High-speed joining of tubes to panel sheets using electro-hydraulic forming

Vahid Babalo1 · Mohammadreza Mirzahosein1 · Ali Fazli1 · Mahdi Soltanpour1

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Abstract
This study presents a new method for high-speed joining of the sheet to the end of a tube without the need for any additional processes. Joining of the AA3105 sheets to the AA1170 tube is carried out with a thickness of 0.5 mm. The process is performed using electro-hydraulic forming which is a local deformation of the tube and sheet. In this method, the mechanical force is transmitted by working media in a very short time. The shock wave accelerates the panel sheet towards the die and tube to create a form-fit joint. To avoid friction between the mandrel and the flat sheet, the panel sheet is pre-drilled. The experimental tests were performed to show the effect of process parameters including washer housing angle, sheet hole diameter, and the gap between the mandrel and top of the sheet. In addition, the pull-out test is utilized to determine the strength of the joints in different conditions. Accordingly, the usage of electro-hydraulic forming on joining thin tubular parts to flat sheets was successful and the feasibility of this technique, as an advanced joining approach, was verified.

Keywords Electro-hydraulic forming · Mechanical joining · Joining tube to sheet · High-speed joining · Thin tubular parts

1 Introduction
The lightweight design of the material is generally related to using a material with a higher strength to weight ratio where it is necessary [1]. The body structure of cars, planes, and trains in the case of the frame and shell structure can be different. Their designers are commonly focused on specific materials: aluminum in the case of frame structure and steel in the case of shell structure [2]. The basic design of lightweight frame structures in the automotive industry is frequently based on tubular profiles; joining strategies and technologies for these profiles have to be developed accordingly [3].

In terms of joining tube to the sheet, the conventional techniques can be classified by four types of joints named mechanical fastener (Fig. 1a), adhesive bonding (Fig. 1b), welded joint (Fig. 1c), and brazed joints (Fig. 1d). Fasteners are widely used, but they have some issues in terms of water leakage and corrosion sensitivity. The performance of adhesive joints decreases under severe environmental conditions. Welded joints have some issues in joining materials with different melting points and, they may also twist by the heat-cooling cycles. Eventually, in the case of the brazed joints, there are some difficulties in fitting the tube and the sheet together with very tight tolerances [4]. These limitations have led to the invention of some modern techniques such as joining by forming.

Joining by plastic deformation has been used in the joining process as a new technique without the necessity of the external heat which is classified into two main categories named metallurgical and mechanical joining [5]. In the case of mechanical joining, the local plastic deformation is applied to one or more joining partners which results in the mechanical interlock between the partners [6]. This technique potentially offers improved accuracy, reliability, and environmental safety and provides an opportunity to join new dissimilar products [7].

Alves et al. utilized the principal modes of the plastic deformation of the tube for joining sheet metal to tabular profiles [8]. This technique is carried out in two steps: compression beading and external inversion, as shown in Fig. 2a. They reported that the joint quality depends on the initial gap height and the radius of the tube ($l_{\text{gap}}/r_0$). The
The die radius must be higher than 1.5 \times t_0 (t_0 \text{ is tube thickness}). The maximum torque tolerated by the joint was about 300 N.m.

Sheet-bulk forming of tubes has been used for the joining applications. Alves et al. used the local thinning (boss forming) by compressing the wall thickness of the tube along its axial direction for joining the tube to the sheet, as shown in Fig. 2d [11]. The proposed method is suitable for connections where the inner diameter of the joint must be identical to the tube which is hard to obtain by conventional methods like fasteners. They also used this technique to join the sandwich panel (with a thickness of 2 mm) to the tube (AA6063-T6 tubes with a wall thickness of 1.5 mm) [12]. In the destructive test, the failure mode takes place when the deformed tube end back to its original geometry. Development of the cracks in the free edge of the piled-up material is one of the drawbacks of joining by sheet-bulk forming of tubes [13]. Therefore, Alves et al. proposed to close this region which leads to having controlled material. The other drawback of this process is that the joint surface is not flat. This is due to the protrusion of the tube flared-end above the sheet [14]. For the thick sheets (above 3 mm), Alves et al. proposed creating a chamfer at the sheet hole, as shown in Fig. 2e. This causes the mechanical locking process to change from tube flaring into tube upsetting. Afonso et al. utilized this method to join rod to sheet [15]. To prevent the failure as a result of the crack, controlling the width of the die cavity and a ring pressure is carried out.

