

COMBINED EFFECT OF PRE-STRAIN AND AGEING TREATMENT ON THE TENSILE- SHEAR STRENGTH BEHAVIOURS OF AL6082 ALUMINIUM ALLOYS JOINED BY CLINCHING

Abdulkhik Shukurea Rahmato 

PhD student, Institute of Materials Science and Technology, University of Miskolc
3515 Miskolc-Egyetemváros, e-mail: abdulkhik.shukurea.rahmato@student.uni-miskolc.hu

Péter Zoltán Kovács 

associate professor, Institute of Materials Science and Technology, University of Miskolc
3515 Miskolc-Egyetemváros, e-mail: peter.kovacs@uni-miskolc.hu

Abstract

Clinching is the joining process in which two or more materials are joined by plastic deformation without the use of consumable parts. Therefore, it has no effect on the components' weight. Nowadays, most vehicle industries use this technology. When joining Al6082 aluminium alloys in the as-received condition by clinching, the joint cannot be formed due to the material's poor formability compared with other aluminium alloy series. Therefore, solution heat treatment (SHT) is performed on the sheet to increase the material's ductility before joining. Additionally, a pre-strain is applied to the sheet before joining, since most car components are pre-strained during stamping, stretching, or forming processes, thereby introducing internal strain. Therefore, this study investigates the combined effect of pre-straining and post-clinching ageing on tensile-shear energy absorption and failure during the clinching of Al6082 sheet. The results show that as the post-clinching time increased, the joint's tensile-shear and energy absorption increased. Additionally, the sheet's pre-strain before joining affects joint strength. A fully neck-crack failure mode is observed in all combined effects. The study highlights that the combined effect of pre-strain and post-clinching ageing significantly affects the structural integrity of the clinched joint.

Keywords: Al6082, pre-strain, ageing, clinching, tensile-shear load, energy absorption, failure mode

1. Introduction

Lightweight materials are increasingly prevalent in the production of components across the automotive, aerospace, and home appliance sectors. Many industries aim to decrease the weight of their products by incorporating these materials, which are characterised by their low density and high strength-to-weight ratio. This shift not only enhances fuel efficiency in transportation but also reduces emissions and boosts overall performance (Bai et al., 2023; Cole and Sherman, 1995; Starke and Staley, 1996; Taub and Luo, 2015). As a result, various joining methods, including welding, friction stir welding, resistance spot weld, brazing, and clinching, are employed to connect components made from lightweight materials. Among these, clinching stands out as the preferred method, thanks to its advantages, such as avoiding additional weight and enhancing the structure's unique benefits. Moreover, clinching does not require consumable components and can effectively join dissimilar materials, making it one of the most promising joining techniques in the industry.

Several researchers have investigated the effects of process parameters on static strength and fatigue, as well as methods for improving the clinched joint (Jónás and Tisza, 2018; Kovács and Jónás, 2023; Szabolcs and Kovács, 2022). The static strength of the clinched joint depends on neck thickness, interlock thickness and bottom thickness of the joint (Nguyen et al., 2024; S et al., 2022; Szabolcs and Tisza, 2019). These geometric parameters depend on the process parameters. Studies conducted by Li et al. (Li et al., 2022) examined the influence of process parameters on the geometrical characteristics of clinched joints, revealing that punch diameter, clamp outer diameter, clamp inner diameter, and chamfer width affect the neck and interlock thicknesses of the joints. Ren et al. (Ren et al., 2023) investigated clinched joints produced with fixed and extensible dies and reported that the extensible die enhances material flow and improves the formation of mechanical interlocks during the clinching process. The results indicated that using an extensible die increased the shear and tensile strengths by 9.4% and 14.34%, respectively, compared with a fixed die. Qin et al. (Qin and Chen, 2022) experimentally investigated the clinching of dissimilar aluminium alloys and recommended placing the sheet with higher deflection resistance on the upper side to achieve better mechanical performance. A clear understanding of failure modes in clinched joints is essential for evaluating joint performance. The most common failure modes are button separation and neck fracture. Kim (Kim, 2013) examined the fatigue performance of clinched joints without accounting for the stresses and strains generated during clinching. The findings of these studies indicate that clinch joints cannot be optimally designed beforehand. Su et al. (2015), and Zhang et al. (2018). highlighted the complex failure behaviours of clinched joints under fatigue loading. As a result, the characteristic values and process parameters obtained cannot be directly applied to or transferred to other joint configurations.

