DESIGN AND DEVELOPMENT OF A RIVETING EQUIPMENT FOR IMPROVING PERFORMANCE OF AIRCRAFT JOINTS

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Certification

This is to certify that **Wajdan Majeed**, **00000326675** has successfully completed the final project **Design and Development of a Riveting Equipment for Improving Performance of Aircraft Joints,** at the **NUST, CAE**, to fulfill the partial requirement of the degree **BSc.**

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Abstract

This project focuses on the design, development, and testing of novel electromagnetic riveting equipment to improve the performance of aircraft joints. The choice of electromagnetic riveting as a potentially effective method was made after a thorough examination of the literature. The equipment was carefully designed and manufactured in accordance with our requirements, ensuring accuracy and effectiveness during the riveting process.

During the development stage, electromagnetic principles were incorporated into the riveting equipment to ensure a precise and significant force application during the joint formation. Testing of equipment and joint was put in place to verify the equipment's usefulness and ability to strengthen joints. The effectiveness of the electromagnetic riveting technology is demonstrated by the experimental findings, which indicate a notable increase in the strength of aircraft joints.

The effective use of the designed equipment not only demonstrates its potential for use in the aerospace sector but also advances the field of manufacturing technology. This project highlights the importance of innovative solutions in addressing challenges related to aircraft structural integrity, ultimately paving the way for more robust and reliable aerospace systems.

Keywords: Electromagnetic Riveting; microstructural analysis; MSL of riveted joint

Undertaking

I certify that the project **Design and Development of a Riveting Equipment for Improving Performance of Aircraft Joints** is our own work. The work has not, in whole or in part, been presented elsewhere for assessment. Where material has been used from other sources it has been properly acknowledged/ referred.

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Chapter 1

1.1 Introduction

The project's primary objective is to design and manufacture specialized riveting equipment that will improve the performance of aircraft joints. The limitations associated with pneumatic and conventional riveting techniques used in aviation maintenance were initially identified through a thorough investigation. These restrictions include things like poor precision and consistency, the possibility of damaging nearby structures, and difficulties reaching the ideal joint strength.

The design and development of the electromagnetic riveting equipment took place in the ensuing stages. Modern engineering concepts were incorporated into this procedure to ensure that the method would effectively address the limitations that were found. The equipment that was developed was intended to form aircraft joints in a more regulated, dependable, and efficient manner, ultimately leading to enhanced overall performance.

Finally, after the development, the equipment's practicality was put to test. Strength testing of joints was carried out for both pneumatic and electromagnetic riveting. Comparison of results was done to comment on the improvement of joint strength.

1.2 Statement of the problem

Rivet failure in aircraft structures poses a significant challenge in aircraft maintenance, leading to safety concerns and increased maintenance costs. Traditional pneumatic riveting methods used for joint assembly often exhibit limitations such as inadequate joint strength, susceptibility to fatigue, and constraints on edge distance. These shortcomings necessitate the exploration of alternative riveting techniques to improve joint performance and reliability. Therefore, the problem statement of this project is to develop a specialized riveting equipment utilizing electromagnetic riveting technology to address the limitations of traditional pneumatic riveting methods and enhance the performance of aircraft joints. Additionally, the project aims to conduct a comparative microstructural analysis of riveted samples produced by electromagnetic and pneumatic riveting methods, and to experimentally determine the maximum shear load values of riveted samples to evaluate the strength differences between the two riveting techniques.

1.3 Goals

The goal of my project is to design, develop, and validate specialized riveting equipment utilizing electromagnetic riveting technology for improving aircraft joint performance. Additionally, the project aims to conduct a comparative microstructural analysis of riveted samples produced by electromagnetic and pneumatic riveting methods. Furthermore, the project seeks to experimentally determine the maximum shear load values of riveted samples to evaluate the strength and performance differences between electromagnetic and pneumatic riveting techniques.

1.4 Motivation

The motivation of this project is to use innovative riveting techniques to improve the performance and reliability of aircraft joints. Though commonly employed in aviation maintenance, traditional pneumatic and conventional riveting techniques have drawbacks that include inconsistent force application, too much dependability on operator skill and varied joint strength. These flaws have the potential to compromise an aircraft's structural integrity, raising maintenance costs and creating safety issues. Blown off rivet heads can act as internal object damage that can cause damage to engine. This project intends to overcome these constraints and create a more accurate, effective, and non-destructive technique of producing aircraft joints by investigating and using electromagnetic riveting technology. By equipping maintenance staff with advanced instruments and methods that maximize joint strength and reduce maintenance downtime, the goal is to contribute to safer and more dependable aircraft operations.

