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Experimental and Numerical Analysis of the Clinching Process with Segmented Die in Comparison to Alternative Joining Methods

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ABSTRACT

Clinching is an advanced cold joining method for sheet metals that eliminates the need for additional materials to assemble parts. It involves the plastic deformation of metal sheets to create a joint. The process relies on the interaction between a punch and a die, without the use of any coatings or additives. The punch applies a predetermined force, causing the metal sheets to be pressed through the die cavity and filling the groove, resulting in an interlock point. The final shape of the clinched joint is determined by the tool's geometry. In this study, we investigated the clinching process using segmented die and finite element (FE) methods. The numerical analysis was conducted using LS-DYNA software on AA5052 aluminium and mild steel sheets. Additionally, we compared the compression between spot welding and clinching. The results of our study revealed that various process parameters significantly influence the clinching process, including the bottom thickness, neck thickness and interlock length. Among these factors, die height emerged as the primary influencing factor. Furthermore, we found that the energy absorption and stiffness of the clinched joints were lower compared to those of spot welding.

1. Introduction

In recent years, there has been a growing interest in the use of advanced and lightweight materials due to their unique properties that make traditional welding methods difficult. Industries such as aerospace and automotive are actively exploring new technologies for joining different material sheets. Mechanical joining techniques, such as self-pierce riveting and mechanical clinching, have been successfully employed in the automotive sector. Consequently, several processes, including self-pierce riveting [1,2], friction stir welding [3,4] and mechanical clinching, have been modified and developed to overcome these limitations. Numerical simulation offers a powerful tool for studying clinching in more detail, allowing analysis of the forming process and prediction of joint

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constraints using finite element tools. This approach can effectively reduce product development costs, such as those associated with die and punch manufacturing [5].

Experimental investigation of material flow during the formation of clinched joints using the extendable dies clinching process has been conducted under various forming loads. Additionally, finite element modelling has been employed to determine and evaluate contact loads affecting the die segments during the clinching joining process [6]. Clinching involves creating a suitable material flow between two sheets using appropriate punch and die geometry to achieve a mechanical undercut. Extensive literature reviews have covered both the mechanical properties and finite element evaluation of the clinching process [7]. Compared to fixed dies, extensible die clinching offers several advantages, such as better interlock length due to material flow inside the die segments [8]. Furthermore, an experimental study demonstrating reduced forming loads in clinched joints [9]. In a recent experimental and numerical investigation, the optimal parameters for the extensible die clinching process were evaluated using tensile testing results in addition, an experimental and numerical study on material flow during the clinching process using the extensible die, highlighting the importance of boundary conditions established by the opening of the die segments [10]. Additionally, they observed similar material flow behaviour between the extensible and fixed die in the initial stages [6].

Various publications have shown that extensible die clinching yields better results in terms of neck thickness and interlock length compared to fixed dies [9,11]. This paper aims to investigate the effect of process parameters to determine the optimal parameters using finite elements and extended to use the design of experiments and Taguchi methods. A series of numerical simulations, validated with experiments, were conducted to compare the finite element results with measurements of quality parameters of clinched joints, namely, "bottom thickness x," "interlock length ts," and "neck thickness tn," as shown in Figure 1. Additionally, numerical reshaping of the punch was performed to increase interlock penetration between the upper and lower sheets, thereby enhancing the strength of the clinched joint.

