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Different Reshaping Methods of Clinched Joints to Reduce the Protrusion Height

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ABSTRACT

The widespread adoption of mechanical clinching technology is hindered by its drawbacks, with the most prominent being the protrusion above the sheets in conventional clinched joints. This protrusion creates a raised bump on the sheets, rendering the use of conventional clinching impractical in visible areas where a flat surface is required. The application of mechanical clinching could be limited due to the outward bulge on the surface of the sheets, which can impact the performance of the joints. To overcome this issue, this study seeks to identify a technique for decreasing protrusion height while simultaneously enhancing the strength of clinched joints. Indeed, a reshaping method for clinched joints has been employed, including the utilization of reshaping rivets, to effectively reduce the protrusion height and enhance the joint strength. The investigation of the reshaping process will be conducted, involving the creation of a finite element (FE) model for both the clinching process and the reshaping of clinched joints, utilizing LS-DYNA software. The FE model will be validated through experimental results to ensure its accuracy and reliability. The results show that the reshaping process reduces protrusion, but not strength. While reshaping with additional materials rivet and foam enhances material flow and joint strength. The rivet reshaping exhibits the highest compressive stress, indicating superior sheet metal strength.

1. Introduction

The automobile industry is increasingly focusing on lightweight structure design to meet the demand for more efficient vehicles. The manufacturing of lightweight structures involves two key considerations: the use of lightweight materials and the selection of a suitable joining method. A comprehensive evaluation of various techniques is necessary to choose the optimal joining technique for lightweight structures. In recent years, conventional mechanical clinching has garnered significant attention and has become increasingly favored. The utilization of clinching for joining lightweight sheet materials opens new possibilities in the manufacturing field. Notably, several automobile manufacturers have adopted the clinching method for body assembly, enhancing reliability and

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flexibility. This implies an increased demand for clinching in the automotive industry, with the potential to entirely replace conventional spot welding. Conventional mechanical clinching offers numerous advantages over other mechanical fastening techniques, as extensively discussed in reference [1].

An advanced investigation into the clinching of dissimilar materials, while the paper provides a comprehensive review of finite element modelling for clinching, emphasizing the significance of geometric tool parameters in controlling joint quality and strength, addressing challenges in simulations, process parameter optimization, joint quality and suggesting further research for enhancing clinching's industrial applicability [2,3]. These advantages include the ability to join similar or dissimilar sheet materials, improve fatigue properties, preserve material surfaces, be environmentally friendly, and save both time and cost. However, the broad use of mechanical clinching is hindered by the disadvantage of exterior protrusion above the sheets in conventional clinched joints [4]. This protrusion results in visible bumps, rendering conventional clinching unsuitable for applications requiring a flat surface. Consequently, the focus of this study is to prioritize the improvement of the clinching method through the incorporation of reshaping rivets. This approach aims to reduce protrusion and enhance the strength of the metal sheets.

Numerous research efforts have been dedicated to the study of mechanical clinching, including finite element simulations, mechanical properties analysis, process parameter investigation, and evaluation of static and fatigue behavior [1]. Investigates failure modes through numerical and experimental methods. A new develops in a finite element model to study material flow in mechanical clinching with extensible dies [4]. An efficient finite element method with automatic remeshing is proposed to obtain accurate solutions, with the remeshing technique proving effective in avoiding large mesh distortions [5]. Additionally, numerical simulations are performed to verify a testing-based procedure for the mechanical clinching process [6]. Another study introduces a shear/tensile testing the clinched joints, employing it to experimentally analyse the multi-axial behaviour of steel sheet clinched connections. The research validates numerical models for multi-axial loading, emphasizing material properties and friction's role in accurate FEA simulations and investigating their influence on the two sheets connection [7]. A research investigates mechanical clinching with extensible dies using finite element analysis, validated through experimental tests [8]. Mechanical clinching allows for the joining of various materials, such as magnesium, titanium, aluminum, and their alloys [9], including dissimilar metal sheets.

Although conventional mechanical clinching has rapidly advanced to accommodate diverse materials, the significant protrusion above the joint poses limitations. Consequently, recent research has explored new technologies aimed at reducing the height of the exterior protrusion, with several studies summarizing alternative clinching methods that generate lower protrusions. Another study examined the numerical modelling of the reshaping process employing DEFORM2D software, the researchers found that the neck thickness enhanced through the height-reducing technique can elevate tensile strength and energy absorption in the joint [10]. During compression, material from the protrusion flows towards the neck region, leading to increased joint interlock and neck thickness. When positioned in the upper layer, the thicker sheet results in a larger interlock compared to the lower layer in the compression process [11,12]. The study explores the impact of protrusion height on clinched joint appearance and demonstrates the effectiveness of a height-reducing method using AL5052 and AL6061 sheets, rivets, and flat dies to enhance joint strength, cross-tensile and tension-shearing strengths, enlarge neck thickness, and improve energy absorption during failure [13]. A new study introduces a novel Two-Step Fat Clinching (TSFC) method that produces clinched joints with double-sided fat surfaces. Results reveal a consistent decrease in protrusion height with increasing fattening force, achieving double-sided fat surfaces. The joint's protrusion height was reduced from 1.23 mm to an insignificant 0.04 mm [14].

In this study, three reshaping methods were explored to reduce protrusion height in clinched joints. These methods involved compressing the protrusion: one utilized a rivet and foam embedded in the joint, while another involved reshaping without a rivet. Numerical comparisons were conducted between the reshaping method with a rivet, mechanical clinching, and reshaping without a rivet. Experimental verification followed this investigation. The reshaping method significantly improved the strength of the clinched joint. Specifically, when the protrusion height was reduced to 1.0 mm, the reshaping method without a rivet demonstrated increased average strength. However, the reshaping method with a rivet proved more effective in reducing protrusion height and enhancing joint strength.

2. Methodology

2.1 Mechanical Clinching Technique

Clinching, a novel mechanical fastening technique, effectively joins sheet metal parts. It has gained significant traction in the automotive industry for connecting various components of automobile bodies. The cold-forming process creates a distinct button-type connection, eliminating the need for additional elements as the parts are locally deformed. Clinching can be classified into round and square variants, depending on the tools employed. The clinching equipment comprises a tooling set consisting of a punch and die, enabling joint formation with or without cutting. Figure 1 illustrates the tooling set used in the clinching process. To achieve successful joining of two or more metal components, precise movement of the punch into the die is crucial. The fundamental principle of this method entails overlapping the sheets to establish a secure connection.

