Double-sided self-pierce riveting on polymer-metal joints

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Abstract: Double-sided self-pierce riveting is a recently proposed new joining by forming technology [1]. As the name suggests, this technology draws inspiration from the already well-established self-pierce riveting process and aims to provide an alternative solution for diverse applications due to its unique differentiation from already existing mechanical joining technologies in terms of inherent advantages and applicability. Conceptually, double-sided self-pierce riveting consists in joining together two components by pressing between them a tubular rivet with chamfered ends on both sides through the action of a punch. The interaction between the solicited compressive force and the geometry of the rivet causes it to gradually pierce and flare through both materials, generating a mechanical lock between the components.

The main goal established for this thesis is to develop knowledge regarding double-sided self-pierce riveting by providing further experimental and computational investigation and analysis to the process and its key variables, while expanding its range of material applications to polymers and subsequently dissimilar polymer-metal applications.

1. Introduction

Pressured by the present fast-paced technological modernization period fueled by environmental and socio-economic challenges, the industrial sector is actively shifting and seeking new solutions and technologies capable of responding to present demands and requirements. Consequently, a growing in innovation, developments, and introduction of new materials to most industries, as well as the adaptation of existing materials to novel applications increased the need to develop technologies capable of handling such variations. Parallel to this, development needs equally grow in the technologies that come with industrial manufacturing, namely joining technologies.

This thesis is therefore focused in extending both the knowledge and the application range of double-sided self-pierce riveting, an innovative mechanical joining technology, by studying its implementation in commonly used materials and material combinations presently used. The interest in extending the development of this technology was fueled by the promising outcomes generated in initial studies. Characterized as a joining by forming process, double-sided self-pierce riveting presents itself as an appealing alternative to existing mechanical joining technologies like self-pierce riveting or clinching, providing comparative performance behaviors with inherent benefits that could better serve certain industrial applications.

By further investigating double-sided self-pierce riveting, this thesis provides enough advancements in the joining technology to assert its benefits and challenges, to ultimately seek its industrial implementation as a compelling, efficient, and effective alternative to current joining technologies. Given the early stage of development of the technology, the driving proposition of this thesis was to expand its range of applications in terms of materials to be joined, initially to polymers and later in dissimilar materials with very different mechanical strengths, to provide a proof of concept while simultaneously differentiating it and highlighting its main advantages from well-established joining technologies.

Nonetheless, work and analyses conducted were carefully and intently adjusted to ultimately pursue the industrial implementation of double-sided self-pierce riveting by experimenting potential optimizations that could benefit both the joint performance and its application.

2. DSSPR of polymer sheets [2]

The experimental work on double-sided self-pierce riveting (DSSPR) made use of polyvinylchloride (PVC) sheets with 6 mm and AISI 304 stainless steel tubular rivets with an outer $d_0 = 10$ mm and a wall thickness $t_0 = 1.5$ mm. The flow curve of the PVC in compression was determined by means of stack compression tests performed in cylinder test specimens that were assembled by pilling up three discs with 15 mm diameter and 5 mm thickness. The discs were machined out from the supplied polymer sheets and the stack compression tests were carried out at room temperature in a hydraulic testing machine (Instron SATEC 1200 kN) with a crosshead speed of 10 mm/min.

The flow curve of the PVC in tension was not characterized because the main acting stresses during DSSPR are compressive. The flow curve of the AISI 304 stainless steel tubular rivets was retrieved from a previous work of the authors [1].

The flow curves of both materials are shown in Figure 1.

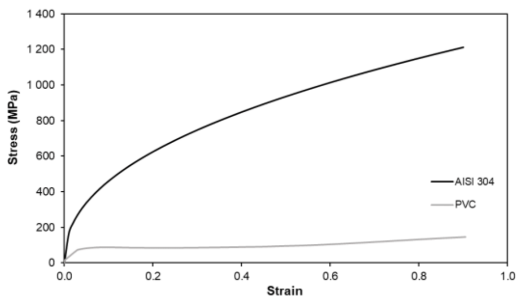


Figure 1 Flow curves of the polyvinylchloride (PVC) sheets and of the AISI 304 stainless steel tubular rivets.