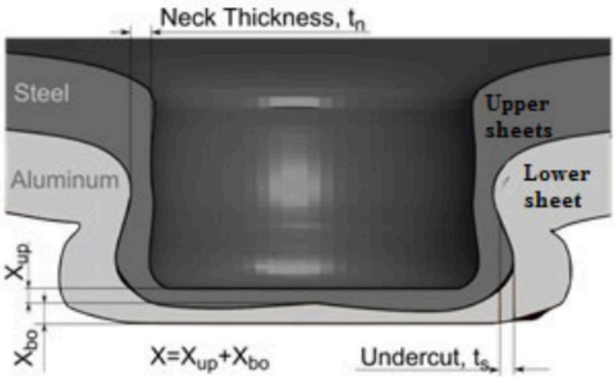


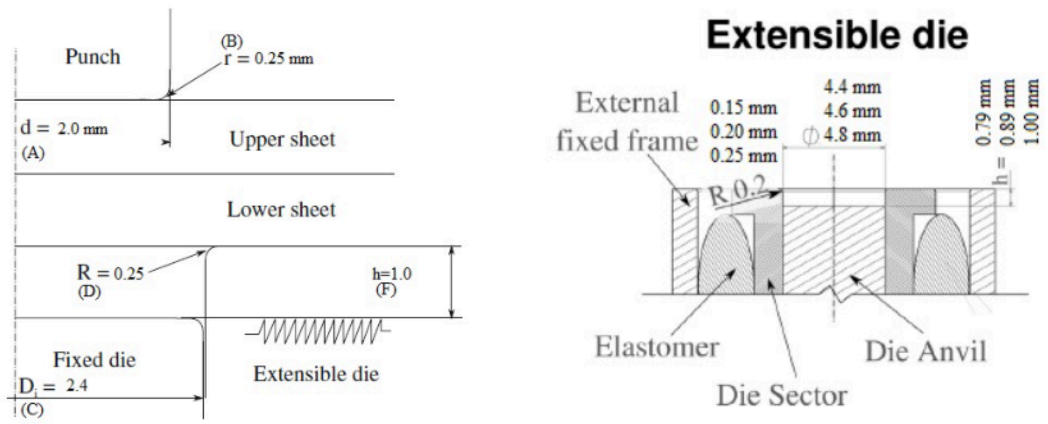
Fig. 1. The quality parameters of the clinched joints namely “bottom thickness x”, “interlock length ts” and “the neck thickness tn”

Resistance spot welding continues to hold its position as the primary method for joining vehicle body parts [12-14]. The cost-effectiveness and high productivity make it an ideal choice for automotive production. Fatigue strength and the reliability of spot weld joints are crucial factors in the fabrication process for automobiles. Although the static strength of ultra-high strength steel plates joined using RSW is high, the fatigue strength is relatively low due to the rapid propagation of cracks. Spot welding aluminium sheets with steel sheets poses challenges [15,16]. Resistance spot welding belongs to the category of welding processes where heat is generated in the parts due to the resistance caused by the flow of electrical current [17]. The quality of a resistance spot welding joint depends on factors such as joule heat generation, current profile and the dynamic resistance change from its initial value. RSW processes involve controlling several welding parameters (such as current, voltage, input energy) and varying the electrode force throughout the welding cycle to ensure optimal results [18]. In this study, we investigate the strength of joints and compare different joining methods using a tensile testing machine. Various combinations and joining techniques were employed during the research. It was found that the addition of adhesive bonded material between the two sheets before mechanical joining significantly improved the joint strength. The results demonstrate that dissimilar materials can be effectively joined using different mechanical joining methods.

2. Methodology

2.1 Background of Mechanical Clinching

The upper sheet material is forced into the lower sheet towards the die cavity, causing material to flow into the die cavity volume and creating a mechanical interlock between the two sheets. During the formation of the clinched joint, the upper sheet experiences neck thinning due to the punch corner, while the lower sheet encounters the die anvil. The strength of the clinched joint is determined by the quality of penetration or undercut between the two sheets. Optimization of the clinching tool parameters can prevent excessive thinning of the punch-sided sheet during the early stages of the clinching process. This can be achieved by reducing the die depth or increasing the fillet corner of the punch [19]. Figure 1 illustrates the parameters of the clinching process that contribute to a good, clinched joint, namely undercut length and neck thickness. Figure 2(a) shows the clinching process parameters, while Figure 2(b) depicts the schematic drawing of the extensible die with different die diameters and anvil depths used in the simulation.



