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Abstract

This paper is focused on hybrid busbars, which are key elements in modern electric vehicles for distributing electric power to multiple equipment such as the electric motor, the electric power steering unit, and the AC/DC converters. The authors investigate the possibility of replacing fastening by a new joining by forming process to assemble the copper and aluminum conductors of hybrid busbars at ambient temperature. For this purpose, the paper starts by analyzing the influence of the bolts, of their tightening torque and of the sheet surface preparation conditions in current flow and electric resistance of fastened hybrid busbars. Then, the new joining by forming process named ‘injection lap riveting’, with a two-stage fabrication route is introduced, and comparisons are made between the current flow and electric resistance of the two different types of hybrid busbars. The work is based on a combined experimental and numerical investigation, and results show that the electric performance of injection lap riveted hybrid busbars made from sheets in the as supplied condition is similar to that of fastened hybrid busbars made from sheets with previous surface preparation by grinding. The electric performance of the injection lap riveted hybrid busbars is stable and not compromised by the loosening effects that are commonly experienced by fastened hybrid busbars, which give rise to a significant increase of the electric resistance.

Keywords: Hybrid busbars, Electric vehicles; Fastening, Joining by forming

1. Introduction

Electric mobility is keeping the forming industry on their toes due to the opportunities in the production of components for asynchronous motors and to the challenges derived from the growing body-in-white lightweight requirements of the new generation of vehicles.

Body-in-white lightweight requirements are expected to increase the demand for structural parts made from dissimilar materials like, for example, carbon fiber reinforced polymer laminates with steel and aluminum sheets and joining by forming is among the key technologies to be used in the assembly of these parts. In fact, the use of joining by forming processes such as self-pierce riveting [1] and clinching [2] to assemble structural parts made from dissimilar materials avoids the technical difficulties of resistance spot welding and flow drill screws as well as the long production run times of adhesives.

This paper is focused on another opportunity in the field of joining by forming that has so far received little attention - the fabrication of busbars. Busbars are utilized to distribute electric current to multiple pieces of equipment in electric vehicles because they are easy to install and maintain, and because they are advantageous in terms of safety, cost, and space limitations. Busbars are preferentially made of copper due to its high electric conductivity and low coefficient of linear thermal expansion, but because copper is a heavy and expensive material there is a growing interest in using aluminum in busbars for electric vehicles. Aluminum is a good electrical conductor that is both lighter and cheaper than copper, but the switch from copper to aluminum comes at the cost of diminishing the current carrying capacity and increasing the overall impedance of the busbars [3]. In practical terms this means that the cross section of the aluminum busbars must be increased to obtain an electric conductance like that of copper.

A solution to combine the technical advantages of copper with the lightweight and economic advantages of aluminum is by using hybrid busbars, in which the thinner and costlier parts made of copper are only used in specific key locations. In current state-of-technology, this requires assembling the copper and aluminum conductors by means of the currently available joining processes such as laser beam welding, friction stir spot welding, ultrasonic welding, resistance spot welding, self-pierce riveting or fastening (Figure 1).
Laser beam welding (Figure 1a) is used for connecting cell terminals to busbars and for joining busbars [4]. The main advantage of the process results from concentrating the energy of light beams on very small surface areas to minimize the heat-affected zones, where distortions and changes in the metallurgical structure and mechanical strength of the materials are likely to occur. However, its utilization in hybrid busbars is challenging due to the low absorptivity of copper in the typical wavelength working ranges of industrial lasers, to the differences in the physical and thermal properties of copper and aluminum and to the limited solubility of copper and aluminum (giving rise to the formation of hard and brittle intermetallic compounds) [5].

Friction stir spot welding (Figure 1b) uses a rotating, threaded pin tool with a convex shaped shoulder to generate heat by friction and create a solid bond between two sheets by plastic deformation. Its utilization in the fabrication of hybrid busbars is difficult because the overall quality and performance of the copper-aluminum joints is very sensitive to process parameters, to differences in material mixing and to the final distribution of intermetallic compounds [6].

Ultrasonic welding (Figure 1c) [7] is used for assembling cell terminals to busbar connectors in pouch-cells and is used in several electric vehicles such as the Nissan Leaf, the Chevrolet Volt, the Chevrolet Spark, and the Chevrolet Bolt [8]. The process combines pressure and localized high-frequency vibration to generate enough plastic deformation and friction to deform asperities, break-up oxides and create a metallurgical bond by direct exposure and intimate true metallic contact between the clean surfaces of the copper and aluminum sheets. However, its utilization in hybrid busbars may lead to plastic deformation of the upper sheet surface due to differences in the mechanical strength of the copper and aluminum sheets.