2.1 Joining tests

Double-sided self-pierce riveting (DSSPR) of polymer sheets was carried out in 'unit cells' (Figure 2) representative of its application in large sheets connected by multiple joints. The tests were performed at room temperature in the hydraulic testing machine that had been used for determining the flow curves of the materials

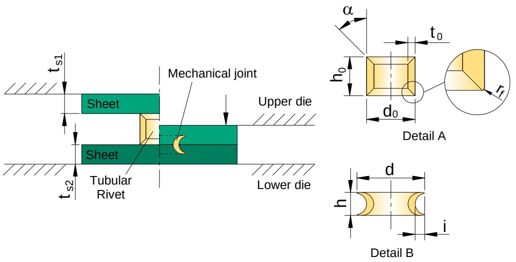


Figure 2 Working principle of double-sided self-pierce riveting. The details 'A' and 'B' show the tubular rivets at the beginning and end of stroke.

The tests allowed identifying six main geometric process parameters. Five of these parameters are identical to those previously identified in DSSPR of metal sheets; (i) outer diameter d_0, (ii) height h_0, (iii) wall thickness t_0 and (iv) chamfered angle α of the undeformed tubular rivets, and (v) thickness t_{si} of the upper and lower polymer sheets. The sixth parameter, not considered in DSSPR of metal sheets, is the chamfered fillet radius r_f of the tubular rivet (refer to the magnification in detail 'A' of Figure 2).

2.2 Finite element tests

Figure 3 shows the finite element model utilized in the numerical simulation of a test case corresponding to $h_0 = 8$ mm and $\alpha = 45º$ at the beginning and end of stroke. The model made use of rotational symmetry and the longitudinal cross section of the sheets and rivet were discretized by approximately 3000 quadrilateral elements. Local and global remeshings at intermediate strokes were carried out to repair the elements that became too much distorted during the numerical simulation and to progressively increase the overall number of elements up to approximately 7500.

The flat compression platens were modelled as rigid bodies and discretized by means of linear contact-friction elements.

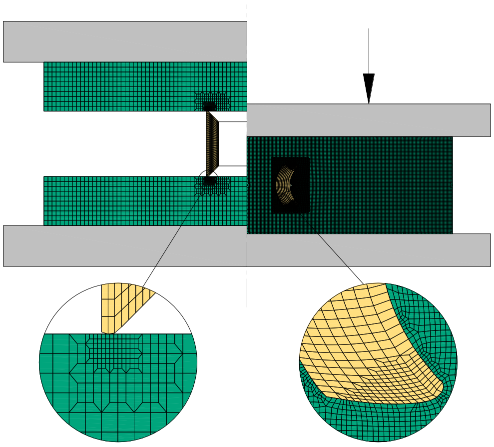


Figure 3 Finite element modelling of double-sided self-pierce riveting of polyvinylchloride sheets with a stainless-steel rivet at the beginning and end of stroke (h_0= 8 mm and α = 45º).

2.3 Results and discussion

Figure 4 shows the cross-sections of the experimental test cases corresponding to $h_0 = 8$ mm and $\alpha = 45°$ with two different chamfered fillet radius r_f of the tubular rivets. As seen, the tubular rivets with sharp chamfered ends (i.e., $r_f \cong 0$ mm) produce a near-straight cut in the polymer sheets without creating a mechanical interlocking (Figure 4a). This mode of deformation was not observed in metal sheets and is attributed to the fact that the tubular rivet made of AISI 304 stainless steel has a mechanical strength much higher than that of the polyvinylchloride sheets.