Fig. 1. Punch and die [6]

The mechanical clinching process involves the generation of a mechanical interlock between two sheets using fixed dies. It comprises the use of a blank holder, punch, fixed die, and metal sheets [6]. Within the punch-die cavity volume, a suitable deformation of the sheets is achieved, resulting in the development of a mechanical interlock that joins the sheets together. This interlock is created as the material flow forms an undercut that hooks the sheets. As a consequence of this process, a protrusion appears on the lower surface of the sheets, while a pit is formed on the upper surface [6]. The mechanical clinching process consists of four main phases, as illustrated in Figure 2. Firstly, when the punch comes in contact with the upper sheet, plastic deformation occurs in both the lower and upper sheets. Then, as the lower sheet contacts the fixed die, the material of both sheets spreads radially. This radial spreading continues as the punch moves, resulting in ongoing plastic deformation in the direction of the punch's movement. Finally, the material continues to spread until the undercut between the upper and lower sheets is formed, completing the joining process.

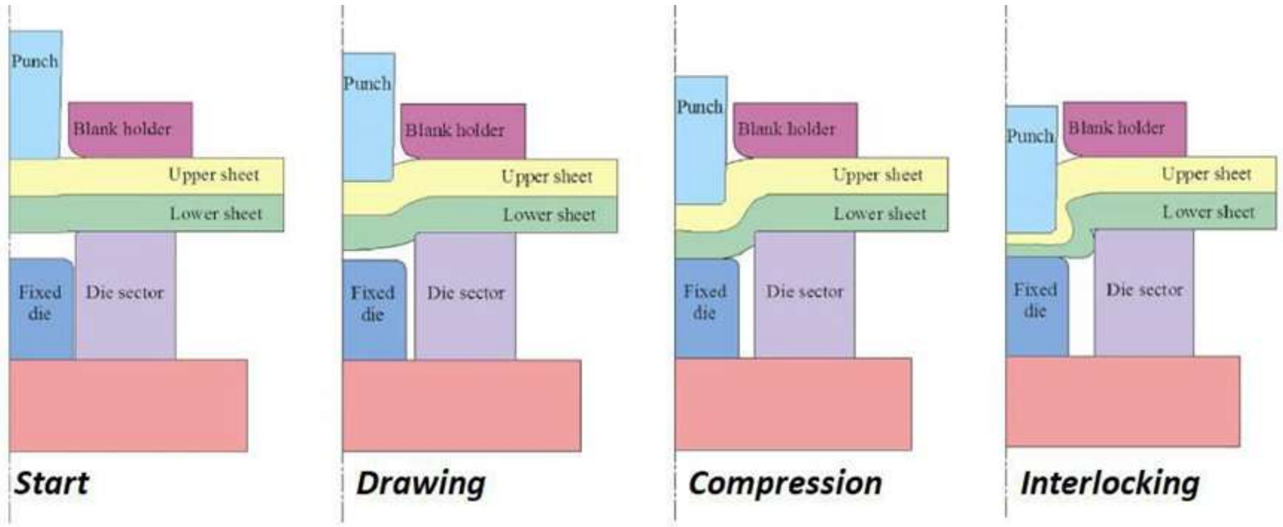

Fig. 2. Mechanical clinching process with fixed dies [8]

2.2 Mechanical Reshaping Process

Mechanical clinching technology is widely employed to join diverse material sheets, including metals (such as aluminum, steel, titanium, magnesium), polymers, composites with different fibers, and wood. However, the presence of a pronounced protrusion on the clinched joint poses limitations for its application in visible areas. To address this concern, an optimized reshaping process has been developed to reduce protrusion height and enhance joint strength [4]. This method has been proven effective, although it requires an additional rivet, which may result in increased joint weight. While this technique effectively reduces joint protrusion, it does not significantly improve joint strength. The reshaping process complements the clinched joint, utilizing a flat die to reshape it. Importantly, this process does not damage the interlock between the sheets, ensuring they remain securely joined even after reshaping. Consequently, the reshaped joint can be confidently used in visible areas where a lower protrusion is required. Following the mechanical clinching process, the clinched joint can undergo a reshaping process. This involves compressing the protrusion using a pair of flat dies. To enhance joint strength and regulate material flow, a reshaping rivet embedded in the clinched joint is utilized [15]. The reshaping process modifies the shape of the clinched joint, consisting of two primary phases. In Figure 3: (a), the top die contacts the lower sheet, resulting in localized plastic deformation of the clinched joint and reshaping rivet. (b) The top die continues to compress the clinched joint until the protrusion height reaches a specified level. Subsequently, the mechanical reshaping process yields a reshaped joint, wherein the metal sheets remain securely joined with no damage, as depicted in Figure 4.

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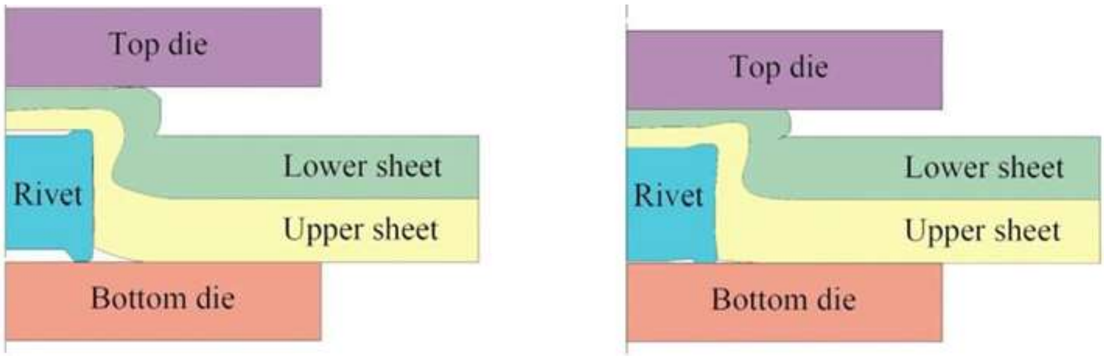