1.6 Methods

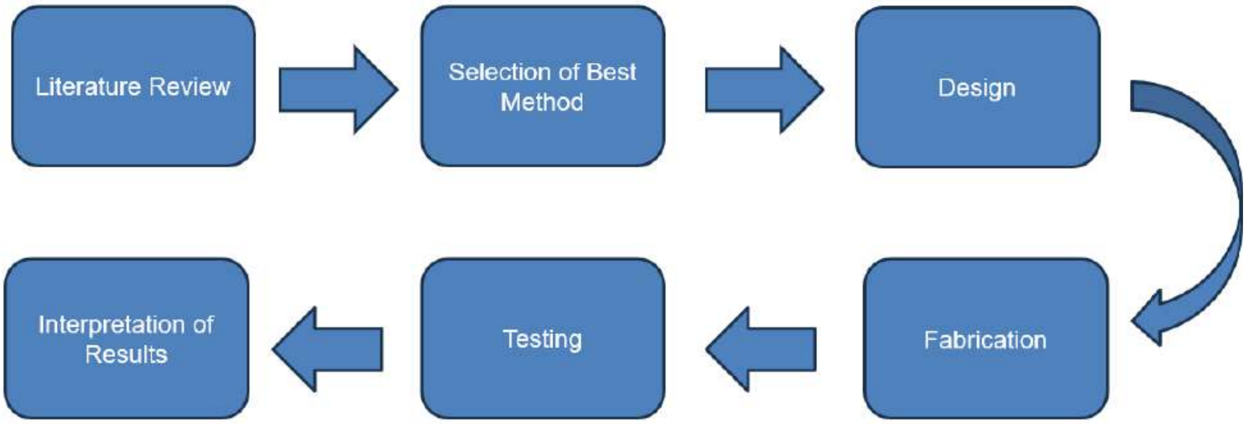


Figure 1: Methodology

1.7 Report Overview

The project aims to make airplane maintenance operations efficient by addressing the inherent constraints of pneumatic and traditional riveting techniques through the design and development of an electromagnetic riveting system. The research actively uses ideas from a thorough literature analysis to choose electromagnetic riveting as a potential option. The following phases require the rigorous design and development of equipment, which is engineered to improve joint performance through precision and efficiency. The project has the potential to improve the overall structural integrity and performance of aircraft joints and is well-suited to make a significant contribution to the improvement of aerospace production and maintenance practices

Chapter 2

2.1 Loads on Aircraft Riveted Joints

Various types of loads are experienced by aircraft structures including mechanical fasteners (bolts, rivets). These include: -

2.1.1 Aerodynamic loads

The aerodynamic loads tend to apply pressure which causes shear stress on the riveted joints. Additionally, high speeds coupled with directional changes of the aircraft / rapid throttle movement cause load fluctuations.

2.1.2 Structural loads

The aircraft structural load is transferred from wing spars to fuselage bulkheads. Furthermore, a portion of loads on fuselage is also borne by stringers. The joining of the major load-carrying components is generally carried out by bolts and rivets, which mostly experience flexural and shear stresses.

2.1.3 Vibrations

Vibrations from main structural component such as wing (aero-elastic phenomena such as flutter), engine (itself or engine-airframe mismatch), rotary components (Pumps, Environmental control system compressor/turbine etc.) also contribute to the form of fatigue loads. These fatigue loads cause shear and normal stresses on the riveted joints.

2.1.4 Airflow (shear) loads on on-conforming rivet heads.

If for some reason, the rivet heads are not flushed with the airflow, would cause additional shear loads on rivets.

2.2 Pneumatic Riveting

For years, the most common method of riveting by hand is by using a hammer on one side and a bucking bar on the other[1]. This method uses the plastic deformation of the rivet for joining of two metal sheets. Holes are drilled before riveting. The rivet is placed in the hole which is supported by a reaction which is a die. On the riveting head, pressure is applied with hydraulic power or hammer. This impact deforms both the head and the tail of the rivet which takes the shape of die. It has two types namely cold and hot riveting which depends on the size of the rivet.

If rivet diameter is not large then heating is not necessary otherwise the rivet needs to be heated to make it more malleable.

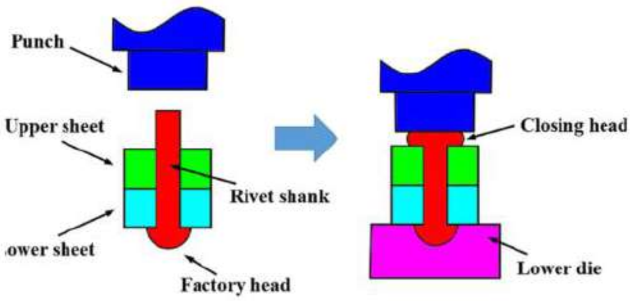


Figure 2: pneumatic riveting]

2.3 Limitations

One of the biggest disadvantages of pneumatic riveting is the variation in the quality and strength of rivet joints. It is solely dependent on the operator. The force applied on every joint is not the same and the inspection is based on flushness measurement which is not enough. The impact can also damage the structure especially in case of composite materials. Another problem is of alignment of the joint, if the force applies and the reaction bar are not perpendicular then some portion of the force is wasted, and the quality of the joint is compromised. This can happen especially in cases where both the operators cannot see each other or even while riveting on curved surfaces.

Another problem is the worker fatigue. There are many rivets installed on a structure. The K8 aircraft has 7000 rivets. Also, if the rivet is large then it also needs a large hammer and more pounding force. Thus, a great amount of strength and stamina of worker is utilized which in turn reduces the productivity of worker. This costs the manufacturer/maintenance unit time. Such riveting techniques also make a lot of noise ranging from 118 to 130dB [3]which can lead to medical problems regarding the hearing of staff and workers.