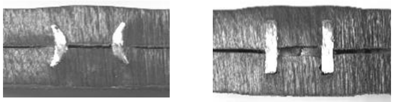
In contrast, when the chamfered ends are blunt due to a small fillet radius $r_f = 0.2$ mm, there is flaring of the tubular rivets as they pierce the polymer sheets and creation of a mechanical interlocking that clamp the sheets tightly together (Figure 4b).

The conclusion is that blunt chamfered ends are necessary to create a mechanical interlocking in double-sided self-pierce riveting of polymer sheets. The corresponding mode of deformation was confirmed by finite element modelling

a) b)

Figure 4 Cross-section of two different double-sided self-pierce riveted joints obtained (h0= 8 mm and α = 45º) with a) sharp chamfered ends rf ≅ 0 mm; b) blunt chamfered ends rf ≅ 0.2 mm.

Another geometric process parameter that influences material flow and mechanical interlocking is the initial chamfered angle α of the tubular rivets. Figure 5 shows the experimental results obtained for two different test geometries obtained with rivets having $h_0 = 8$ mm, and $\alpha = 30º$ and $\alpha = 90º$. As seen, the smaller the chamfered angle α (and longer the blunt chamfered end), the larger flaring curvature is obtained and, therefore, the greater mechanical interlocking distance i is produced. This is because low values of the chamfered angle α promote outward tubular material flow as opposed to high values, which in the extreme case of $\alpha = 90º$ will mainly lead to vertical penetration of the rivet through the upper and lower adjoining sheets with almost no signs of flaring curvature.



a) b)

Figure 5 Double-sided self-pierce riveted joints that made use of tubular rivets having an initial height $h_0 = 8$ mm and (a) $\alpha = 30º$, (b) $\alpha = 90º$

2.3.1 Riveting forces

Figure 6 presents the experimental and finite element predicted evolutions of the riveting force with stroke for two different test cases

The first observation of the evolutions allows concluding that the chamfer angle does not have a significant influence on the evolution of the force with the displacement. The maximum riveting forces for the tubular rivets with two different chamfered angles α are identical.

A more detailed observation of the force vs. stroke evolutions allows identifying three different stages (labelled as I, II and III). The increase in the riveting force during the first stage (I) results from the compression of the polymer sheets against the rivets, which compel them to flare as they are pierced through the sheets, and their wall thicknesses progressively increase up to the nominal value t_0. The second stage (II) corresponds to clamping during which the upper and lower adjoining sheets are progressively brought into contact. The third and final stage (III) corresponds to overload and exhibits a steep increase of the riveting force because of the two sheets being compressed against each other.

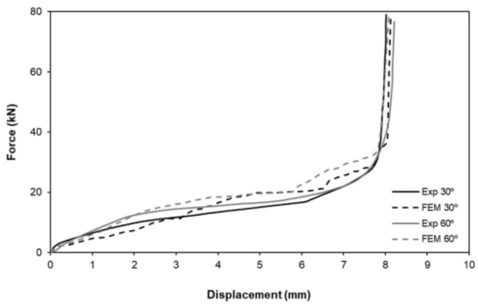


Figure 6 Experimental and finite element computed evolutions of the riveting force with stroke for the three different double-sided self-pierce riveted joints ($h_0 = 8$mm and $\alpha = 30º, 60º$).

2.3.2: Destructive tests

Figure 7 shows the results of the destructive tests that were carried out to determine the maximum peel and shear forces that double-sided self-pierce riveted joints can withstand without failure.

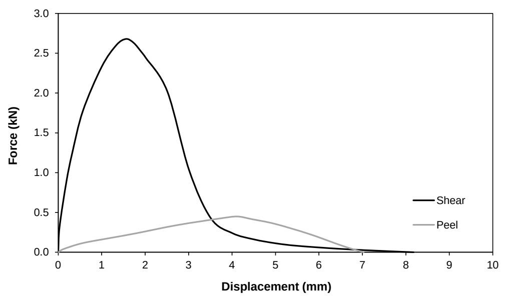


Figure 7 Experimental evolution of the force with displacement for the destructive test cases corresponding to ($h_0 = 8$mm and $\alpha = 45^o$).

