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Design of flat hole-clinching for joining polymer and metal sheets

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Abstract

There is a growing need for joining processes capable of joining dissimilar materials, specifically lightweight materials. In this study, flat hole-clinching (FHC) is developed for joining polycarbonate and AZ31 magnesium alloy sheets. A ductile fracture criterion is calibrated using tensile tests and employed in the finite element analysis of the process to investigate the effect of geometric parameters on the joint characteristics and strength. A tool concept is also proposed for the FHC process. Results show that the FHC process enables to successfully connect these sheets without fracture. The flat hole-clinched joint resisted the maximum force of 0.9 kN in the pull-out test, and failed with bottom separation mode.

1. Introduction

The ability to join dissimilar materials is of great importance in the transportation industries such as the aeronautical or automotive industry because of the manufacturing of multiple material structures. These structures obtained by joining components made of polymers, composites and metals enable a decrease in vehicle weight, without affecting structural performance (Lambiase et al. 2021). However, joining of polymer and metal sheets requires special attention since they have very different mechanical properties. Clinching, a mechanical joining by plastic deformation, is very commonly used to perform multi-material joints because of the low cost and high levels of productivity (Lee et al. 2014). In order to attain a sound joint with this process, both materials being joined need to have high ductility because of the plastic deformation that they must endure. New variations of the clinching process, such as hole-clinching (HC) (Lee et al. 2014) and flat hole-clinching (FHC) (Wen et al. 2016), have then been introduced to allow the joining of a high ductility material to a low ductility material. To create a mechanical interlock, the upper sheet with high ductility is formed into the hole of the lower sheet with low ductility.

In this study, FHC is designed for joining polycarbonate (PC) and AZ31 magnesium alloy sheets. Tensile tests are performed to characterize the mechanical properties of the sheets. Then, a ductile fracture criterion is calibrated by combining the experimental and numerical results of these tests. The finite element simulations of the FHC process and the pull-out test are performed to determine the Influence of the FHC geometrical parameters on joint characteristics and joint strength. Finally, a tool concept is proposed to implement the FHC process.

2. Flat Hole-clinching

In the FHC process, a ductile material is placed on top of a brittle material, both on top of a flat die. The lower sheet has a hole with a slight inclination β. A punch then indents the upper sheet through the hole of the lower sheet, creating a mechanical interlock. The main geometric parameters of FHC are punch radius R_p, punch corner radius r_p, punch conicity α, and hole conicity β. Changes in these have various effects on the joint characteristics, mainly neck thickness t_n, bottom thickness t_b, and undercut t_u (Wen et al. 2016). All these parameters are shown in Figure 1.

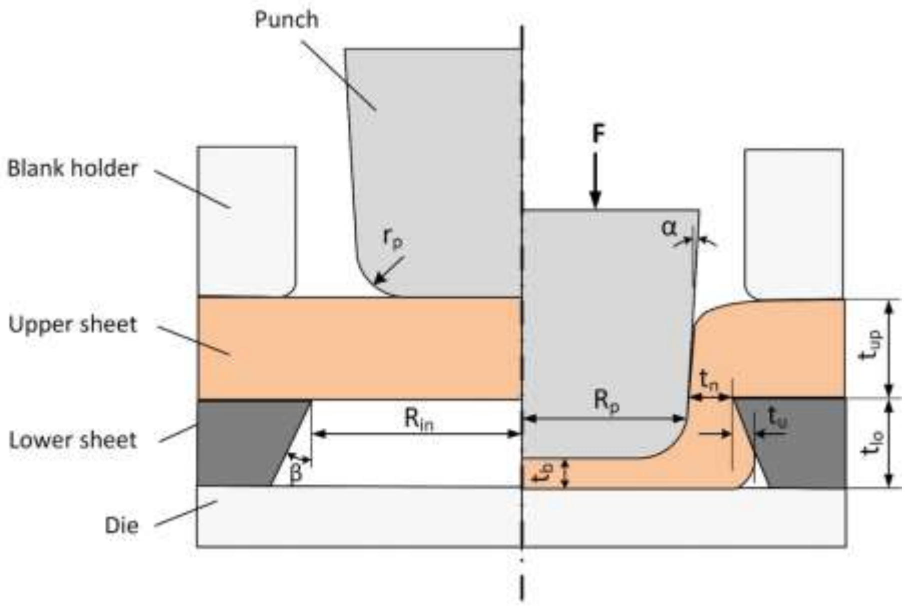


Figure 1: Schematic representation of the geometric parameters of the flat hole-clinching process and its joint characteristics