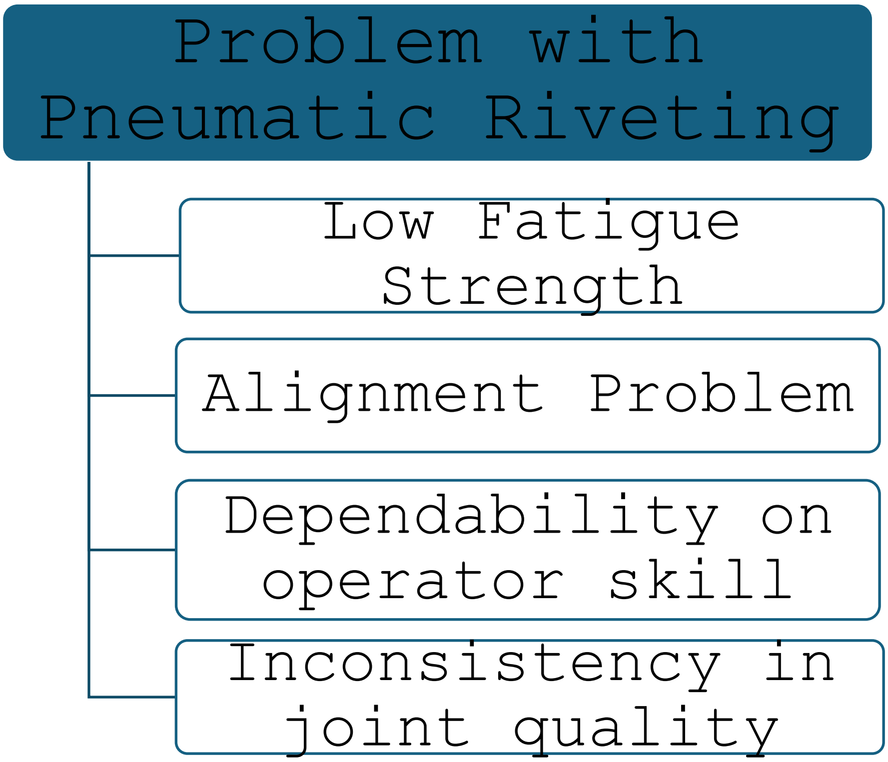


Figure 2: problems with pneumatic riveting

2.4 Advanced Riveting Techniques

The objective of improving aircraft efficiency and safety is a never-ending endeavor in the field of aircraft engineering. The way the parts are assembled is one factor to consider, particularly when riveting is involved. Although they have been used for a long time, traditional riveting techniques have drawbacks. Better methods of joint formation are needed as they get more sophisticated. More advanced riveting techniques can help with that. These techniques, such as electromagnetic riveting, provide greater reliability, speed, and precision. Let us explore some novel riveting techniques.

2.4.1 Self-Piercing Riveting

As the name suggests, instead of drilling a hole in our metal sheets, the rivet is forced into the material. It is a cold forming joint, and the power is provided either by a hydraulic press or a servo motor. When compared with conventional riveting, it provides better appearance and efficiency. Semi tubular rivets are used in this process. It has high static and fatigue strength without giving much weight penalty [4].

The process is shown in Fig. 2. There are two important parts: the blank holder and punch. The blank holder holds and compresses the metal sheets while the punch inserts the rivet into the sheet. When the rivet tail enters the lower sheet, it expands and plastically deforms the lower sheet into the female die. In this way a mechanical interlock is formed that holds the sheet together. The process is completed when the rivet head is in line with the upper sheet giving it a relatively smooth finish.

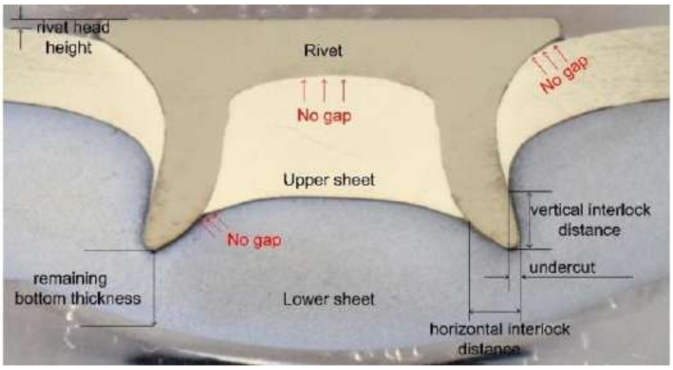


Figure 3 : self-piercing riveting [14]

2.4.2 Shape Memory Alloy Riveting

This novel riveting process uses the phenomenon of shape memory effect (SME). The shape memory alloys have this special ability to return to its original shape when heated. In this technique, an SMA rivet is inserted between materials, and then the rivet is heated to activate the shape memory effect, creating a strong and secure joint.

Due to the excellent shape memory effect of Ni-Ti alloys, it is used to make rivets. In the Fig 4, we can see that the rivet end is cooled in dry ice to make it straight. It is then inserted into the hole after which its temperature rises, and it regains its original shape. The rivet tail can then be tightened[5].

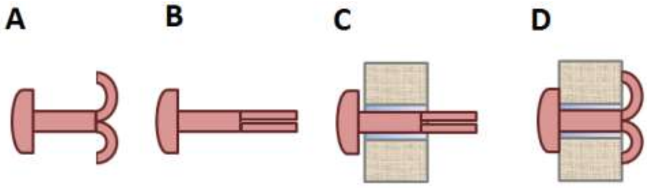


Figure 4: use of shape memory alloy fastening rivets [15]

They are much beneficial in an environment where conventional riveting is difficult to achieve. Such as in a closed vacuum environment, SMA rivets provides an allowable option[6]. They are also being developed by NASA for the connection of composite tube structural members where minimum energy is the constraint. Using penetrating fasteners affects the structural integrity of members used for the connection of payload in space shuttle. Using SMA connectors provides viable solution[7].

