High-Speed Joining of Tubes To Panel Sheets Using Electro-Hydraulic Forming

Vahid Babalo (v.babalo68@gmail.com)
Imam Khomeini International University Faculty of Technical and Engineering
Mohammad Reza Mirza Hossein
Imam Khomeini International University
Ali Fazli
Imam Khomeini International University
Mehdi Solanpour
Imam Khomeini International University

Research Article

Keywords: Electro-hydraulic forming, mechanical joining, joining tube to sheet, high speed joining, thin tubular parts

Posted Date: August 9th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-739462/v1

Version of Record: A version of this preprint was published at The International Journal of Advanced Manufacturing Technology on January 13th, 2022. See the published version at https://doi.org/10.1007/s00170-021-08496-z.

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, 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.

Introduction

The design of lightweight structures, which is based on lightweight design of material, structure, and system, is a key concept in the automotive industry. 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 utilization of lightweight design of materials contributes to a reduction of structure weight, which is in line with decreasing the Co2 emissions produced by the automotive sector. Since 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].

Joining hybrid structures are quite challenging owing to considerable differences among their mechanical properties and geometrical shapes. In terms of joining tube to the sheet, the conventional techniques can be classified by four types of joints named; mechanical fastener (Fig. 1(a)), adhesive bonding (Fig. 1(b)), welded joint (Fig. 1(c)), and brazed joints (Fig. 1(d)). 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. Finally, 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 generated in processes like fusion welding. It is commonly classified into two main categories named; metallurgical and mechanical joining [5]. In the mechanical joining category, the local plastic deformation is applied to one or more joining partners which result in the mechanical interlock between the partners [6]. This technique mostly is interesting in light-weight structures since it removes the mechanical fasteners like rivets, bolts, and others just by a local deformation. 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. 2(a). They reported that the joint quality depends on the initial gap height and the radius of the tube (l_{gap}/r_0). The l_{gap}/r_0 ratio must be large enough to create a tube bead by the axial compression, and on the other hand; it should be small enough to prevent the inward material flow. Alves and Martins introduced the joining of tubes to the sheets along planes inclined with respect to the tube axis, as shown in Fig. 2(b)[9]. Alves and Martins also developed a single-stroke joining of sheet panel to the tube profile, as shown in Fig. 2(c) [10]. Joining is gained by two different modes of plastic deformation that are often seen in tube end forming; flaring and compression beading. To prevent local buckling in the flange creation, the die radius must be higher than $1.5 \times t_0$ (t_0 is tube thickness). The maximum torque tolerated by the joint was about 300 N.m.

Sheet-bulk forming of tubes has been also 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. 2(d) [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. This may be important where the joint should convey the fluids from one place to another place to prevent changes in flow and pressure drops. 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 flared tube end backs 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 3mm), Alves et al. proposed creating a chamfer at the sheet hole, as shown in Fig. 2(e). Eventually, 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]. The failure by cracking is prevented by controlling the width of the die cavity and using a ring pressure.

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 in order to form an inner tube bead until a mechanical interlock is created, as shown in Fig. 2(f). The mechanism of the joint is based on form-fit, but it changes to force-fit when the pressure is not enough. To obtain a sound sheet-tube 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 pull-out failure by shearing happened under 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. Results indicate that there is a slight increase in squeezing pressure due to the additional effort required to form the tube into the annular cavity[19].

Radhakrishnan et al. studied joining dissimilar tube-sheet joints (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. 2(g). The rotational speed of the punch plays an important role which 950 rpm is found to be the best to enhance the joint strength. Also, the compressive strength of the joint with threaded pairs is higher. Park et al. investigated the combination of tube expansion and electromagnetic forming to join tubular parts to sheet panels, as shown in Fig. 2(h) [21]. The aluminum sheet (AA7075-T6) and tube (AA6063-O tube) both have 3mm thickness, and the sheet is pre-drilled. To induced 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 can create 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. 2(i). 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 (α). When the angle of the chamfer is small and about 15°, fishhook interlocking appears. Successful clamping by piercing and flaring tube inside the sheet 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 large about 60°. Langstädtler et al. introduced high-speed joining of the tube end to the sheet by the application of electrohydraulic forming[23]. In this method, the tube ends are deburred at the inner edge, and the sheet is formed into the tube to make an interlock. The mechanical interlock volume has been influenced by the tube inner edge.

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 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 to 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 by means of a destructive test. In addition, the morphology of the cross-section of the joint is evaluated.

Exprimental 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. A capacitor is charged to a certain voltage. By short-circuiting the capacitor, through electrodes submerged in a chamber, the plasma channel is formed. The shock waves created in the pressure chamber transfer the forming force towards the sheet. 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 Figs. 4 (a) and (b), respectively. The main joining workpiece is a two-separate conical washer which is called washer housing, as shown in Fig. 4(c). The tube and sheet joint are mechanically formed in this area. There is an inner and outer die, as shown in Fig. 4(d) 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 which 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. 4(f), fixing the whole apparatus is accomplished by 4 bolts from the blank-holder. The main process dimensions are listed in Table 1.

Table.1. Initial design parametrrs for joining tube to sheet by the EHF

Items	Value
The thickness of th tube (t_t)	0.5 mm
The thickness of the sheet(t_s)	0.5 mm
The diameter of the tube(d_t)	27 mm
The washer thickness (h_w)	5 mm
The gap length between the bottom of the mandrel and the top of the sheet(m_d)	3,4,5
The washer housing angle (A°)	50°, 60°
The inner diameter of the sheet(dis)	12, 15, 18 mm
The thickness of rubber pad(t_p)	1.5 mm
The Outlet pressure diameter(dp)	20 mm
The wave effective diameter(DP)	120 mm
The electrodes distances(E_d)	3 mm

As shown in Fig. 5, this technique consists of four phases. First, the pressure chamber is completely filled with a fluid such as water (Fig. 5(a)). To prevent the entrance of the water to the forming region, a rubber pad with a thickness of 1.5 mm is used at the outlet of the pressure chamber. 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 in this method and needs to be accurately positioned relative to the tube. In the second phase, as shown in Fig. 5(b), 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 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. 5(c)). 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 correctly using four M12 bolts, then; the whole set is fixed to the pressure chamber. After clamping the whole system, the shock wave is created by discharging the stored electrical current from the capacitor (as shown in Fig. 5(d)). This causes a sudden shock wave in the pressure chamber, in which the fluid moves at a high speed towards the rubber pad. The rubber pad, with the high-speed movement, makes a deformation of the sheet and tube in the washer housing. The total joining process time is about a few milliseconds. Because of the high strain rate of the EHF, there is an improvement in terms of 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 total capacitance of 250 μF is utilized for the EHF system. The specimens are joined with the same discharge energy of 1 kJ.

2.2 Material

The experimental tests are carried out for the AA3105 sheet to the AA1170 tube with a thickness of 0.5mm. The chemical composition of the sheet and tube materials 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 8M 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. This indicates that the strain hardening coefficient of the AA3105 is low since the fracture region determines ductile damage rather than a brittle one. To have a better investigation, the bulge test according to the ISO 16808 is performed. The result at the topmost location in the bulge test was 0.47 which revealed medium formability of the metal sheet [24].

Table.2. chemical compostion (wt. %) **of materials used in joining**

Elements 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

Table.3. Mechanical properties of the materials used for preparation of the specimens.

Material	Thickness, t [mm]	Yield stress, $\sigma_{0.2}$[MPa]	Elongation [%]	Ultimate strength, σ_{μ} [MPa]
AA1170-O	0.5	55	20	98
AA3105	0.5	180	3	187

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 applied 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 schematically shows 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 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 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.

