and testing arrangement is shown in figure 45

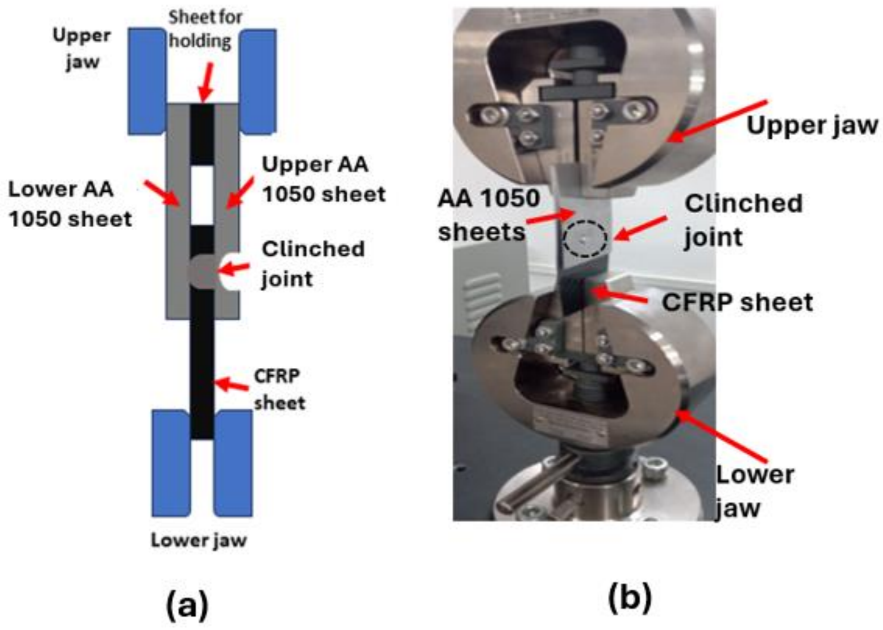


Figure 45 a) Schematic b) UTM setup for shear test

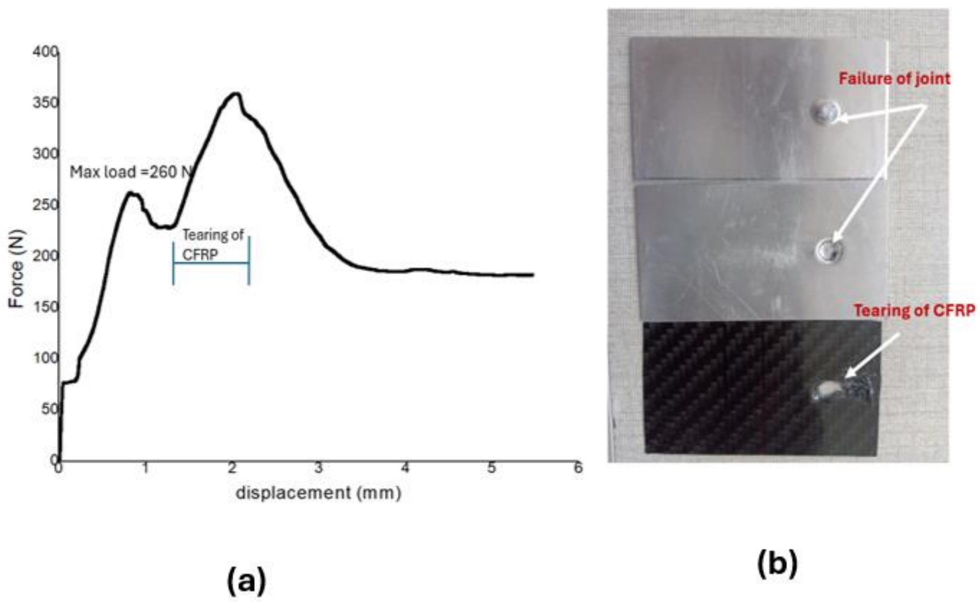
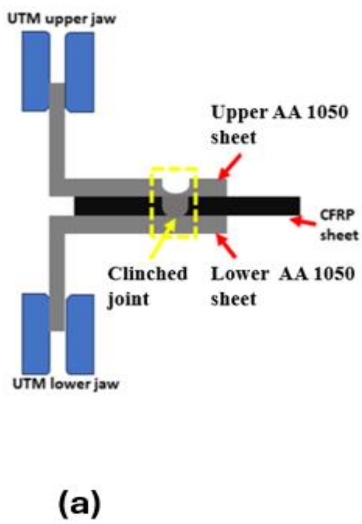


Figure 46 (a) Result of shear test (b) Sample after shear test

As Figure 46 a depicts, after observing the shear test curve maximum load carried by the joint was 260 N than tearing of CFRP was observed. Joint strength depends on pre-drilled hole diameter in CFRP that should be optimized. If the drilled hole is of a large diameter, then a loose joint will form and if a hole is of a small diameter than it will distort the CFRP sheet.

5.2.2 Peel test

A Peel test was performed on the samples prepared . The CFRP sheet was kept free mean while two L-shaped edges of mild steel were held in between two jaws of the Universal testing machine as shown in figure 47



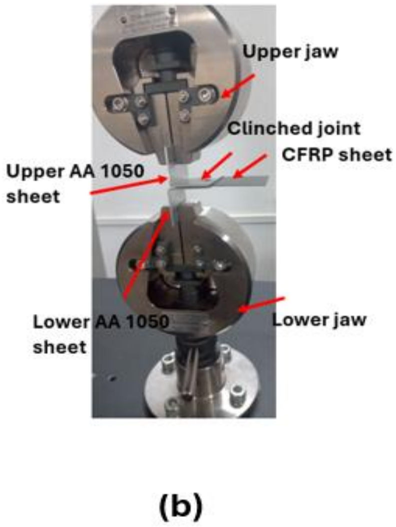


Figure 47 a) Schematic b) Setup of peel test.

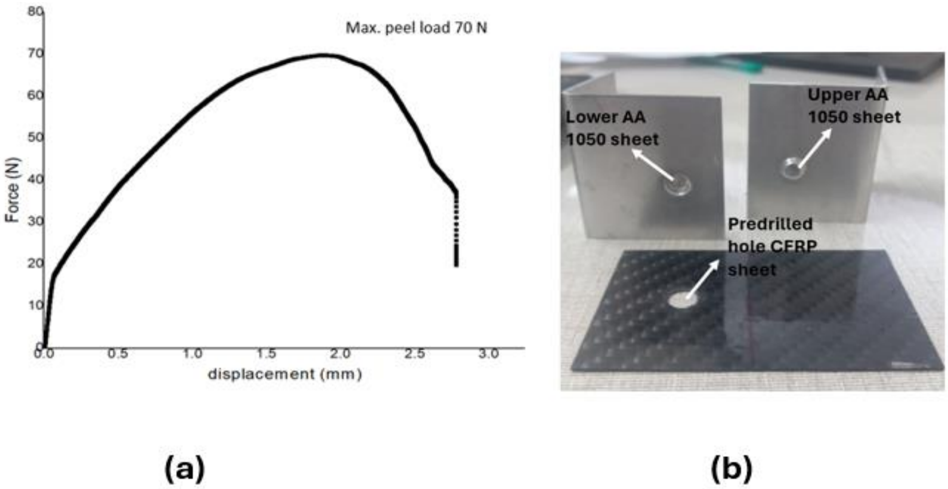


Figure 48 a) Result of peel test b) Failed sample after peel test

As shown in Figure 48 (a). The maximum peel load was observed to be 70 N which shows the strength of the joint was very good in shear and less in the peel test because there was no effect of the CFRP sheet during the peel test. Figure 48 (b) shows joint failure and imprints in samples.