Resistance spot-welding (Figure 1d) is mainly used for connecting battery cell terminals to busbars [9]. The process utilizes electric current to locally heat and melt the sheets and produce a joint but its application to the fabrication of hybrid busbars is only feasible for thin conductors due to the elevated energy input that is needed to compensate the high thermal conductivities of copper and aluminum.

Self-pierce riveting (Figure 1e) is a joining by forming process that makes use of a semi-tubular rivet to produce a form-fit mechanical interlocking between the copper and aluminum sheets. The process is carried out at room temperature and avoids the metallurgical problems that are inherent to other previously mentioned processes such as laser beam welding, friction stir spot welding, and resistance welding. However, its application to hybrid busbars is limited by the total sheet thickness of the joints (usually between 1.5 and 4 mm) and by the necessity of placing the thinner or softer sheet on the rivet side [10].

Fastening (Figure 1f) is the most widespread technology to assemble busbars because the resulting joints are easy to assemble and disassemble during installation, maintenance, and removal at the end of service life. Several electric vehicles such as the Nissan Leaf and the Toyota Prius make use of fastened joints. The main disadvantages of fastening are the non-uniform contact pressures, the condition of the surfaces and the unintentional self-loosening, which causes distortion of the electric current flow [11, 12].

The aim of this paper is twofold. First, to focus on the fastened hybrid busbars made from copper and aluminum with the purpose of analyzing the influence of the bolts, tightening torque, contact pressure and sheet surface condition on the electric current flow and electric resistance. Second, to present a new joining by forming process named ‘injection lap riveting’ that was recently developed by the authors [13] for the assembly of hybrid busbars. The process is carried out at room temperature, thereby preventing the brittleness associated to the occurrence of intermetallic compounds and avoids the formation of material protrusions above and below the sheet surfaces. Comparisons are made between the electric performance of the hybrid busbars produced by this new joining by forming process and by conventional fastening.

The presentation combines experimentation in unit cells that are representative of the hybrid busbars and numerical simulation using the electro-mechanical capabilities of an in-house finite element computer program developed by the authors. Numerical predictions obtained for an ideal hybrid busbar with perfect contact and no contaminant/oxide films on the copper-aluminum interface are utilized for reference purposes.
2. Methods and procedures

2.1. Mechanical and electrical characterization of materials

The hybrid busbars utilized in the investigation were made from C11000 copper and AA6082-T6 aluminum sheets with 2 mm and 5 mm thickness, respectively. The mechanical behavior of the copper and aluminum sheets was obtained by means of tensile and stack compression tests performed at room temperature and the results of these tests are summarized in Table 1. Table 1 also includes the mechanical properties of the medium carbon steel (class 8.8) bolts and nuts that were used in the fastened joints [14]. The stress-strain curves resulting from the tensile and stack compression tests are shown in Figure 2.

<table>
<thead>
<tr>
<th></th>
<th>C11000 copper</th>
<th>AA6082-T6 aluminum</th>
<th>Steel (class 8.8)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic modulus (GPa)</td>
<td>110</td>
<td>69</td>
<td>205</td>
</tr>
<tr>
<td>Yield stress (MPa)</td>
<td>333</td>
<td>260</td>
<td>640</td>
</tr>
<tr>
<td>Poisson ratio</td>
<td>0.36</td>
<td>0.33</td>
<td>0.29</td>
</tr>
<tr>
<td>Electric resistivity (µΩm)</td>
<td>0.0170-0.0187</td>
<td>0.0361-0.0394</td>
<td>0.213</td>
</tr>
</tbody>
</table>

Figure 2. True-stress vs. true strain curves of the C11000 copper and the AA6082-T6 aluminum.

The electric resistivities of C11000 copper and AA6082-T6 aluminum were determined in the experimental setup shown in Figure 3. The setup consists of two copper blocks, where the specimens are clamped and connected to the power supply of a micro-ohmmeter Kocsos PROMET R600. A current of 600 A is passed through the specimens during approximately 2 s to allow measuring the induced voltage drop $V$ between two probes spaced 100 mm apart. The electric resistance is then calculated from Ohm’s law.