(a) (b)

Fig. 3. Mechanical reshaping process (a) The top die contacts the lower sheet, resulting in localized plastic deformation of the clinched joint and reshaping rivet (b) The top die continues to compress the clinched joint until the protrusion height reaches a specified level [16]

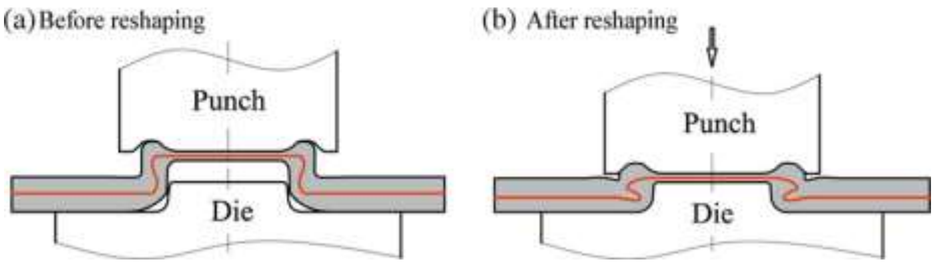


Fig. 4. Before-and-after reshaping process [17]

2.3 Mechanical Reshaping using Additional Materials

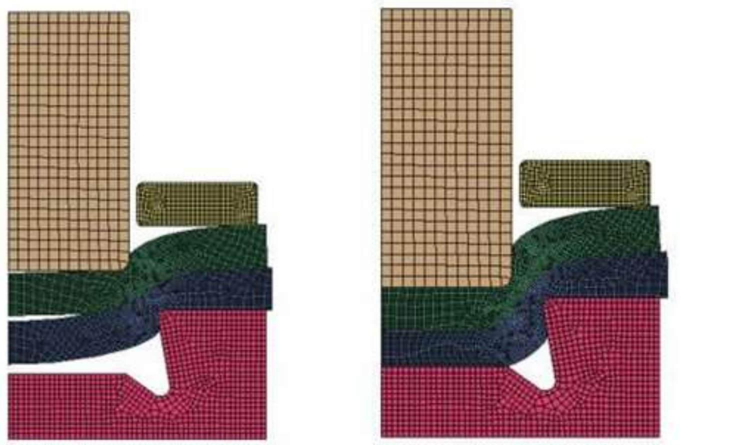
In this research, one of the simulation techniques for reshaping involves mechanical reshaping with polyurethane foam. In this process, the rivet is replaced with polyurethane foam, which undergoes a similar reshaping technique. Polyurethane is a versatile family of plastics or polymers, available in various forms such as rigid or flexible foams. It can be solid or have an open cellular structure, commonly referred to as foam. Polyurethanes have been in use since the late 1930s and are known for their flexibility and durability. They are widely employed in industries for surface lamination and as solid plastics.

The production of polyurethanes involves a mixture of materials, including isocyanates and polyols. Isocyanates are critical components in creating polyurethanes, while polyols are important substances that contribute to their formation. Both substances contain large alcohol (OH) groups. Recent investigations have focused on studying the mechanical behavior of elastic-plastic polyurethane foams under high-velocity local impact loading. These studies have demonstrated that foam exhibits high energy absorption as density increases [18]. Consequently, polyurethane foam is well-suited for the reshaping process as it helps prevent material defects. Figure 5 provides an example of polyurethane foam.

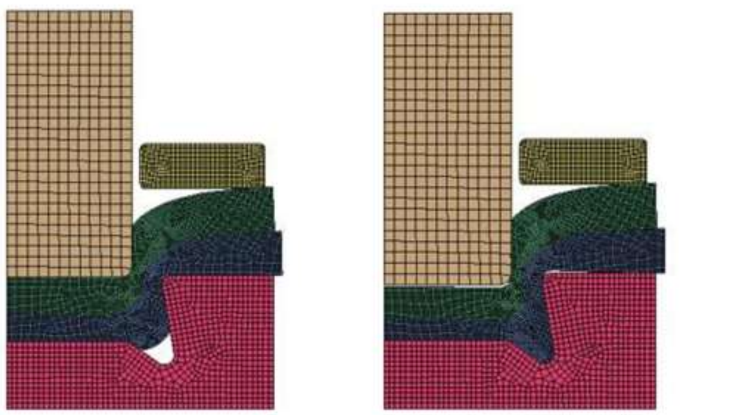
Fig. 5. Polyurethane foam [18]

2.4 Simulation of Clinching and Reshaping Process

The simulation of the clinching process replicates the geometrical parameters used in previous experimental studies [19,20]. Similar metal sheets were employed, consisting of 1.0 mm thick aluminum and mild steel. Five different punch displacements were tested during the simulation to measure compressive strain and compressive stress. Figure 6 illustrates the deformed shape of the upper and lower sheets throughout the clinching process at various stages: 25%, 50%, 75% and 100% of the assigned punch displacement. An example results of the clinching simulation, featuring a 2.0 mm protrusion height and a punch displacement of 3.70779 mm, is presented in Figure 7. Additionally, Figure 8 provides data on the compressive strain and compressive stress recorded for the metal sheets, measuring 1.20449 mm/mm and 0.13975 GPa, respectively.