Table.4. The list of experiment test for joining tube to sheet

Ex.	The thikness of the washer (h_w)	The gap length between the bottom of the mandrel and the top of the sheet (md)	The washer housing angle (Á°)	The inner diameter of the sheet (ds)	Aim of the expriments
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	

Working Principles Of The High-speed Tube-sheet Joining

Figure 8 shows three main phases of the new technique for joining tubes to the sheets. 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. 8(a)). In stage 2, the electrical current discharges (Fig. 8(b)), and the created shock wave in the pressure chamber moves water quickly towards the rubber pad. 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 to the bottom of the mandrel. At this stage, the material flow changes from the axial to the radial direction (Fig. 8(c)). 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.

Result And Discusion

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 Sec. 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.

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, and 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 5 mm and an angle of 50°. For the experimental tests, sheets with pre-drilled diameters of 12 and 15 mm are provided. The obtained results are shown in Fig. 10. Having the sheet with a 12 mm pre-drilled diameter shows an inappropriate connection, as shown in Fig. 10(a). 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 to rupture. This protrusion is due to excessive material and causes some disadvantages. Emerging tearing in rubber pad is also another side effect of inappropriate sheet hole diameter. Increasing the sheet hole diameter to 15 mm shows a promising result, so that no extra edge is seen at the joining region (Fig. 10b)). There is a direct relation 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.

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 (3,4,5 mm) are utilized. Also, to have a better comparison, two other parameters, such as sheet hole diameter and washer housing angle, is 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. 12(a)). The low gap length acts as a barrier. In this case, a significant amount of energy 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. 12(b), 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. By creating a 5 mm gap, the mandrel has the same level as the inner die (Fig. 12(c)), the area for stretching the sheet and tube is 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. Geometrical evaluation of the created joints in different washer housing angle

As mentioned above, the obtained results indicated that 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 according to the achieved results in the previous section. In this section, the effect of washer housing angle on thickness variation during the formation of the joining is assessed, in which other parameters are considered to be constant. Figure 13(a) 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. 13(b) and (c) respectively. According to Fig. 13(b), 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 and the inappropriate angle of the washer. The washer housing angle provides more space for stretching which in turn causes thinning at the neck of the tube. 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 to 20) has the same thickness which is varied between 0.4 mm to 0.5 mm. This examination was also performed for the sheet, and further thinning occurred in the area of bending into the forming chamber. (Fig. 13(c)). 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 mm to 0.4 mm.

Figures 14(a) and (b) show the cross-section of the joints in washer housing with an angle of 60° and thickness variation of the tube, respectively. 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 tube from moving upwards, which occurred in the washer housing with an angle of 50°. This upward movement is another factor in thickness reduction due to the impact that happens on 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 a 50°, as shown in Fig. 14(c). 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.

4.4. Mechanical behaviour of the joined samples in two different washer housing angle

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 mention in sec.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. 15(a)). 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 then decreases by a different slope. (Fig. 15(b)). Ex. 1 shows a fast initiation of crack which results in a fast-dropping load. This behavior initially can be related to more stretch that occurs in the washer housing and leads to its early failure. In addition, the presence of cracks at the edge of the tube can affect this issue. It can also be seen that Ex.2 indicates a different rising to the peak load than two other joints. This difference 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 to some extent 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. Figures 16(a) and (b) show two modes of failures that happened in two different types of experimental tests. The failure mode with washer housing 50°, as shown in Fig. 16(a), shows severe rupture at the edge of the tube and separation from the flat sheet. As can be seen in Fig. 16(a), the sheet does not fully return and this indicates that the rapid growth of cracks causes the tube to separate from the sheet. This may be associated with the cutting operation of the tube during preparing samples since the tubes are cut with a shearing tool. This leads the joint to fail to reach its maximum strength. In contrast, washer housing with 60° shows better condition than washer housing with 50°, as shown in Fig. 16(b). 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 shown in the figure, 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.

4.5 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.17. 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 Figs. 17(a) 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.17(c)). 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 the high neck thickness in the tube and delayed crack growth during the pull-out test of the connections with the washer housing 60.

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 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. 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.
6. 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.
7. The type of failure observed is a combination of separating and growth of cracks and tearing at the edge of the tube. The growth of cracks is mostly associated with the issue of cutting operation of tubes.

Declarations

a) Funding (The authors have no affiliation with any organization with a direct or indirect financial interest in the subject matter discussed in the manuscript)

b) Competing interests (The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper)

c) 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.)

d) Code availability (Yes applicable)

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

f) Consent to participate(Yes applicable)

g) Consent for publication (Yes applicable)

h) Authors' contributions (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.)

References

1. Hahn M, Gies S, Tekkaya AE (2019) Light enough or go lighter ? Mater Des 163:107545. doi:10.1016/j.matdes.2018.107545
2. Kleiner M, Geiger MI, Klaus A (2003) Manufacturing of lightweight components by metal forming. CIRP Ann 52:521–542
3. Marré M, Ruhstorfer M, Tekkaya AE, Zaeh MF (2008) Manifacturing of lightweight frame structures by innovative joining by forming procrsses. J Manuf Process 151:45–52
4. Gonçalves A, Alves LM (2014) Ã PAFM. Inclined Tube-Sheet Plastically Deformed Joints. Steel Res Int 85:67–75. doi:10.1002/srin.201300078
5. Mori K, Bay N, Fratini L, Micari F, Tekkaya AE (2013) Joining by plastic deformation. CIRP Ann - Manuf Technol 62:673–694. doi:10.1016/j.cirp.2013.05.004
6. Salamati M, Soltanpour M, Fazli A, Zajkani A. Processing and tooling considerations in joining by forming technologies; part A — mechanical joining. Int J Adv Manuf Technol 2018
7. Rosenthal S, Maaß F, Kamaliev M, Hahn M, Gies S, Tekkaya AE (2020) Lightweight in Automotive Components by Forming Technology. Automot Innov. doi:10.1007/s42154-020-00103-3
8. Alves LM, Dias EJ, Martins PAF (2011) Joining sheet panels to thin-walled tubular pro fi les by tube end forming. J Clean Prod 19:712–719. doi:10.1016/j.jclepro.2010.12.014
9. Alves LM, Ã PAFM (2012) Mechanical Joining of Tubes to Sheets Along Inclined Planes. Steel Res Int 83:1–6. doi:10.1002/srin.201200035
10. Alves LM, Martins PAF (2013) Single-stroke mechanical joining of sheet panels to tubular profiles. J Manuf Process 15:151–157. doi:10.1016/j.jmapro.2012.12.001
11. Alves LM, Gameiro J, Silva CMA, Martins PAF (2017) Sheet-bulk forming of tubes for joining applications. J Mater Process Tech 240:154–161. doi:10.1016/j.jmatprotec.2016.09.021
12. Alves LM, Afonso RM, Silva CMA, Martins PAF. Joining sandwich composite panels to tubes. Mater Appl 2018:1–10. doi:10.1177/1464420718763463
13. Alves LM, Afonso RM, Silva CMA, Martins PAF (2017) Boss forming of annular flanges in thin-walled tubes. J Mater Process Tech. doi:10.1016/j.jmatprotec.2017.07.011
14. Alves LM, Afonso RM, Silva CMA, Martins PAF (2017) Joining tubes to sheets by boss forming and upsetting. J Mater Process Tech. doi:10.1016/j.jmatprotec.2017.10.047
15. Afonso RM, Alves LM, Martins PAF (2020) Joining by boss forming of rods and tubes to sheets. J Adv Join Process. doi:10.1016/j.jajp.2019.100001
16. Alves LM, Silva FLR, Afonso RM, Martins PAF (2019) Joining sheets to tubes by annular sheet squeezing. Int J Mach Tools Manuf 143:16–22. doi:10.1016/j.ijmachtools.2019.05.002