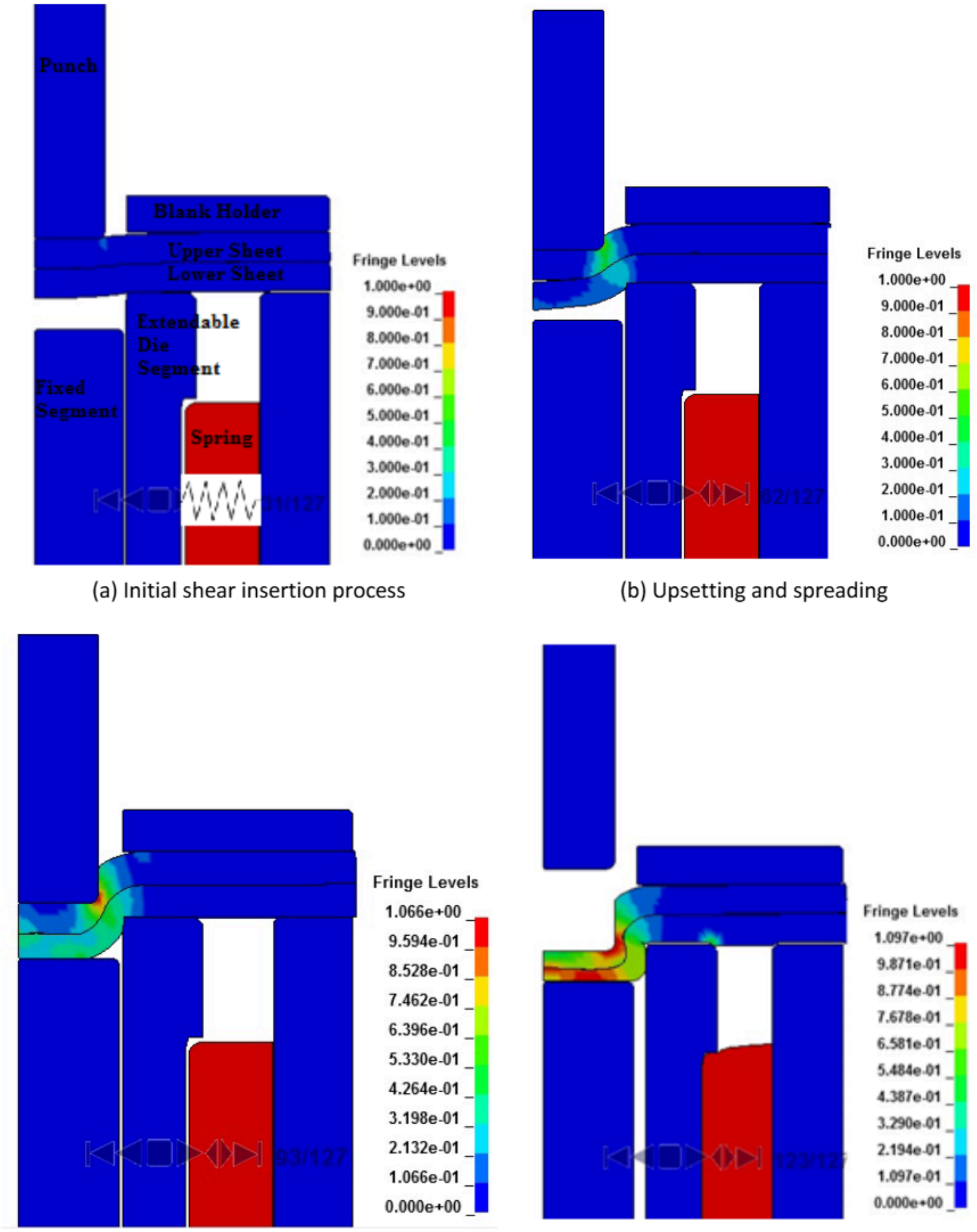
(a) (b)

Fig. 2. (a) The clinching parameters using extensible die type (b) Schematic drawing of the extensible die

The extensible die clinching process can be divided into four steps, as shown in Figure 3:

i. Initial shear insertion process
ii. Upsetting and spreading
iii. Filling of the upper die section
iv. Retraction of the punch indirect extrusion.

During the clinching process, plastic deformation occurs in the upper sheet near the punch corner, resulting in neck thinning. Similarly, the lower sheet experiences localized plastic deformation due to the pressure exerted by the upper sheet with the punch stroke against the die corner radius. When a punch with a larger diameter is used, it induces significant radial sliding of the die segment, leading to enlargement of the die cavity. Figure 3(c) demonstrates the flow of material from both sheets, while the die segment moves accordingly. In the final stage of joint formation, depicted in Figure 3(d), the upper and lower sheets penetrate each other, creating an undercut between them and establishing a solid connection.