Alves et al. introduced the joining of the sheet to the tube by squeezing the sheet into the outer diameter of the tube instead of applying deformation on the tube [16]. In this technique, the sheet is compressed to its thickness direction until a mechanical interlock is created, as shown in Fig. 2f. The mechanism of the joint is based on form-fit, but it turns to force-fit when the pressure is not enough. To obtain a sound tube-sheet joint, the deformation zone (the cross-section length of the punch) should be 2 or 3 mm [17]. Large squeezing depth results in small thickness below the punch; therefore, the joint can only withstand a small load [18]. In addition, large squeezing gives a large reduction of the inner tube radius. To control this, joining by the squeeze-grooving process is introduced which makes use of two independent mandrels. This causes more pressure to be required to form the tube into the annular cavity [19].

Radhakrishnan et al. studied the joining of dissimilar tube-sheet connections (with or without threaded pairs) by friction welding process [20]. In this technique, the material is heated up by the friction created between a rotational punch and adjacent material, as shown in Fig. 2g. The rotational speed of the punch plays an important role which 950 rpm is found to be the best to enhance the joint strength. Park et al. investigated the combination of tube expansion and electromagnetic forming to join tubular parts to sheet panels, as shown in Fig. 2h [21]. To induce magnetic pressure at the joining region, an assembly-type bitter coil was utilized. Experimental tests were conducted at several charging voltages in which 9.2 and 11.2 kV are capable of creating a complete joint without looseness. The specimens that completely joined were indicated higher joint strength than the yield strength of the tube. Alves et al. investigated self-pierce riveting of the carbon steel tube to the aluminum sheet. In this technique, the tube end needs to be chamfered, as shown in Fig. 2i. Since the tube penetrates the sheet, the joint region is invisible [22]. Three different modes of deformation are characterized due to the angle of the tube end chamfer (\( \alpha \)). When the angle of the chamfer is small and about 15°, fishhook interlocking appears. Successful clamping is achieved when the angle of the chamfer is in the range of 30 to 45°. The joint failed when the chamfer of the tube is larger than 60°. Langstädtler et al. introduced high-speed joining of the tube to the sheet by the application of electrohydraulic forming [23]. The tube end is deburred at the inner edge. The mechanical interlock is created by the deformation of the sheet into the tube, and its size depends on the deburred edge of the tube.

As mentioned above, most research has been done on materials with a thickness of more than one millimeter. This paper is aimed to propose the possibility of joining a thin tubular part to a thin panel sheet. This contributes to having...
Recent developments in the joining of a tube to a sheet by forming
a higher strength-to-weight ratio needed in lightweight construction. In this technique, electrohydraulic forming acts as an expansion force for the connection. The high strain rate of the process helps improve the material formability, and the joint is created just in a fraction of a millisecond. The components are joined within the form-fit interlocking. The study carries out the experimental investigation and evaluates the pull-out strength using a destructive test. In addition, the morphology of the cross-section of the joint is evaluated.