17. Alves LM, Afonso RM, Martins PAF. Deformation-assisted joining of tubes to sheets made from dissimilar materials 2020. doi:10.1177/1464420720959103
18. Alves LM, Silva FLR, Afonso RM, Martins PAF. A new joining by forming process for fixing sheets to tubes. Int J Adv Manuf Technol 2019
19. Alves LM, Afonso RM, Martins PAF. Mechanical joining of sheets to tubes by squeeze-grooving. Mater Appl 2019:1–10. doi:10.1177/1464420719876965
20. Radhakrishnan E, Kumaraswamidhas LA, Palanikumar K, Muruganandam D (2019) Strength and hardness studies of C44300 tube to AA7075-T651 tube plate threaded and unthreaded dissimilar joints fabricated by friction welding. Integr Med Res 8:3424–3433. doi:10.1016/j.jmrt.2019.06.008
21. Park H, Lee J, Lee Y, Hoon J, Kim D (2019) Electromagnetic expansion joining between tubular and fl at sheet component. J Mater Process Tech 273:116246. doi:10.1016/j.jmatprotec.2019.05.027
22. Alves LM, Afonso RM, Martins PAF. Self-pierce riveting of tubes to sheets. Int J Adv Manuf Technol 2020:3351–60
23. Langstädtler L, Herrmann M, Schenck C, Kuhfuss B. Joining of Sheets with Tubes by Electrohydraulic Forming. ESAFORM 2021, vol. 05, 2021, p. 1–10
24. Babalo V, Soltanpour M, Fazli A (2019) High speed circular hemming; a novel joining process for thin and low-ductile sheets. Thin-Walled Struct 142:98–115. doi:10.1016/j.tws.2019.04.059

Figures

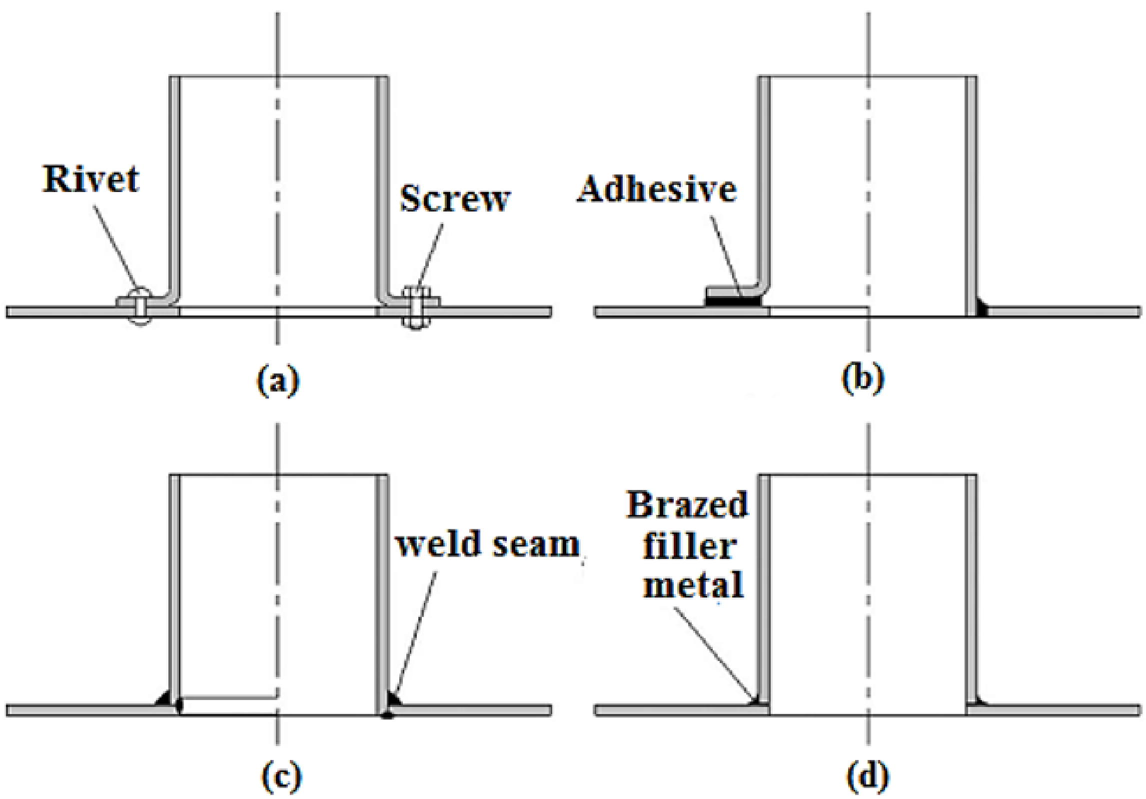


Figure 1

Conventional tube-sheet joining[4] (a) mechanical fastening (b) adhesive bonding (c) welding (d) brazing

