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Enhancing Mechanical Strength and Reducing Protrusion in Clinched Joints: A Comparison of Reshaped Clinching Methods

Mohanna Eshtayeh[2], Meftah Hrairi[1], Hanan Mokhtar[1,*], Qamarul Rohadi[1]

[1] Department of Mechanical and Aerospace Engineering, Kulliyyah of Engineering, International Islamic University, 50728 Kuala Lumpur, Malaysia
[2] Research and Development Department, Aeon Metal Industries, Amman 11910, Jordan

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ABSTRACT

In recent years, mechanical clinching technology has gained increasing attention. However, the significant protrusion at the clinched joint could restrict its potential applications. This study investigates the mechanical strength of reshaped clinched joints and clinch rivets, addressing the common issue of protrusion in conventional clinching. By reshaping the protrusion to reduce its height, the strength and integrity of the clinched joints are enhanced. The experimental setup includes a fixed die and two sets of flat surface dies, using aluminium alloy AL5052 sheets. Results indicate that reshaped clinching significantly improves mechanical strength compared to conventional methods. Additionally, the tension-shearing strength of the reshaped joints shows a slight increase. Key findings reveal that reduced protrusion height correlates with increased joint strength and reshaping with a rivet provides superior joint strength compared to both conventional clinching and normal reshaping. The study also highlights the impact of metal thickness on joint strength, demonstrating that varying thicknesses lead to improved outcomes. These insights underscore the importance of punch depth control, reshaping strategies and material thickness in optimizing clinched joint performance, showcasing the potential of reshaping techniques in enhancing manufacturing processes.

1. Introduction

In the automotive and aerospace industries, reducing vehicle weight is a primary objective driving extensive research and development efforts. One effective strategy involves utilizing lighter materials, such as aluminium (Al) and magnesium alloys, for vehicle components. These materials are favoured in the automotive sector due to their low density, anti-corrosion properties and excellent machining performance. However, traditional joining techniques like spot welding often fail to effectively connect these materials.

Mechanical clinching has emerged as a significant advancement in joining methodology. It is a highly efficient and cost-effective joining process based on plastic deformation to assemble sheet

* *Corresponding author.*
E-mail address: hananm@iium.edu.my

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components without requiring additional elements. The main characteristics of a clinched joint that affect the mechanical properties of the joint are neck thickness, interlock and bottom thickness [1]. Mechanical clinching offers several advantages over thermal joining methods like spot welding, including lower acquisition and operational costs [2]. The welding heat input significantly influences the microstructure and mechanical properties of metal sheets in the Coarse Grain Heat-Affected Zone, whereas no heat affects the mechanical properties of the clinching joint [3]. Studies have shown that clinching can effectively join dissimilar joints, extending beyond purely metallic components [4,5]. Finite Element Analysis (FEA) has been extensively used to explore and optimize mechanical joining techniques [6]. Typically, the clinching process incorporates a phase of pressure retention to prevent material springback [7,8]. However, a major drawback of mechanical clinching is the relatively prominent protrusion above the metal sheet's surface, which can limit its applications.

Recent research has focused on enhancing joint connection quality by correlating mechanical interlock parameters with tool parameters, often using genetic algorithms [9,10]. Various methodologies have emerged to optimize clinching tools and process parameters, including Kriging metamodel, Taguchi methods and Grey-based Taguchi method [10-12]. Additionally, optimizing machine design to achieve the desired rigidity has been pursued [13]. Experimental investigations have explored modifications to the clinching process, such as incorporating clinch-rivet technology, which highlight the pivotal role of sheet arrangement in bolstering joint strength [14].

To address the challenge of protrusion height, several clinching techniques have been introduced. These include flat clinching, dieless clinching and reshaping methods, which notably reduce protrusion height while maintaining robust joint integrity [15-18]. Another innovative method involves using a reshaping rivet to reshape the clinched joint, concurrently reducing protrusion height and bolstering joint strength. Tensile shearing tests on specimens have validated the effectiveness of this technique [19]. Building on the reshaping concept, the latter study introduced a novel technique that further reduces protrusion while enhancing strength by reshaping a rivet along with the metal sheet. Experimental evidence supported the efficacy of this rivet-based reshaping technique in achieving exceptional mechanical joint strength. This advancement promised to realize high-strength mechanical joints and address the challenges posed by protrusion in clinching processes [19].