(a) Initial shear insertion process (b) Upsetting and spreading

(c) Filling of the upper die section (d) Retraction of the punch – indirect extrusion

Fig. 3. Clinching phases with extensible dies

2.2 Materials and Methods

The clinching process utilizing an extendable die was simulated using a two-dimensional axisymmetric model implemented in the finite-element software LS-DYNA. The die, punch and blank-holder were treated as rigid bodies, while the two blank sheets were modelled as elasto-plastic materials. Quadratic elements with four nodes were employed for all components. The average element dimension of 0.05 mm was chosen to mesh the deformable sheets, ensuring that excessive distortion between elements was avoided. An adaptive remeshing approach was employed during the simulation. The contact between the rigid tools and the blank surfaces, as well as between the two sheets, was modelled using a 2D automatic surface-to-surface approach. This approach enabled the transmission of contact loads between the deformable sheets (slave nodes) and the rigid tools (master surface nodes). Coulomb friction was considered to account for friction between the rigid bodies and the sheets. The friction coefficient was set to μ=0.25 for the tools and sheets, while it was μ=0.3 at the sheet-sheet interfaces. A constant displacement was assigned to both the punch and the blank holder. The motion of the punch and blank holder was halted upon reaching the maximum displacement. The mechanical properties of the sheets, including the material flow stress described by Hollomon’s model, are summarized in Table 1.

Table 1
Mechanical properties of AA5052 and mild steel [20,21]

Material	Elastic Modulus (GPa)	Yield stress (MPa)	Tensile strength (MPa)	Poisson’s ratio	Flow stress (MPa)
Mild Steel	197	163	299	0.29	$\sigma = 527.56\varepsilon^{0.229}$
AA5052	71	132.08	244	0.33	$\sigma = 366\varepsilon^{0.11}$

2.3 Experimental Setup

The tensile shear testing was employed in this study. Figure 4 shows the testing setup. The experiment was conducted with three repetitions to ensure precise outcomes. To apply the tensile load, a SHIMADZU universal testing machine is utilized. The dimensions of the specimen, including its thickness, width and gage length, are measured using callipers. Specifically, a gage length of 70 mm is marked on the specimen, as illustrated in Figure 4. Furthermore, a section is fixed to be gripped at a distance of 15 mm from the end of the specimen. The marked section indicates the specific area that is intended to be gripped during the test.

Fig. 4. Tensile shear testing setup

The joint configuration depicted in Figure 5 illustrates the configuration and composition of the joint. This visual representation provides valuable insight into the specific design and characteristics of the joint under consideration.

(a) (b)

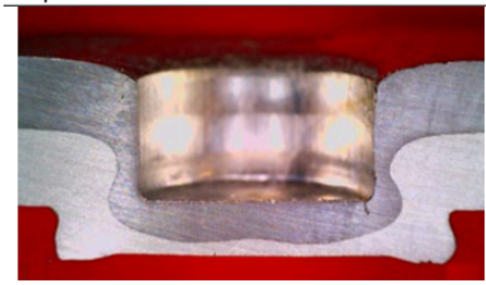
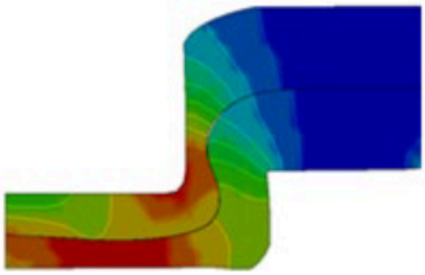
Fig. 5. Visual representation of the (a) spot welding joint (b) clinching joint configurations

3. Results and Discussion

3.1 Validation of the FE model

The numerical model was validated by comparing the experimental measurements with the predictions of the model for the geometric parameters of the clinched joints, namely bottom thickness, interlock length and neck thickness. To obtain these measurements, the clinched joints were sectioned along the symmetrical axial plane and three samples were tested for each processing condition using the same materials. The values of the geometric parameters for the quality factors were obtained from both the numerical simulation and the experiments. Figure 1 displays the bottom thickness (x), neck thickness (tn) and interlock length (ts) of the clinched joints. Table 2 presents a comparison between the numerical results and the experimental data, along with a cross-sectional view of the clinched joints. Additionally, a stereoscopy device was used to measure the geometrical parameters (quality factors) of the clinched joint (tn, ts, x). The results indicate a reasonable agreement between the predictions of the finite element model and the experimental values, with an error of 1-2% or less.

Table 2
Validation of experimental results for quality parameters (a) Cross section along a random axial plane (b) Simulation of the clinching process using the extendable die

Experimental	Simulation
	
Cross Section (along random axial planes) Stereoscopy Results (mild steel, aluminium alloy 5052)	Simulation Results (mild steel, aluminium alloy 5052)

Type of Results	'X" (mm)	tn (mm)	ts (mm)
Experiment	0.69	0.22	0.13
FE prediction	0.696	0.225	0.13
Error (%)	1%	2%	--

3.2 Tensile Shear Test

Following the completion of the experiment, the obtained results are carefully analysed to derive the output parameters. In this research, the energy absorption, maximum stress and maximum displacement for each joint are recorded in Table 3, focusing on simple joint techniques. The analysis of this experiment considers the various types of joints, the materials used and the length of overlap or joint configuration. To determine the energy absorption of the joints, the area under the load-displacement curve is calculated. The maximum force recorded represents the fracture force for the joints. The stiffness of the joint is determined by the ratio between the maximum force and maximum displacement, which is inversely proportional to the modulus of elasticity, E.