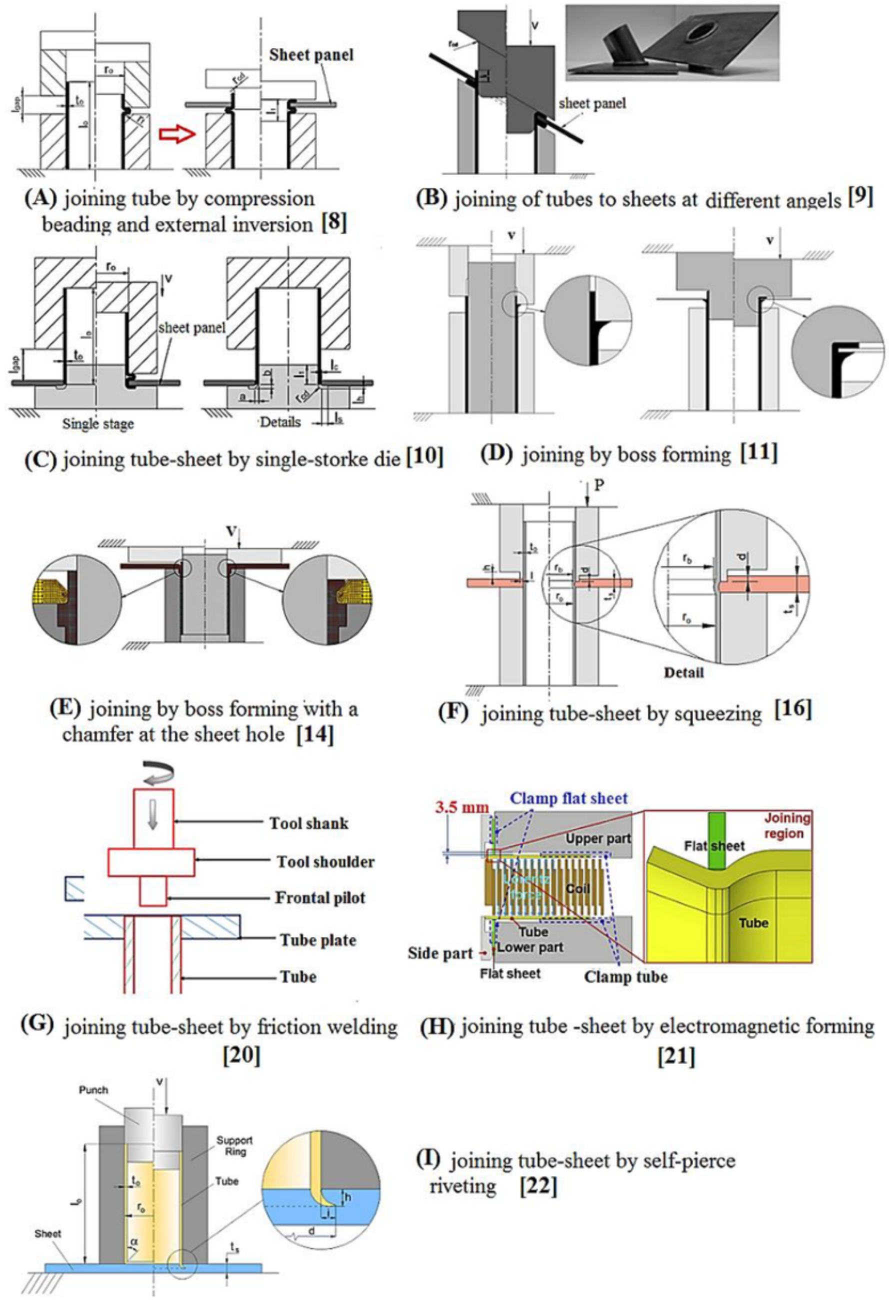


Figure 2

Recent developments in the joining of a tube to a sheet by forming

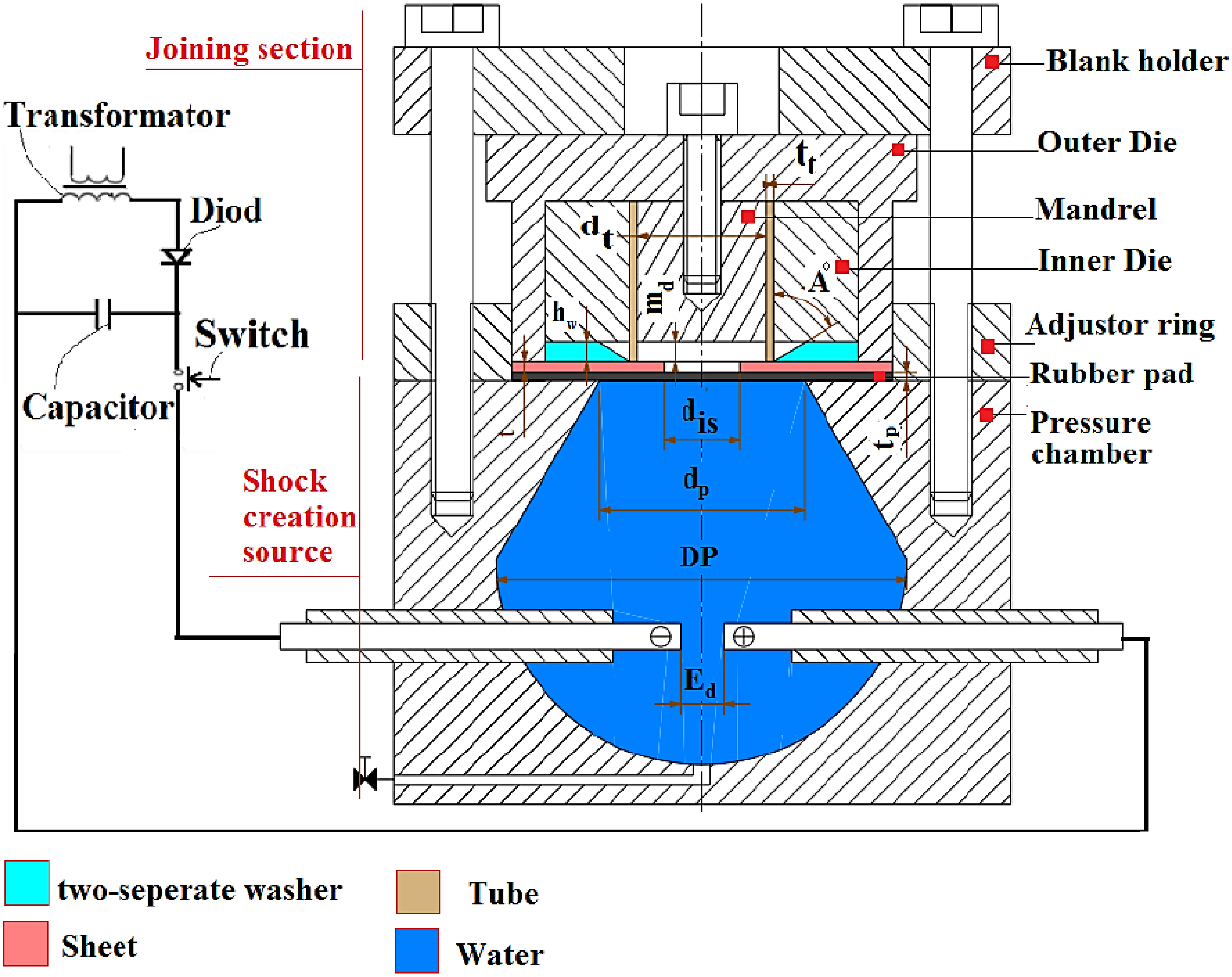


Figure 3

The schematic of joining tube to the sheet by the EHF

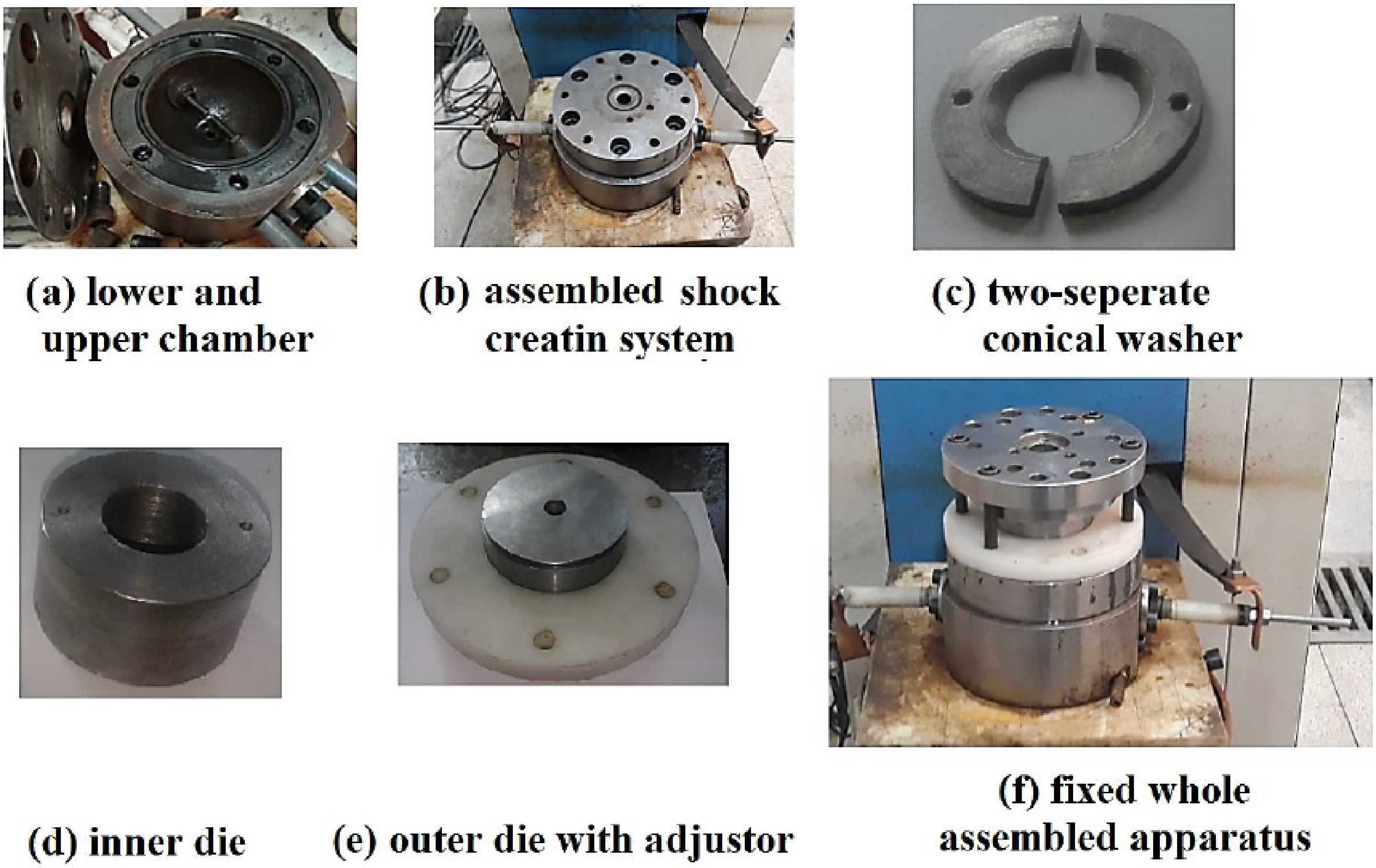


Figure 4

Main workpieces for this new joinig technique