Research has explored the prediction of shear and pull-out strength in clinched sheet metal and enhancing clinch connection quality by minimizing protrusion depth. Remarkable results have been achieved, reducing protrusion from 1.7 mm to 0.68 mm and increasing tension-shearing strength [20]. Reshaping clinching tools to join Carbon Fiber Reinforced Polymer (CFRP) with aluminium has also been investigated, focusing on a two-step clinching approach. Integrating diverse reshaping tools after the initial clinching process with split dies proved to significantly enhance mechanical characteristics. Under optimal conditions, this additional step yielded a 32% increase in shear strength and a 30% increase in absorbed energy compared to joints without reshaping [21]. Recently, a study showing a continuous damage model was developed to investigate the tensile-shear damage mechanisms and mechanical responses of CFRP/Al clinched joints at different loading rates, incorporating strain rate effects and nonlinear in-plane shear behaviours. The finite element algorithm, implemented via VUMAT in Abaqus, analysed the responses of joints with various layups, showing high consistency with experimental results. This research highlights the significant impact of strain rate on joint performance, particularly noting differences in damage and energy absorption across orthogonal, diagonal and hybrid layup joints [22]. Another study investigated the effect of service temperature on the mechanical properties of CFRP/Al alloy self-piercing riveting joints. Results showed that at 125°C, there was an average reduction of 35.4% in maximum load and a 21.9%

degradation in energy absorption compared to room temperature, highlighting the significant impact of elevated temperatures on joint performance [23].

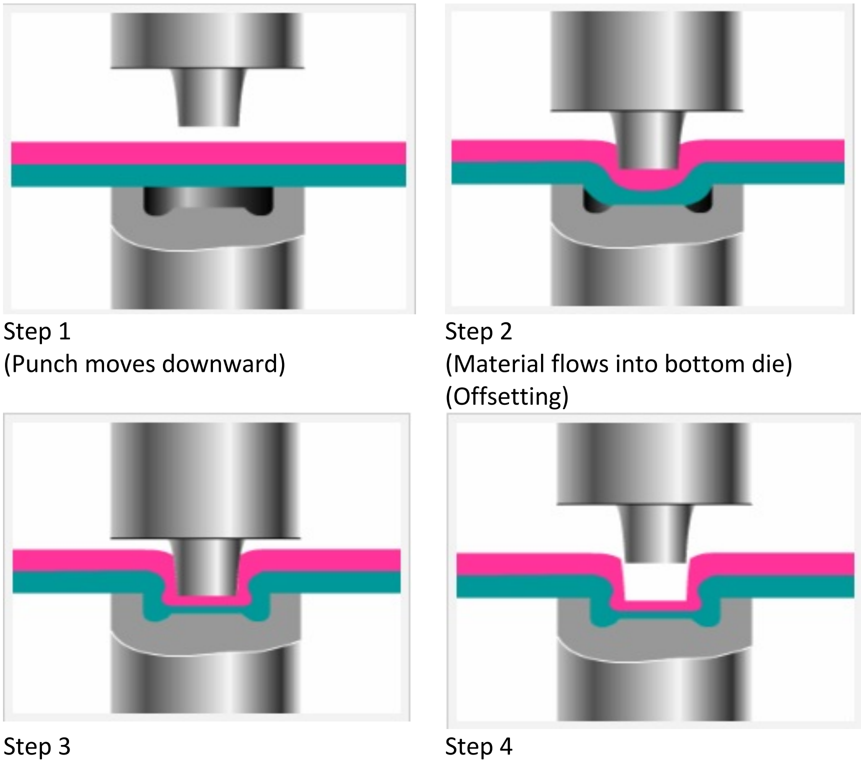
The current study stands out due to its novel approach to rivet-based reshaping in clinching processes, addressing the limitations of previous techniques and providing substantial improvements in joint strength and protrusion height reduction. This innovation fills a critical gap in the current body of research and offers practical solutions for the automotive and aerospace industries.

2. Background

2.1 Concept of Mechanical Clinching

The conventional clinched joint is established through the utilization of a punch and fixed dies. The primary focus of the joint's deformation revolves around the mechanical S-interlock formed between the metal sheets, with strength being positively correlated to the extent of the S-interlock.

At the outset, as depicted in Figure 1, the metal sheets arranged for joining are secured by a blank holder. The metal sheet is drawn inwards, effectively aligning it with the surfaces of the metal sheets. The punch's vertical motion is adjusted to achieve a desirable bottom thickness. As the punch engages, the metal sheet is deformed into the die cavity and the metals expand as they move into the die's cavity volume. Upon the punch's contact with the base of the die, a mechanical interlock is created between the upper and lower sheets. This interlock serves as a secure connection, effectively joining the upper and lower sheets together.



Step 1
(Punch moves downward)

Step 2
(Material flows into bottom die)
(Offsetting)

Step 3
(Upsetting and material forced into die groove)

Step 4
(Pressing, punch retracted)

Fig. 1. The basic clinching process steps [24]

2.2 Concept of Reshaping

Subsequent to the mechanical clinching process, the clinched joint undergoes a reshaping procedure, both with and without the incorporation of a rivet. This reshaping step aims to enhance the conventional clinching outcome. The reshaped clinching technique involves the compression of the initial protrusion using a pair of flat dies. The introduction of a rivet into the protrusion pit serves to elevate the overall strength of the joint. The reshaping process entails two distinct primary steps, as illustrated in Figure 2. In Figure 2(a), the flat dies come into contact with the protrusion, initiating compression. This compression leads to an enhancement of the S-interlock between the two sheets, consequently strengthening the joint's integrity. In Figure 2(b), the dies persist in compressing the protrusion of the clinched joint, gradually reducing it to a specific pre-determined height. This reshaping process represents a deliberate effort to optimize and reinforce the clinched joint, illustrating the complex relationship between deformation, material interaction and structural enhancement.