5.2.3 Cross-section test

A cross-section of CFRP sheet thickness of 0.5 mm with AA 1050 clinched is shown in Figure 49. Pre-drilling the CFRP sheet reduce damage to the fibre because of its brittleness. Proper optimization of hole in CFRP plays important role due tool is deforming upper sheet through the hole in the lower sheet.

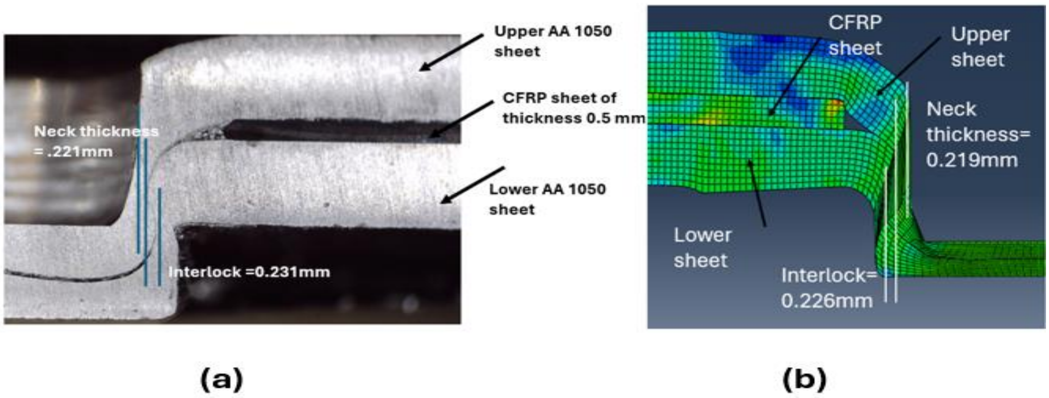


Figure 49 a)Experiment cross-section b) Simulation cross-section

Comparison between numerical and experimental results shows that Interlock of 0.226 and 0.231 mm, neck thickness of 0.219 and 0.221 mm are obtained for the AA1050-CFRP-AA1050 sandwich joint with 6 mm pre-drilled hole, respectively some variations in values were obtained because of some assumption in simulation like 2D analysis and material was considered as isotropic.

5.3 Joining of Mild steel with CFRP sheet of thickness 1mm with upper sheet pre-deformed by clinching and joining by Resistance spot welding.

The combination of clinching and spot-welding results in a robust joint interface, the localized heat input during resistance spot welding facilitates metallurgical bonding between upper and lower mild steel sheets, creating a fusion zone that contributes to the joint's strength. However, challenges persist in this hybrid joining technique, one notable concern is the potential for thermal damage to the CFRP due to the heat generated during resistance spot welding which is why the diameter of the hole in the CFRP is more than the deformed sheet diameter. The shear test strength depends on the amount of fusion between two mild steel sheets, joint diameter, the yield stress of the material, pre-drilled hole in CFRP, and welding time. Making a sandwich joint among 1.5 mm thick mild steels and 1 mm thick CFRP is very challenging as manually pre-deform mild steel by 1 mm is difficult. To make this sandwich joint between 1.5 mm mild steel and 1 mm CFRP sheets, a clinching machine was used to pre-deform the upper mild steel sheet equal to the thickness of CFRP i.e. by 1 mm. This approach gives proper deformation and more contact points during welding, after pre-deformation from the clinching machine a cup section was formed which gives more strength to the joint.

5.3.1 Lap shear test

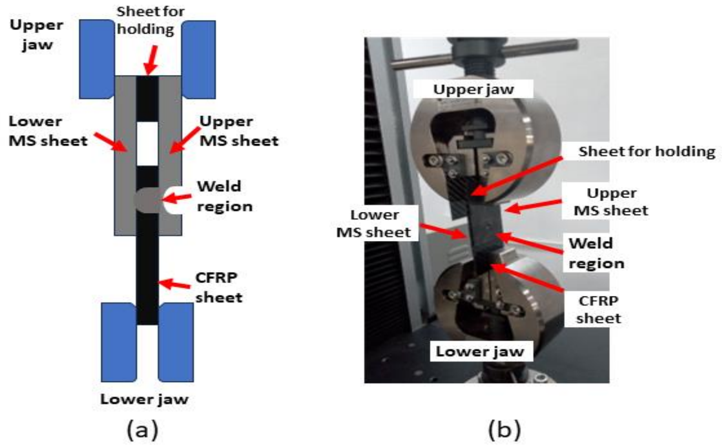


Figure 50 a) Schematic b) UTM setup for shear test.

The Lap shear test of a sandwich joint among 1.5 mm mild steel and 1 mm CFRP sheets prepared using pre-deformation of upper mild steel sheet was performed on the Universal Testing Machine with 10 kN capacity. Where 50 mm was taken as gauge length and 22 mm was kept for the grip at both ends. The pull-out test was performed at the speed of 1 mm/min. The schematic and testing arrangement is shown in figure 50

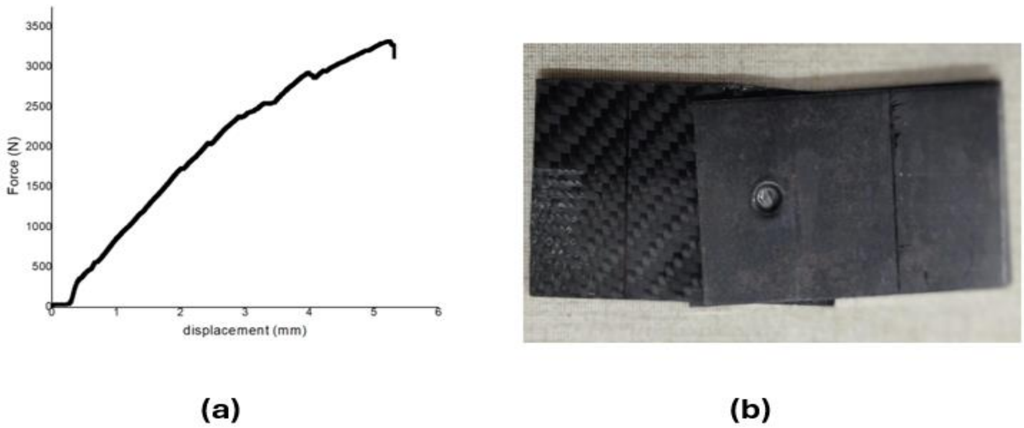


Figure 51 a) Shear test result b) Failed sample after shear test for weld time of 0.25sec

As Figure 51 depicts, after observing the shear test curve maximum load carried by the joint was 3300 N still CFRP didn't come out from the joint as shown in Figure 52 (b)because some portion of the joint was still intact. Joint strength depends on pre-drilled hole diameter in CFRP that should be optimized. If the drilled hole is of a large diameter, then a loose joint will form and if a hole is of a small diameter than it will affect the CFRP sheet.