The results indicate that spot welding exhibits higher energy absorption and stiffness compared to the clinching joints, considering their distinct configurations and the use of different materials.

Table 3
Experimental result

Overlaps	Materials	Energy Absorption (N.mm)	Maximum Stress (MPa)	Maximum Force (N)	Stiffness (N/mm)	Modulus of elasticity, E
Spot Welding						
30 mm	St-St	13491.84	83.7988	7541.9	2978.54	23.17
	Al-Al	116.13	4.2995	386.953	2036.60	22.60
	St-St	20757.61	188.758	10095.2	3516.06	32.86
45mm	Al-Al	364.72	7.7398	696.58	1257.77	7.85
CLINCH						
2 dots	St-St	13470.58	17.880	4168.95	2490.42	12.608
(30mm)	Al-Al	1178.49	39.689	3571.99	2268.29	11.926
	St – Al	7872.56	39.685	3481.63	2137.97	17.054
3 dots (45mm)	St-St	13962.09	61.873	5624.18	2795.00	21.549

Figure 6 presents the results of energy absorption for samples with 30 mm overlaps. The graph illustrates the varying energy absorption values obtained from different experimental conditions and joint configurations However, it is worth mentioning that future studies could expand this comparison to include additional joining methods such as rivets, adhesive bonding and others. This comprehensive analysis would provide a more comprehensive understanding of the relative performance and suitability of various joining techniques in different applications.

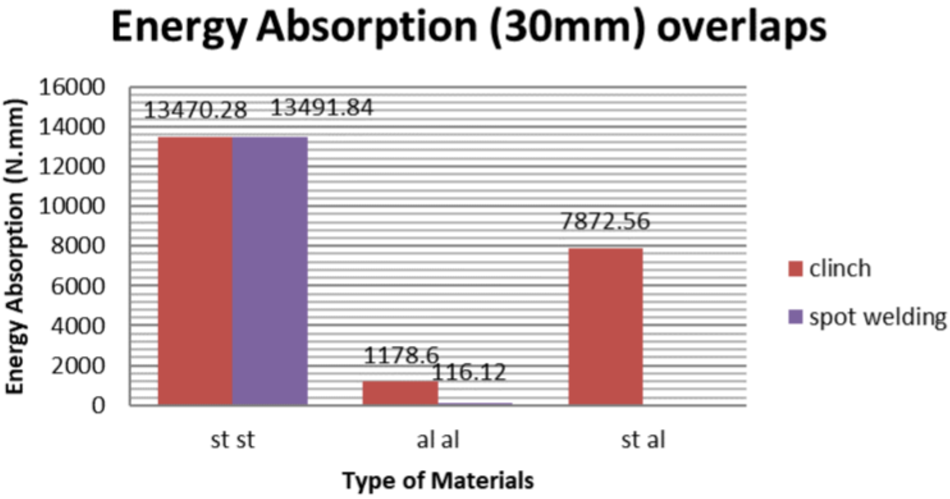
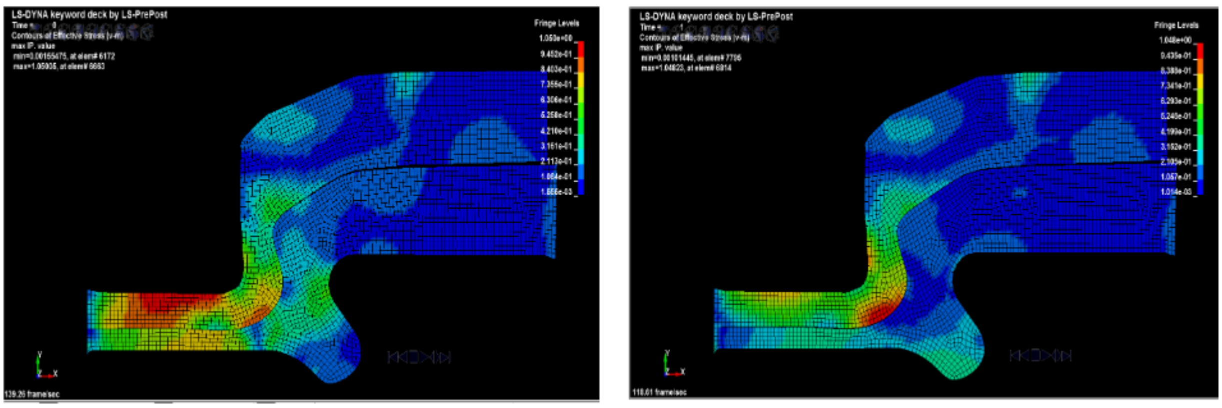