3. Material Characterization

This study was conducted on PC and AZ31 magnesium alloy sheets with 2mm and 1.5mm thickness, respectively. PC, which falls in the thermoplastic category, is transparent, tough and ductile, with good electric isolation properties. Apart from those, it has excellent resistance to impact (da Silva et al. 2013; Lambiase 2015). Magnesium is the lightest structural metal, being, for example, 77% lighter than steel and 33% lighter than aluminum. It also has a good resistance to impact that justifies the common use of this material in the medical, transport and aerospace industries (da Silva et al. 2013; Jayasathyakawin et al. 2020). However, magnesium alloys have very low ductility at room temperature as well as a high specific strength and, as a result of this, AZ31 was chosen for the lower sheet (Han et al., 2022; Jayasathyakawin et al. 2020). To determine the elastic and plastic properties of the materials, tensile tests were performed on PC and AZ31 specimens according to BS 2782 and ASTM E8, respectively. A digital image correlation system was employed to measure surface displacement and strain over the gauge region. Summary of the mechanical properties of the materials are listed in Table 1.

Material	Thickness (mm)	Density (Kg/m^3)	Modulus of elasticity (GPa)	Yield strength (MPa)
Polycarbonate (PC)	2	1200	2.3	55
AZ31	1.5	1780	44	158

Table 1: Summary of the mechanical properties of PC and AZ31 sheets

4. Finite Element Analysis

The finite element simulations of the FHC process and the subsequent pull-out test were performed with the commercial software ABAQUS. A dynamic explicit solver with a time scaling technique was used. An axisymmetric assumption was considered to decrease the computation time. The elastic and plastic behavior of the materials were modeled based on the results of the tensile tests. The die, punch and blank holder were considered as rigid bodies.

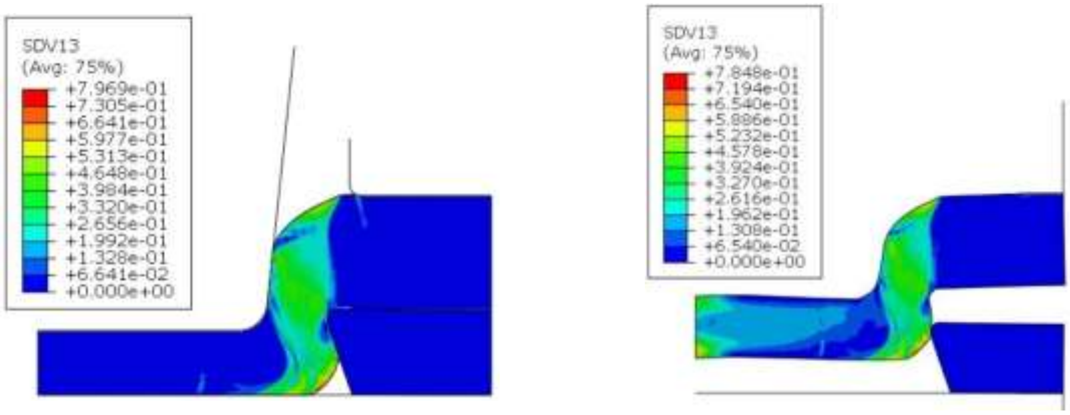
To predict the ductile fracture in the finite element simulation, the normalized Cockcroft and Latham criterion, (Equation (1)), was defined by a VUSDFLD subroutine. In this equation, η and $\bar{\theta}$ show stress triaxiality and normalized Lode angle, respectively.

$$D = \int_0^{\bar{\varepsilon}_p} \left(\frac{\sigma_{max}}{\bar{\sigma}}\right) d\bar{\varepsilon}_p = \int_0^{\bar{\varepsilon}_p} \left(\eta + \frac{2}{3}\ cos\left(\frac{\pi}{6}(1-\bar{\theta})\right)\right) d\bar{\varepsilon}_p \quad \textbf{(1)}$$

By simulating the tensile test and combining its results with the experimental data, the critical damage value for the PC sheets was determined to be 0.8. In the simulations, the punch radius R_p, the punch corner radius r_p, the punch conicity α, and the hole inclination β are variable while the hole radius is constant and equal to 5.1 mm.