2.4.3 Friction Riveting

This riveting employs the force of friction between the rivet and the joining sheets. It is a basic technique that has further types including friction stir blind riveting, friction self-piercing riveting, friction element welding etc... Its procedure is depicted in figure 3. In this technique the metallic rivet is connected to a spindle. The two sheets to be combined are held together with a clamp. As the spindle starts rotating, the rotating rivet is forced into the sheets. In the upper sheet, heat is generated due to axial and friction force. This allows the rivet to be inserted into the sheet due to melting of the material. When the rivet reaches the lower sheet, the molten material is squeezed out and the temperature of rivet tail increases. The spindle stops and the rivet is forged in the shape of mushroom by the application of axial force. The rivet then cools down and the joint consolidates.

Tensile testing on riveted joint[8] suggested that larger rivet diameter leads to a higher tensile strength. Increasing rivet tip diameter demands more rotational velocity and axial force. Borba et al.[9] did experimentation to compare the mechanical properties of friction riveted and a bolting joint. The results showed that the friction riveted joint had a lower quasi static shearing strength but an improved fatigue life.

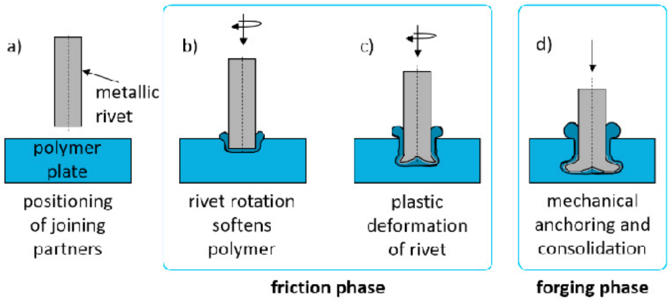


Figure 5: process of friction riveting [2]

2.4.4 Hybrid Adhesive Riveting

Hybrid joining techniques involves the combination of different fastening or joining techniques to have a joint with improved qualities and performance. Hybrid adhesive riveting leverages the advantages of both adhesive bonding and riveting to achieve improved performance in terms of strength, flexibility, and resistance to various environmental factors. Traditional riveting is characterized by good mechanical strength but also cause stress concentrations and potential damage to the materials being joined. Adhesive joining involves the use of special adhesive coated between the materials to be joined. This solves the problem of stress concentration by evenly distributing the load between the sheets. No visible fasteners improve aesthetics and good surface finish which is important in areas where the surface is subjected to high-speed air flow like the outer surface or intake of an aircraft. But this comes at the cost of reduced mechanical strength as compared to mechanical fasteners. Thus, hybrid adhesive riveting combines the benefits of both methods. However, this method has complications like the glass transition range of adhesives. The joint strength is greater than the individual strength of adhesive and rivet joint but is not the sum of strengths of both joints. If not properly designed, the joint can have strength lower than their individual joint strength[10]. It has also been found that the contribution of adhesive in hybrid rivet method is more as compared to a weld-bonded joint[11]

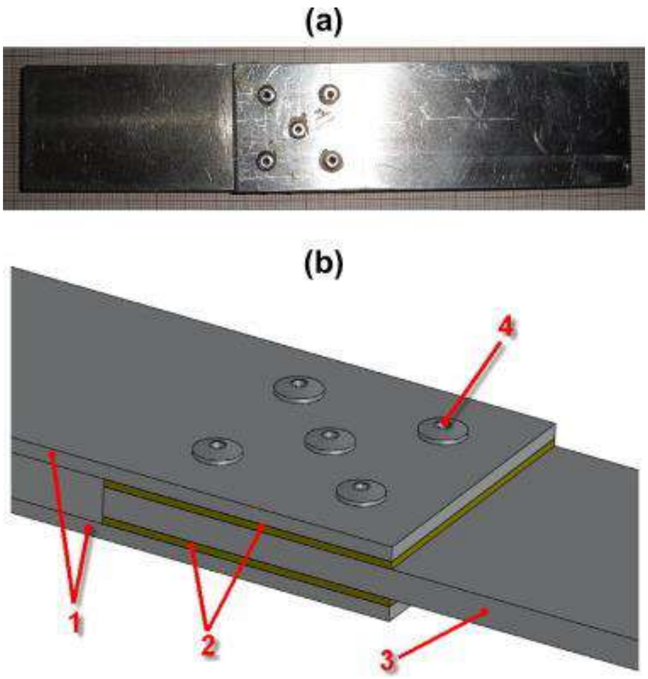


Figure 6: hybrid adhesive riveted joint.

In the figure[12], we have a hybrid adhesive riveted joints with 1) two aluminum plates 2)two adhesive laps 3) one aluminum plate 4) five rivets.

T. Sadowski et al.[12] carried out the strength and failure analysis of three aluminum plates and used five rivets and the polyurethane adhesive (two laps 40 × 40 mm). The experimentation showed that strength of hybrid joint is 11% higher than an adhesive based joint and 130% higher than simple riveted joint.