Despite existing studies, significant research gaps remain in understanding the relationships among the geometric parameters of clinched joints, their failure modes, and the resulting mechanical properties, highlighting the need for further investigation in this field. Therefore, this investigation focuses on the combined effect of pre-staining before joining the sheet and post-clinching ageing time on the tensile-shear strength, energy absorption, and failure modes of the joint created by the clinching process. During this investigation, Al6082 heat-treatable alloy was used. Solution heat treatment (SHT) is used to enhance the formability of the sheet before joining. The SHT sheet and a 2% pre-strain were applied, and then the sheet was joined using a clinching process. The samples were to undergo artificial ageing for 30, 60, and 120 minutes. Finally, the sample's tensile-shear behaviour and failure mode were investigated.

2. Materials and methods

2.1. Materials

In this study, Al6082 is used because it has good corrosion resistance, excellent machinability, and heat-treatability. As a result, it can be used to produce various automotive components, such as subframes, suspension components, and structural frames. The mechanical properties of Al6082 were measured using an electro-hydraulic testing machine, shown in Table 1.

Table 1. Mechanical properties of Al6082

Material	Ultimate tensile strength (MPa)	Yield strength (MPa)	Elongation (%)	Modulus of elasticity (GPa)	Poisson ratio (-)
Al6082	348	303	15	72	0.3

Initially, in the as-received form of Al6082, the clinching process was done. However, it cannot be joined, and a crack is visible around the joint's neck. Therefore, a solution heat treatment (SHT) was performed at a solution heat treatment temperature (T_{SHT}) of 485 °C for 20 minutes to enhance the material's formability. The process involves heating the primary sample to a temperature at which alloying elements dissolve into a single-phase solid solution, holding it at that temperature for a specific time, and then rapidly quenching it to retain the dissolved elements in a supersaturated solid solution (Bayat and Carlberg, 2017). The entire process of creating a joint with different pre-strains and ageing times is depicted in Figure 1.

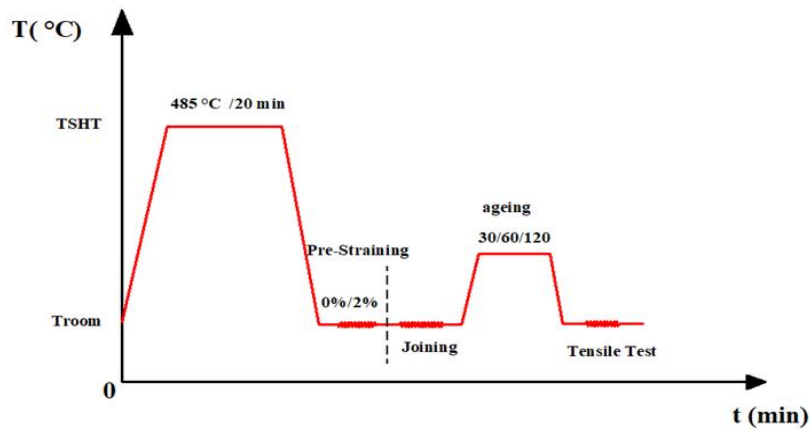


Figure 1. Schematic representation of the entire process

To investigate the combined effect of the pre-strain and post-clinching artificial ageing on the tensile-shear strength of the joint, the primary 1mm thickness of Al6082 sheet is prepared as shown in Figure 2. Initially, on the primary sample, an SHT is applied, followed by a pre-strain, and the centre parts are then cut and used in the clinching process.