Although the orders of magnitude of the results obtained in these two tests are lower than those achieved in the earlier tests carried out in metal sheets, the ratio between the values obtained in the peel and shear tests are in the same order of magnitude.

Double-sided self-pierce riveting (DSSPR) can be utilized to produce invisible lap joints in polymer sheets without material protrusions above and below the sheet surfaces, which require neither heating nor surface preparation like in welding or bonding.

3. DSSPR of dissimilar materials [3]

There is a fundamental question to be addressed with respect to the utilization of DSSPR that is often claimed to limit its overall applicability - the aptitude to connect sheets made from dissimilar materials with very different strengths.

Under these circumstances, this section is focused on the application of DSSPR to the connection of sheets made of AA5754-H111 aluminum and polyvinylchloride (PVC) at ambient temperature.

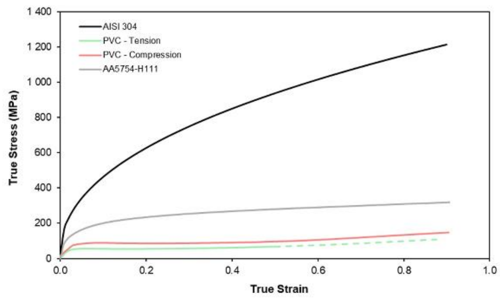


Figure 8 Stress-strain curves of the AA5754- H111 and PVC sheets and of the AISI 304 stainless-steel rivets.

3.1 Joining tests

The objectives of the experimental workplan were accomplished by means of two different strategies. The first strategy, which coincided chronologically with the beginning of this investigation, aimed at extending the applicability of single stroke DSSPR to dissimilar sheet materials with significant differences in strength.

The first set of test runs made use of rivets having equal chamfered angles α in the contact with the aluminium and PVC sheets ($\alpha_{alu} = \alpha_{PVC}$). The second set of test runs explored the possibility of using different chamfered angles ($\alpha_{alu} \neq \alpha_{PVC}$) in the contacts with the two different sheets.

The second strategy is based on a new two-stroke DSSPR concept in which the tubular rivet is first forced through the harder sheet with the help of a dedicated compression tool consisting of a bolster and a conical punch, and then pressed through the softer sheet to obtain a symmetric joint with good undercuts in both sheets. The working principle of the two-stroke DSSPR concept is shown in Figure 9.

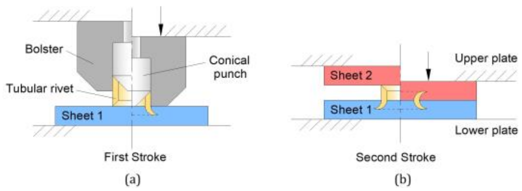


Figure 9 The new proposed two-stroke double-sided self-pierce riveting process at the (a) beginning and end of the first stroke and at the (b) beginning and end of the second stroke (i.e., end of the process).

3.2 Finite element tests

Figure 10 shows the initial and final meshes of a cross-sectional joint produced by single stroke DSSPR. The initial mesh was automatically generated and refined in the pre-processor module of i-form by combination of a grid-based and a quadtree subdivision strategy. The tools were modelled as rigid objects and discretized by means of linear contact-friction elements.