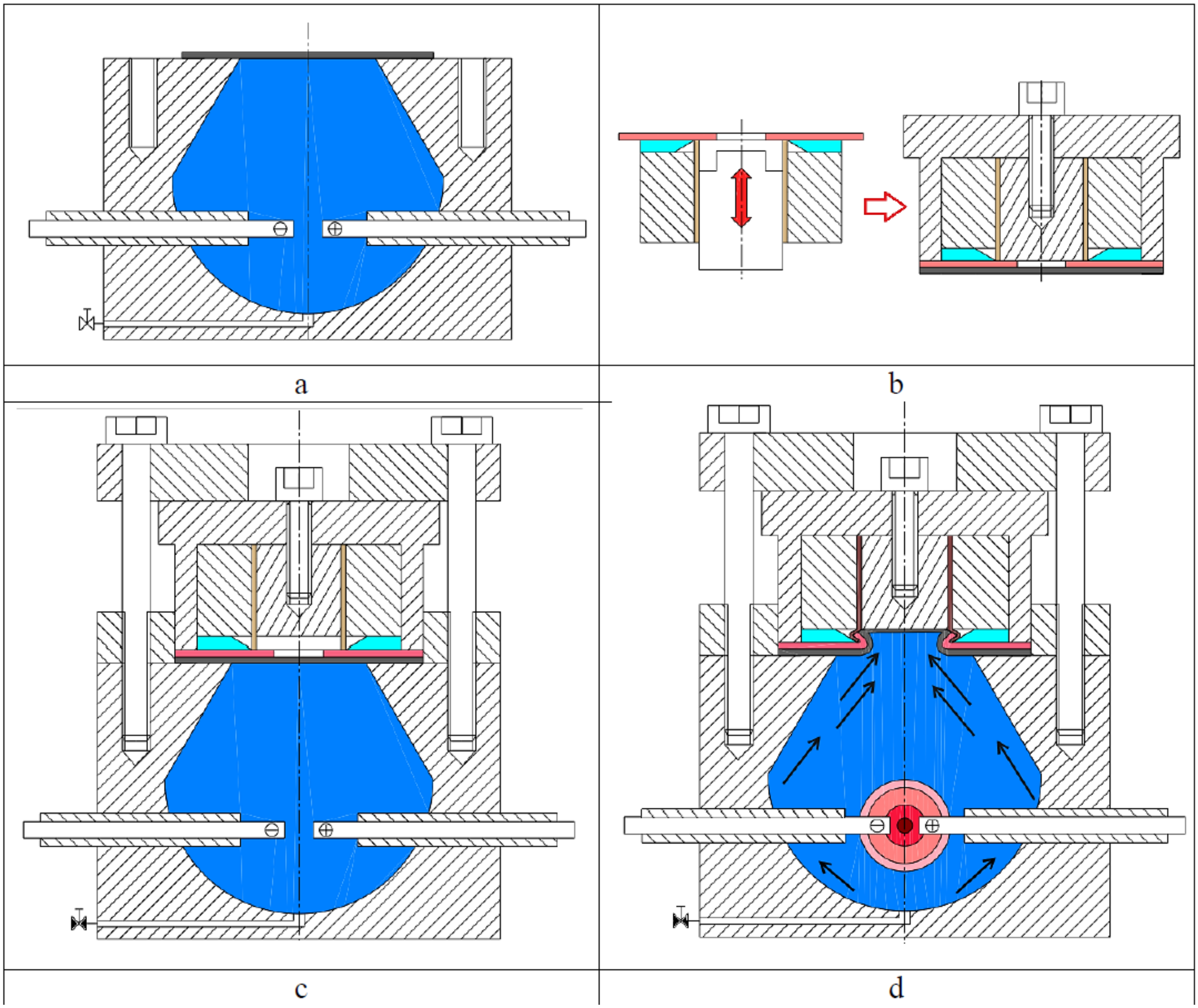


Figure 5

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

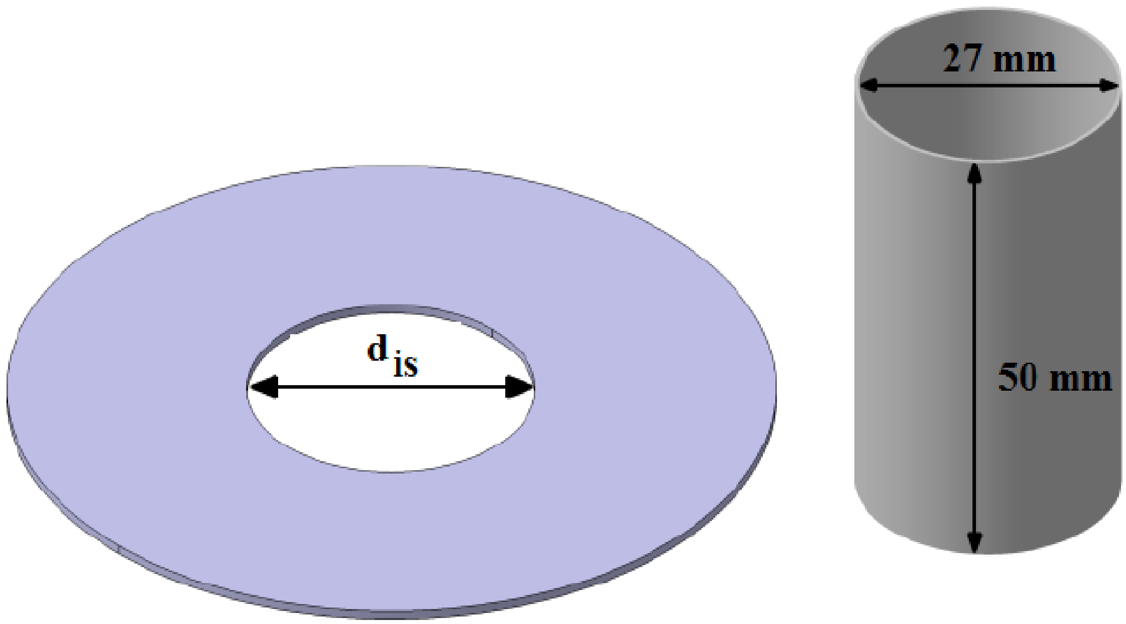


Figure 6

Detailed geometry diamension of tube and sheet

Figure 7

Utilized fixture for measuring joint strength of the tube-sheet joined