5.3.2 Peel test

A Peel test was performed on the samples prepared , The CFRP sheet was kept free meanwhile two L-shaped edges of mild steel were held in between two jaws of the Universal testing machine as shown in figure 52.

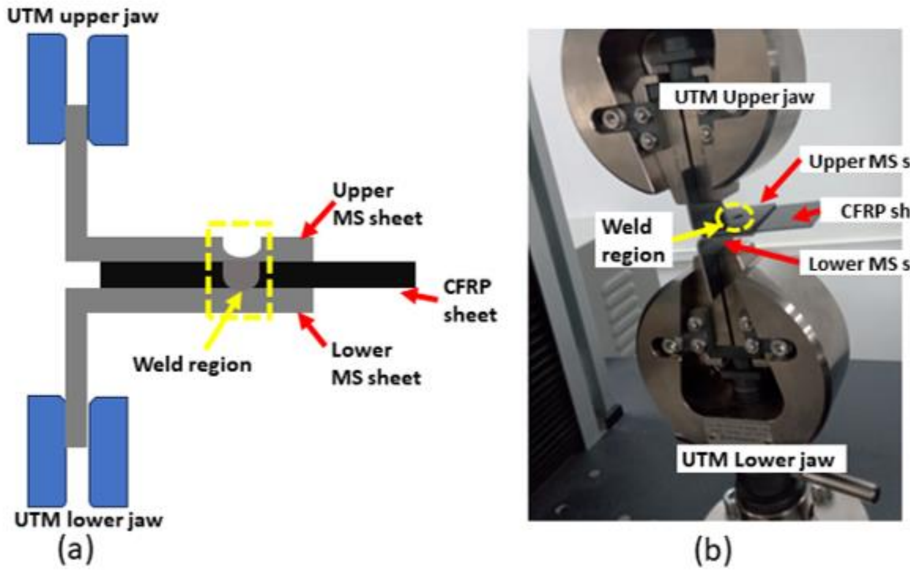


Figure 52 a) Schematic b) UTM setup for peel test

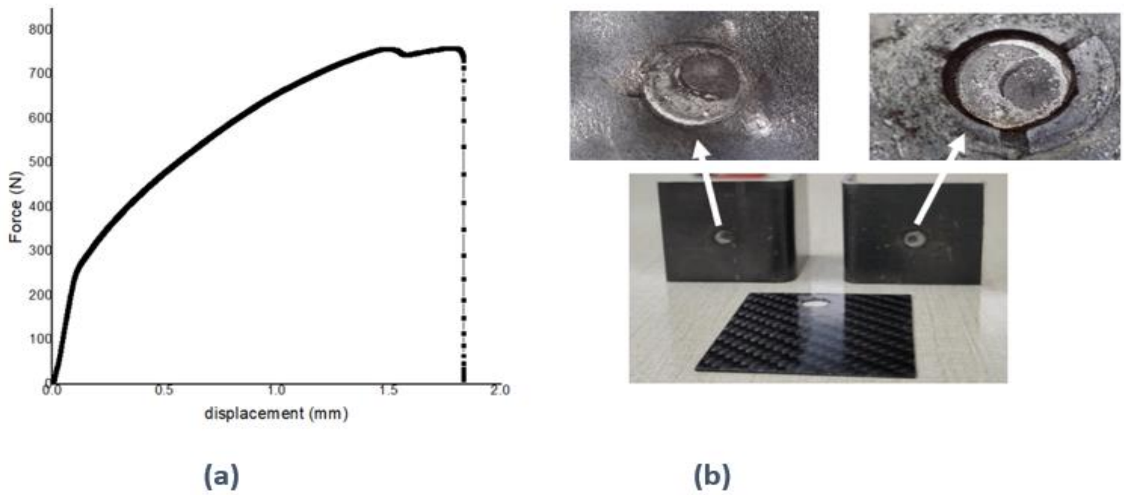


Figure 53 a) Peel test result b) Failed sample after peel test for weld time of 0.25 sec.

As shown in Figure 53 (a), The maximum peel load was observed to be 760 N which shows the strength of the joint was very good in shear and less in the peel test because there was no effect of the CFRP sheet during the peel test. Figure 53 (b) shows joint failure and imprints in samples.

5.3.3 Cross-section analysis

A cross-section of CFRP sheet thickness of 1 mm with mild steel spot weld is shown in Figure 54. Pre-deforming the upper mild steel sheet increases the contact surface area between the materials, potentially improving the bonding strength during spot welding. Proper deformation techniques, such as using a clinching machine, can create features that enhance joint strength. Resistance spot welding applies localized heat and proper deformation of the upper sheet reduces the heat exposure to the CFRP, reducing potential damage caused by excessive heat

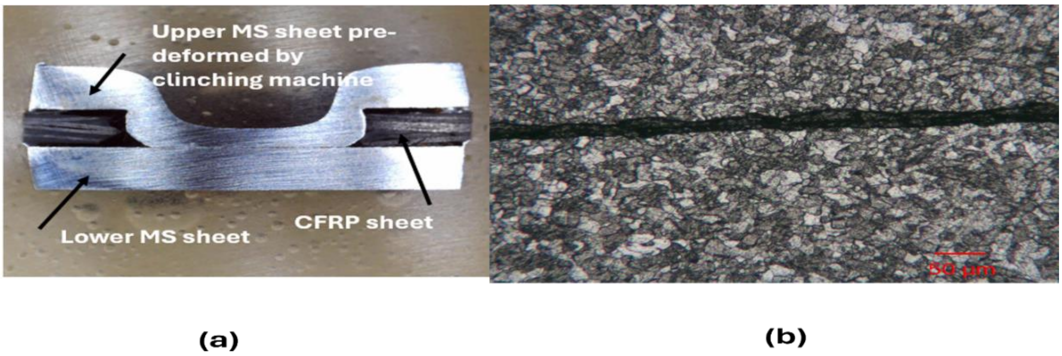
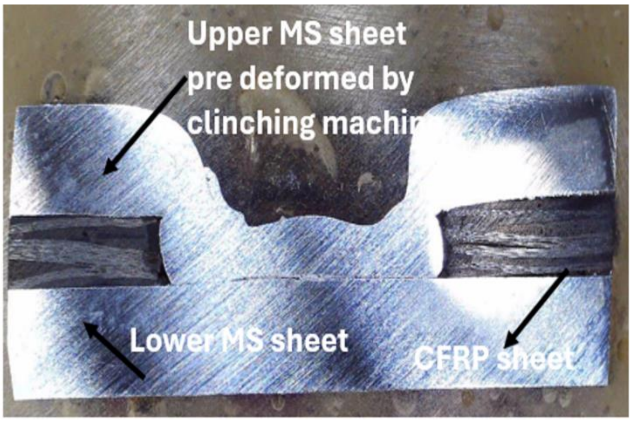
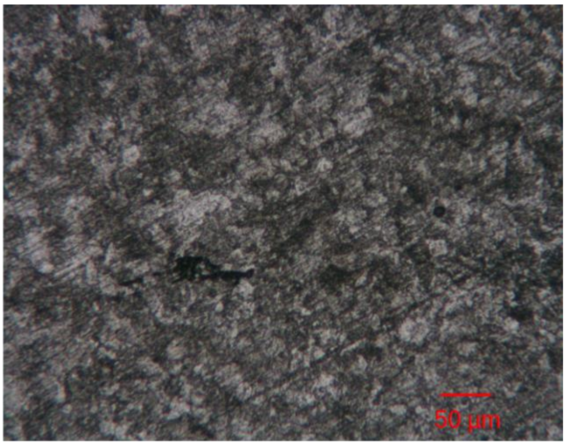