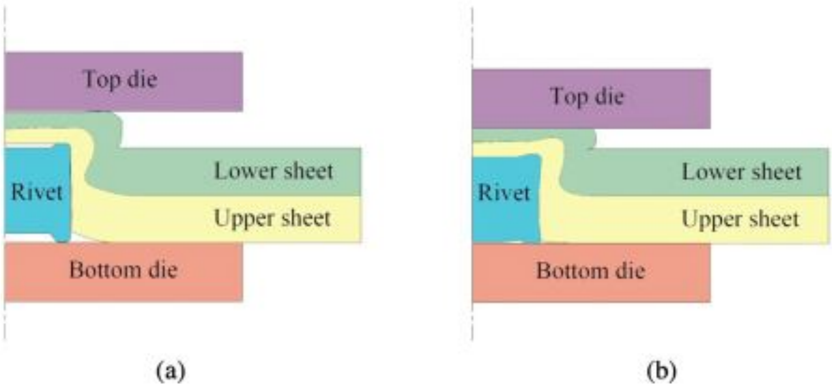


Fig. 2. Reshaping steps [19]

3. Methodology

3.1 Experimental Procedure

Aluminium sheets (AL5052) with two different thicknesses 1.0 and 0.7 mm were used, to investigate the clinching joints. The elastic modulus of AL5052 (71 GPa) and the tensile strength is 244 MPa as shown in Table 1, rendering it exceptionally suitable for mechanical clinching due to its commendable ductility. To facilitate experimentation, the AL5052 material is carefully cut into 80 mm lengths with a width of 25 mm. The rivet material is made from the same material (AL5052) but configured in the form of cylindrical rods. Figure 3 shows the rivet dimensions and shape.

Table1
Mechanical properties of AA5052 [25,26]

Material	Elastic Modulus (GPa)	Yield stress (MPa)	Tensile strength (MPa)	Poisson's ratio	Flow stress (MPa)
AA5052	71	132.08	244	0.33	$\sigma = 366\varepsilon^{0.11}$

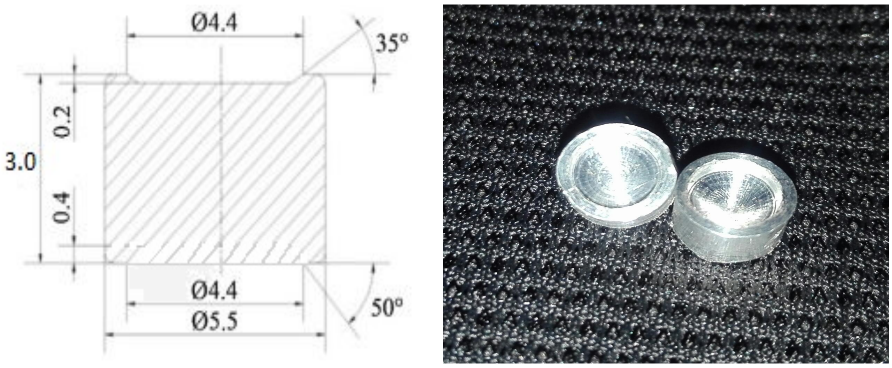


Fig. 3. Dimensions (mm) and the sample of the rivet

3.2 Mechanical Clinching Test

The production of a clinched joint within this research involves the utilization of fixed dies. The experimental execution of mechanical clinching is facilitated through installation of the clinching tools (punch and die) into the tensile shear testing machine INSTRON 3367 with a load capacity of 30 kN. The maximum speed is 500 mm/min, with a minimum speed of 0.01 mm/min and a total crosshead travel distance of 1122 mm. The loading direction is maintained perpendicular to the clinched point. This apparatus enables the realization of the experiment by constructing the required tools. The configuration of the punch and fixed dies is presented in Figure 4. The machine was operated at a speed of 0.5 mm/s, which represents the maximum speed, while the punch is placed into motion. During the process, two aluminium sheets are securely held together by a blank holder. As the punch descends, the sheets undergo deformation in accordance with the punch's depth. This deformation ends in the formation of an interlock, joining the upper and lower sheets. A key factor contributing to the successful outcome of the clinched joint is the precise alignment of the punch with the centre of the metal sheets. This alignment, in conjunction with the achievement of an appropriate penetration depth, is fundamental for attaining optimal results in line with previous study [27].

Fig. 4. Mechanical clinching tools

3.3 Reshaping Test

Mechanical reshaping using polyurethane foam is a key simulation process undertaken in this article, replacing rivets in the reshaping method. Polyurethane foam's versatility allows it to exist as rigid or flexible foams or as solid materials, developed in the late 1930s for durable and adaptable industrial applications such as surface lamination and solid plastics. Polyurethanes are synthesized from isocyanates and polyols, with isocyanates crucial in the synthesis and both containing large alcohol (OH) groups. Recent studies highlight the high energy absorption capabilities of elastic-plastic polyurethane foams under high-velocity local impact loading [28], making polyurethane foam ideal for reshaping processes to mitigate material defects. Furthermore, polyurethane foam serves as a promising alternative for reshaping processes, leveraging its mechanical properties and forms to enhance manufacturing capabilities and material integrity.