5. Parametric Study

Figure 2 shows the damage distribution at the PC during the FHC process and the pull-out test. As seen in Figure 2(a), there are two regions prone to fracture: the neck and undercut of the upper sheet. The first one is damaged due to the drawing of the upper sheet by the punch while the second one is damaged by the radial flow of the material during the formation of the undercut. However, damage reaches the critical value in the undercut after creating a mechanical interlock. Figure 2(b) shows that, due to the lower strength of the PC than the AZ31, the undercut deforms and comes out of the mechanical lock during the pull-out test. Thus, the failure mode in the pull-out test of the hybrid PC-AZ31 joint is button separation that is mainly affected by undercut t_u.



(a) (b)

Figure 2: Damage distribution during the FHC process (a) and the pull-out test (b)

Nine different cases of the FHC process were simulated. In each one the value for a specific geometric parameter was altered and the dimensions of t_n, t_u and t_b were extracted at the onset of fracture, as presented in Table 2. Furthermore, for each case, a pull-out test was performed to assess joint strength, which is defined as the maximum load reached during the test (Wen et al. 2016). The values obtained are also presented in Table 2. The results show that apart from the punch radius R_p altering the geometric parameters does not lead to a significant change in neck thickness t_n. In addition, an increase in the punch radius R_p or in hole conicity β leads to an increase of the undercut t_u which in turn results in a higher joint strength. Variations in punch corner radius r_p and punch conicity α do not lead to any noteworthy changes in the joint strength, mainly because these variations also do not result in a serious change in t_u. It was also found that fracture occurs at almost the same bottom thickness t_b. It should be noted that a lower bottom thickness t_b causes a higher material flow in the radial direction. Maximum join strength was obtained for Case 9, where both undercut t_u and neck thickness t_n are high at the same time.

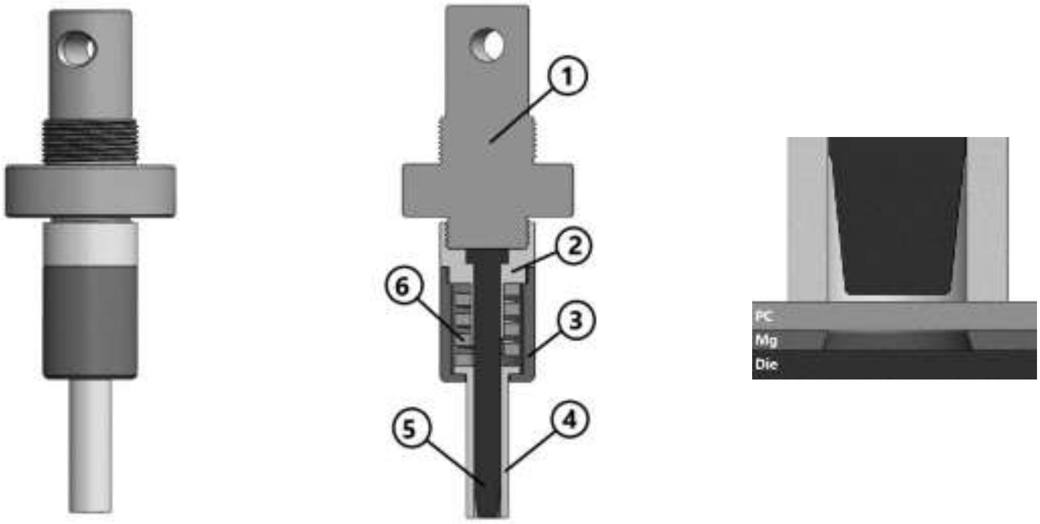
Test cases	R_p (mm)	r_p (mm)	α (deg)	β (deg)	t_n (mm)	t_u (mm)	t_b (mm)	F_{max} (N)
Case1	3.8	0.5	3	20	1.33	0.11	1.13	346.6
Case2	4	0.5	3	20	1.12	0.19	1.11	683.6
Case3	4.2	0.5	3	20	0.97	0.25	1.18	797.5
Case4	4	0.25	3	20	1.09	0.19	1.14	663.6
Case5	4	0.75	3	20	1.19	0.18	1.09	616.5
Case6	4	0.5	0	20	1.18	0.16	1.17	560.5
Case7	4	0.5	6	20	1.13	0.21	1.12	677.1
Case8	4	0.5	3	10	1.07	0.13	1.11	260
Case9	4	0.5	3	30	1.19	0.2	1.12	899.9

Table 2: Joint characteristics and strength with different process parameters

6. Tool Concept

The final step of the proposed study was to conceptualize a tool capable of performing hybrid polymer-metal joints of good quality. Figure 3 shows the concept created using SolidWorks software, which was inspired by the punch stripper CSR for TOX®-Flanged Punches from TOX® PRESSOTECHNIK (TOX 2021). The proposed concept with its different parts numbered from 1 to 6 is shown in Figure 3(b). The tool is locked into a universal testing machine from its top, by the means of part 1, which is in turn also locked into part 2, with a thread. The flat die is also locked in place. Then, the PC and AZ31 sheets are placed on the die to be joined (Figure 3(c)).