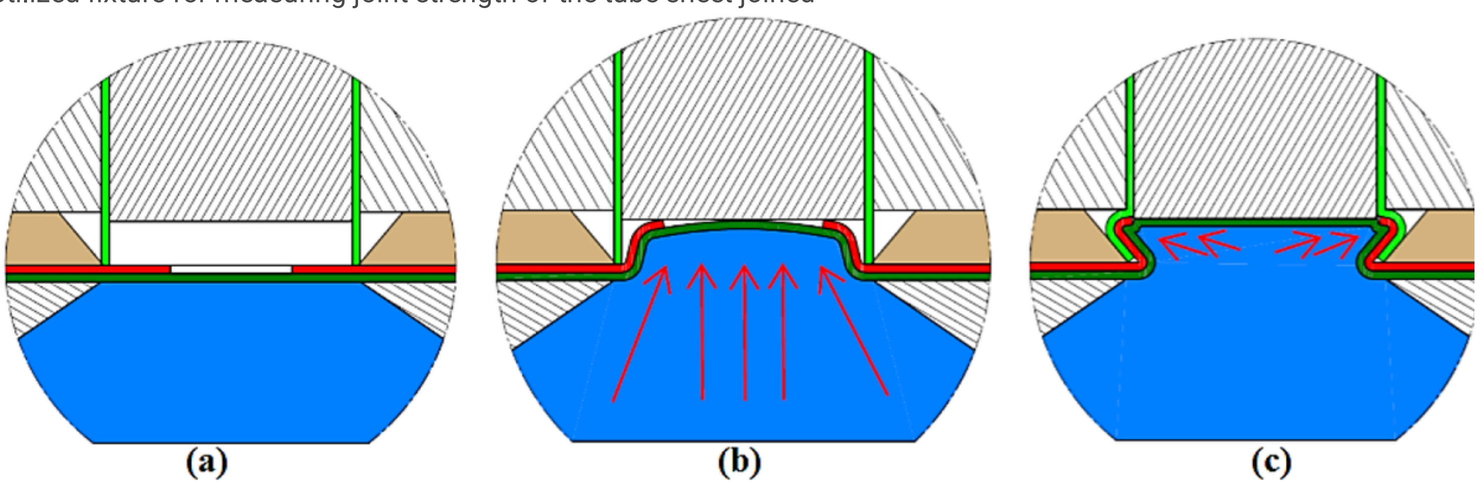
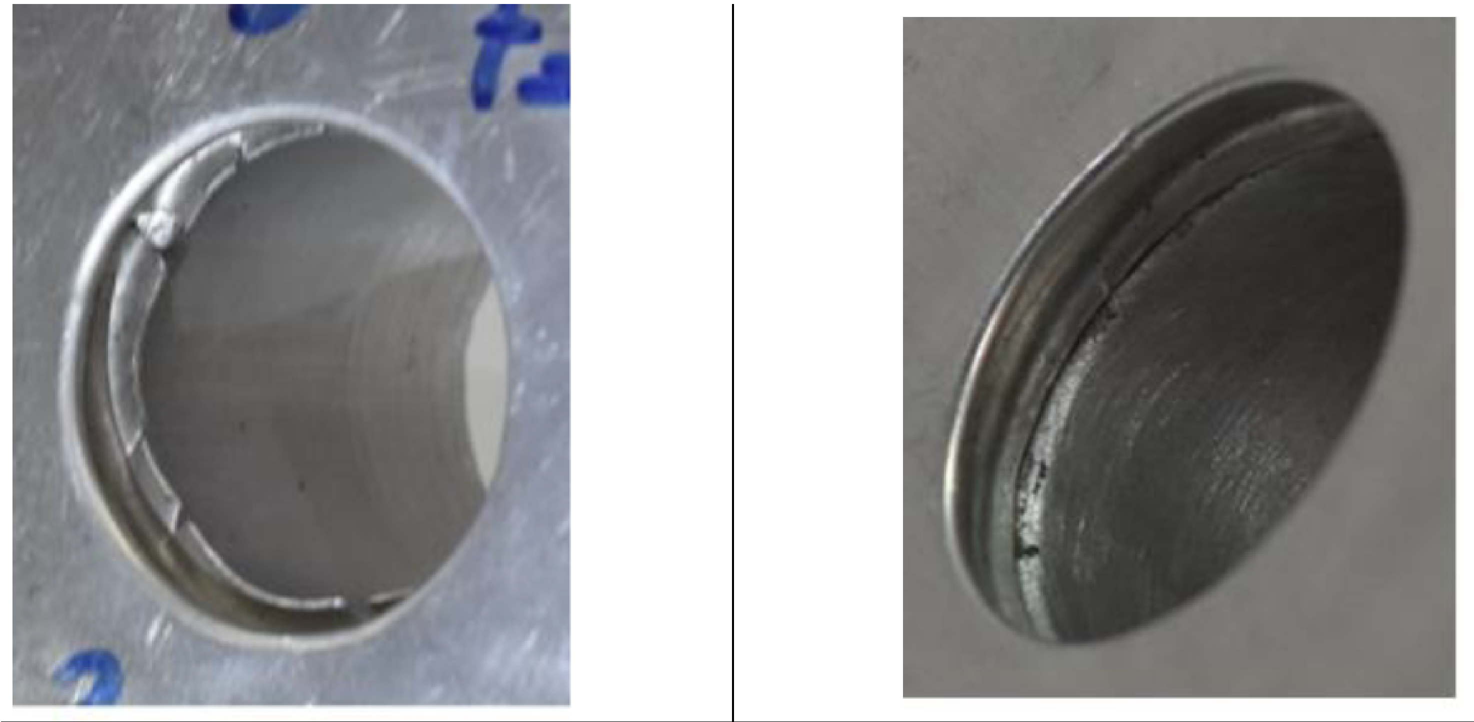


Figure 8

Different working principles of electrohydraulic tube-sheet joining a) clamping stage b) discharging energy and forming in axial direction c) Completing stage

Figure 9

Prepared joining samples for investugation



(a) (b)