In this research, a protrusion naturally forms at the bottom of the clinched specimen upon successful interlocking of metal sheets. To optimize this joint, a hydraulic press is used for reshaping, aiming to decrease protrusion heights from 2.0 mm to 1.0 mm and to 0.5 mm, respectively. The reshaping of the clinched joint was investigated under various conditions, including without any additional element, with a rivet and with Polyurethane foam, employing the same mechanism across all tests. Four samples were produced for each case (16 specimens in total including the normal clinching ones).

The rivet, made from AL5052, features a cylindrical shape matching the internal clinching joint cavity dimensions, with a truncated cone shape at the upper surface and a flat base. Similarly, polyurethane foam is prepared meticulously using a defined mixture of polyols and isocyanates to ensure optimal composition and characteristics. During the reshaping procedure, precise control is exerted over the displacement of the upper flat die, systematically reducing it to achieve the desired reshaped configuration. For both the rivet and polyurethane foam reshaping processes, a parallel approach is adopted where each material is embedded within the pit of the clinching joint. Figure 5 illustrates the upper flat die's critical role in facilitating controlled deformation during the reshaping process.

Fig. 5. Flat die for reshaping process

3.4 Shear Test

To examine the strength of the clinched joint, a series of tension shearing tests were performed. The evaluation included multiple circumstances: starting with the conventional clinching joint, followed by the reshaped clinched joint and extending to the reshaped joint with a rivet and with foam. Figure 6 shows the INSTRON 3367 machine employed for conducting the tension shearing strength tests. Within the tensile test, the maximum load achieved reflecting the clinching joint's strength. The testing speed for tension-pulling was consistently set at 2 mm/min, ensuring controlled and uniform test conditions. The experimental arrangement for these tests is presented in Figure 6, providing an illustration of the testing setup's configuration and the key elements involved in the evaluation process.

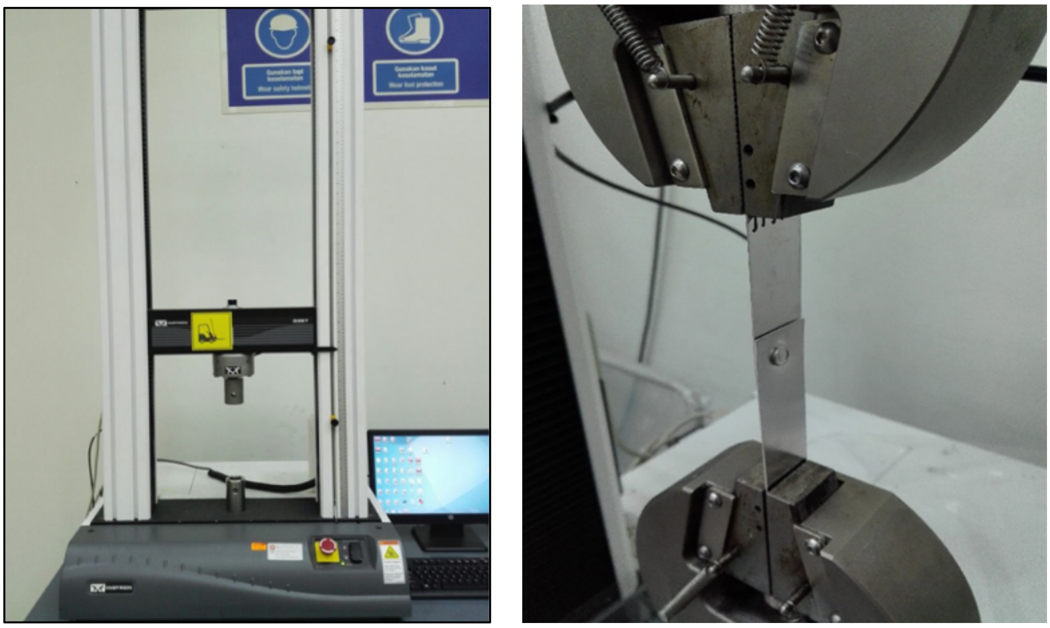


Fig. 6. Tensile test machine INSTRON 3367,and the tensile testing set up

4. Results and Discussion

4.1 Clinching Test

The comprehensive dataset derived from the tensile shearing tests conducted on the conventionally clinched joints, took into consideration two distinct metal thicknesses. Evidently, the mechanical clinched joints with sheet thickness of 1.0 mm indicate a higher level of strength. Analysis of the force-displacement curve, as in Figure 7, indicates that the specimen with a metal thickness of 1.0 mm has a maximum static shearing strength of 758.56 N. In contrast, the specimen with a metal thickness of 0.7 mm demonstrates a comparatively lower strength, recording a maximum shearing strength of 517.14 N. These findings emphasize the significant impact of metal thickness on the resulting strength of the clinched joint, in line with the observed trends within the collected data.