Because each test took approximately 2 s to be performed, the temperature changes in the specimens are negligible and the electric resistivity values included in Table 1 are assumed to remain constant during the entire duration of the tests.

Figure 3. Experimental setup utilized for measuring the electric resistance.
2.2. Design and fabrication of the hybrid busbars

The design of hybrid busbars requires the thicknesses of the copper and aluminum sheets to account for the differences in electric resistivity $\rho$ of the two materials (Table 1) in order to obtain a constant electric conductance $G$. Because the electric conductance $G$ of a sheet is proportional to its cross-sectional area $A$ and inverse proportional to its electric resistivity $\rho$ and length $l$, the following relation between the cross-sectional area ratio and the electric resistivity ratio of the two sheets, is obtained,

$$G = \frac{A}{\rho r l} \rightarrow \frac{A_\text{Al}}{A_\text{Cu}} = \frac{\rho_\text{Cu}}{\rho_\text{Al}} = 2.3 \quad (1)$$

The result obtained in (1) corresponds to the highest value calculated from the experimentally measured electric resistivity values that are included in Table 1. Considering that the unit cells utilized in the experiments were fabricated with a constant width of $w=50$ mm, it follows that the utilization of C11000 copper and AA6082-T6 aluminum commercial sheets with 2 and 5 mm thickness copes (from a practical point of view) with the cross-sectional area requirements given by (1).

The experimental work was carried out in hybrid busbars that are representative of the ones produced by fastening and by the new joining by forming process named as ‘injection lap riveting’ that was developed by the authors. The fabrication procedures that were utilized to fabricate the two different types of unit cells are schematically illustrated in Figures 4a and 4b.

Figure 4. Schematic representation of the procedures that were utilized to fabricate the unit cells by (a) fastening and (b) injection lap riveting with photographs of the real test specimens. (c) Self-pierce riveting is included for comparison purposes.

The fastened unit cells (Figure 4a) were fabricated by drilling through holes of 8.4 mm diameter in the copper and aluminum sheets to allow the utilization of the M8 hexagonal socket head bolts made from medium carbon steel (class
Before clamping the two sheets together by applying a tightening torque $T$ on the bolt, the surfaces of the sheets were prepared by mechanical grinding with emery paper.

The injection lap riveted unit cells (Figure 4b) were fabricated in two-stages. First, a dovetail ring hole (hereafter designated as ‘dovetail hole’) and a countersunk hole were machined in the lower (aluminum) and upper (copper) sheets, respectively. Then, a semi-tubular rivet made from copper was injected through the upper sheet into the dovetail hole of the lower sheet to obtain the form-fit mechanical interlocking. The working principle of this new joining by forming process is solely based on plasticity and friction, in contrast to self-pierce riveting (Figure 4c), which is based on plasticity, friction, and fracture to allow the rivet to create an undercut while it is pierced through the sheets.

The main advantages of the proposed injection lap riveting process over self-pierce riveting are listed as follows:
(a) Absence of material protrusions above and below the sheet surfaces,
(b) The rivets can be made from the materials of the sheets, which is of paramount importance in hybrid busbars,
(c) There is no upper limit on the total thickness of the sheets to join,
(d) There is no requirement of the thinner and/or softer sheet to be placed on the punch side,
(e) There is no need of two-side access if the lower sheet is thick and stiff enough to withstand the injection of the rivet without (or, with minor) plastic deformation.

The main disadvantage of injection lap riveting is the two-stage fabrication derived from the necessity of pre-drilling the dovetail and the countersunk holes. This makes the process slower than self-pierce riveting.

2.3. Testing the hybrid busbars

The experimental plan carried out with the unit cells of the fastened hybrid busbars was conceived with the aim of analyzing the combined influence of the sheet surface conditions and of the tightening torques applied on the bolts on the electric resistance. Four different surface preparations corresponding to the ‘as supplied’ condition and to grinding with emery paper of 40, 80 and 1200 grit size were used in conjunction with tightening torques varying from 1 Nm (near loosening) to 30 Nm (Table 2).