2 Experimental procedure

2.1 Electro-hydraulic tube-sheet joining equipment

Electro-hydraulic forming (EHF) is utilized to mechanically join the thin aluminum tubes to the panel sheets. The experimental apparatus used in this technique is schematically shown in Fig. 3. As seen, this technique consists of two main parts: shock wave creation source and joining section. The main workpieces of the apparatus are also illustrated in Fig. 4. The shock creation source consists of two separate chambers which are shown individually and assembled in Fig. 4a and b, respectively. The main joining workpiece is a two-separate conical washer which is called washer housing, as shown in Fig. 4c. The tube and sheet joint are mechanically formed in this area. There is an inner and outer die, as shown in Fig. 4d and e. The washer housing is embedded inside the inner die, and then, the whole set is placed inside the outer die. A stiff polymer that is used as an adjusting ring provides a precise alignment between the upper section (blank holder) and a lower section (the pressure chamber). As it is shown in Fig. 4f, fixing the whole apparatus is accomplished by 4 bolts from the blank-holder. The main dimensions of the process are listed in Table 1.

As shown in Fig. 5, this technique consists of four sequence operations. First, the pressure chamber is filled with a fluid such as water (Fig. 5a). To prevent the entrance of water to the forming region, a rubber pad (which is made of NBR) with a thickness of 1.5 mm is used at the outlet of the pressure chamber. In 100% strain, it has approximately 6 MPa stress. Since the depth of the die cavity (washer housing) is low, the total stress is around 3 MPa which has little effect on the output energy. The aluminum sheet lies between a rubber pad and a two-piece die. The tube is placed on top of the aluminum sheet through the two-separate washer. The sheet is pre-drilled and needs to be positioned accurately relative to the tube. In the second phase, as shown in Fig. 5b, the alignment is accomplished by a centering component. The geometry of this component is made according to the sheet hole diameter. Firstly, the washer is attached to the inner die; then, the centering component aligns the sheet through the inner die. A common glue is used between the sheet and washer to fix the sheet in its place, after removing the centering component (it should be noted that the sheet is easily removable from the surface of the washer after

Fig. 3 The schematic of joining tube to the sheet by the EHF
joining). Afterward, the mandrel is positioned in the inner die. To connect the inner die to the blank holder, an external die is used as the interface. In the third phase, another alignment between the outer die and pressure chamber is carried out by a polymer ring (Fig. 5c). Aligning and clamping happen at the same time. This ring, which is called the adjusting ring, is surrounded the outer die. The blank holder is initially positioned the outer die using four M12 bolts; then, the whole set is fixed to the pressure chamber. After clamping the whole system, the shock wave is created. The rubber pad, with the high-speed movement, makes a deformation of the sheet and tube inside the washer housing. The total joining process takes about a few milliseconds. In this technique, the high strain rate due to the EHF process has improved the material formability. This indicates a promising technique for the joining of material with lower ductility. A pulse generator with a maximum energy of 8 kJ, and a total capacitance of 250 µF, is utilized for the EHF system. The specimens are joined with the same discharge energy of 1 kJ. The initial setup was based on the setup of our previous articles, where the materials are joined using the same forming energy. According to different experimental tests, discharge energy of 1 kJ does the best result. When the output energy is less than 1 kJ, the connection does not perform. In the contrast, when it goes over kJ, it causes more friction with the bottom of the mandrel and decreases the durability of the rubber pad.

2.2 Material

The experimental tests are carried out for the AA3105 sheet to the AA1170 tube with a thickness of 0.5 mm. The chemical composition of the sheet and tube is measured by the quantum method, which is presented in Table 2. The mechanical properties of joining samples are determined at room temperature according to ASTM E 8 M standards, which are summarized in Table 3. The aluminum tube AA1170 has the same metallurgical and mechanical properties as the fabricated solid rod. Due to the lack of tube proportional dimension to the diameter of the pressure chamber, the tube was machined. Therefore, to relieve residual stress, the tubes are completely annealed. The failure strain in the AA3105 is about 0.03 which shows to be low ductile. To have a better investigation, the bulge test according to the ISO 16808 is performed. This indicates that the strain hardening coefficient of the AA3105 is low since the fracture region determines ductile damage rather than a brittle one.
The result at the topmost location in the bulge test was 0.47 which revealed medium formability of the metal sheet [24].