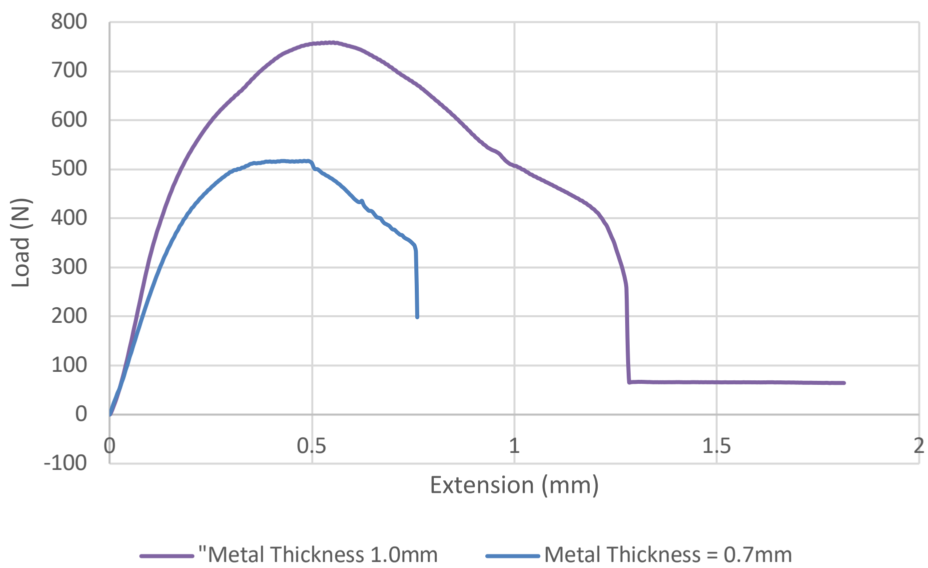


Fig. 7. Tensile test of conventional clinching for metal thickness 0.7mm and 1.0mm

4.2 Reshaping of Conventional Clinched Joints

Figure 8 provides an understanding overview of the data derived from the tensile shearing tests conducted on the traditionally reshaped joints with a 1.0 mm aluminium thickness, considering two distinct protrusion heights. Notably, the shearing strength is markedly higher for the specimen with a protrusion height of 0.5 mm. Analysis of the graphs illustrate a clear trend: the maximum static shearing strength is significantly elevated for the specimen featuring a protrusion height of 0.5 mm, reaching an impressive strength of 819.78 N. In contrast, the specimen with a protrusion height of 1.0 mm records a relatively lower shearing strength of 766.76 N. These findings highlight the profound impact of protrusion height on joint strength. It is particularly interesting to note that in comparison to the conventional clinching involving a 1.0 mm thickness, the 0.5 mm and 1.0 mm protrusions exhibit strength enhancements of 8% and 1%, respectively. This quantitative comparison emphasizes the physical benefits gained through the reshaping process, emphasizing on the potential to optimize joint strength through the alteration of protrusion height.

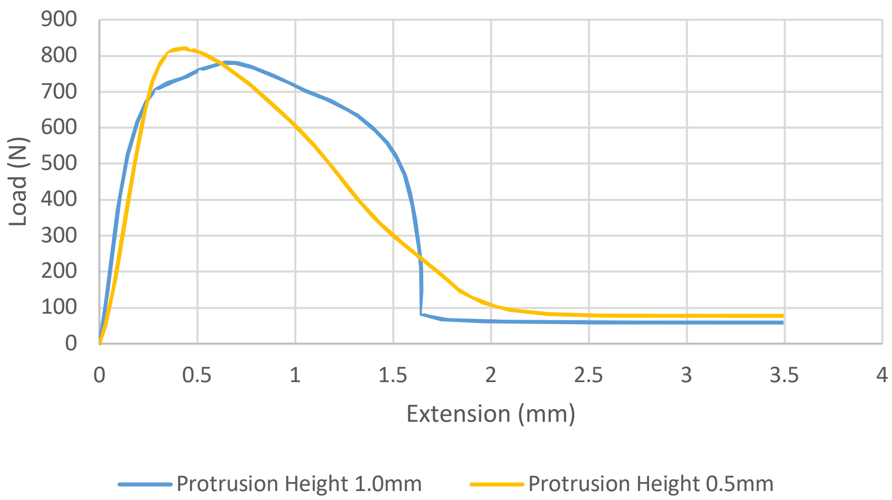


Fig. 8. Tensile test of reshaped clinching for metal thickness 1.0 mm

4.3 Reshaping of Clinched Joints using Rivet

Figure 9 serves as a comprehensive representation of the data gathered from the tensile shearing tests conducted on the clinch-rivet joints featuring a 1.0 mm aluminium thickness, in which two distinct protrusion heights were examined. Particularly, the specimen with a protrusion height of 0.5 mm appears significantly stronger. This observation is featured by the force-displacement curves, which show that the specimen with a protrusion height of 0.5 mm achieves a remarkable maximum static shearing strength of 1351 N. In contrast, the specimen characterized by a protrusion height of 1.0 mm attains a comparatively lower shearing strength of 1247 N. Comparative analysis with conventional clinching with 1.0 mm thickness highlights substantial strength enhancements for the 0.5 mm and 1.0 mm protrusions, realizing a notable increase of 78% and 64%, respectively. These findings underscore the pronounced impact of protrusion height within the clinch-rivet methodology, confirming its efficacy in significantly bolstering joint strength and highlighting its potential as an effective technique for achieving robust and durable connections.