Fig. 6. Displays the energy absorption results for samples with 30 mm overlaps

3.3 Springback Simulation

To compensate for springback in metal forming, finite element analyses provide numerical procedures to design the metal forming processes tools such as die and punch in clinching forming. Springback predicted in terms of the vertical displacement from the total load conditions until material flow fills the die cavity (saturation condition-depression of the punch at which the two sheets metal just takes the shape of the die). This is done to induce a different level of plastic strain in both sheets. In addition, the punch systematically moving forward from the die position going back to the start point, while the two blanks liberated that allowed to release the elastic energy gradually. Whereas, the final shape of the clinching joint before and after the release of the load were depicted in Figure 7.



(a) Von Mises Stress before (stress release) Springback analysis with value 1.050 GPa

(b) Von Mises Stress after Springback analysis with value 1.048 GPa (with stress release)

Fig. 7. Final shape of the joint before and after stress release (springback analysis)

As illustrated in Figure 8, there are an opening between the upper sheet and the lower sheet after removing the load of the punch and the blank holder, this gap due to the Springback created from the remaining internal stress of the two sheets.

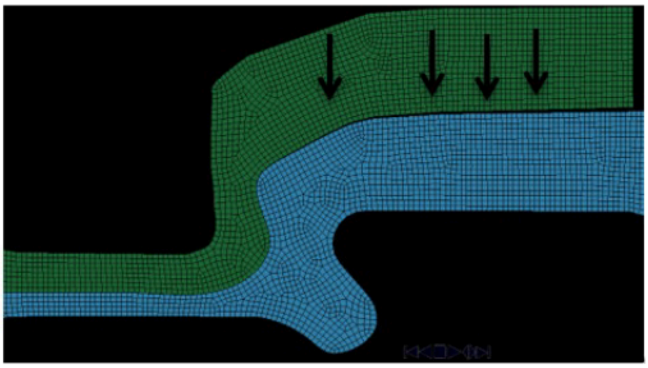


Fig. 8. The springback between the two joints before the release of the stress (springback analysis) [22]

Furthermore, Figure 9 presents the upper and lower sheet with the lower surface before and after Springback analysis where the black line showing the lower surface before Springback and the red one after Springback.