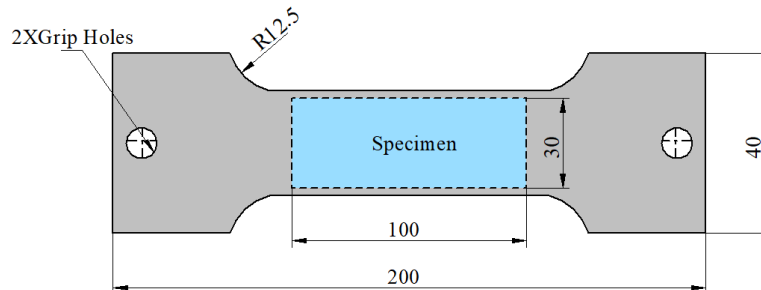


Figure 2. Dimensions of Primary Sample

2.2. Clinching joining process

Clinching is the joining of two or three materials without the use of consumable parts, achieved through plastic deformation, as shown in Figure 3. The sheet is placed between the holder and the die, and the punch is then lowered to push the top sheet into the die cavity. Further movement of the punch pushes the top and bottom sheets to the die cavity bottom surface. As a result, the material began to fill towards the die cavity. Therefore, the sheets became locked due to the plastic deformation of the material

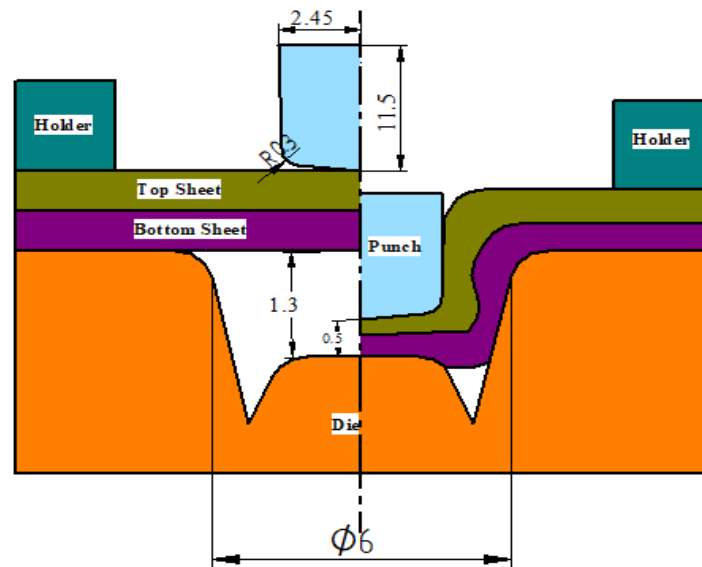


Figure 3. Clinching Joining Process

After the SHT and pre-straining, the Al6082 sheet was joined using the TOX Pressotechnik GmbH tool. A total of 10 joints were created to investigate the combined effect of pre-strain and ageing on the joint's tensile-shear and energy-absorption characteristics.

2.3. Tensile-shear strength behaviours

To investigate the static strength and energy absorption behaviours of the joint under pre-strain and post-clinching ageing, a tensile-shear test was conducted using an electro-hydraulic MTS machine, with a load applied to one end of the joint at 1 mm/s until failure, as shown in Figure 4. The computer recorded the applied joint force and displacement. This provides a clear understanding of the joint characteristics' behaviours under quasi-static loading.

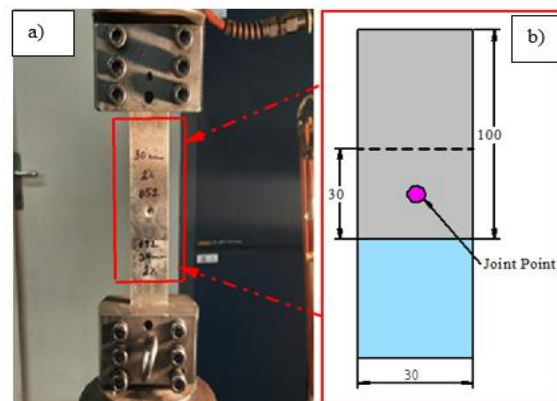


Figure 4. Tensile test: a) tensile loading by MTS, b) dimensions of joint specimen

3. Results and discussions

3.1. Process parameters

To investigate the influence of combined pre-strain and ageing time on the process parameters of the clinched joint, a joint cross-section image was captured with an inverted microscope, and the neck and interlock thicknesses were measured using AxioVision software. The two process parameters affect the joint's tensile-shear and pull-off strengths (Shukurea Rahmato and Zoltán Kovács, 2024). Figure 5 shows the neck and the interlock thickness of the clinched joint with 0% pre strain and 2% pre strain. Pre-strain significantly affects the neck and interlock thicknesses of the joints. As the pre-strain increased from 0% to 2%, the neck and interlock decreased from 0.289 mm to 0.277 mm and from 0.237 mm to 0.227 mm, respectively, due to stretching the sheet before joining, which reduced its thickness. Therefore, the fill of materials toward the die cavity is reduced.