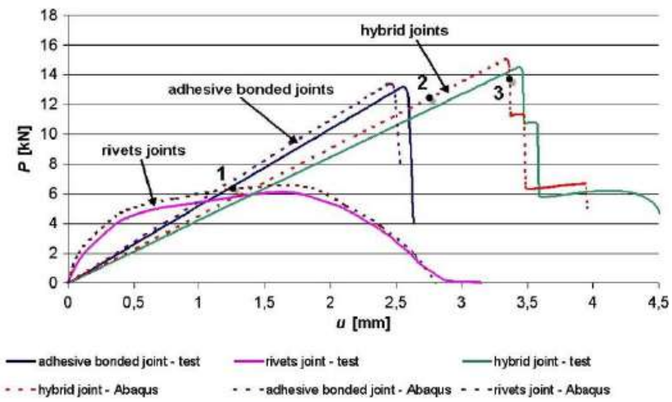


Figure 7: Comparison of the force–displacement tests results [23]

2.4.5 Electromagnetic Riveting

Electromagnetic riveting is an alternative to conventional riveting. Electromagnetic riveting is a solid-state joining process that utilizes Lorentz force[13] [14] [15] [16]to rapidly form a mechanical joint between two or more work pieces. The process involves the use of a pulsed magnetic field generated by an electromagnetic coil, which induces a current in the rivet or work pieces, leading to localized heating and plastic deformation. Its characteristics are:

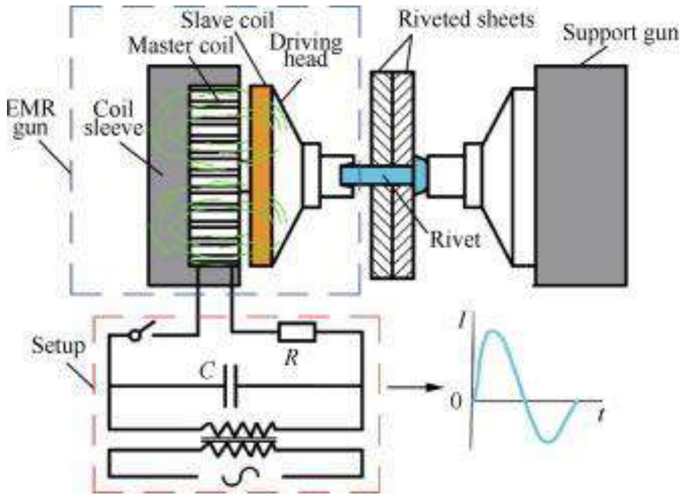


Figure 8: electromagnetic riveting [8]

There are typically three types of EMR systems namely the automatic, semi-automatic and the handheld system. EMR limitations include high recoil with large rivets and a short service life of the master coil[17]. The simulations done using ANSYS suggest that the electromagnetic force is a axial forces is applied non-uniformly i-e it changes radially[18].

The handheld EMR equipment has also proved effective. The handheld HH500 EMR system is a good alternative when it comes to the installation of large diameter rivets. Also, its one shot operation not only reduces the installation time but the noise and vibration as experienced by the operator as compared to the pneumatic riveter which uses compressed air[19].

An important characteristic of electromagnetic riveting is the formation of adiabatic shear bands (ASB)[20] [21]. Adiabatic shear bands are localized zones of intense shear deformation that form in materials under high strain rates and are often associated with intense plastic deformation. These bands are characterized by significant temperature rises due to the rapid deformation.

Chapter 3

3.1 Expected Deliverables

Expected deliverables are as following:

a) Identification of non-conformities in existing methods

b) Identification of model riveting methods/processes and feasibility of adopting those methods

c) Fast tracking and completion of a proposed implementation of more advanced riveting process.

d) Strength testing of riveted joint

3.2 Resources Required

Following resources are required for this project:

a) Pneumatic hammer with air pressure to prepare samples for testing

b) Aluminum sheets for strength testing samples

c) Aluminum rivets

d) Metal sheet cutting machine.

e) Ultimate tensile testing machine

f) Industrial partner for fabrication of equipment

3.3 Methodology

The following methodology was adopted

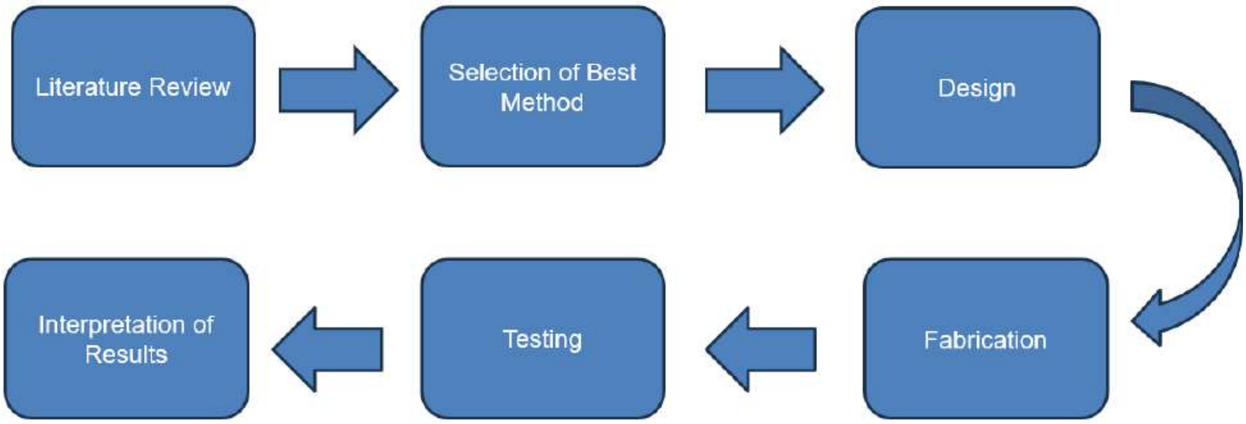


Figure 9: Methodology

Chapter 4

4.1 Design

A cost-friendly solution holds paramount importance in any project due to its multifaceted implications. Firstly, it ensures financial feasibility by keeping expenses within budgetary constraints, thereby safeguarding against potential overruns that could jeopardize the project's completion. Moreover, a cost-friendly approach facilitates efficient resource allocation, allowing for the optimal utilization of funds, materials, and manpower throughout the project lifecycle. This not only enhances productivity but also minimizes wastage, contributing to sustainability goals. Additionally, cost-friendly solutions enhance competitiveness by enabling organizations to offer competitive pricing without compromising on quality, thereby positioning them favorably in the market. Furthermore, such solutions foster stakeholder satisfaction by meeting budgetary expectations and maximizing return on investment. Ultimately, prioritizing cost-effectiveness ensures the long-term success and viability of projects, aligning financial objectives with organizational goals and societal needs.