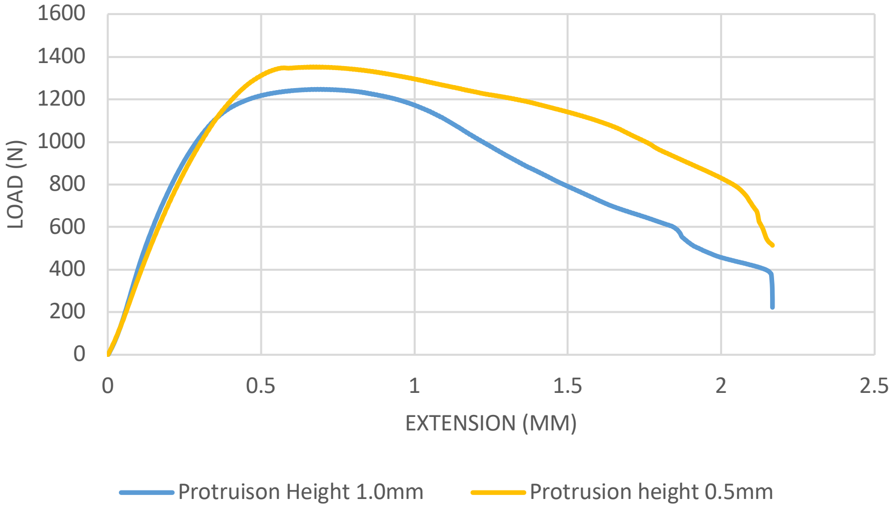


Fig. 9. Tensile test of clinch-rivet for metal thickness 1.0 mm

4.4 Reshaping of Clinched Joints using Polyurethane Foam

Figure 10 illustrates a comprehensive depiction of the data obtained from the tensile shearing tests performed on reshaped joints with foam, utilizing a 1.0 mm aluminium thickness while exploring two distinct protrusion heights. It is evident that the specimen characterized by a protrusion height of 0.5 mm demonstrates notably heightened strength. Analysis of the achieved force-displacement curves reveals that the specimen featuring a protrusion height of 0.5 mm attains a significant maximum static shearing strength of 947 N. In contrast, the specimen capable of a protrusion height of 1.0 mm records a comparatively lower shearing strength of 820 N. Drawing a comparison with the conventional clinching involving a 1.0 mm thickness, it becomes apparent that the protrusion heights of 0.5 mm and 1.0 mm demonstrate strength enhancements of 24% and 8%, respectively. These findings emphasize the efficacy of the reshaped foam technique in strengthening joints, validating its potential as a feasible approach for supporting the integrity and durability of clinched joining technique.

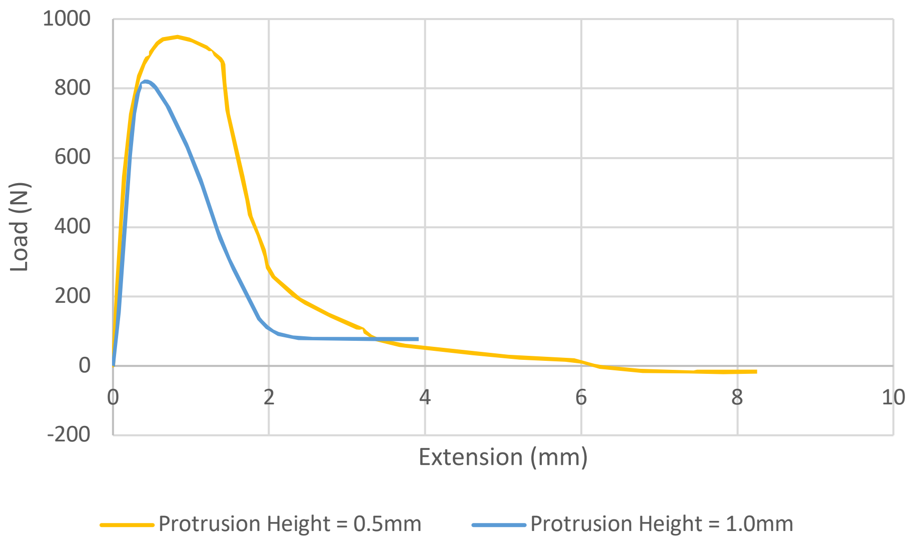
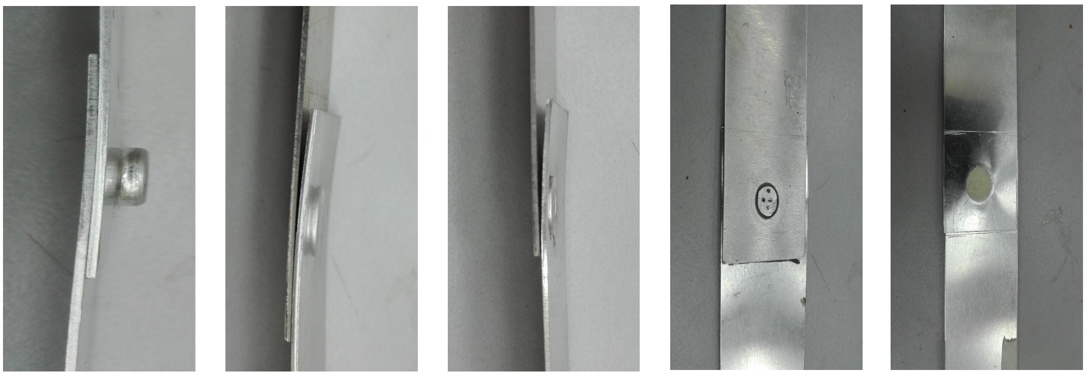