Figure 54 a) Joining of CFRP with Mild steel sheet by resistance spot welding with welding time of 0.2 sec b) cross-section after etching





(a) **(b)**

Figure 55(a) Joining of CFRP with MS by Resistance spot welding with weld time of 0.25 second (b) Cross-section after etching

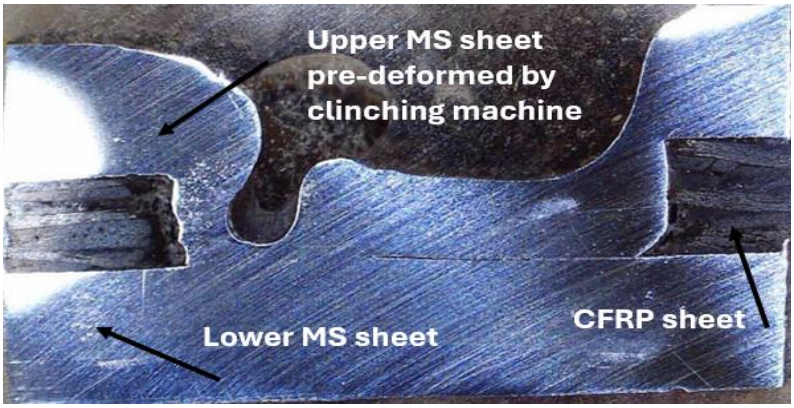


Figure 56 Joining of CFRP with MS by Resistance spot welding with weld time of 0.3 second

It was observed from the figure 54,55,56 that more fusion and less expulsion was observed in weld time of 0.25 second so that is considered as optimum welding time for joining.

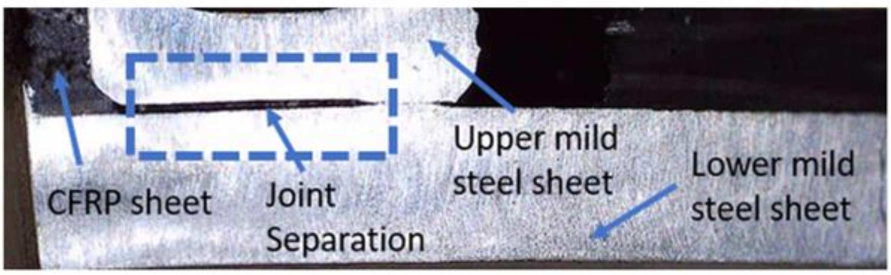


Figure 57 Cross-section of the failed Sample after the Shear test join by weld time of 0.25 second

5.3.4 Micro hardness test

A Vickers microhardness investigated the hardness distribution perpendicular to the joint interface was applied to the sample. The micro-Vickers hardness test was executed using a 0.5 kg f load with a dwell time of 20 seconds using an indenter of 73 microns size. To avoid the data of pre hardening, the initial indentation was applied some distance away from the surface of the pre-deformed upper MS sheet and subsequently progressed towards the lower MS sheet, as illustrated in Figure 58. As visible in Fig 58 it is evident that the hardness value exhibited a notable peak in proximity to the joint interface, gradually diminishing as one moved away from this juncture. This surge in hardness can be attributed to the influence joining of the sheets. The hardness values at the interface induce compressive residual stress.

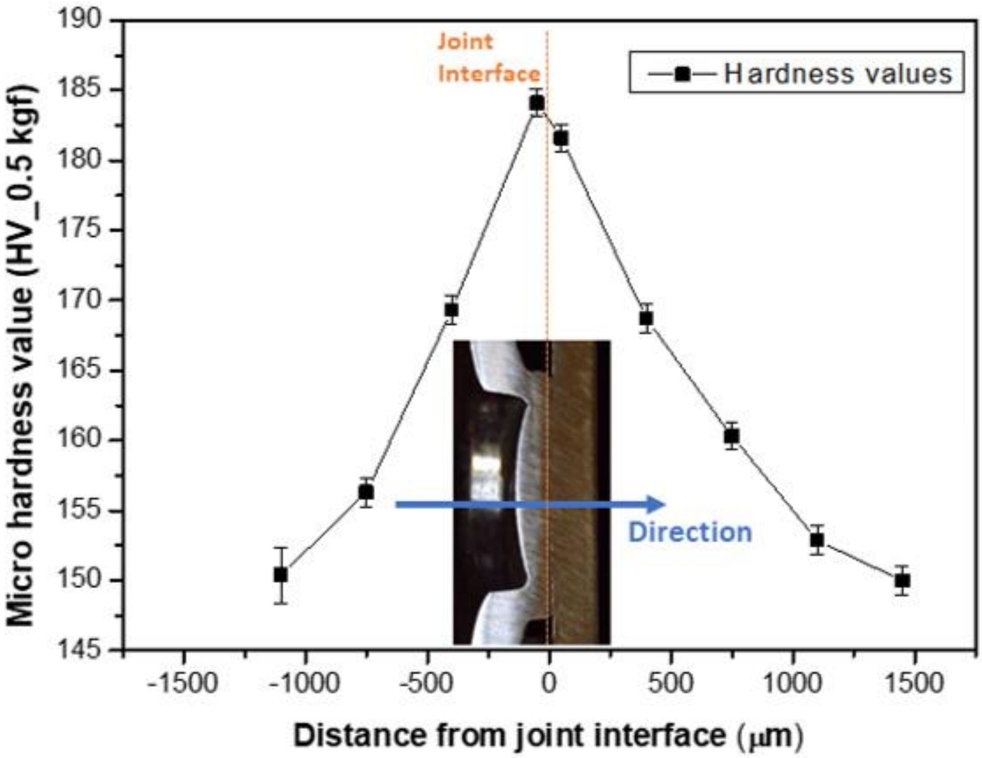


Figure 58 Micro hardness result of Weld time 0.25 second

5.4 Effect of Spot welding After Clinching

Combining clinching and spot welding is an increasingly common approach in the manufacturing industry for joining mild steel sheets. This hybrid technique involves the mechanical interlocking of clinching with the fusion of spot welding, aiming to enhance the joint's structural integrity and strength. The sequential application of clinching followed by spot welding capitalizes on the strengths of each method while reducing their individual limitations.