The aluminum tube has an inside diameter of 27 mm with a thickness of 0.5 mm and a length of 100 mm. The sheet utilized is cut in 50 mm diameter, and it is pre-drilled in three different diameters (12, 15, and 18 mm). The specimen’s configuration is shown in Fig. 6. The tube-sheet joined samples were evaluated at room temperature using a specific fixture. Figure 7 shows schematically the fixture used to measure the strength of the joints. It consists of two sections: upper and lower sections. The sheet lies between the lower and upper blank holder, and it fixes with four M6 bolts. The lower section is mounted using a shaft inside the lower gripper of the tensile machine. To attach the tube inside the upper gripper, a connection called mandrel and holding ring is used. The end of the mandrel is attached to

![Image](57x330 to 539x733)

**Fig. 5** The sequence of joining operation using electrohydraulic forming: a filling the pressure chamber; b aligning flat sheet with inner and outer die; c clamping; d discharging stored energy

| Table 2 Chemical composition (wt%) of materials used in joining |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Material       | Al   | Fe   | V    | Si   | Mn   | P    | Cr   | Ni   | Pb   | Cu   | Pb   |
| AA3105 Base    | 0.54 | 0.002| 0.398| 0.514| None | 0.258| None | None | 0.110| 0.022|
| AA1170 Base    | 0.088| 0.016| 0.066| 0.003| 0.0033| 0.0012| 0.0035| 0.0023| 0.0078| 0.0023|
the upper gripper, and another side is placed inside the tube. The holding ring surrounded the tube from outside with 6 M6 bolts. To obtain the strength of joints, a universal testing machine with a constant cross-head speed of 1 mm per min is used.

To gain the capability of this new technique on the joining of the sheet to the tube, four sets of experiments are performed. Table 4 is listed these four experiment sets with their purpose. Experimental studies are performed with a variation of the parameters including washer housing angle, gap length between the bottom of the mandrel and the top of the sheet, and the inner diameter of the sheet. In Experiments 3 and 4, three samples are used to determine the joint strength, and the left one is used for microsection evaluation of the joint. The samples are cut in their transverse direction to see how the connections are formed, and the distribution of thickness is evaluated on the joining path.

3 Working principles of the high-speed tube-sheet joining

Figure 8 shows three main steps of connection formation in this new technique. At the first stage, the sheet is clamped between the upper and lower sections, and the tube is placed inside the inner die (as shown in Fig. 8a). In stage 2 (Fig. 8b), a capacitor is charged to a certain voltage. By short-circuiting the capacitor, the plasma channel is formed through the electrodes submerged in a pressure chamber. The shock waves created in the pressure chamber transfer the forming force towards the sheet. In this case, the rubber pad initially prevents the penetration of water inside the washer housing; then, it draws the sheet into the die. The sheet is stretched in its axial direction until it hits the bottom of the mandrel. At this stage, the material flow changes from the axial to the radial direction (Fig. 8c). Throughout this stage, the sheet allowed to plastically deform the tube inside the washer housing. As the deformation of the tube begins, the geometry of the mechanical interlock is formed. The mechanical interlock is increased as the plastic deformation intensifies. The high-speed joining of this procedure helps to create a sound joint just in a few milliseconds.

4 Results and discussion

Some primary process parameters such as sheet hole diameter, the gap length between the bottom of the mandrel and the top of the sheet, and washer housing angle were experimentally performed to obtain an appropriate range for joining. As mentioned in Sect. 2, the thickness of both sheet and tube are the same, and all experiments were joined at the same discharging energy. Figure 9 shows a sample were joined by this new method. The joined sample was investigated in both terms: mechanically and morphologically. The results obtained from these studies are described below.