Figure 10

The effect of sheet hole diameter on the joining sample a) 12 mm b)15 mm

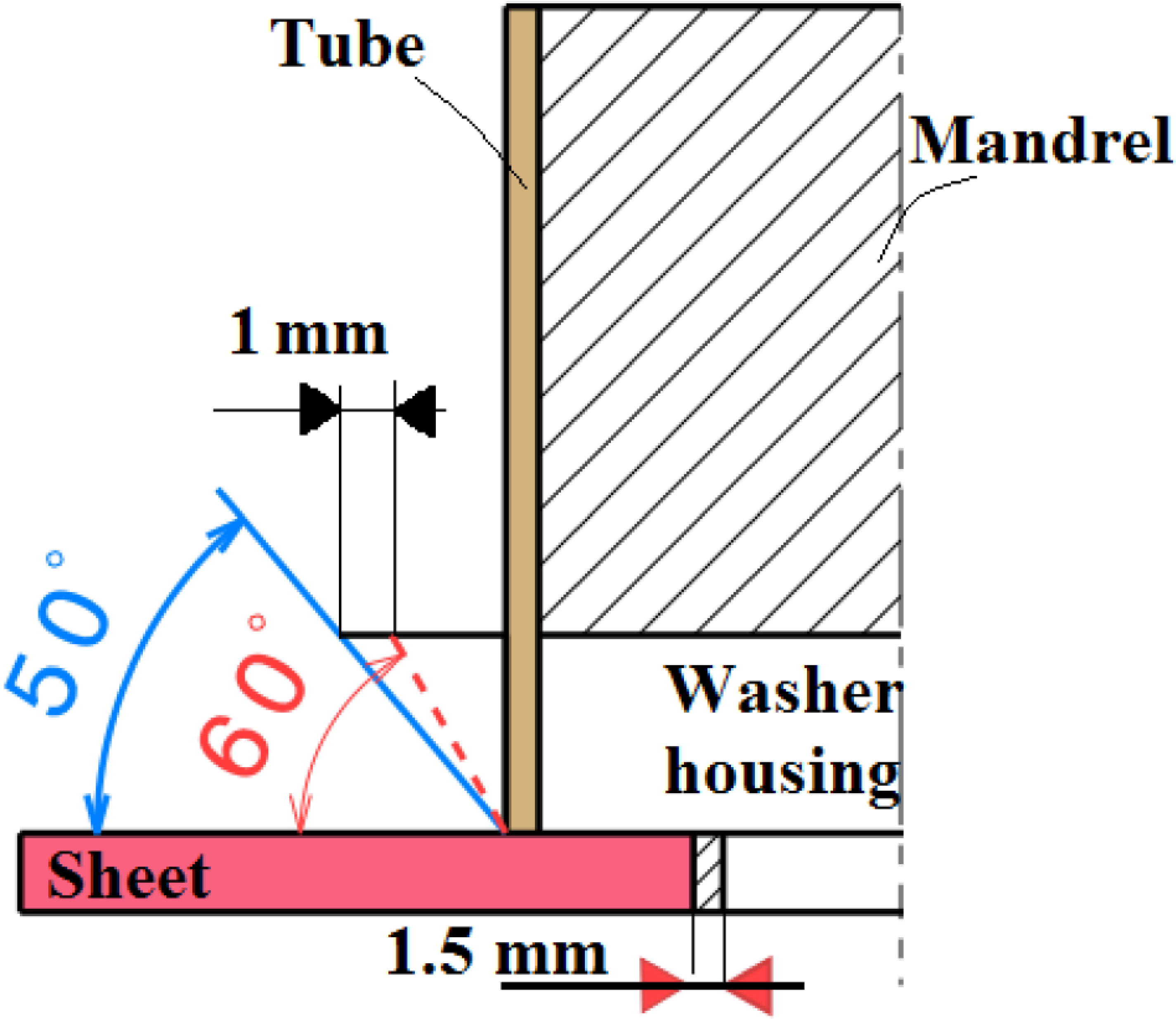


Figure 11

The relation between sheet hole diameter and washer housing angel

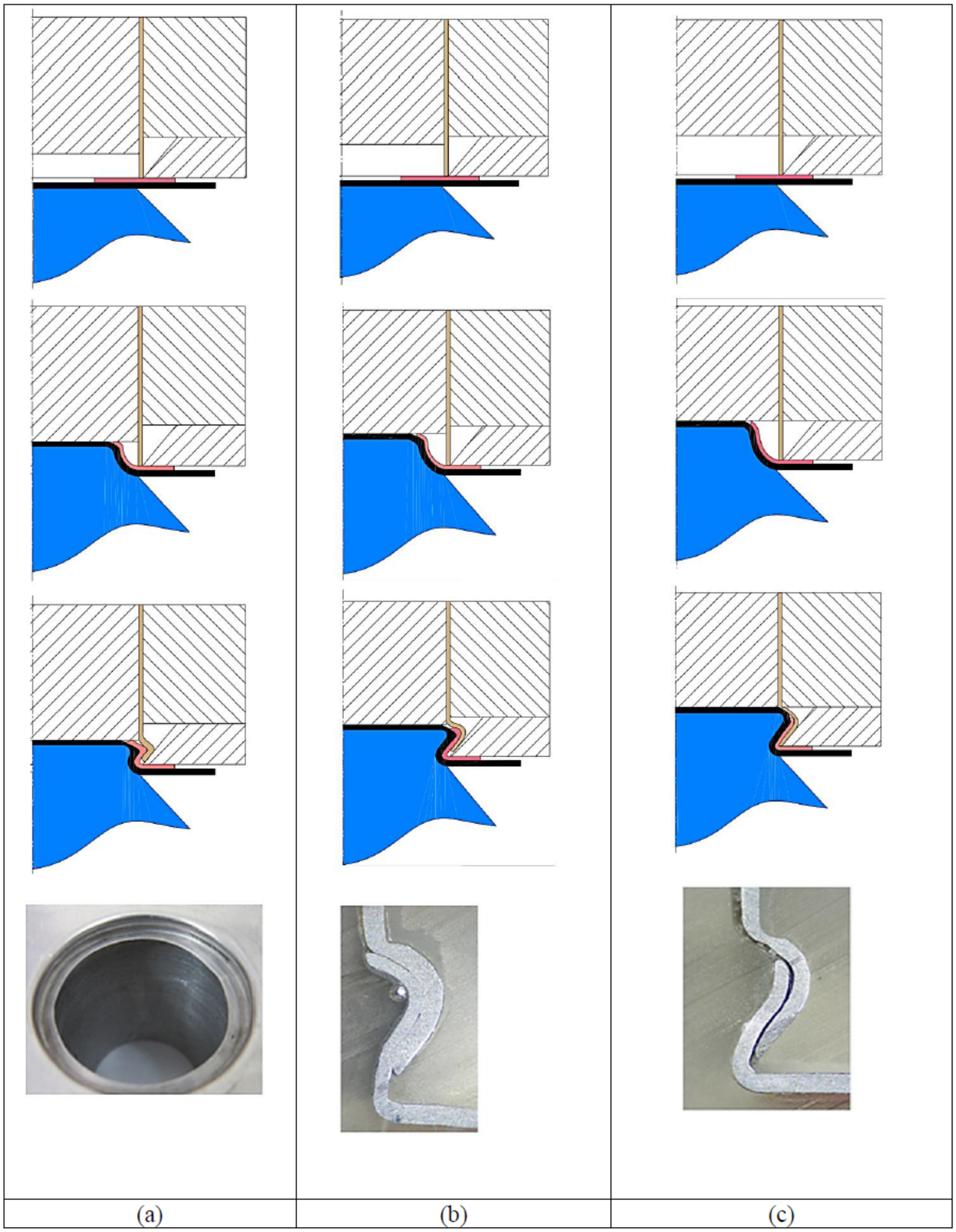


Figure 12

The effect of the gap length between top of the sheet and mandrel (a) 3 mm (b) 4 mm (c) 5 mm

Figure 13

(a) cross-section of the joint with washer housing 50 (b) thickness variation in the tube (c)) thickness variation in the flat sheet

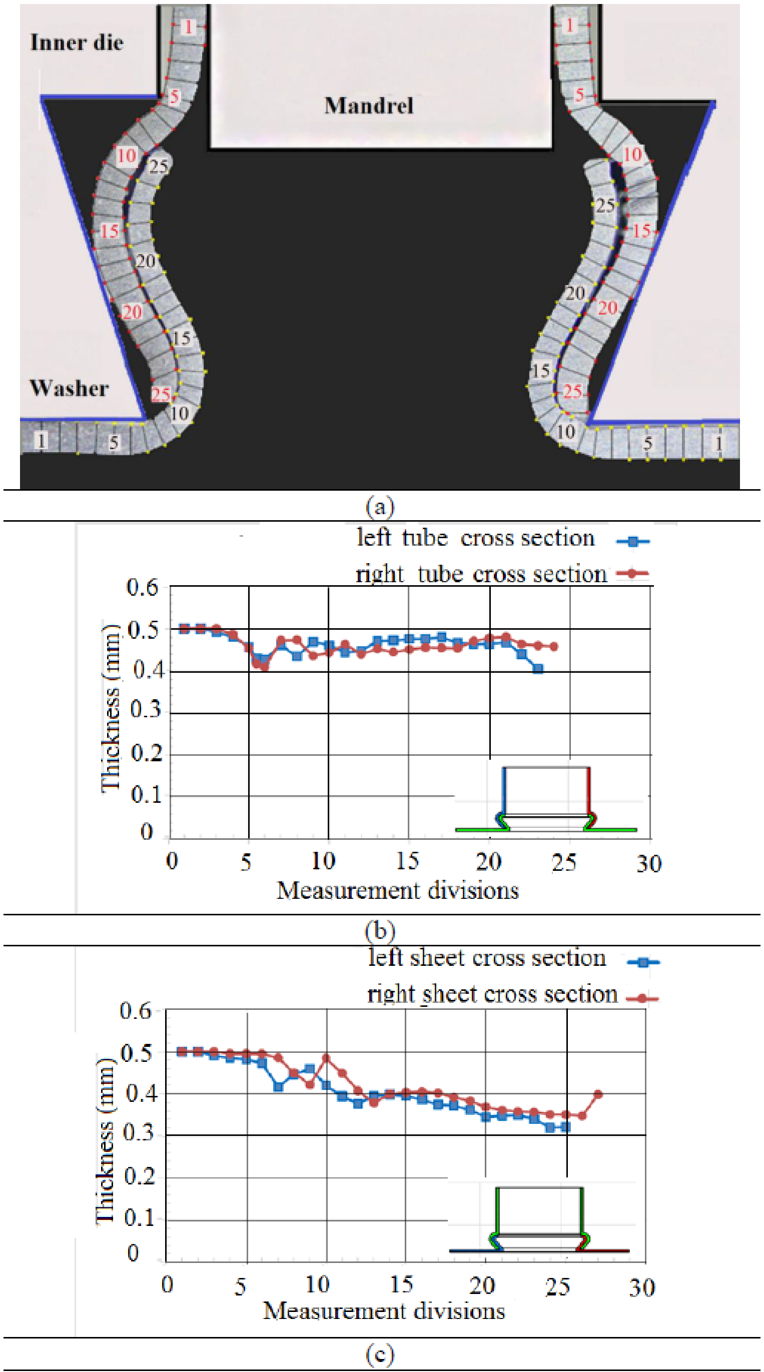


Figure 14

(a) cross section of the joint with washer housing 60° (b) thickness variation in the tube (c)) thickness variation in the flat sheet