Fig. 10. Tensile test of reshaped clinching with foam for metal thickness 1.0mm

4.5 Joint Strength

From the experimental results, it was established that the forming force of the punch remained constant at 40 kN. Variation in displacement was systematically applied to ensure the achievement of well-interlocked and securely hooked clinched joints. Notably, insufficient punch extension could lower the generation of the interlock between the two sheets. Throughout the clinching process, a consistent protrusion height of 2.0 mm was achieved across all specimens. Subsequently, during the reshaping process, the protrusion heights were reduced to 1.0 mm and 0.5 mm, respectively, for each joint. The comparative assessment of the clinched and reshaped joints is visually depicted in Figure 11, highlighting the apparent differences resulting from the reshaping process.



(a) (b) (c) (d) (e)

Fig. 11. (a) Clinching joint (b) Reshaping to 1.0 mm (c) Reshaping to 0.5 mm (d) Reshaping with rivet (e) Reshaping with foam

Table 2 provides a comprehensive overview of the outcomes obtained from the tensile shearing test. Notably, the 1.0 mm metal thickness achieved better strength than the 0.7 mm thickness in both types of specimens. The highest level of strength is observed in the clinch-rivet method, registering an impressive 1352 N, while the lowest strength is recorded in the normal reshaping method, yielding only 821 N. However, it is worth highlighting that despite the consistently lower strength of the 0.7 mm thickness specimens across all methods, there is an apparent improvement in strength compared to the conventional clinched joint category with the same thickness. This underlines the efficacy of the various methods in enhancing the strength of joints, even when applied to the thinner 0.7 mm specimen. The results show the dynamic relationship of factors and methodologies that influence the overall strength of clinched joints across different metal thickness.

Table 2
Summary of overall result obtained

Method	Protrusion height	Maximum strength (N)		The strength difference (N)	
		Sheet Thickness. 1.0mm	Sheet Thickness; 0.7mm	Sheet Thickness. 1.0mm	Sheet Thickness; 0.7mm
Conventional Clinching	2.0mm	758.5	517.1	-	-
Clinch-Rivet	1.0mm	1247.8	1065.6	489.3	548.5
	0.5mm	1352.0	1144.5	593.4	627.4
Reshape Clinching	1.0mm	790.0	639.3	31.4	122.2
	0.5mm	821.2	758.3	62.6	241.2
Reshape with foam	1.0mm	820.2	761.5	61.6	244.4
	0.5 mm	949.0	783.9	190.5	266.89

Analysing the accumulated results, the tension shearing strengths corresponding to various protrusion heights are displayed in Figure 12. Evidently, specimens featuring an aluminium thickness of 1.0 mm consistently exhibit greater strength when contrasted with those possessing a 0.7 mm thickness. The reshaped clinched joints, in general, outperformed their conventionally clinched counterparts. Remarkably, the reshaping method involving a rivet yielded the highest strength among all approaches.

To elaborate, the maximum static shearing strength for specimens with a metal thickness of 1.0 mm reached 758.5 N, while the corresponding value for 0.7 mm thickness was 517.1 N. Furthermore, it is evident that across all reshaping tests, strength consistently exhibited an upward trajectory. This observation is logically attributed to the role of the reshaping process in increasing neck thickness, a factor significantly influencing joint strength. Notably, the tensile test outcomes for the reshaped joints with rivets demonstrated the highest joint strength. This can be attributed to the rivet's capacity to bear tensile loads, effectively enhancing joint strength while accommodating deformation to absorb greater energy.