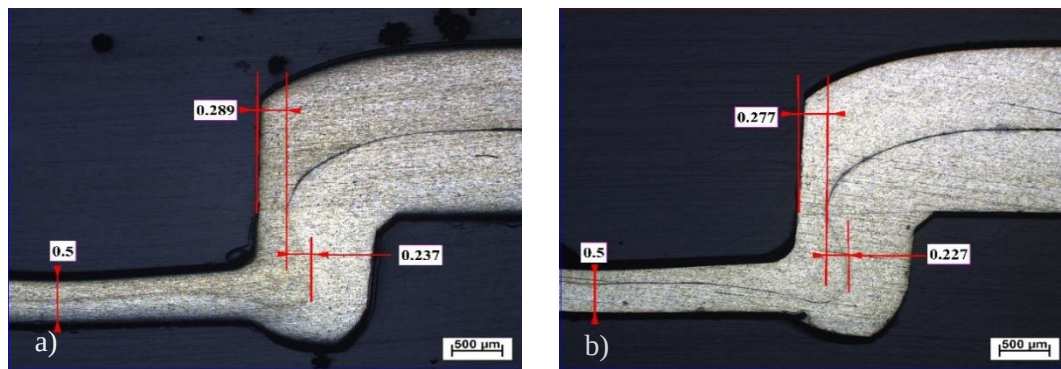


Figure 5. Neck and Interlock thickness measurements a) without pre-strain (0%), b) with 2% pre strain

3.2. Combined Effect of pre-strain and ageing time on tensile-shear load characteristics

Figure 6 depicts the tensile-shear load and displacement behaviours of the clinched joint with varying ageing time without pre-strain. Even though all the curves are characterised by the rapid increases in tensile-shear load with displacement, followed by a peak region and subsequently softening stages until failure. But differences are observed in the maximum load, deformation capacity and post-peak behaviours.

The joint without pre-strain and with ageing time of 120 minutes (0–120) exhibited the highest initial stiffness and reached maximum tensile-shear load of approximately 1.82 kN at a displacement of around 0.4 mm. This indicated that the longer the ageing time, the greater the load-carrying capacity during the early loading stage. Nevertheless, after reaching its maximum, it dropped sharply, indicating a partial recovery of its properties due to the longer ageing time, and it became stronger. When the joint is post-clinched and aged for 60 minutes, the maximum load is close to 1.78 kN, with a smoother post-peak descent compared to the 0–120 joint. These features indicated improved energy absorption and better damage tolerance. The gradual decrease in load after peak load suggests that the specimen maintained residual load-bearing capacity over a longer displacement range, indicating a more stable failure.

In contrast, the 0–30 joint exhibits the lowest peak load, approximately 1.68 kN, but the most ductile response among all three joints. Although its strength was comparatively lower, the joint sustained loading over a larger displacement interval before complete failure. The softer behaviours indicate the

enhanced deformation capacity and higher structural stability during failure. Overall, increasing the post-clinched ageing time improved the maximum load and initial stiffness. However, an excessive increase led to a more brittle response and reduced deformation capacity.

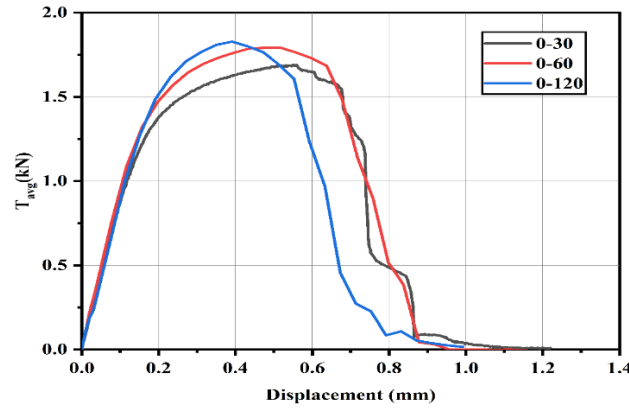


Figure 6. Tensile-shear load behaviour of the joint under varied ageing time without pre-strain