(a) 25% of total punch displacement (b) 50% of total punch displacement



(c) 75% of total punch displacement (d) 100% of total punch displacement

Fig. 6. The deformed shape of upper and lower sheets during the clinching process [19,20]

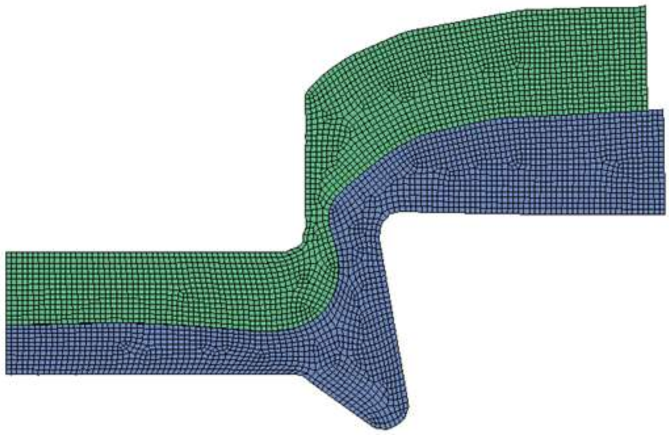


Fig. 7. The metal sheets after simulation with 2.0 mm protrusion height

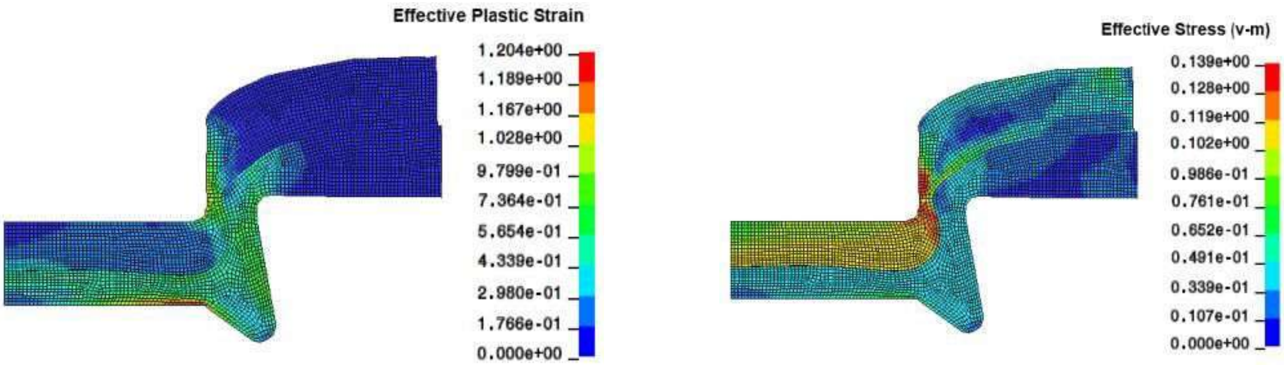


Fig. 8. The compressive strain and compressive stress recorded for the metal sheets after clinching simulation

3. Results and Discussion

3.1 Normal Reshaping

The initial step involves simulating the normal reshaping process based on the clinching simulation results. The extension or displacement of the top die is set to 0.7095 mm. Figure 9 showcases the deformed shape of the upper and lower sheets during the normal reshaping process, highlighting the progression at 25%, 50%, 75% and 100% of the assigned top die displacement. Through this process, the protrusion height of the metal sheets is successfully reduced from 2.0 mm to 1.0 mm, as demonstrated in Figure 10. Figure 11 presents the recorded compressive strain and compressive stress for the metal sheets, measuring 0.197 mm/mm and 0.014 GPa, respectively.

After conducting clinching and reshaping simulations, numerical results are validated experimentally. Tensile tests were carried out on lab-prepared samples. The specimens were loaded in tension (Universal Machine INSTRON-3367) with a load capacity of 30 kW, maximum speed of 500 mm/minute, minimum speed of 0.01 mm/ minute, and total crosshead travel of 1122 mm. The clinching process utilized a BTM Pneumo-hydraulic Clinch Unit, specifically the ULG7-10 system. Comparison ensures accuracy of FE models. Both clinching and reshaping simulation data will be verified against experimental results for compressive strain and stress.

For clinching, stress and strain from five simulations with varying punch displacements closely match experiments. Table 1 summarizes strain and stress comparison. Figure 12 displays stress graph for numerical-experimental contrast.

The depicted figure illustrates the maximum compression stress from clinching test 2, with numerical at 0.13975 GPa and experimental at 0.14472 GPa. The minimum values are 0.08947 GPa (numerical) and 0.09194 GPa (experimental) in test 3.