<table>
<thead>
<tr>
<th>Torque $T$ (Nm)</th>
<th>Surface preparation (emery paper grit size)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1, 2, 3, 4, 5, 10, 15, 20, 25, 30</td>
<td>40, 80, 1200, as supplied</td>
</tr>
</tbody>
</table>

On the other hand, the experimental plan carried out with the unit cells of the injection lap riveted hybrid busbars was conceived with two different objectives. First, to identify the main process parameters and to analyze the influence of the dovetail hole geometry on material flow and on the riveting and destructive forces. Second, to measure the electric resistance of the joints and compare the results obtained with those of the unit cells of the fastened hybrid busbars. The experiments made use of copper and aluminum sheets in the as supplied condition.

The main process parameters of the injection lap riveting process are indicated in Table 3 as: (i) the inclination angle $\alpha$, (ii) the depth $d_p$, (iii) the thickness $t$ of the dovetail holes, and (iv) the inner diameter $d_i$, (v) outer diameter $d_o$ and (vi) the shank length $S$ of the rivets.

<table>
<thead>
<tr>
<th>Aluminum (AA6082-T6) sheets with dovetail ring holes</th>
</tr>
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<tbody>
<tr>
<td>$\alpha$ (°)</td>
</tr>
<tr>
<td>15</td>
</tr>
<tr>
<td>30</td>
</tr>
<tr>
<td>45</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Semi-tubular rivets (99.9% electrolytic copper)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_i$ (mm)</td>
</tr>
<tr>
<td>2.0±0.1</td>
</tr>
</tbody>
</table>
The first objective of the experimental plan performed with the unit cells of the injection lap riveted hybrid busbars consisted of injecting the semi-tubular rivets into the dovetail holes with different inclination angles and depths by compressing their heads with a punch. The thickness $t$ of the dovetail holes, which is defined by the geometry of the cutter, and the inner $d_1$ and outer $d_2$ diameters of the semi-tubular rivets, which must be compatible with the geometry of the dovetail holes, were kept constant to reduce the overall number of tests to be performed. The shank length $S$ of the semi-tubular rivets was calculated for each testing condition to ensure complete filling of the dovetail holes.

The second objective of the experimental plan consisted of fabricating the unit cells of the injection lap riveted hybrid busbars and measuring their electric resistance.

The electric resistances of the fastened and injection lap riveted unit cells were determined in the experimental setup that had been previously used to determine the electric resistivities of the copper and aluminum sheets (Figure 3). A similar procedure based on a 600 A current passing through the specimens during approximately 2 s was utilized for measuring the voltage drop $V$ and calculate the electric resistance.

2.4. Numerical modelling

Numerical modelling was carried out with the finite element computer program i-form that was developed by the authors [15, 16]. Two different types of simulations were carried out: (i) mechanical and (ii) electro-mechanical.

The mechanical simulations consisted of replicating the injection of the semi-tubular rivets into the dovetail holes of the sheets (Figure 5) and the assembly of the copper and aluminum sheets through a form-fit mechanical interlocking. The sheets and rivets were modelled as deformable objects and the plastic deformation of the rivets and neighboring sheet materials were assumed to be rotational symmetric. In contrast, the punches and dies were assumed to be rigid contact-friction objects.

![Figure 5. Initial and final computed meshes of the injection of a semi-tubular rivet made from electrolytic copper into a dovetail hole of an aluminum AA6082-T6 sheet ($\alpha = 30^\circ$, $d_p = 4$ mm).](image)

The electro-mechanical numerical modelling made use of a staggered coupling between the mechanical and electric modules of i-form and was performed with the objective of replicating the testing conditions described in Figure 3. The simulations allowed authors to obtain the distribution of electric potential in the unit cells of the fastened and injection lap riveted joints, from which, after differentiation and multiplication by the electric conductivity, it was possible to determine the distribution of current density $j$ and the electric resistance. Three-dimensional finite element models had to be used because rotational symmetric conditions are not applicable for the testing conditions of Figure 3.

Figure 6 shows half of the electro-mechanical finite element model that was utilized for the unit cells of the fastened hybrid busbars. The sheets, bolt, nut, and thin-interface layer located in-between the two sheets (not seen in the figure) were assumed as deformable objects and their material behaviors were modelled as elastic-plastic. The tightening torque was modelled by applying the corresponding tension directly on the bolt end (refer to the arrow in Figure 6). The dependence of the electric resistivity $\rho^e = C/\sqrt{p_n}$ on the normal pressure $p_n$ applied on the thin-interface layer followed the model proposed in [17], where $C$ is a constant to be experimentally determined.