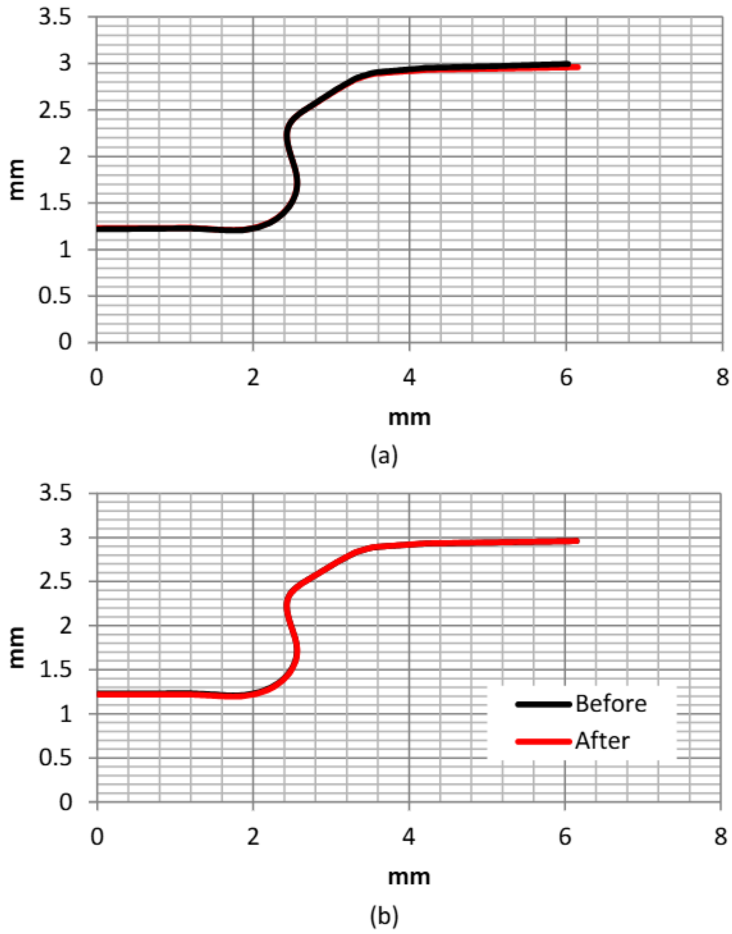


Fig. 9. Springback analysis for (a) Upper sheet lower face (b) Lower sheet upper face

The simulation results illustrate that the upper and lower sheets, both exhibiting their lower surfaces, before and after undergoing Springback analysis. The lower surface's condition prior to Springback is depicted by the black line, while the red line portrays the altered shape after Springback. Upon releasing internal forces using the springback mechanism, a striking alignment between the two lines is observed. This alignment signifies the potential elimination of the "opening" gap that initially existed between the upper and lower sheets.

This phenomenon opens the door for further exploration, necessitating comprehensive numerical and experimental investigations involving diverse materials. By delving into these avenues, a deeper understanding of the intricate dynamics at play can be achieved, contributing to the advancement of this field.

3.4 Compression of Clinch Protrusion

The deformed shape of upper and lower sheets during the normal reshaping process at the stages of 25, 50, 75 and 100 % of the assigned top die displacement displayed in Figure 10.

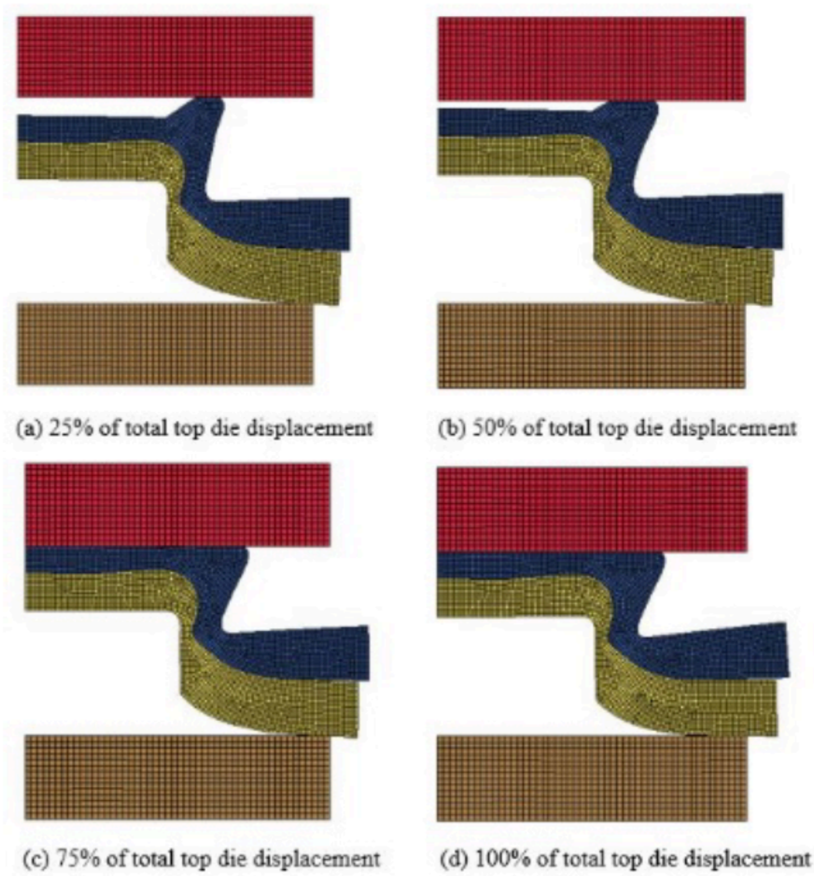


Fig. 10. The deformed shape of upper and lower sheets during the normal reshaping

At the latter stage, the protrusion height of the metal sheets is successfully reduced from 2.0mm to 1.0mm and is shown in Figure 11.