Table 3 Mechanical properties obtained from the tensile test for joint specimens

| Material   | Thickness, t (mm) | Yield stress, σ₀.₂ (MPa) | Elongation (%) | Ultimate strength, σₜₚ (MPa) |
|------------|------------------|--------------------------|----------------|-----------------------------|
| AA1170-O  | 0.5              | 55                       | 20             | 98                          |
| AA3105    | 0.5              | 180                      | 3              | 187                         |
4.1 The influence of sheet hole diameter on the joining formation

The first attempts in this technique were to joint parts without pre-drilling operation and the rubber pad, but it was not successful. The results of experimental tests indicated that the existence of friction between the sheet and the mandrel prevents the complete formation of the sheet and the tube in the washer housing. To address this issue, the sheet is pre-drilled. Also, to prevent the penetration of water in washer housing, a thin rubber pad with a thickness of 1.5 mm is used. Not only does this remove the friction, but it also reduces the required forming force for joining. To investigate the effect of sheet hole diameter on the connections, both washer housing angle and gap length between mandrel and sheet were considered constant. The preliminary tests were conducted on washer housing with an initial gap of 4 mm and an angle of 50°. The experimental tests are performed on pre-drilled sheets with 12 and 15 mm. The obtained results are shown in Fig. 10. Having the sheet with a pre-drilled diameter of 12 mm shows an incomplete connection, as shown in Fig. 10a. As can be seen, due to the small hole diameter, the sheet does not form inside the washer housing and the extra sheet remains at the edge of the hole. In addition, the high peripheral strain rate causes the edge of the sheet and rubber pad to rupture. This results in the entrance of water to the washer housing and prevents material deformation. Increasing the sheet hole diameter to 15 mm shows a promising result in which no extra edge is seen at the joining region (Fig. 10b). There is a direct correlation between increasing washer housing angle and sheet hole diameter, as shown in Fig. 11. Since the washer housing angle is increasing, the chamber is decreased by 1 mm in the radial direction and 0.45 mm at the chord length. Therefore, to have a suitable joint in washer housing with an angle of 60°, the sheet hole diameter is 18 mm selected and indicated satisfying results, as shown in Fig. 10c.

4.2 The effect of gap length between mandrel and top of the sheet

The gap between the top of the sheet and mandrel is shown to be an effective parameter for joining. To investigate this, three gap lengths with a sequence of 1 mm (3, 4, and 5 mm) are utilized. Also, to have a better comparison, two other parameters, such as sheet hole diameter and washer housing angle, are considered constant which are 15 mm and 50°, respectively. Figure 12 illustrates schematically and realistically the results in the initial conditions, during the process, and at the end of the process. When the gap between sheet and mandrel is 3 mm, the plastic deformation of the sheet inside washer housing is limited and does not form a complete connection (as shown in Fig. 12a). The low gap length acts as a barrier. In this case, a significant amount of energy

| Ex | The thickness of the washer (hw) | The gap length between the bottom of the mandrel and the top of the sheet (md) | The washer housing angle (A°) | The inner diameter of the sheet (ds) | Aim of the experiments |
|----|---------------------------------|---------------------------------|-----------------------------|---------------------------------|-----------------------|
| 1  | 5                               | 4                               | 50                          | 12.15                           | Showing the effect of sheet hole diameter |
|    |                                 |                                 | 60                          | 18                              |                       |
| 2  | 5                               | 3                               | 50                          | 15                              | Investigating the effect of gap length between mandrel and top of the sheet |
|    | 4                               |                                 |                             |                                 |                       |
|    | 5                               |                                 |                             |                                 |                       |
| 3  | 5                               | 4                               | 50                          | 15                              | Evaluating joint strength, thickness variation, and fracture mode |
| 4  |                                 | 60                              |                             | 18                              |                       |
is lost, and the rubber pad does not penetrate sufficiently into the washer housing to establish a joint. Increasing the distance to 4 mm, the condition is becoming better than the previous stage. As shown in Fig. 12b, due to sufficient area between the mandrel and metal sheet, the rubber pad draws the sheet into the washer housing sufficiently. The sheet completely deforms the tube into the washer housing and provides a good interlock. As the gap increases to 5 mm (Fig. 12c), the area for stretching the sheet and tube was increased. In this case, overstretching of the tube is happened and causes the thickness of the tube neck to be decreased. The results indicate that a good joint is achieved when having a 4-mm gap length, and the study continued under these obtained results.