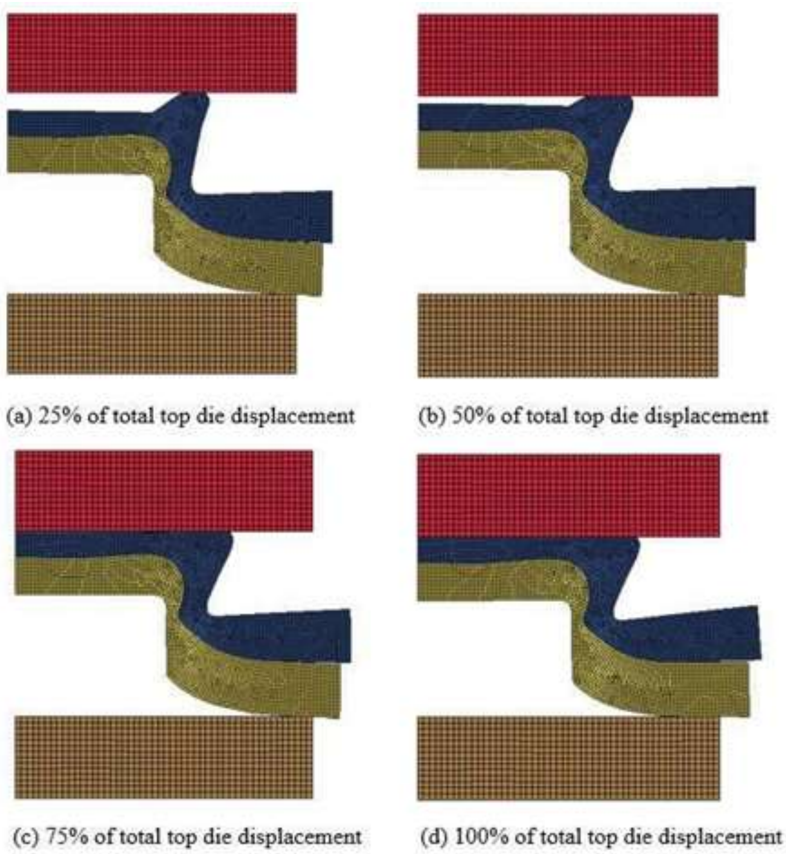


Fig. 9. The deformed shape of upper and lower sheets during the normal reshaping

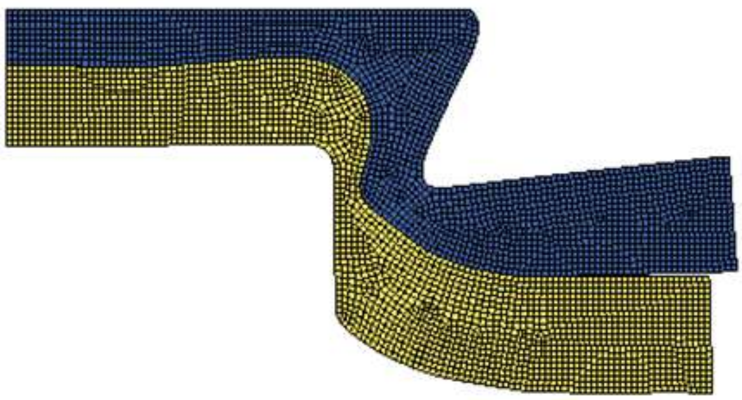


Fig. 10. The metal sheets after simulation with 1.0 mm protrusion height

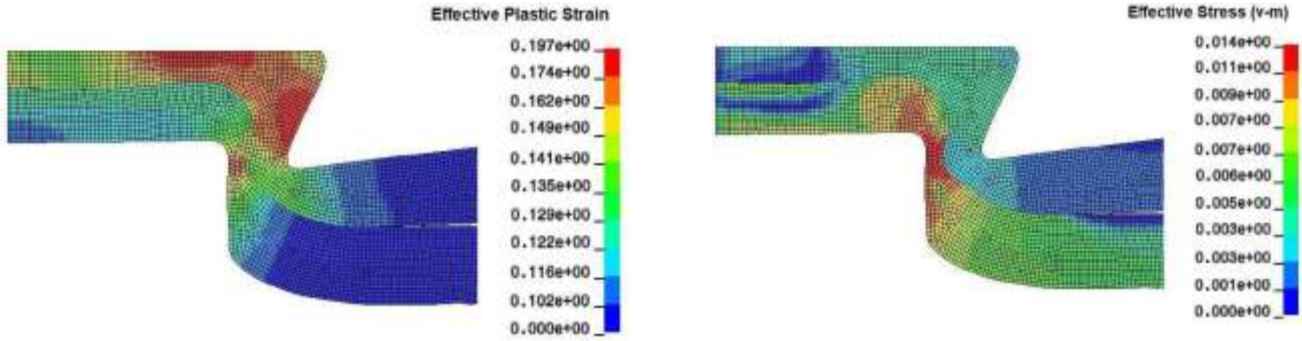


Fig. 11. The compressive strain and compressive stress recorded for the metal sheets

Table 1
The comparison of compressive strain and compressive stress

No. of Test	Punch Displacement	Compressive Strain (mm\mm)		Compressive Stress (Gpa)	
		Numerical	Experimental	Numerical	Experimental
1	3.70768	1.18741	1.23589	0.11798	0.11979
2	3.70779	1.20449	1.23593	0.13975	0.14472
3	3.70811	1.20784	1.23593	0.08947	0.09194
4	3.70843	1.21522	1.23614	0.10158	0.10323
5	3.70918	1.22576	1.23639	0.12385	0.12665

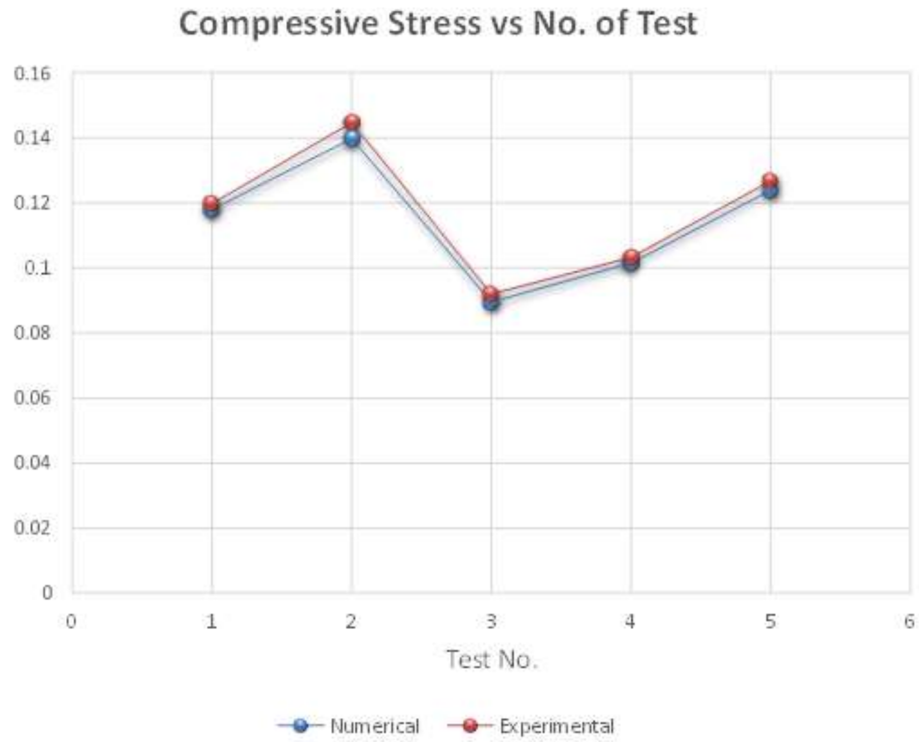


Fig. 12. Comparative compressive stress: numerical vs. experimental

Figure 12 depicts peak compression stress in clinching test 2: numerical 0.13975 GPa, experimental 0.14472 GPa. Minimums: numerical 0.08947 GPa (test 3), experimental 0.09194 GPa. Numerical data closely aligns with experimental results, indicating a strong match.