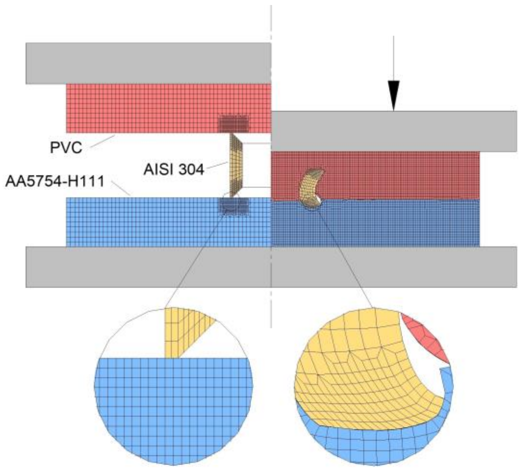


Figure 10 Finite element model utilized in the numerical simulation of the single-stroke double-sided self-pierce riveting of AA5754-H111 aluminum and PVC sheets with AISI 304 stainless-steel rivets at the beginning and end of the process ($\alpha_{alu} = 45º, \alpha_{pvc} = 45º$).

3.3 Results and discussion

3.3.1 Conventional DSSPR

The results shown in Figure 11 reveal that the cross-sectional joints are asymmetric with the deformed rivets showing greater penetration in the PVC sheets than in the aluminum sheets due to greater mechanical strength of the latter. The conclusion from the entire set of experimental and numerical tests performed by the authors, was that although single stroke DSSPR can produce good mechanical interlockings (e.g., Figure 11b), the above-mentioned horizontal and vertical asymmetries justified the need to develop a new process variant where these problems could be minimized or even eliminated

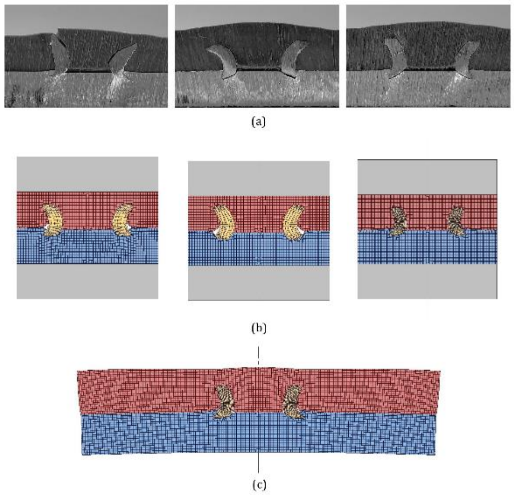


Figure 11 Application of single-stroke double-sided self-pierce riveting to the connection of AA5754-H111 aluminum and PVC sheets with AISI 304 stainless-steel rivets.

3.3.2 Two-stroke DSSPR

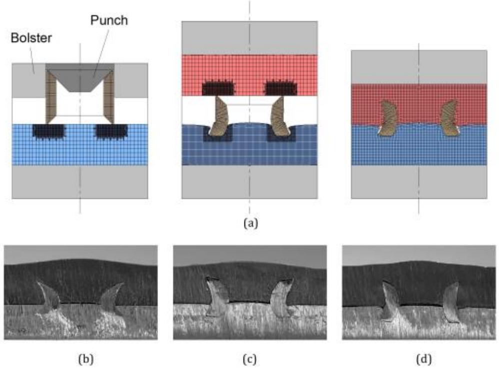


Figure 12 Application of double-stroke double-sided self-pierce riveting to the connection of AA5754-H111 aluminum and PVC sheets with AISI 304 stainless-steel rivets.

As seen from the finite element simulation results and from the photographs of the cross-sectional joints that are included in Figures 12b-d, the new two-stroke DSSPR is effective in minimizing both the horizontal and vertical asymmetries. The improvement in horizontal symmetry is due to a better control of the total amount of rivet height that is forced through the aluminum sheet during the first punch stroke. The lower sensitivity to variations in manufacturing tolerances, which were responsible for the vertical asymmetries that were observed in the single stroke DSSPR, is because rivets are now guided during piercing and flaring in the sheet with greater mechanical strength.

3.3.3 Destructive tests

Figure 13 shows such a comparison for the test case ($\alpha_{alu} = 45º, \alpha_{pvc} = 45º$) previously shown in Figures 8a and 8c, in which it is possible to conclude that the maximum force for detaching the AA5754-H111-PVC sheets is in-between the values obtained for the monolithic joints.