4.3 The interlock and outer diameter of the created joints

As mentioned in the previous section, the hole diameter 15 and 18 mm on the flat sheet is appropriate for washer housing with 50° and 60°, respectively. In addition, selecting a 4-mm gap length provides a sound joint. Figure 13a and b show the joined samples according to the chosen parameters. When the washer housing with 50° is utilized, some cracks reveal at the neck of the joint. However, in washer housing with 60°, the joined samples are free of cracks and indicate a quality connection. The main reason for the creation of cracks is that when the chamber angle is 50°, more space is created for the tube to stretch, which eventually leads to the cracks due to the larger deformation. It is also observed that the tightness of the joined sample reduces due to the cracks. This causes the tube to rotate inside the sheet. However, the joint with washer housing 60° creates a tight connection and is capable of withstanding quite good torsional torque. Figure 14a and b show the outer diameter and interlock of the joined area. Decreasing the negative angle of washer housing from 60 to 50° is along with increasing the internal lock and the outer diameter of the joint area. However, this decrease results in some cracks as mentioned above. When the washer housing with an angle of 50° is used, a greater amount of interlock is created, which is between 0.9 and 0.93 mm. It also has an outer diameter of 30.9 mm. On the contrary, the interlock of the created join using washer housing with 60° is varied between 0.76 and 0.85 mm. Also, the outer diameter of the bulge area has decreased by about 5%, which is 29.5 mm. The differences between the left and the right sides of the interlock are 0.09 mm. This small deviation could be due to the tolerances in the alignment of the axes of the sheet hole and the tube or the start position of the shock wave.

4.4 Geometrical evaluation of the created joints in different washer housing angle

In this section, the effect of washer housing angle on thickness variation after joining is evaluated, in which other
parameters are considered to be constant. Figure 15a shows the cross-section of the conducted joint in washer housing with an angle of 50°. The relative position of each measurement is labeled on the joint cross-section. Furthermore, the thickness variation of the tube and sheet is separately investigated and shown in Fig. 15b and c, respectively. According to Fig. 15b, the thickness reduction of the tube locally happens at the corner of the inner die (in measured divisions with numbers 4 and 5 on both sides). The main cause for this, which reduces the thickness by 0.2 mm, is the small radius at the corner of the inner die. As can be seen, the amount of thinning on the left side is greater. This can be attributed to the tolerances of the positioning electrodes in the pressure chamber. It defines the start position of the shock wave. When it is not along the sheet hole axes, a non-uniform pressure may be applied to the tube and sheet. This causes an irregular drawing of the sheet and tube to the washer housing. This 40% reduction in thickness can be a source of beginning fracture in this area. This has a considerable effect on joint strength. However, the other measured division (between numbers 6 and 20) has the same thickness which is varied between 0.4 and 0.5 mm.

This examination was also performed on the sheet, and further thinning occurred in the area of bending within the forming washer housing (Fig. 15c). The thickness of measured divisions 10–15 decreases to 0.3 mm, which indicates that this area has the most stretch during forming. The other measured division thicknesses are varied between 0.3 and 0.4 mm.