Figure 7 shows the tensile-shear load and displacement characteristics of a joint initially pre-trained at 2% and with varying post-clinching ageing time. The joint with 2% pre-strain and 120 minutes of ageing (0–120) showed the steepest initial slope in the elastic region, indicating the highest initial stiffness among the three joints. It reached a peak load of approximately 1.9 kN at a displacement of approximately 0.4 mm. This suggests that after 120 minutes of ageing, the joint improved its tensile-shear strength. However, a sudden load reduction indicates rapid crack propagation and failure due to the pre-strain imposed on the sheets prior to joining.

The 2% pre-stained, with a 60-minute post-clinched ageing time, reached a maximum load of approximately 1.8 kN. Compared to the 2–60 joint, the descending curves were smoother and extended over a large displacement range. These behaviours show the improved energy absorption and more stable failure. However, the 2% pre-stained sample with a 30-minute post-ageing time exhibited the lowest peak load of around 1.68 kN but showed the most gradual post-peak response. Although its initial stiffness and strength were lower, it maintained load resistance over a wider displacement range before collapse. The extended softening region suggests improved ductility and better deformation tolerance compared to other joints.

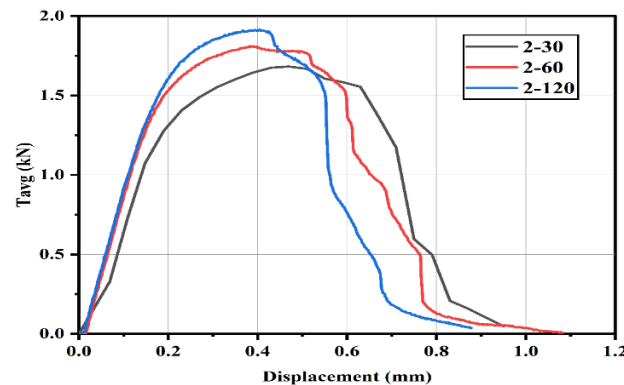


Figure 7. Tensile-shear load behaviour of the joint under varied ageing time and 2 % pre-strain

3.3. Energy absorption

Figure 8 depicts the combined effect of pre-strain and post-clinched ageing time on the energy absorption and maximum tensile-shear load of clinched joints. As the pre-strain changed from the as-received (0%) to 2% pre-strained, the maximum tensile-shear strength was increased due to the pre-strain enhancing the hardness of the materials. Additionally, increasing the post-clinching ageing time enhances the joint's tensile-shear capacity by improving load-carrying capacity. In contrast, the energy absorption generally decreases as the post-clinching ageing time increases. The highest energy absorption is observed for the 0–60 ageing joints, at around 1.14 kN·mm, while the lowest is observed for the 2–120 ageing joints, at approximately 0.90 kN·mm, due to reduced material elongation resulting from pre-strain induced in the sheet. Overall, the results indicate the relationship between the joint's maximum load and energy absorption characteristics. As the combined parameters increase, the joint demonstrates enhanced strength but reduced displacement. Therefore, the optimal combination of parameters should be selected based on the specific application requirements, depending on whether higher load-carrying capacity or greater energy absorption is the primary design objective.

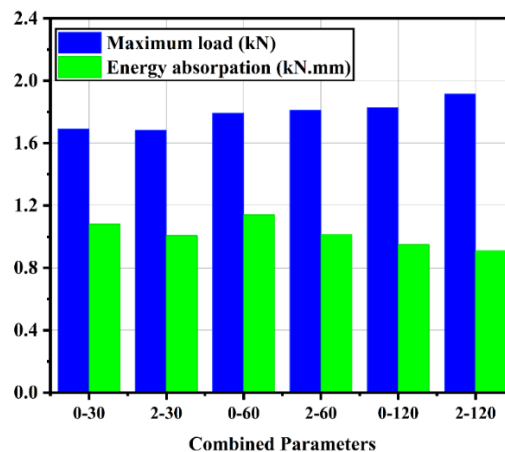


Figure 8. Maximum load and Energy absorption of the joint with combined parameters