When combining clinching and spot-welding techniques for joining mild steel sheets, a observation has been made regarding the sequence and interaction between these two processes. Specifically, if a clinched joint is placed directly on the electrodes used for resistance spot welding, there is a significant risk that the joint will open or fail. The reason behind this was Clinched joints are designed to distribute load across a wider area than spot welds. The localized heat and subsequent structural changes caused by spot welding can concentrate stress at the weld point, rather than distributing it. This concentration of stress can lead to premature failure of the joint under mechanical loading.

To avoid directly apply clinched sheet in between resistance spot welding electrodes a detachable electrode was made which is increasing area of contact and increased fusion in resistance spot welding process due to protrusion on the lower clinched sheet shown in figure 59

Figure 59 Protrusion on lower clinched sheet.

Detachable electrode shown in figure made by copper rod shown in the figure 60 in lathe machine

(a) **(b)**

Figure 60 a) Copper rod b) Manufacturing of detachable electrode in lathe machine.

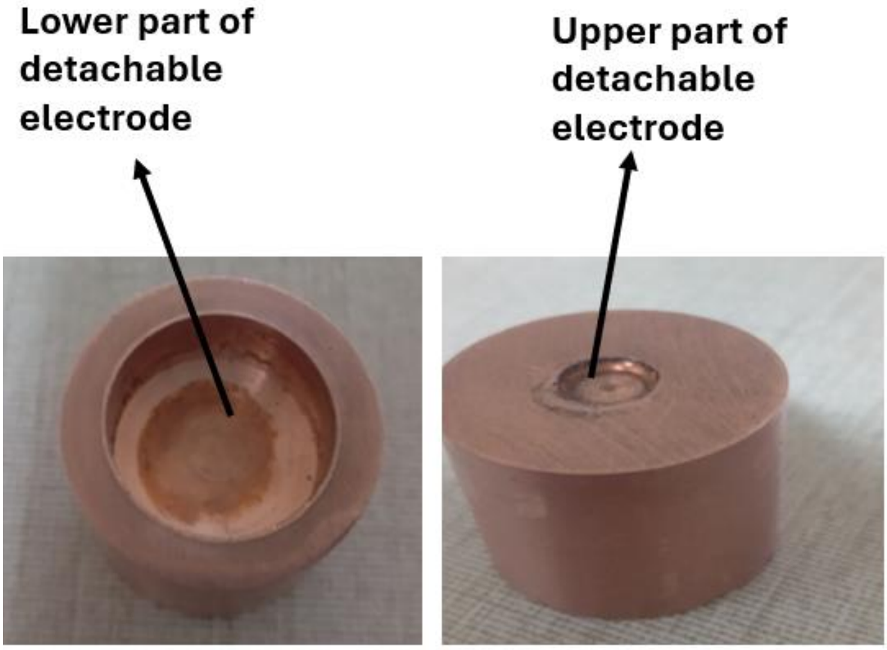


Figure 61 Detachable electrode.

Upper part of the detachable electrode will come in contact with protrusion portion of clinched sheet and lower part of detachable electrode will come in contact with lower electrode of resistance spot welding as shown in figure 61

Figure 62 Detachable electrode in contact with Resistance spot welding electrode

5.4.1 Cross-section analysis

A cross-section is shown in figure some fusion was observed which is shown by optical microscopy at different points

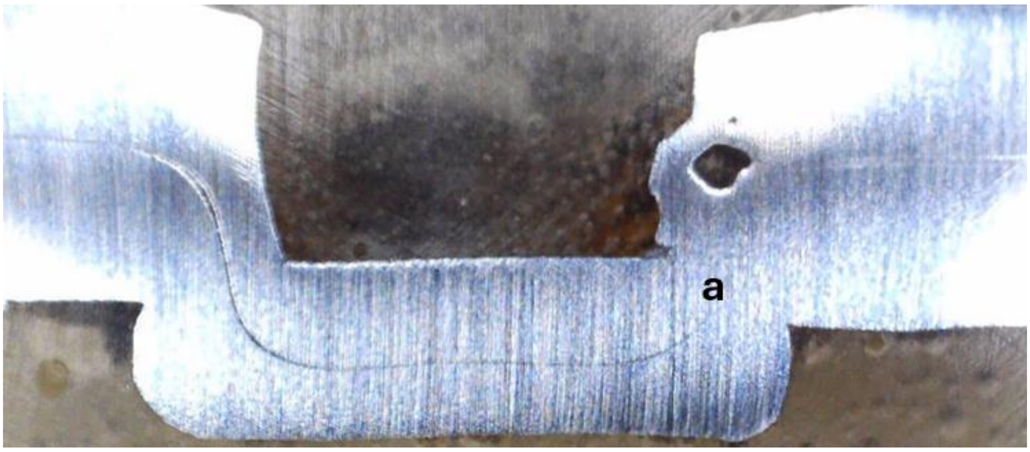


Figure 63 Cross-section of resistance spot welding after clinching.

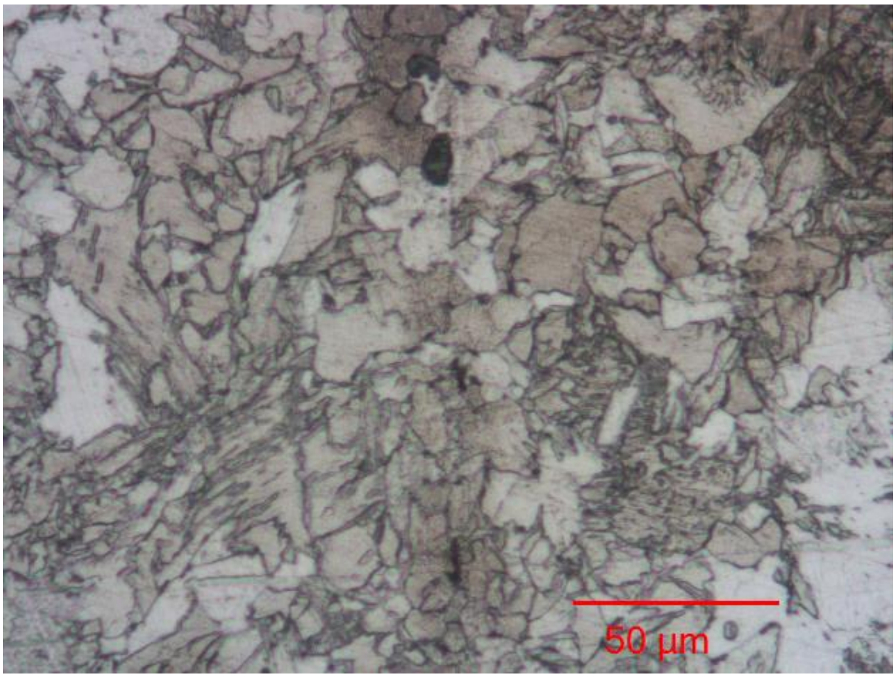


Figure 64 Microstructure at point a

It was observed from figure 64 that more fusion was observed at point a than at any other point.