4.2 Calculation of design parameters

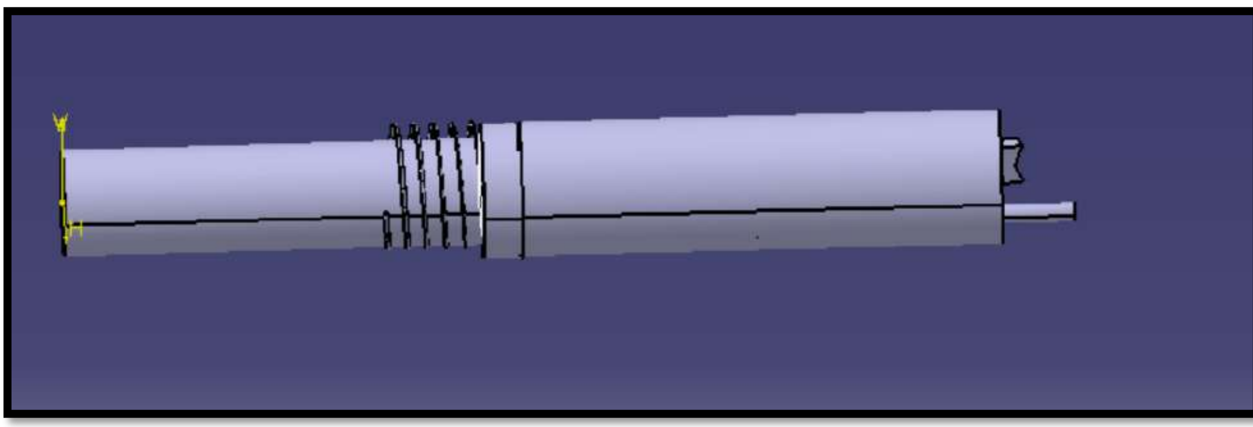
- Force of attraction from an electromagnet is calculated using the formula

$$F = \frac{\mu N A I^2}{2g^2}$$

- Where:
- F is the force of attraction in Newtons
- μ is the permeability of free space, $1.25663706 \times 10^{-6}$ m kg s^{-2} A^{-2}
- N is the number of turns in the coil
- I is the current following in the coil in amperes
- A is the cross-sectional area of coil in square metres
- G is the air gap
- Consider F = 40 N
- G= 10 cm
- N = 2000 turns
- A = 2.82×10-3 m^2
- So using the formula we find out that we need
- I= 11 amps
- Using formula V=IR , we get
- R= 20 ohms

4.3 CAD Model

CAD modeling using software like CATIA V5 holds immense importance across various industries due to its ability to streamline the design process and optimize product development. By providing a digital platform for creating detailed 3D models, CAD software enables engineers and designers to visualize, analyze, and iterate upon their designs with precision and efficiency. This not only accelerates the design phase but also facilitates collaboration among team members by enabling them to share and review designs in real-time. Furthermore, CAD modeling allows for thorough simulation and analysis of product performance, helping to identify potential issues early in the design stage and ultimately reducing costly errors during manufacturing.