3.4. Failure behaviours

One method to investigate the mechanical static performance of the clinched joint is to load the sample along its central axis and pre-strain it uniformly at a specified rate. During this process, the tensile-shear force and elongation of the clinch are recorded (Chen et al., 2021). The results indicate different failure modes of the joint. Generally, inadequate interlock and insufficient neck thickness can lead to failure modes such as bottom separation (Figure 9a) and neck fracture (Figure 9b). The static failure of a clinched joint mainly occurs in two forms: the first is caused by insufficient deformation during the forming process, which leads to poor interlock and subsequent separations of the joined components. The second failure mode is caused by insufficient material in the neck region of the upper sheet, typically due to a small tool diameter or excessive die depth, which induces excessive elongation within the die cavity (Lee et al., 2010). In this study, all joint failure modes are neck fractures. Therefore, the combined effect does not affect the joint's failure modes, as shown in Figure 10.

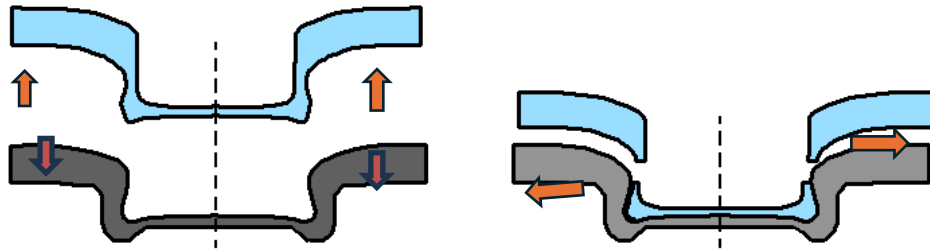


Figure 9. Failure modes: a) bottom separation, b) neck crack failure

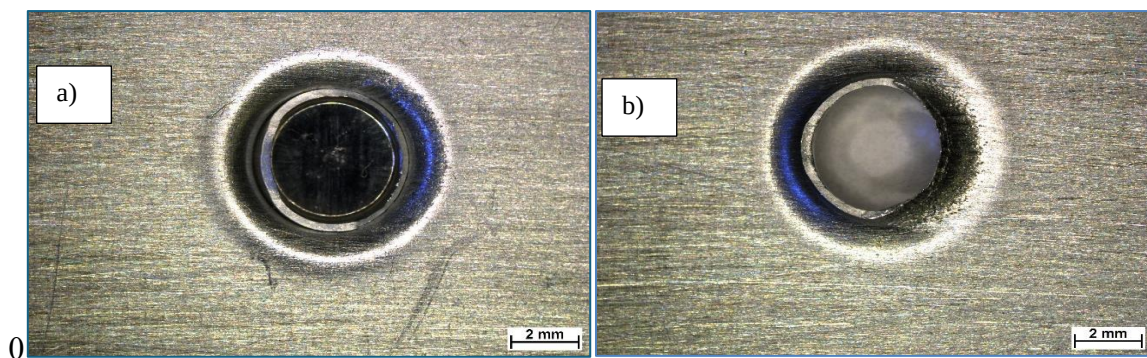


Figure 10. Neck crack failure a) bottom sheet, b) top sheet

4. Conclusions

This study investigates the combined effect of the pre-strain and post-ageing treatment on the tensile-shear strength, energy absorption, and failure of the Al6082 sheet joined by clinching. Therefore, the following conclusions were drawn from this study.

- In the as-received form of Al6082 sheet joined by clinching, but it was observed that cracks were around the joint. Therefore, after applying SHT to the sheet, it was joined without any cracks.
- The neck and interlock thickness are significantly affected by the pre-strain before joining the sheet. As the pre-strain changed, both the neck and interlock thicknesses were approximately reduced by 4.12%.
- Based on the results, the joint without pre-strain but applying post-clinched ageing time increased the tensile-shear load capacity of the joint. The 0–120 joint was the highest maximum load and stiffness, indicating improved load-carrying capacity.
- Adding pre-strain to the sheet before joining improved joint strength.
- The results show that the combined parameters significantly influence both maximum load and energy absorption characteristics of the joint. Overall, the 0–60 joint provides the most balanced performance, while the 2-120 joint offers the highest strength performance.

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