Figure 16a and b show the cross-section and thickness of the tube in a jointed sample within the washer housing with an angle of 60°. Increasing the washer housing angle to 60° reduces the thinning of the tube that happened at the corner of the inner die. This improvement in thickness variations is due to the reduction of tube stretch by shrinking the forming chamber. In this case, it also prevents the upward movement of the tube, which occurred in the washer housing with an angle of 50°. This is another factor in thickness reduction that occurs due to excessive impact with the corner of the inner die. The minimum measured thickness in this region is about 0.4 mm which is close to the thickness of the basic material, and no crack has emerged on the tube. Furthermore, the thickness variation of the sheet shows an improvement at 10 to 15 measured divisions in comparison to the washer housing with an angle of 50°, as shown in Fig. 16c.
Fig. 12  The effect of the gap length between top of the sheet and mandrel: a 3 mm; b 4 mm; c 5 mm
The minimum thickness of the sheet, which is 0.3 mm, is seen at the measured division 25 which is happened due to the initial hitting of the sheet to the mandrel face.

4.5 Mechanical behavior of the joined samples in two different washer housing angles

This section is concentrated on the destructive test of Experiments 3 and 4 in Table 4. It was carried out to obtain the pull-out joint strength of the new joining technique. The specific fixture, which is mentioned in Sect. 2.2 (Fig. 7), is utilized to attach the joined samples in a universal tensile machine. The joined samples with a constant cross-head of 1 mm per mine were pulled until to its failure. To obtain reliable results, each test is repeated three times. The load–displacement curve of the pull-out test for both samples that connected with washers housing 50° and 60° are shown in Fig. 15. The maximum pull-out strength gained from joined specimens is 900 N which is related to the test of washer housing with a 60° and hole diameter of 18 mm. The pull-out strength increases uniformly to 900 N, and after reaching the peak load, the pulling load begins to decrease with a gentle slope due to the appearance of the initial rupture. (Fig. 17a). The load–displacement curves of these joined samples show good repeatability. In contrast, in the case of connection to a washer housing with a 50° and sheet hole diameter of 15 mm, the pulling load increases to the peak of 600 N and
Fig. 15  a Cross-section of the joint with washer housing 50; b thickness variation in the tube; c thickness variation in the flat sheet
Fig. 16  a Cross section of the joint with washer housing 60°; b thickness variation in the tube; c thickness variation in the flat sheet
then decrease by different slopes (Fig. 17b). Experiment 1 shows a fast growth of crack which results in a fast-dropping load. This behavior originates from the presence of cracks in the throat area of the joint. This is related to the number and amount of cracks. It can also be seen that Experiment 2 indicates a different rising to the peak load than two other joints. This can be attributed to the loading fixture, in which there is a possibility of slipping of fixing points at the beginning of the loading on the tube wall. Due to this slip, the sample under pulling load shows a lower slope to the peak load.

Generally, in joining processes, the maximum strength that a connection can withstand depends somewhat on the type of failure. In this method, the type of failure observed is a combination of separating and growth of cracks which causes rupture at the edge of the tube. As it is mentioned in Sect. 4.3, the potential of separating and growth of the cracks in joined samples with washer housing 50° is greater than washer housing with 60°. Figure 18a and b show two modes of failures that happened in two different types of experimental tests. The failure mode with washer housing 50°, as

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**Fig. 17** Destructive tests of a washer housing with 60 angle and 18 mm sheet hole diameter and b washer housing with 50 angle and 15 mm sheet hole diameter
shown in Fig. 18a, indicates severe rupture at the edge of the tube and separation from the flat sheet. As can be seen in Fig. 18a, the sheet does not fully return and this indicates that the rapid growth of cracks causes the tube to separate from the sheet. In contrast, washer housing with 60° shows better condition than washer housing with 50°, as shown in Fig. 18b. The fully formed sheet is unfolded to its 90° bent and caused to reach the maximum strength. In this case, the number of ruptures is decreased because of lower stretching that happened during joining. As can be seen, only one of the connected tubes to the sheet remains intact; however, the other two joints show ruptures. This issue needs more study, which is in progress.