A current of 600 A was passed through the objects and no temperature effects were taken into consideration due to the very small duration of the tests (approximately 2 s). The probes for measuring the electric resistance of the unit cells were spaced 100 mm apart and modelled by means of the left and rightmost parallelepipedic rigid objects of Figure 6.
Before finishing this section, it is worth mentioning that the term ‘unit cell’ will not be used in the following sections of the paper. In what follows, the experimental and numerical test specimens will simply be designated as ‘fastened’ or ‘injection lap riveted’ hybrid busbars.

![Figure 6. Electro-mechanical finite element model of the experimental test for measuring the electric resistance of a fastened hybrid busbar. The purple arrow indicates tension corresponding to the tightening torque applied to the bolt.](image)

3. Results and discussion

3.1. Fastened hybrid busbars

Figure 7 shows the electric resistance of the fastened hybrid busbars made from sheets with different initial surface preparation conditions as a function of the tightening torque applied to the bolts. The solid markers correspond to experimental measurements obtained under two extreme surface preparation conditions corresponding to grinding with emery papers of 40, 80 and 1200 grit sizes.

![Figure 7. Electric resistance as a function of the tightening torque applied on the bolts for fastened hybrid busbars made from sheets with four different initial surface preparation conditions.](image)

The utilization of emery papers of 40 or 80 grit size resulted in average initial surface roughness $R_a$ of the sheet surfaces equal to 1.27 µm and 0.87 µm, respectively, and clearly visible marks (asperities) and grinding directions, whereas the use of emery paper of 1200 grit size allowed obtaining surfaces with much lower average surface roughness $R_a \geq 0.20$ µm. The dashed lines included in Figure 7 correspond to fittings of the experimental values of electric resistance for the two above-mentioned extreme surface preparation conditions.
Two main observations are derived from Figure 7. First, the electric resistances of the fastened hybrid busbars made from sheets that were ground with the emery papers of 40 or 80 grit sizes are always smaller than those of the hybrid busbars made from sheets that were ground with emery papers of 1200 grit size, regardless of the tightening torque applied to the bolts. Second, the evolutions of the electric resistance with the tightening torque for specimens with identical initial surface preparation is characterized by two different regions (labelled as ‘A’ and ‘B’). In region ‘A’ the electric resistance increases rapidly as the tightening torque decreases, whereas in region ‘B’ the electric resistance is approximately constant, regardless of the tightening torque applied to the bolts.

The first observation allows concluding that surface grinding is very important to reduce the electric resistance because it cleans and breaks out the contaminant and oxide films into small particles, thereby permitting electric current to flow easier due to a reduction in the electric resistance. In fact, the sheets ground with emery paper of 1200 grit size provided a minimum electric resistance (\( R = 18.8 \, \mu\Omega \)) that is slightly greater than that obtained for the sheets ground with emery paper of 40 or 80 grit sizes (\( R = 18.3 \, \mu\Omega \)). Because the electric resistance obtained for the fastened hybrid busbars that were made from sheets in the as supplied condition (\( R = 23.3 \, \mu\Omega \)) is significantly higher than the electric resistance of the sheets ground with emery paper of 1200 grit size, one concludes that grinding with emery paper is effective for cleaning and breaking out the contaminant and oxide films along the contact interface between the two sheets.

The second observation allows concluding that for small tightening torques (say \( T < 5 \, \text{Nm} \) for initial surface sheet preparations with emery paper of 40 or 80 grit size, or \( T < 20 \, \text{Nm} \) for initial surface sheet preparations with emery paper of 1200 grit size), the asperities and the films across the thin-interface layer located in-between the two sheets create difficulties to the passage of electric current and, therefore, increase the electric resistance. In contrast, when the tightening torques are greater and the normal pressure on the thin-interface layer becomes significant, the asperities are sufficiently flattened out and the films are broken enough to facilitate the passage of current and reduce the electric resistance. The diminishing of electric resistivity on the regions of the thin-interface layer located in-between the two sheets where the normal pressure is higher is shown in the finite element results that are included in Figure 8.
Figure 8. Finite element analysis of the fastened hybrid busbars ($T = 25$ Nm, emery paper 80 grit size) showing: (a) the distribution of vertical stress (MPa), (b) the distribution of electric resistivity ($\mu\Omega m$) at the thin-interface layer and (c) the distribution of electric current density ($A/mm^2$).