5.4.2 Lap shear test

The Lap shear test of a joint among 1.5 mm mild steel first join by clinching and then resistance spot welding and performed on the Universal Testing Machine with 10 kN capacity. Where 50 mm was taken as gauge length and 22 mm was kept for the grip at both ends. The pull-out test was performed at the speed of 1 mm/min. The testing arrangement is shown in figure 65

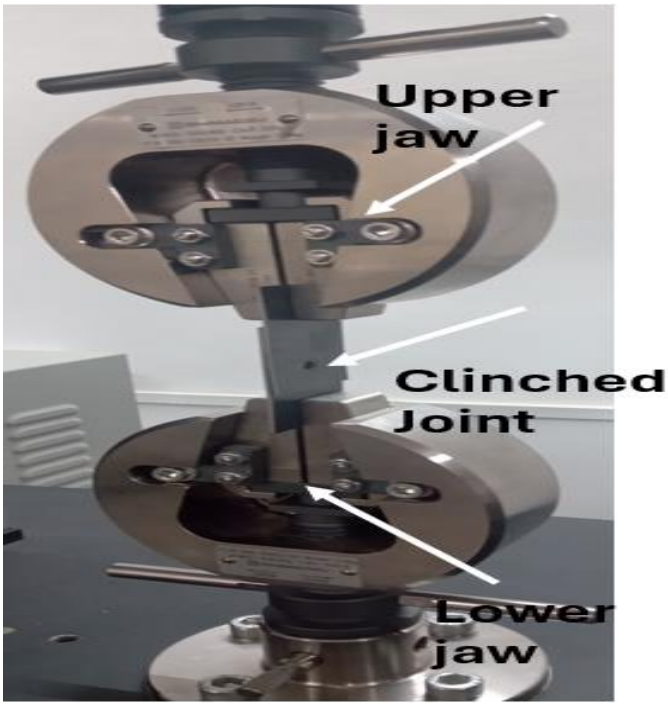


Figure 65 UTM setup for MS -MS spot welding after clinching joint.

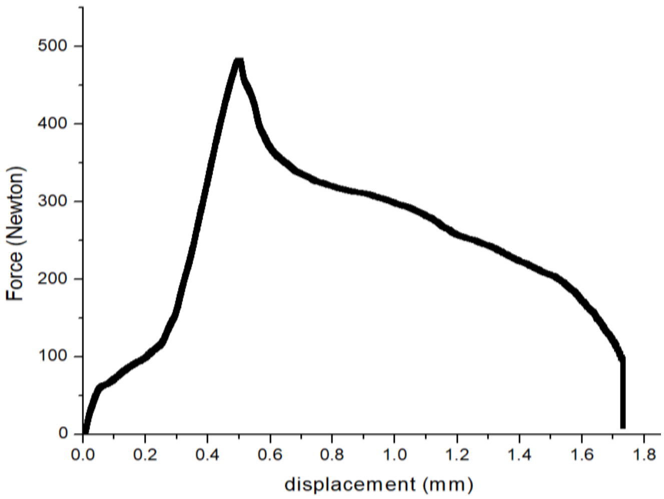


Figure 66 Shear test result of MS_MS spot weld after clinching

It was observed from the figure 66 that maximum load carried by the joint was 480N.

5.4.3 Peel test

Peel test was performed in UTM machine of capacity 10 kN . Peel test setup was shown in figure 67

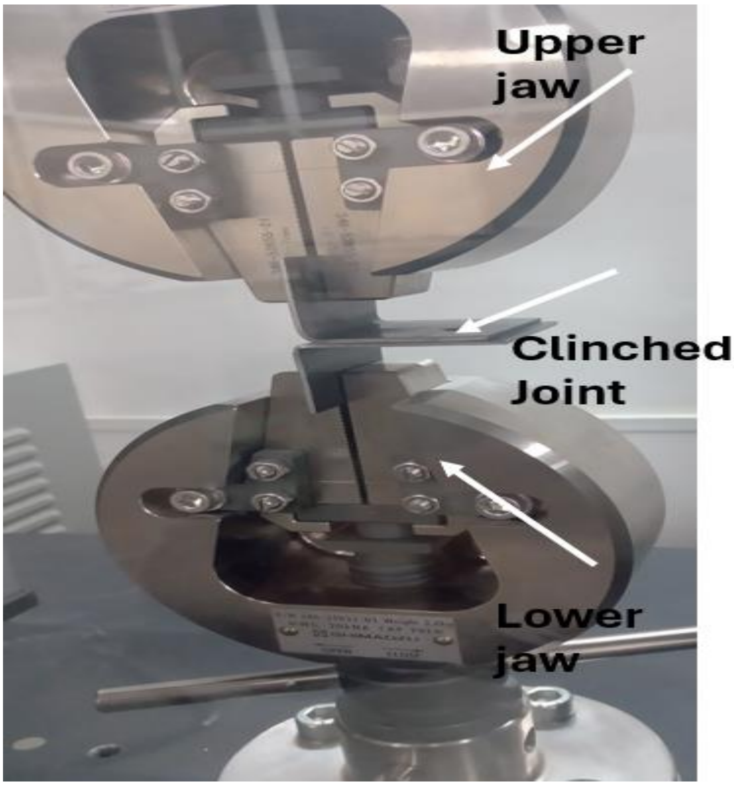


Figure 67 UTM setup for peel test.

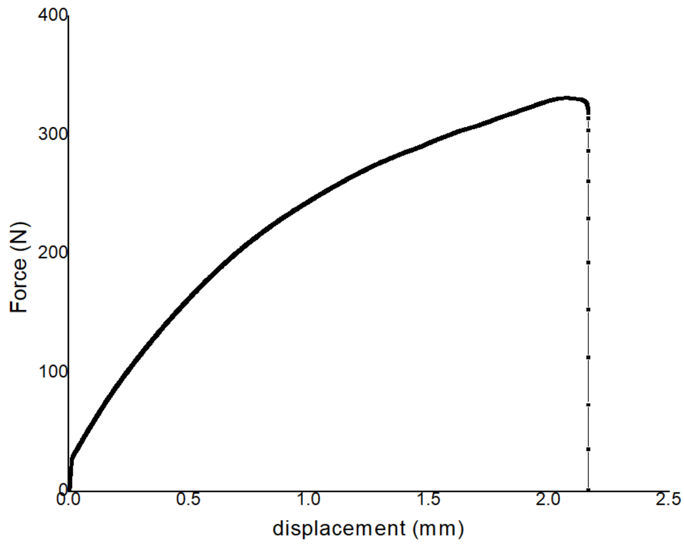


Figure 68 Peel test curve of spot welding after clinching.