3.2 Reshaping with a Rivet

Following the simulation of normal reshaping, the subsequent step is to simulate reshaping with a rivet. The process of reshaping with a rivet is similar to normal reshaping, but with the addition of a rivet. The simulation model consists of a top die, bottom die, rivet, and the deformed metal sheets from the clinching simulation. The extension or displacement of the top die is set to 1.0005 mm. Figure 13 showcases the deformed shape of the upper and lower sheets during the reshaping with rivet process, illustrating the progression at 25%, 50%, 75% and 100% of the assigned top die displacement. Through this simulation, the protrusion height of the metal sheets is successfully reduced from 2.0 mm to 1.0 mm, as demonstrated in Figure 14. Figure 15 presents the recorded compressive strain and compressive stress for the metal sheets, measuring 0.469 mm/mm and 0.05091 GPa, respectively.

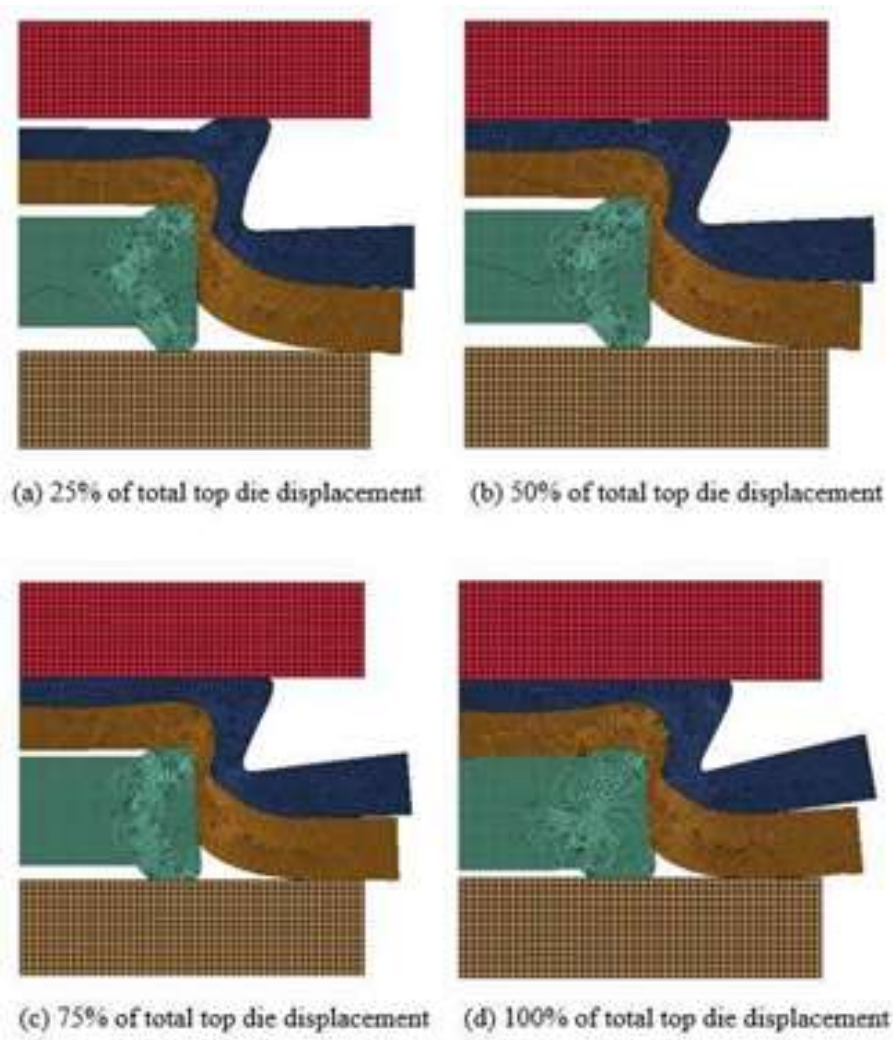


Fig. 13. The deformed shape of upper and lower sheets during the reshaping with rivet

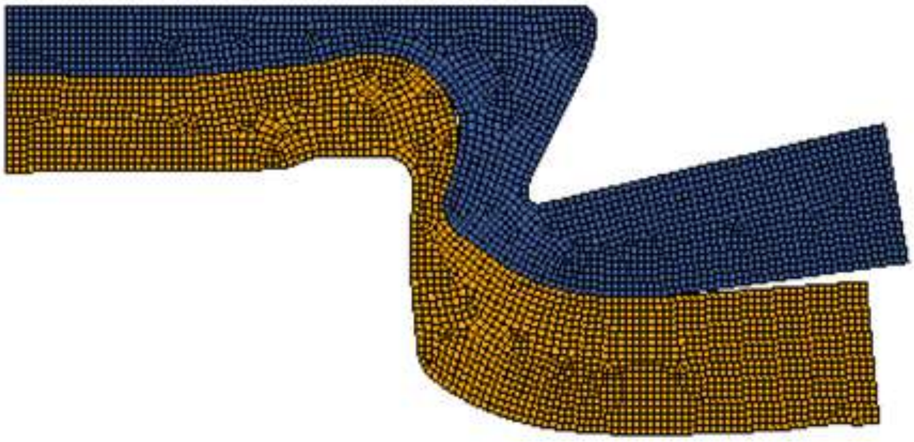


Fig. 14. The metal sheets after simulation with 1.0 mm protrusion height

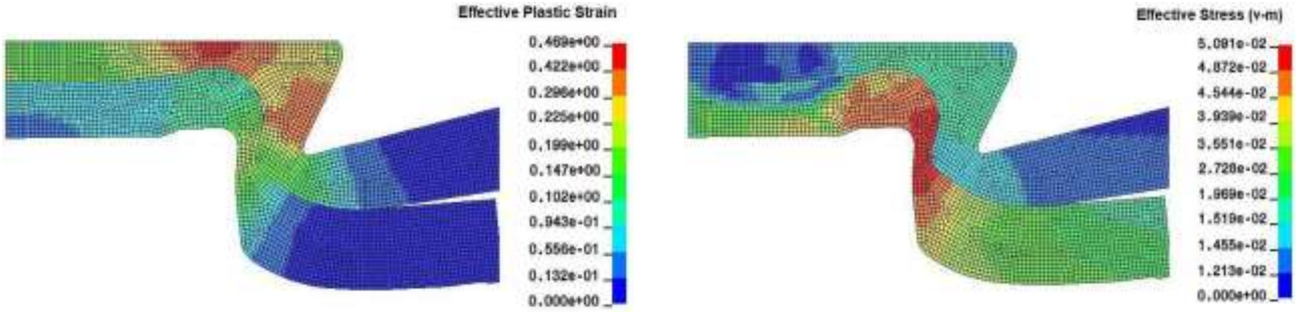


Fig. 15. The compressive strain and compressive stress recorded for the metal sheets after reshaping with rivet simulation