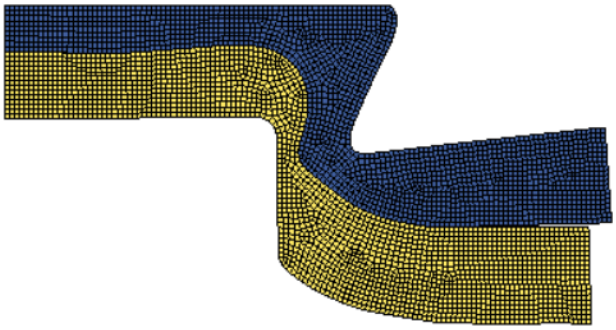


Fig. 11. The metal sheets after simulation with 1.0 mm protrusion height

Figure 12 shows the compressive strain and compressive stress recorded for the metal sheets which are 0.197 mm/mm and 0.014GPa respectively.

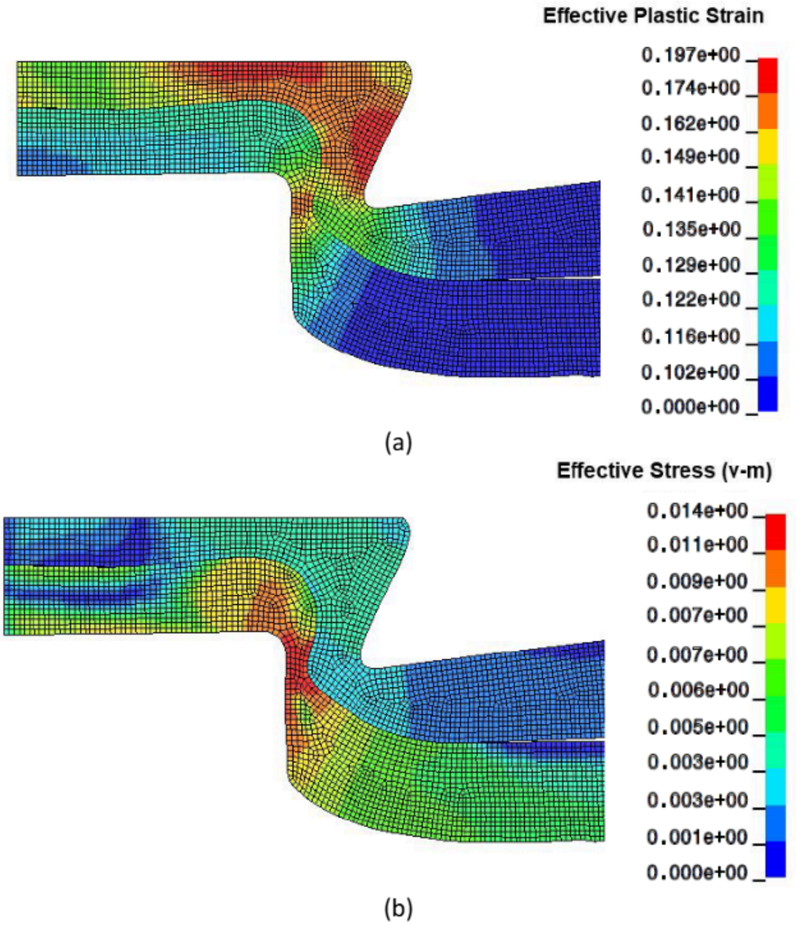


Fig. 12. The (a) compressive strain and (b) compressive stress recorded for the metal sheets

4. Conclusions

In conclusion, the segmented die clinching process demonstrated its effectiveness in numerically joining dissimilar metals. To ensure accurate simulations, adaptive remeshing was essential due to the significant distortion of elements during the clinching process. Encompassing numerical simulations and experimental validations were conducted to investigate and compare the performance of clinching joints. Comparing spot welding and clinching joints, the results indicated that spot welding exhibited superior energy absorption and stiffness due to differences in configuration and material usage. However, future research could enhance this comparison by including additional joining methods like rivets and adhesive bonding, enabling a more comprehensive understanding of different joining techniques' performance and suitability across various applications. Furthermore, springback analysis and reshaping of the clinch protrusion was also carried out numerically. However, further experiments and investigations are required. Future research endeavours can focus on experimental validation and optimization studies. For instance, finite element simulations can be utilized to optimize the geometrical parameters in the extensible die clinching process. Additionally, the numerical reshaping of the punch proved to be an effective approach in increasing the interlock length of the clinched joint.

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