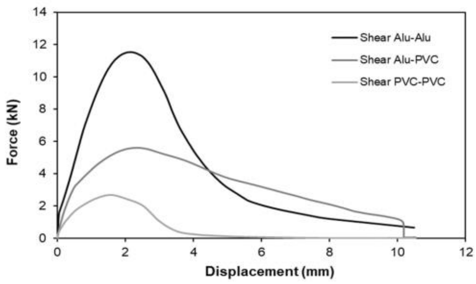


Figure 13 Experimental evolution of the destructive shear test force with displacement for the AA5754-H111-PVC joints ($\alpha_{alu} = 45º, \alpha_{pvc} = 45º$) produced by two-stroke double-sided self-pierce riveting.

Two-stroke double-sided self-pierce riveting can join overlapped sheets made from dissimilar materials with very different strengths. Extension of the conventional single stroke double-sided self-pierce riveting to the connection of overlapped sheets made from dissimilar materials with very different strengths are feasible if the tubular rivets are prepared with different chamfered angles (e.g. 30º and 60º degrees) at their ends. However, the advantage of joining dissimilar sheets in a single stroke comes with the price of the resulting cross-sections being highly asymmetric due to greater or lesser penetration of the rivets into the sheets

4 DSSPR with flat-bottom holes [4]

This section is focused on solving the problems of positioning and alignment of rivets in double-sided self-pierce riveting by means of flat-bottom holes that are previously machined in the overlapped sheets with greater mechanical strength.

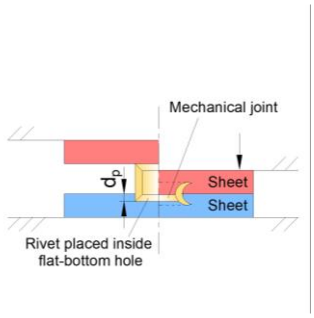


Figure 14 Proposed DSSPR with flat- bottom hole showing the geometries at the beginning and end of joining.

4.1 Joining and numerical tests:

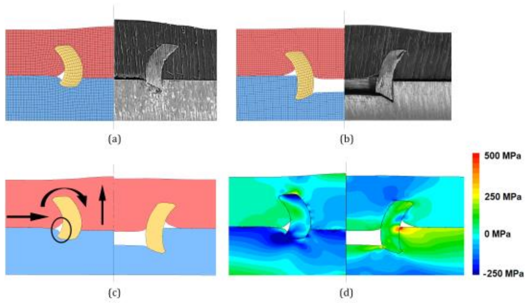


Figure 14 Double-sided self-pierce riveting (DSSPR) of AA5754-H111 aluminum and PVC sheets with AISI 304 stainless-steel rivets having chamfered angles equal to 45º at both ends.

As seen in Figures 14a and 14b, the new proposed DSSPR reduces the amount of unfilled volume between the lower sheet and the outer rivet wall that is observed in conventional DSSPR.

The experimental and numerically predicted protrusions of Figure 14 are due to the elimination of the circumferential constrain when halving the specimens lengthwise to reveal their cross-sections. This elimination is not taken into consideration in finite element modelling.

results in Figure 14b and in the right-side detail of Figure 14c indicate that the mechanical interlocking between the rivet and the AA5754-H111 aluminium sheet is smaller and almost disappears. In other words, the form-closed mechanism that prevails in conventional DSSPR is replaced by a force-closed mechanism based on the residual normal pressures (radial stresses) that are created on the contact interface between the rivet and the flat-bottom hole of the aluminium sheet at the end of joining (i.e., after unloading).

Figure 14d shows the finite element predicted distributions of radial stresses for the conventional and new DSSPR with a flat-bottom hole after unloading.

These radial stresses prevent tangential movement due to friction and help keeping the two sheets together.