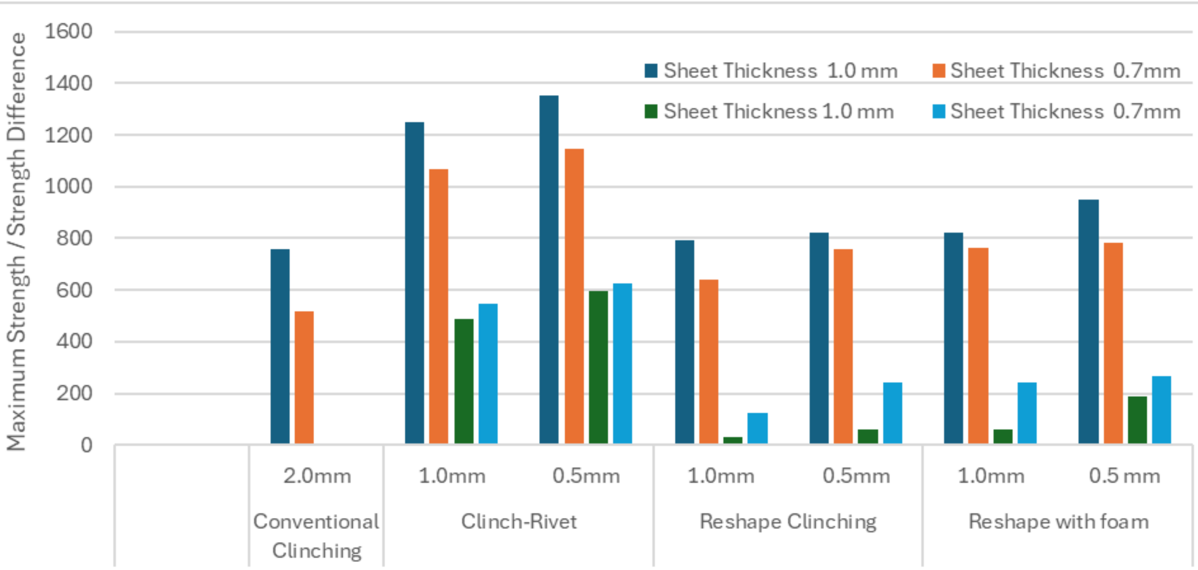


Fig. 12. Comparison of the strength of the four joints

In the reshaping process, the protrusion was compressed by the top die. The material around the pit in the surfaces of the reshaping rivet can flow to enlarge the interlock and at the same time can enable the material of the joint to gather in the neck. Consequently, the neck thickness and interlock of the reshaped joints were all larger than those of the conventional clinched joint.

The failure of specimens during the shearing test is illustrated in Figure 13 showing the fracture mode characterized by neck deformation in the specimen. This comprehensive analysis explains the relationship of the variables and processes in influencing the clinched joint strength and the consequent fracture behaviour.

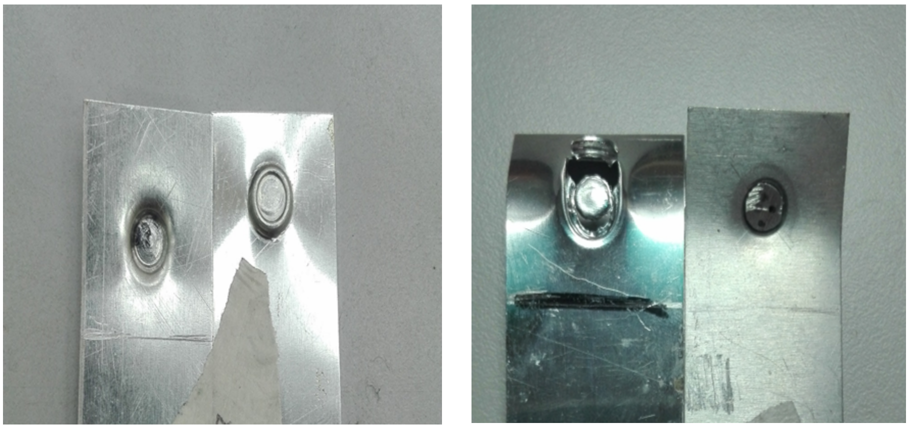


Fig. 13. Type of failure

5. Conclusion

Throughout this research, an in-depth exploration of the clinch joining method was conducted, revealing valuable insights and outcomes. The critical role of appropriate punch depth for achieving a well-formed clinched joint was established, alongside the understanding that varying protrusion heights yield distinct levels of clinched joint strength. The investigation also embraced a comprehensive analysis of the joint's mechanical properties. The key conclusions drawn from this study are summarized below:

i. The strength of the conventional clinching technique exhibited significant enhancement following the reshaping process. A trend appeared wherein reduced protrusion led to increased joint strength.
ii. Reshaping using a rivet demonstrated superior joint strength compared to both conventional clinching and normal reshaping clinched joints. This highlights the potential of the clinch-rivet method for yielding robust joint connections.
iii. The influence of different metal thickness was evident in the study, where varying thickness yield improved clinched joint strength.

These findings emphasize the multifaceted factors that influence clinched joint strength and emphasize the potential for optimizing joint performance through controlled punch depth, reshaping strategies and material thickness considerations. The knowledge obtained from this investigation contributes to a deeper understanding of clinching as a viable and effective joining method with diverse applications.

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