3.3 Reshaping with a Foam

The next step involves simulating reshaping with foam. The process of reshaping with foam is similar to reshaping with a rivet, but with the foam replacing the rivet. The simulation model consists of a top die, bottom die, polyurethane foam, and the deformed metal sheets from the clinching simulation. The extension or displacement of the top die is set to 1.0005 mm. Figure 16 illustrates the deformed shape of the upper and lower sheets during the reshaping with foam process, showcasing the progression at 25%, 50%, 75% and 100% of the assigned top die displacement. Through this simulation, the protrusion height of the metal sheets is successfully reduced from 2.0 mm to 1.0 mm, as depicted in Figure 17. Figure 18 presents the recorded compressive strain and compressive stress for the metal sheets, measuring 0.289 mm/mm and 0.05091 GPa, respectively.

Moving on to reshaping simulations, the recorded compressive stress and strain exhibit minimal disparity compared to experimental outcomes. In the reshaping procedure, the initial 2.0 mm clinching-induced protrusion height is reduced to 1.0 mm and 0.5 mm, respectively. Table 2 offers a compressive strain and stress comparison for reshaping, while Figure 19 presents a graphical comparison of compressive stress between numerical and experimental results.

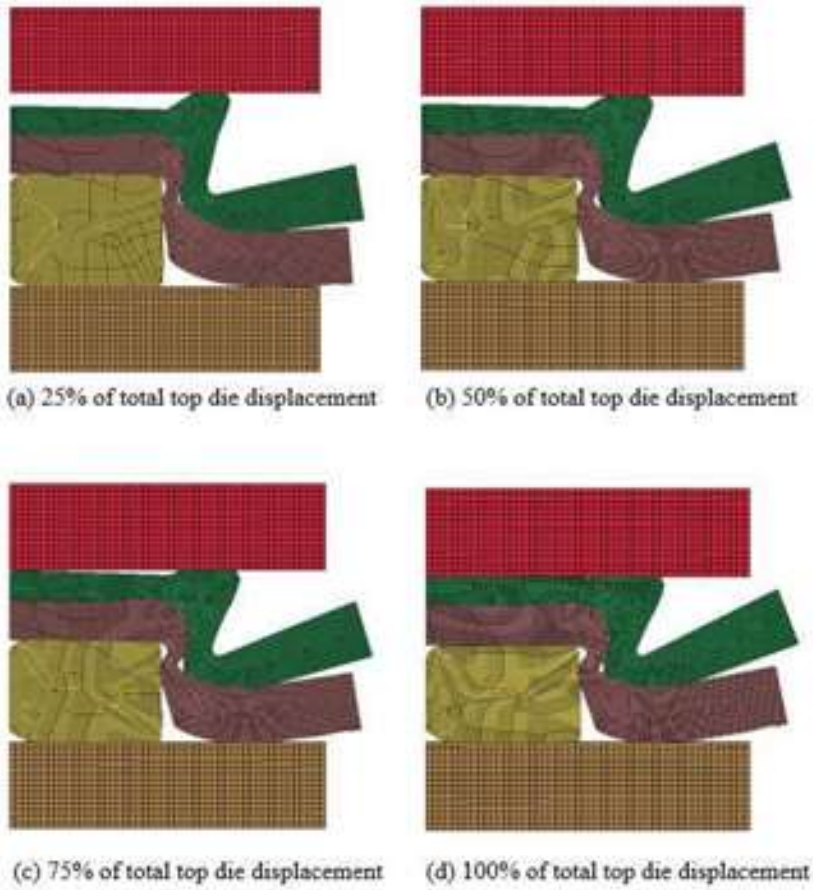


Fig. 16. The deformed shape of upper and lower sheets

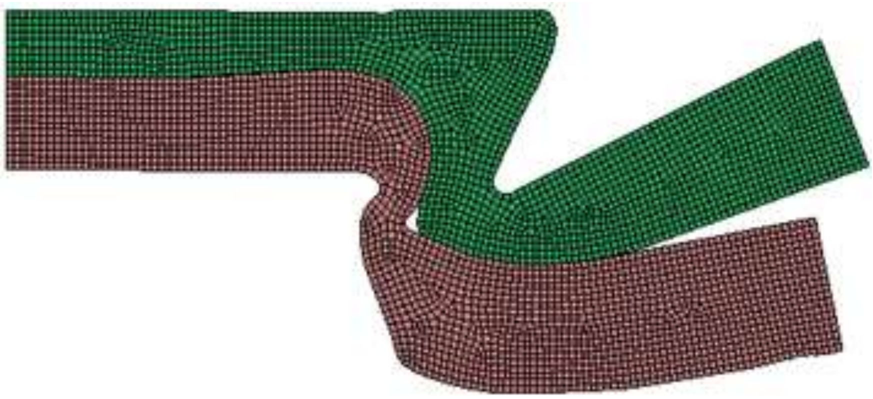


Fig. 17. The metal sheets after simulation with 1.0 mm protrusion height

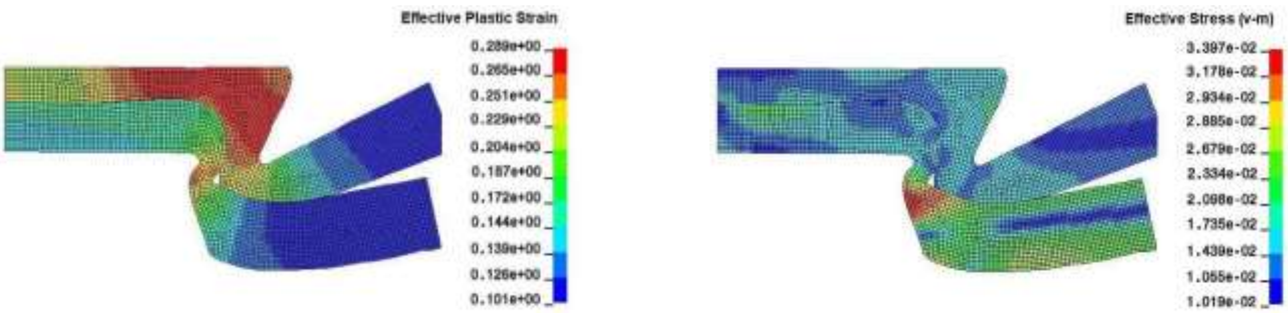


Fig. 18. The compressive strain and compressive stress recorded for the metal sheets after reshaping with polyurethane foam simulation