Chapter 5

5.1 Shear Testing

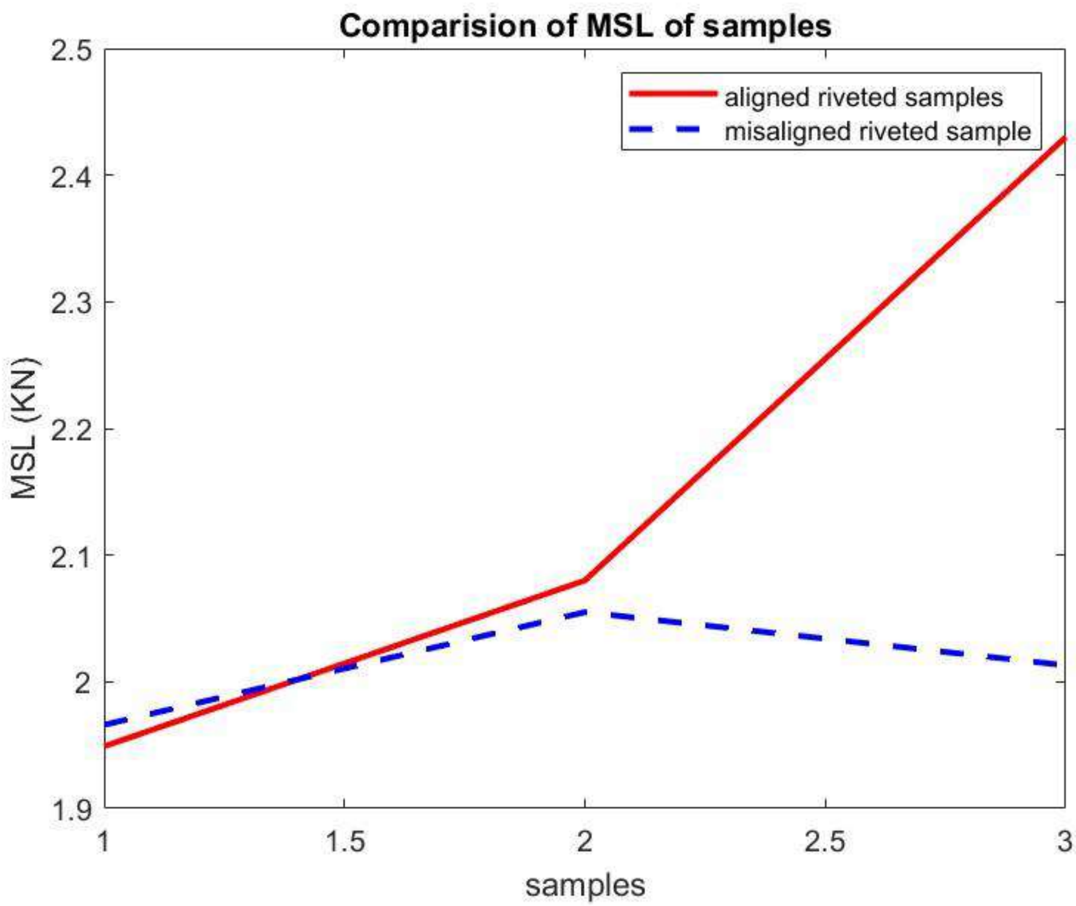
To check how much the joint quality is compromised when riveting is not done with proper alignment, 6 samples were riveted for strength testing in ultimate tensile testing machine available in CAE structure lab. These samples were made with 2mm thick aluminum sheets and 3mm rivets were used. Out of these 6 samples, 3 were riveted with proper alignment while 3 were riveted with misalignment of air pneumatic hammer.

Figure 11: sample before testing

Figure 10: sample after testing

Figure 12: sample in ultimate tensile testing machine

Here is a plot for maximum shear loading (MSL) obtained from the data of experimentation



Avg MSL of aligned rivets	Avg MSL of misaligned rivets	% difference
2.153	2.011	2%

We can see that if the rivets are not properly aligned then there is a decrease in their maximum shear load by 2%

5.2 Fabrication

Fabricating an electromagnetic riveter involves several crucial steps. First, meticulous design is essential, considering factors like size, power requirements, and usage intentions. Next, gather materials such as a robust base, electromagnet coils, a power source, control circuitry, and a riveting tool. Construct a stable base, ensuring it securely holds all components. Assemble the electromagnet coils using insulated wire wound around a ferromagnetic core, connecting them to the control circuit. Install a suitable power source and control circuit to regulate electricity flow to the coils, including switches or relays for activation. Attach the riveting tool securely to the electromagnet assembly, ensuring proper alignment. Test the riveter for functionality, calibrating the control circuit as necessary. Implement safety measures like insulation for wires and safety switches. Finally, conduct a thorough inspection to verify proper assembly and functionality before use. Following these steps ensures the fabrication of a reliable electromagnetic riveter, capable of securely fastening rivets for various applications.

Figure 13: Fabricated equipment

CURRENT	NO. OF TURNS	RESISTANCE	OPERATING VOLTAGE
11 amps	2000	20 ohms	220 V AC

Chapter 6

6.1 Summary and Future work

This project endeavors to address rivet failure problems in aircraft structure through developing a cost-effective novel riveting equipment. For this purpose, a two-stepped approach is employed where initially design and analysis of the proposed equipment was performed while the second stage entails the fabrication of riveting equipment. Finally, the joints obtained through the developed riveting process is compared with the conventional process. Low-cost, one-shot operation, better shear strength and small edge distance were found for the proposed setup.

Moving forward, future work in the realm of electromagnetic riveters could focus on several key areas to further enhance efficiency, versatility, and usability. Firstly, research and development efforts could be directed towards optimizing the design and materials used in electromagnetic coils to maximize magnetic force while minimizing energy consumption. Additionally, advancements in control circuitry and automation technology could enable more precise control over riveting processes, leading to higher quality and consistency in rivet joints. Moreover, exploring novel applications of electromagnetic riveting in emerging industries such as aerospace, automotive, and electronics could uncover new opportunities for cost-effective and innovative manufacturing solutions. Furthermore, integrating sensing and feedback mechanisms into electromagnetic riveters could enable real-time monitoring and adjustment of riveting parameters, enhancing process reliability and product quality. Collaboration with interdisciplinary teams and industry partners could also facilitate the development of customized electromagnetic riveting solutions tailored to specific manufacturing needs and requirements. Overall, future work in this field holds the potential to drive continued advancements in riveting technology, paving the way for more efficient and sustainable manufacturing practices across diverse industries

Chapter 7

7.1 Conclusion

In conclusion, the utilization of an electromagnetic riveter presents a compelling and cost-effective solution for various applications. By harnessing electromagnetic forces, this innovative tool offers efficient and precise riveting capabilities while minimizing operational costs. The streamlined design and automation potential of electromagnetic riveters contribute to increased productivity and reduced labor expenses. Furthermore, the durability and reliability of this technology ensure long-term cost savings through minimal maintenance requirements and enhanced operational longevity. As industries continue to seek sustainable and cost-efficient solutions, the adoption of electromagnetic riveters emerges as a strategic investment, promising not only immediate financial benefits but also long-lasting value and competitive advantage. Thus, embracing this technology underscores a commitment to cost-effective manufacturing practices while driving innovation and excellence in product assembly processes.