When force is applied to part 1 and it starts moving downward, parts 2 and 3, as well as the punch (part 5) will have same movement. This causes the spring (part 6) to be compressed by component 2, which provides the required force of the blank holder for fixing the PC and AZ31 sheets in place while the joint is being formed. This concept has good potential to realize an easy and reliable joining technique for creating hybrid metal-polymer joints, which is rapid, durable and eco-friendly.



(a) (b) (c)

Figure 3: (a) Overall view of the FHC tool (b) section view of the FHC tool (c) detail view showing the tool and the sheets when the joint is ready to be fabricated

7. Conclusions

In this study, the flat hole-clinching was developed for joining polycarbonate and magnesium alloy sheets using finite element analysis. The findings can be briefly summarized as:

1. The critical damage value of the normalized Cockcroft and Latham criterion was obtained 0.8 for the PC sheet, which could allow it to be joined to magnesium alloy by flat hole-clinching.
2. The increase of punch radius R_p or hole conicity β leads to an increase of the undercut t_u which in turn leads to a stronger joint. Variations in punch conicity α and punch corner radius r_p does not lead to significant changes in the pull-out strength. Apart from R_p varying the other geometrical parameters does not have a significant effect on neck thickness t_n. To achieve maximum the pull-out strength, both the undercut t_u and the neck thickness t_n should be sufficiently high.
3. A tool concept was proposed that has great potential for producing hybrid PC-AZ31 joints of good quality.

References

Han, S., Z. Li, Z. Wang, and Y. Li. 2022. "Review on Joining Processes of Magnesium Alloy Sheets." *The International Journal of Advanced Manufacturing Technology* 118:2787-2803. https://doi.org/10.1007/s00170-021-07981-9.

Jayasathyakawin, S., M. Ravichandran, N. Baskar, C. Anand Chairman, and R. Balasundaram. 2020. "Mechanical Properties and Applications of Magnesium Alloy –

Review." In *Materials Today: Proceedings*, 27:909–13. Elsevier Ltd. https://doi.org/10.1016/j.matpr.2020.01.255.

Lambiase, F. 2015. "Mechanical Behaviour of Polymer-Metal Hybrid Joints Produced by Clinching Using Different Tools." *Materials and Design* 87 (December): 606–18. https://doi.org/10.1016/j.matdes.2015.08.037.

Lambiase, F., S. I. Scipioni, C. J. Lee, D. Cheol Ko, and F. Liu. 2021. "A State-of-the-Art Review on Advanced Joining Processes for Metal-Composite and Metal-Polymer Hybrid Structures." *Materials* 14 (8). https://doi.org/10.3390/ma14081890.

Lee, C. J., J. M. Lee, H. Y. Ryu, K. H. Lee, B. M. Kim, and D. C. Ko. 2014. "Design of Hole-Clinching Process for Joining of Dissimilar Materials - Al6061-T4 Alloy with DP780 Steel, Hot-Pressed 22MnB5 Steel, and Carbon Fiber Reinforced Plastic." *Journal of Materials Processing Technology* 214 (10): 2169–78. https://doi.org/10.1016/j.jmatprotec.2014.03.032.

da Silva, L. F. A., F. J. L. Alves, and A. T. Marques. 2013. "*Materiais de Construção"*. Publindústria. ISBN: 9789899101746

TOX. 2021."TOX ®-Clinching Technology Clinching Tools and Accessories". *Data sheet 80.07* TOX® PRESSOTECHNIK GmbH & Co. K.. Accessed July 9, 2022. https://assets.tox.com/f/176476/x/05668defad/tox_tb_8007_en.pdf.

Wen, T., Q. Huang, Q. Liu, W. X. Ou, and S. Zhang. 2016. "Joining Different Metallic Sheets without Protrusion by Flat Hole Clinching Process." *International Journal of Advanced Manufacturing Technology* 85 (1–4): 217–25. https://doi.org/10.1007/s00170-015-7936-y.

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