Table 2
The comparison of compressive strain and compressive stress

Process	No. of test	Protrusion height (mm)	Displacement (Top Die) (mm)	Method	Compressive Strain (mm\mm)	Compressive Stress (Gpa)
Reshaping without additional materials	1	0.5	1.50745	Numerical	0.4302	0.01855
				Experimental	0.5025	0.02246
	2	1.0	0.7095	Numerical	0.1971	0.01488
				Experimental	0.2365	0.01742
Reshaping with rivets	3	0.5	1.50857	Numerical	0.4327	0.05644
				Experimental	0.5029	0.06486
	4	1.0	1.00055	Numerical	0.4695	0.05091
				Experimental	0.5028	0.05719
Reshaping with Foam	5	0.5	1.50852	Numerical	0.4314	0.02514
				Experimental	0.5028	0.03071
	6	1.0	1.00055	Numerical	0.2891	0.03397
				Experimental	0.3335	0.03831

As depicted in Figure 19, the greatest compressive stress is observed in the rivet-assisted reshaping for both protrusion heights in tests 3 and 4. Conversely, the lowest compressive stress is noted in the standard reshaping tests, specifically in trials 1 and 2. Numeric data closely corresponds with experimental findings, signifying a robust correlation.

From the attained outcomes, the maximum compressive stress is registered in rivet-assisted reshaping, succeeded by foam-assisted and standard reshaping. In the case of normal reshaping, the protrusion was compressed between a pair of flat dies post clinching. The upper die descended vertically, causing metal sheet protrusion to flow downward. This approach yields the lowest compressive stress due to the absence of a rivet within the clinched joint to regulate material flow, potentially diminishing the joint's strength.

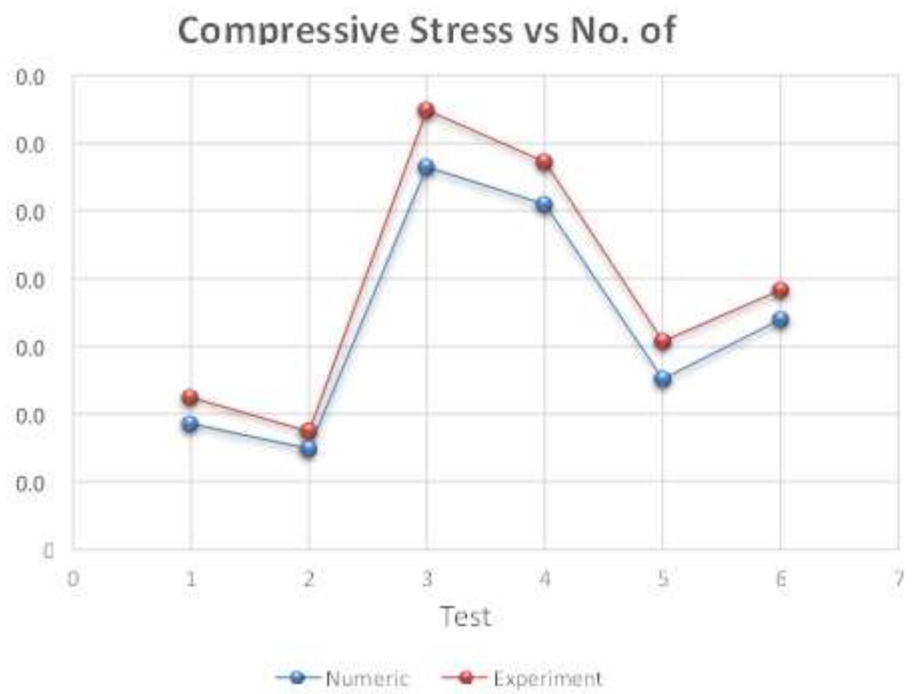


Fig. 19. Comparative compressive stress: numerical vs. experimental

4. Conclusion

In conclusion, this project successfully achieved its objectives, and the results obtained from both numerical simulations and experimental tests are in strong agreement. Three reshaping methods were proposed to reduce protrusion height and increase the strength of the clinched joint. The normal reshaping method effectively reduced protrusion but did not enhance joint strength. On the other hand, reshaping with a rivet and foam, which was embedded in the joint pit, controlled material flow and significantly increased joint strength. Among the three methods, reshaping with a rivet demonstrated the highest compressive stress, indicating superior strength of the metal sheets.

Determining the appropriate punch displacement or penetration depth is crucial in the clinching process. Based on the simulations, a punch displacement of approximately 3.70 mm is found to be the most suitable for clinching (creating sufficient interlock) tests with 1.0 mm material thickness. This punch displacement ensures the creation of well-formed clinched joints. However, when testing metal sheets with thickness below 1.0 mm using the same punch displacement, the joints were found to be ineffective. This limitation may be attributed to the specific tool geometry, which is optimized for a certain range of metal sheet thicknesses. Consequently, throughout the project, a consistent metal sheet thickness of 1.0 mm was utilized.

Overall, the specimens obtained from the reshaping process exhibited significantly stronger clinched joints compared to those from the conventional clinching process. Reshaping with a rivet yielded the strongest joints, closely followed by reshaping with foam and normal reshaping. Additionally, the thickness of the metal sheets played a crucial role in achieving robust clinched joints. Metal sheets with a thickness of 1.0 mm proved to be more suitable than sheets with thickness below 1.0 mm. The recorded data also indicated that reshaping with foam outperformed normal reshaping in terms of specimen strength. Hence, it can be concluded that by utilizing polyurethane foam with an appropriate density, desired specimen strength can be attained.

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