It is observed from the graph maximum load carried by the joint is 350N.

5.5 Effect of Clinching After Spot welding

Clinching, often used in comparison with spot welding, is a mechanical fastening technique particularly important in the automotive and manufacturing industries where sheet metal assemblies are common. This method involves joining metal sheets by plastically deforming the material using a punch and die to interlock the sheets mechanically. When used together spot welding, clinching can significantly enhance the structural integrity and durability of the assembly.

Firstly, the primary advantage of using clinching after spot welding lies in the increased joint strength and robustness it provides. Spot welding alone creates welds that, while strong under certain conditions, can be susceptible to fatigue and stress concentrations which potentially lead to failures under cyclic loads. By adding clinching, the load is distributed more evenly across the joint. The mechanical interlock created by clinching adds shear strength and enhances the overall resistance to peel and tensile forces. This is particularly beneficial in applications where dynamic loads are important.

In conclusion, the integration of clinching after spot welding significantly enhances joint strength, durability, and corrosion resistance while reducing manufacturing costs and environmental impact. It enables the assembly of complex structures with improved performance characteristics, making it a preferred choice in industries where reliability and efficiency are very important. As technologies evolve, the combination of these techniques will likely continue to play a critical role in manufacturing strong metal assemblies.

5.5.1 Cross-section analysis

A cross-section of clinching after spot welding is shown in figure .Cross-section analysis of clinching on spot welding involves examining the internal structure and interface of a joint where both processes have been utilized. This analysis provides into the microstructural changes, weld quality, and the integrity of the joint, aiding in understanding the combined effects of these joining techniques.

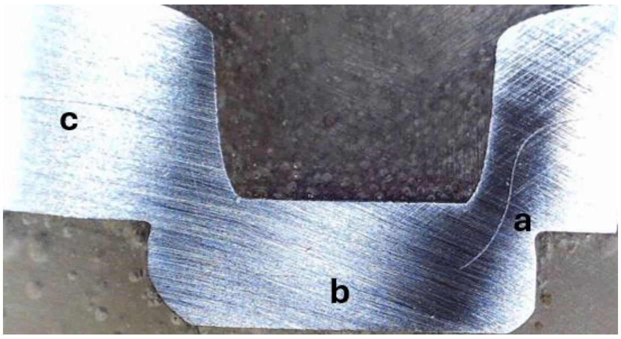
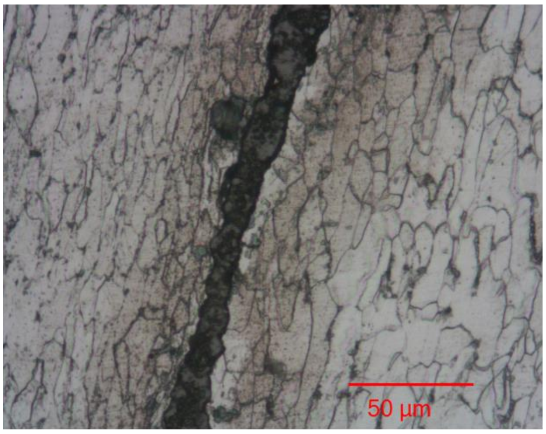
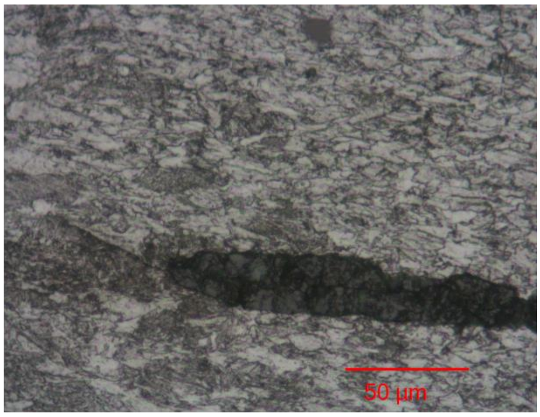
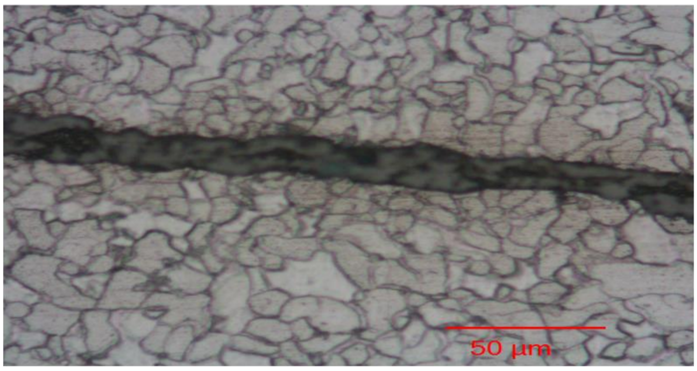


Figure 69 Cross-section of clinching after spot welding.





(a) **(b)**



(c)

Figure 70 a) Cross-section at point c b) Cross-section at point b c) Cross-section at point a

5.5.2 Lap shear test

The Lap shear test of a joint among 1.5 mm mild steel first join by spot welding and then clinching and performed on the Universal Testing Machine with 10 kN capacity. Where 50 mm was taken as gauge length and 22 mm was kept for the grip at both ends. The pull-out test was performed at the speed of 1 mm/min. The testing arrangement is shown in figure 71