References

[1] J. Hartmann, “Development of the handheld low voltage electromagnetic riveter,” *SAE Trans.*, pp. 2371–2385, 1990.

[2] J. Wu, C. Chen, Y. Ouyang, D. Qin, and H. Li, “Recent development of the novel riveting processes,” *Int. J. Adv. Manuf. Technol.*, vol. 117, no. 1–2, pp. 19–47, Nov. 2021, doi: 10.1007/s00170-021-07689-w.

[3] E. Staseva, M. Kvitkina, A. Litvinov, and N. Kobzeva, “The effect of noise

on the human body, in particular, on cardiovascular diseases," in *E3S Web of Conferences*, EDP Sciences, 2020, p. 01028.
[4] J. Wu, C. Chen, Y. Ouyang, D. Qin, and H. Li, "Recent development of the novel riveting processes," *Int. J. Adv. Manuf. Technol.*, vol. 117, no. 1–2, pp. 19–47, Nov. 2021, doi: 10.1007/s00170-021-07689-w.
[5] E. Clithy, "Application of Shape Memory Alloy," *Sci Insigt*, vol. 33, no. 3, pp. 167–174, 2020.
[6] G. M. Lin and Y. H. Li, "Research on Performance Features of Shape Memory Alloys," *Adv. Mater. Res.*, vol. 989, pp. 652–655, 2014.
[7] L. M. Schetky, "Shape memory alloy applications in space systems," *Mater. Des.*, vol. 12, no. 1, pp. 29–32, 1991.
[8] J. Altmeyer, J. F. Dos Santos, and S. T. Amancio-Filho, "Effect of the friction riveting process parameters on the joint formation and performance of Ti alloy/short-fibre reinforced polyether ether ketone joints," *Mater. Des.*, vol. 60, pp. 164–176, 2014.
[9] N. Z. Borba, B. Kötter, B. Fiedler, J. F. dos Santos, and S. T. Amancio-Filho, "Mechanical integrity of friction-riveted joints for aircraft applications," *Compos. Struct.*, vol. 232, p. 111542, 2020.
[10] F. Moroni and A. Pirondi, "Technology of rivet: adhesive joints," in *Hybrid adhesive joints*, Springer, 2010, pp. 79–108.
[11] F. Moroni, A. Pirondi, and F. Kleiner, "Experimental analysis and comparison of the strength of simple and hybrid structural joints," *Int. J. Adhes. Adhes.*, vol. 30, no. 5, pp. 367–379, 2010.
[12] T. Sadowski, P. Golewski, and E. Zarzeka-Raczkowska, "Damage and failure processes of hybrid joints: adhesive bonded aluminium plates reinforced by rivets," *Comput. Mater. Sci.*, vol. 50, no. 4, pp. 1256–1262, 2011.
[13] G. Li, H. Jiang, X. Zhang, and J. Cui, "Mechanical properties and fatigue behavior of electromagnetic riveted lap joints influenced by shear loading," *J. Manuf. Process.*, vol. 26, pp. 226–239, 2017.
[14] H. Jiang, L. Sun, D. Dong, G. Li, and J. Cui, "Microstructure and mechanical property evolution of CFRP/Al electromagnetic riveted lap joint in a severe condition," *Eng. Struct.*, vol. 180, pp. 181–191, 2019.
[15] X. Zhang, H. P. Yu, J. Li, and C. F. Li, "Microstructure investigation and mechanical property analysis in electromagnetic riveting," *Int. J. Adv. Manuf. Technol.*, vol. 78, no. 1–4, pp. 613–623, Apr. 2015, doi: 10.1007/s00170-014-6688-4.
[16] H. Jiang, G. Li, X. Zhang, and J. Cui, "Fatigue and failure mechanism in carbon fiber reinforced plastics/aluminum alloy single lap joint produced by electromagnetic riveting technique," *Compos. Sci. Technol.*, vol. 152, pp. 1–10, 2017.
[17] C. A. O. Zengqiang and Z. U. O. Yangjie, "Electromagnetic riveting technique and its applications," *Chin. J. Aeronaut.*, vol. 33, no. 1, pp. 5–15, 2020.
[18] J. H. Deng, H. P. Yu, and C. F. Li, "Numerical and experimental investigation of electromagnetic riveting," *Mater. Sci. Eng. A*, vol. 499, no. 1–2, pp. 242–247, 2009.
[19] J. Hartmann, T. Brown, B. Pinkerton, and K. Nixon, "Integration and qualification of the HH500 hand operated electromagnetic riveting system on the

747 Section 11," *SAE Trans.*, pp. 470–485, 1993.
[20] D. Song, X. Zhang, K. Liu, Y. Zhang, and Z. Yang, "Experimental Evaluation for the Interference-fit Electromagnetic Rveting Joint with Headless Rivet," in *IOP Conference Series: Materials Science and Engineering*, IOP Publishing, 2020, p. 012083.
[21] X. Zhang, H. Jiang, T. Luo, L. Hu, G. Li, and J. Cui, "Theoretical and experimental investigation on interference fit in electromagnetic riveting," *Int. J. Mech. Sci.*, vol. 156, pp. 261–271, 2019.
[22] P. Zieve, L. Durack, B. Huffer, and T. Brown, "Advanced EMR Technology," presented at the Aerofast Conference & Exposition, Oct. 1992, p. 922408. doi: 10.4271/922408.