Two additional observations can be made from the results shown in Figure 7. First, considering the hybrid busbars made from sheets ground with emery paper with 40 or 80 grit size, it is concluded that for small tightening torques (say $T < 3$ Nm) there are differences between the experimental and finite element predicted values of electric resistance, which become more significant as the tightening torque decreases. These differences disappear and the agreement is good when greater tightening torques are applied to the bolts.

Second, the minimum admissible value of electric resistance $R = 12 \mu\Omega$ is obtained for an ‘ideal hybrid busbar’ finite element model with perfect contact and absence of contaminant and oxide films between the copper and aluminum sheets.

The first observation allows concluding that finite element models fail in modelling of near loosening conditions because they assumed perfect contact and complete absence of films across the bolt head-copper sheet and the nut-aluminum sheet contact interfaces. This means that a similar resistivity dependence on the normal pressure should have been used for these contact interfaces because their asperities and films are only sufficiently flattened out and broken for tightening torques $T > 3$ Nm.

The second observation allows concluding that the $\Delta R = 6.3 \mu\Omega$ difference between the minimum electric resistance of the fastened hybrid busbars and of the ideal hybrid busbar suggests that there is room to develop alternative processes for assembling hybrid busbars that are electrically more efficient than fastening. This conclusion was the motivation to develop the injection lap riveting process, whose results will be presented in the following sections of the paper.

3.2. Injection lap riveted hybrid busbars

Material flow

As previously mentioned, the first part of the experimental development of the new injection lap riveting process consisted of analyzing the influence of the dovetail hole geometry on material flow and on the riveting and destructive forces. For this purpose, semi-tubular rivets were pressed into dovetail holes with different inclination angles and depths by compressing their heads with a punch. The results are summarized in Figure 9, which shows three experimental and finite element predicted cross sections of specimens that were fabricated with dovetail holes having a constant depth $d_p = 4$ mm and different inclination angles $\alpha = 15^\circ$, $30^\circ$ and $45^\circ$ (Table 3).

![Figure 9. Finite element computed and experimental cross sections of specimens made from dovetail holes with $d_p = 4$ mm and inclination angles $\alpha$ equal to (a) $15^\circ$, (b) $30^\circ$ and (c) $45^\circ$. The undercut values are enclosed.](image)

As seen, the dovetail holes of the aluminum sheets behave as die cavities into which the shank length $S$ of the semi-tubular rivets are injected. Complete filling is ensured for the dovetail holes with inclination angles $\alpha = 15^\circ$ and $\alpha = 30^\circ$ but the unfilled pockets that are visible for the largest inclination angle $\alpha = 45^\circ$ are critical because they create resistance to the passage of electric current.

Riveting forces

The analysis of material flow allows concluding that despite the undercut being larger for the inclination angle $\alpha = 45^\circ$ (2.5 mm), the unfilled pockets located along the rivet-sheet contact interface justify the choice of smaller inclination angles, such as $\alpha = 30^\circ$. In addition to this, smaller inclination angles $\alpha$ are also advantageous because the required riveting forces are smaller, as it is shown in Figure 10. As seen from the finite element predicted meshes included in Figure 10 the riveting force vs. displacement evolutions consist of four main zones that are linked to different penetration depths of the semi-tubular rivets inside the dovetail holes:

(a) Zone 1 – contact with sliding of the inner semi-tubular rivet wall along the inner surface of the dovetail hole,
(b) Zone 2 – contact of the semi-tubular rivet end against the inner surface of the dovetail hole,
(c) Zone 3 – contact with sliding of the outer semi-tubular rivet wall along the outer surface of the dovetail hole,
(d) Zone 4 – contact of the rivet head against the sheet surface.
Destructive tests

The selection of a dovetail depth \( d_p = 4 \) mm with an inclination angle \( \alpha = 30^\circ \) for fabricating the injected lap rivet hybrid busbars is further justified by the results obtained in the shear and pull-out destructive tests (Figure 11), in which the maximum forces correspond to collapse by shearing or by detachment of the rivets from the sheets. As seen, the results of these tests are clearly favorable to the dovetail hole depth \( d_p = 4 \) mm because its cross-sectional shear resistant area \( A_{\text{shear}} \) and undercut are larger. This difference is particularly relevant for the undercut and justifies the reason why the variations are bigger in the pull-out forces than in the shear forces.