4.6 Energy absorption

Energy absorption in mechanical joining processes is a measure of how much load a joint can transfer before it fails. In the crash or dynamic loading conditions, the connections are preferred to have higher energy absorption. The absorbed energy of each pull-out joint can be determined by computing the area under the load–displacement curve, as shown in Fig. 19. The absorbed energy of both tests with washer housing 50° and 60° was calculated based on their pull-out tests. Due to the growth of the crack during the pull-out test, the absorbed energy is calculated up to the peak and end of the load–displacement curve, as shown in Fig. 19a and b. The connections with washer housing 60° show more capability to absorb energy, both up to the peak and end of their failure. The maximum absorbed energy is 1500 J which is approximately 60% higher than the joint with washer housing 50° (as shown in Fig. 19c). In addition, this result can be seen in the case of absorbing energy up to the peak load, where the connection with a washer housing 60° can absorb about 50% more energy. This is due to lower stretch in the tube and delayed crack growth during the pull-out test of the connections.

![Failure modes of a washer housing 50° and b washer housing 60°](image-url)
Electro-hydraulic forming of the tube to the sheet is a new joining by forming technique which capable of joining sheet to the end of a tube. The capability of joining the AA3105 flat sheet to the AA1170 tube with a thickness of 0.5 mm is experimentally investigated. Two components are joined within a few milliseconds by applying a sudden load on the flat sheet. This shock wave is created by discharging energy from the capacitor toward the electrodes in the pressure chamber. The obtained results from this new hybrid investigation led to the following conclusion;

1. Due to the existence of friction between the sheet and the mandrel, the flat sheet is pre-drilled.
2. The use of a rubber pad not only helps to prevent the penetration of water inside the washer housing, but also provides a better material deformation.
3. The smaller pre-drilled diameter at the flat sheet causes additional material at the joining area in which led to

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**Fig. 19** Energy absorption a up to peak load, b at the end of complete failure, and c two different pull-out tests

5 Conclusion

Electro-hydraulic forming of the tube to the sheet is a new joining by forming technique which capable of joining sheet to the end of a tube. The capability of joining the AA3105 flat sheet to the AA1170 tube with a thickness of 0.5 mm is experimentally investigated. Two components are joined within a few milliseconds by applying a sudden load on the flat sheet. This shock wave is created by discharging energy from the capacitor toward the electrodes in the pressure chamber. The obtained results from this new hybrid investigation led to the following conclusion;

1. Due to the existence of friction between the sheet and the mandrel, the flat sheet is pre-drilled.
2. The use of a rubber pad not only helps to prevent the penetration of water inside the washer housing, but also provides a better material deformation.
3. The smaller pre-drilled diameter at the flat sheet causes additional material at the joining area in which led to
incomplete joining. Also, this protruded sheet from the joining area causes the rubber pad to be ruptured.

4. The gap between sheet and mandrel is an effective parameter on the joining. The results indicate that a good joint is achieved when the gap length is 4 mm.

5. By selecting the washer housing with a 50°, some cracks occur in the throat area of the tube.

6. The outer diameter of the joined sample in washer housing with 50° is 30.9 mm, which is 5% greater than the joint created in the washer housing with 60°.

7. The thickness variation of the joined samples in washer housing with 50° is influenced by the small corner radius of the inner die. Increasing the washer housing angle to 60° reduces the thinning of the tube that happened at the corner of the inner die.

8. The maximum pull-out strength obtained from the joined specimens is 900 N which is related to the test with washer housing 60° and hole diameter 18 mm.

9. The type of failure observed is a combination of separating, growth of cracks, and tearing at the edge of the tube. The growth of cracks is mostly seen in washer housing with 50° due to the over stretch.

Author contribution All authors have participated in (1) conception and design, and interpretation of the data; (2) drafting the article or revising it critically for important intellectual content; and (3) approval of the final version.

Availability of data and material The material used in this paper is all available in our region, and both of them test mechanically and chemically.

Code availability Yes applicable.

Declarations

Ethics approval This manuscript has not been submitted to, nor is under review at, another journal or other publishing venue.

Consent to participate Yes applicable.

Consent for publication Yes applicable.

Competing interests The authors declare no competing interests.

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