The solution to recover the mechanical interlocking in DSSPR with flat-bottom holes involves the use of different chamfered angles in the rivet ends to account for the greater or lesser difficulty of piercing through sheets with higher or lesser mechanical strength. The result is shown in Figure 14 for a test case using different chamfered angles at the rivet ends ($\alpha_{Alu} = 60º$ and $\alpha_{PVC} = 30º$). Measurements of the undercuts in both the aluminium and PVC sheets provide values of 0.33 mm and 0.88 mm, respectively, demonstrating that it is possible to obtain a combined form and force-closed joint in DSSPR with flat-bottom holes, if different chamfered angles are machined at the rivet ends.

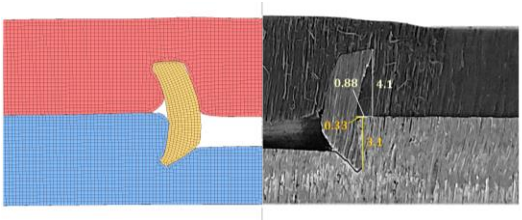


Figure 14 Finite element and photograph of a cross-sectional joint made from AA5754-H111 aluminum and PVC sheets with AISI 304 stainless-steel rivets having different chamfered angles $\alpha_{Alu} = 60º$ and $\alpha_{PVC} = 30º$ ($d_p = 2$ mm).

4.2 Destructive tests

The importance of having a mechanical interlocking in the aluminum sheet is demonstrated by analyzing the results of the destructive tests carried out in joints produced by the conventional DSSPR and the new DSSPR with flat-bottom holes.

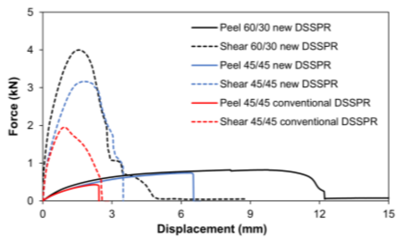


Figure 16 Destructive peel and shear forces vs. displacement for overlapped joints made from AA5754-H111 aluminum and PVC sheets that were assembled with AISI 304 stainless-steel rivets by means of the conventional and the new DSSPR with flat-bottom holes

The shear strength of the joints produced by the new DSSPR using rivets with different chamfered angles is the greatest (4 kN) and equal to twice of the joints produced by conventional DSSPR due to the combined action of the undercut in the aluminium sheet plus friction on the rivet-hole contact interface. In what concerns the resistance to peel, greater values are once again obtained for the joints produced by the new DSSPR with rivets having different chamfered angles.

Positioning and alignment of the rivets in double-sided self-pierce riveting (DSSPR) can be solved by machining flat-bottom holes in the sheets with greater mechanical strength. The geometry of the flat-bottom holes regardless of their depth tends to modify he predominant form-closed mechanism of conventional DSSPR into a predominant force-closed mechanism, in which the friction forces acting along the rivet-hole interfaces are responsible for keeping the overlapped sheets together.

5 Conclusion The work developed in polymers proved its relevancy by confirming the implementation of DSSPR in materials with reduced mechanical strength, and exceeded expectations given the complex interaction between the polymer and the steel rivets, with very distinct properties. Based on the interactions observed in the PVC sheets, the joining of dissimilar materials was expected to be a more difficult task. Initial results did in fact substantiate such expectation, since the produced joints lacked the ability to effectively join both sheets due to the asymmetrical piercing of the rivet in each component, justified by the difference in mechanical strengths of both materials. Despite the less satisfactory results, the existing confidence in DSSPR fuelled the search for meaningful solutions to bypass the challenges present in dissimilar material joints, and two optimization solutions were proposed: two-stroke DSSPR, and DSSPR assisted with flat- bottom holes.

Double-sided Self-pierce Riveting still has a great range of developments to go through before being acknowledged as an alternative to conventional solutions, justified by the vast opportunities in terms of expansion of application range and optimizations.

Acknowledgement

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