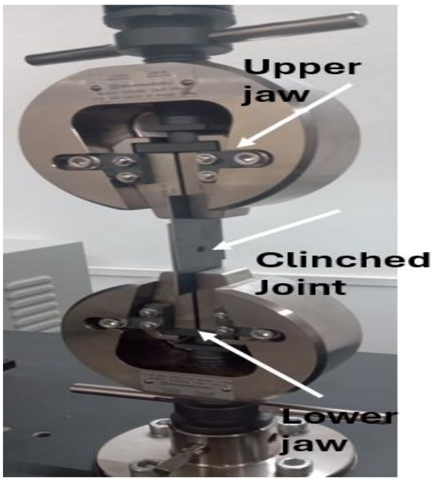


Figure 71 UTM setup for shear test

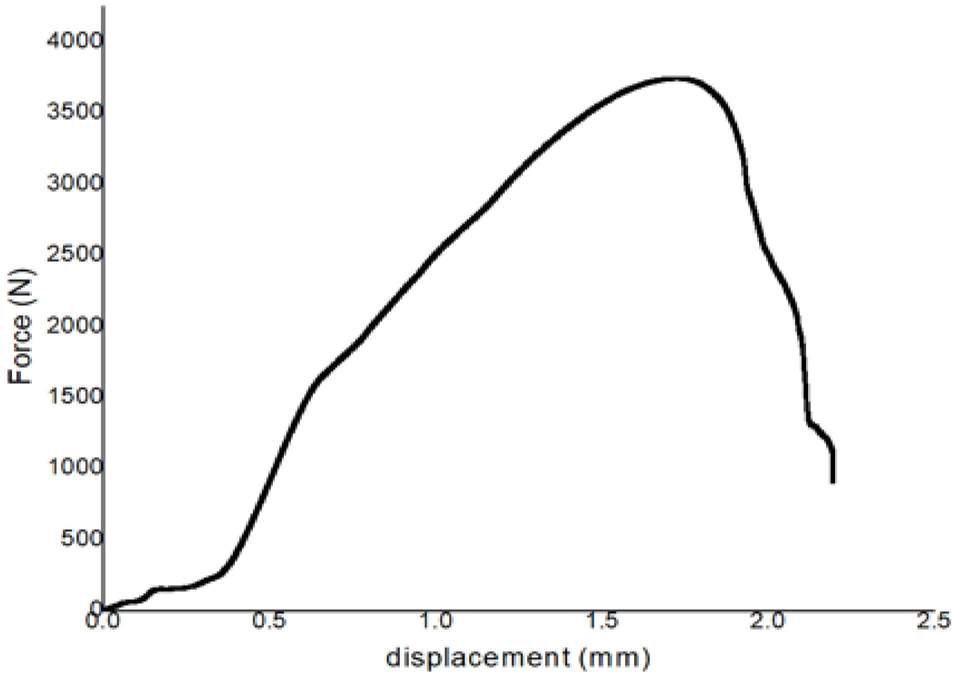


Figure 72 Shear test curve of clinching after spot welding.

It was observed from the figure 72 that maximum strength of the joint was 3600N

5.5.3 Peel test

In peel test mild steel sheets are bending to ninety degree and join by clinching after spot welding

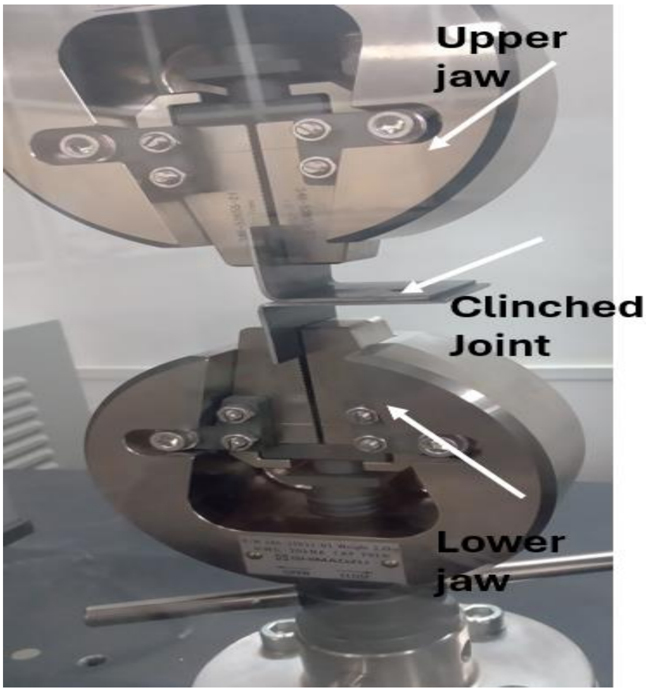


Figure 73 UTM setup for peel test

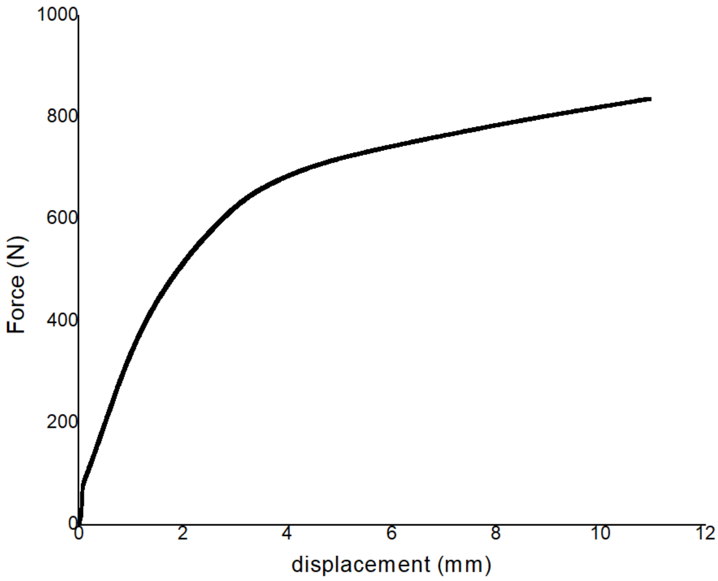


Figure 74 Peel test curve of Clinching after spot welding.

It is observed from the figure 74 that maximum load carried by the joint was 800 N

Chapter 6

Conclusion and Future directions

This chapter presents the conclusions drawn from the comprehensive investigation of joining sandwich carbon fibre with material like AA 1050 and Mild steel. The implications of the findings and the significance of the research are summarized, providing insights into the potential applications and future directions for this field of study.

6.1 Summary of findings

Experiment procedure or research methodology shown in chapter 3 and its results shown in chapter 5 describe joining of CFRP with AA 1050 and Mild steel sheet by clinching and resistance spot welding following observation can be drawn.

- Optimized clinching pressure of **2 and** for AA1050 gives better strength using hit and trial method, respectively.
- Comparison between numerical and experimental results shows that Interlock of **0.226** and **0.225 mm**, neck thickness of **0.219 and 0.232 mm** are obtained for the AA1050-CFRP-AA1050 sandwich joint with 6 mm pre-drilled hole, respectively.
- Attempt to join MS-CFRP-MS sheets by Resistance spot welding with pre deformed upper MS sheet using manual deformation and pre deformation by mechanical clinching with maximum shear load of **3300N** and maximum peel load of **760N**
- Analyze the effect of Spot welding after clinching with maximum shear load of **480N** and maximum peel load of **350**N.
- Analyse effect of clinching after spot welding with maximum shear load of **3600N** and maximum peel load of **800 N**

6.2 Implications and Significance

This research helps in automobile industry which are now a days moving towards light weight manufacturing, use of CFRP in automobile industry not only reduce weight but also increased corrosion resistance, less thermal expansion due to temperature reduce overall emission from automobile.

6.3 Limitations and Future Research

Clinching and spot welding are limited for sheet metals only to join high thickness sheet there is need to use other methods like bolting ,adhesive bonding etc

In future joining of CFRP with AA 5052 sheet can be done with the hole clinching process as there is no research available for joining with extensible die.

6.4 Recommendations for Further Study

Joining carbon fibre-reinforced polymer (CFRP) composites with aluminium alloys, such as AA 1050, presents unique challenges due to the significant differences in physical and chemical properties between the two materials. The main issues include differences in thermal expansion, potential galvanic corrosion, and difficulties in achieving strong and durable bonds due to the inert nature of the carbon fibres and the oxide layer on aluminium.

Here are some key areas for further study to improve the joining of sandwich carbon fibre composites with AA 1050

1) Thermal effect on the joint
2) Surface treatment on the joint
3) Fatigue testing of the joint

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