Fabrication of the injection lap riveted hybrid busbar

Figure 12a shows the finite element simulation of the connection between a C11000 electrolytic (99.9\%) copper sheet with 2 mm thickness and an aluminum AA6082-T6 sheet with 5 mm thickness by means of the new injection lap riveting process. As seen, the copper sheet acts as an injection chamber and the pre-drilled dovetail hole acts as a die cavity. The upper countersunk end of the copper sheet ensures the mechanical interlocking with the semi-tubular rivet and prevents material protrusions above the sheet surface.

The photograph enclosed in Figure 12b shows the injection lap riveted hybrid busbar and the dashed line AB shows the correspondence between the real busbar and the finite element model utilized in the numerical simulation (Figure 12a).
Figure 12. (a) Finite element model of the fabrication of an injected lap riveted hybrid busbar showing the meshes at the beginning and end of the process. (b) Photograph of the injection lap riveted hybrid busbar with identification of the cross-section AB utilized in the axisymmetric finite element model.

Electric resistance

Figure 13 shows the finite element model and the computed distribution of current density for the injection lap riveted hybrid busbar of Figure 12. As seen, the electric current flows through the rivet and through a limited area of the thin-interface layer around the semi-tubular rivet where the normal pressures during joining by forming are big enough to flatten out the asperities and break the contaminants and oxide films. This result is different from that observed in the fastened hybrid busbars, in which the flow of electric current through the bolt and nut is negligible (Figure 8c).

The computed electric resistance $R$ across the 100 mm distance between the two testing probes is equal to 17.7 $\mu\Omega$ and this result is in good agreement with the experimental measured value of $R = 18.9$ $\mu\Omega$. The difference between the two values is attributed to small unfilled pockets that may exist along the contact interface between the semi-tubular rivets and the dovetail sheet holes. The experimental value ($R = 18.9$ $\mu\Omega$) is almost identical to the minimum value of electric resistance that was obtained for the fastened hybrid busbars ($R = 18.3$ $\mu\Omega$), but in contrast to the fastened hybrid busbars that were made from sheets that were ground with emery paper of 40 or 80 grit sizes, the injection lap riveted hybrid busbars were made from sheets in the as supplied condition.

As a result of this it can be said that the new proposed joining by forming process to fabricate hybrid busbars not only eliminates grinding, as it reduces the electric resistance by approximately 19% when compared with a fastened hybrid busbar made from sheets in the as supplied condition ($R = 23.3$ $\mu\Omega$). In addition, it is worth noticing that the injection lap riveted hybrid busbars prevent the protrusions above and below the sheet surfaces (e.g. the bolt head and nut in the fastened hybrid busbars) and ensures stability of the electrical connection because they are not sensitive to loosening effects, which in case of the fastened hybrid busbars may lead to an increase of electric resistance to values beyond 100 $\mu\Omega$ (when the remaining torque is identical to tightening the bolts by hand).

Figure 13. (a) Finite element model and (b) computed distribution of current density (A/mm$^2$) for the injection lap riveted hybrid busbar shown in Figure 12.
4. Conclusions

Injection lap riveting can be successfully applied to the fabrication of hybrid busbars made from copper and aluminum conductors. The process prevents surface protrusions above and below the sheet surfaces and the need for accessories made from other materials (commonly steel) with greater electric resistivity, as in the case of fastened or self-pierce riveted hybrid busbars. Metallurgical problems associated to the heating-cooling cycles of welding-based processes are also avoided because injection lap riveting is carried out at ambient temperature.

Injection lap riveting is carried out in two stages, in which a dovetail ring hole is first machined in the lower sheet and a semi-tubular rivet is subsequently injected through the upper sheet into the dovetail hole of the lower sheet to assemble the hybrid busbars by means of a form-fit mechanical interlocking.

Results show that the electric resistance of the injection lap riveted hybrid busbars made from sheets in the as supplied condition is nearly identical to that of fastened hybrid busbars made from sheets subjected to initial surface preparation by grinding. The avoidance of grinding and the stability of the electric performance, which is not compromised by the loosening effects that are commonly found in fastened hybrid busbars and are characterized by a significant increase of electric resistance when the tightening torque applied to the bolts decreases, makes injection lap riveting suitable to produce hybrid busbars for electric vehicles and for other industrial applications operating under high electric currents.

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