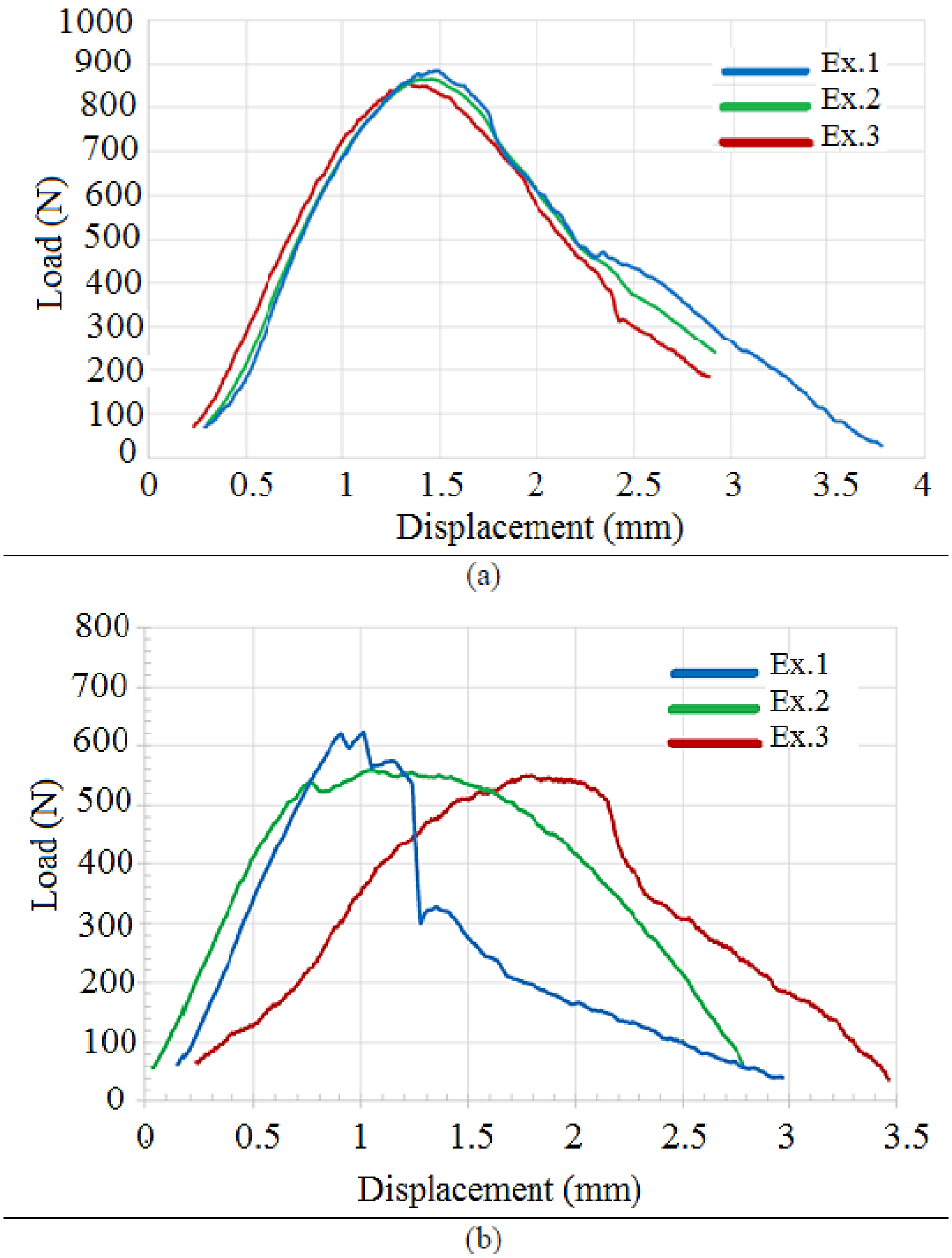


Figure 15

Destructive tests of (a) washer housing with 60 angle and 18 mm sheet hole diameter (b) washer housing with 50 angle and 15 mm sheet hole diameter

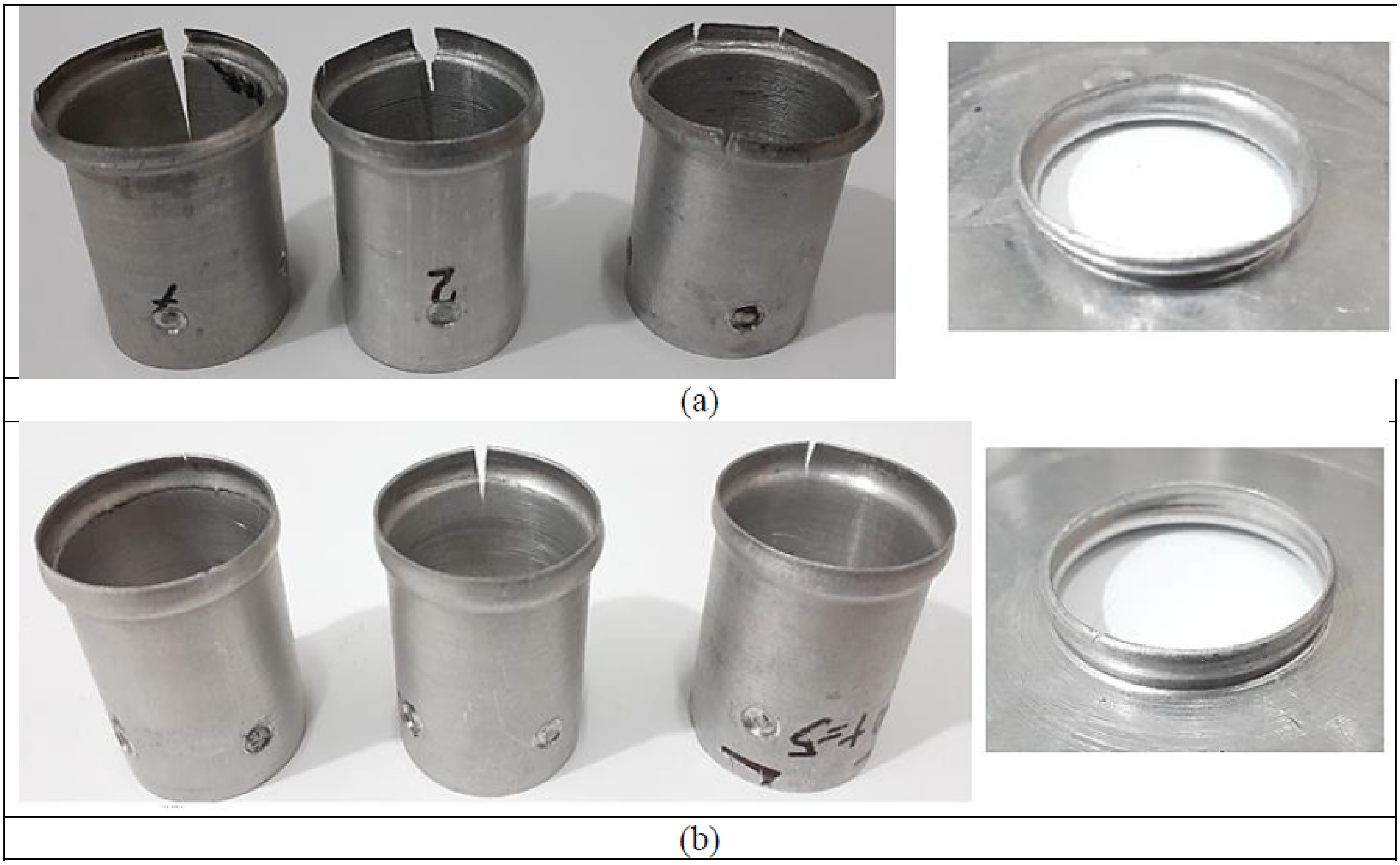


Figure 16

Failure modes of (a)washer housing 50° (b) washer housing 60°

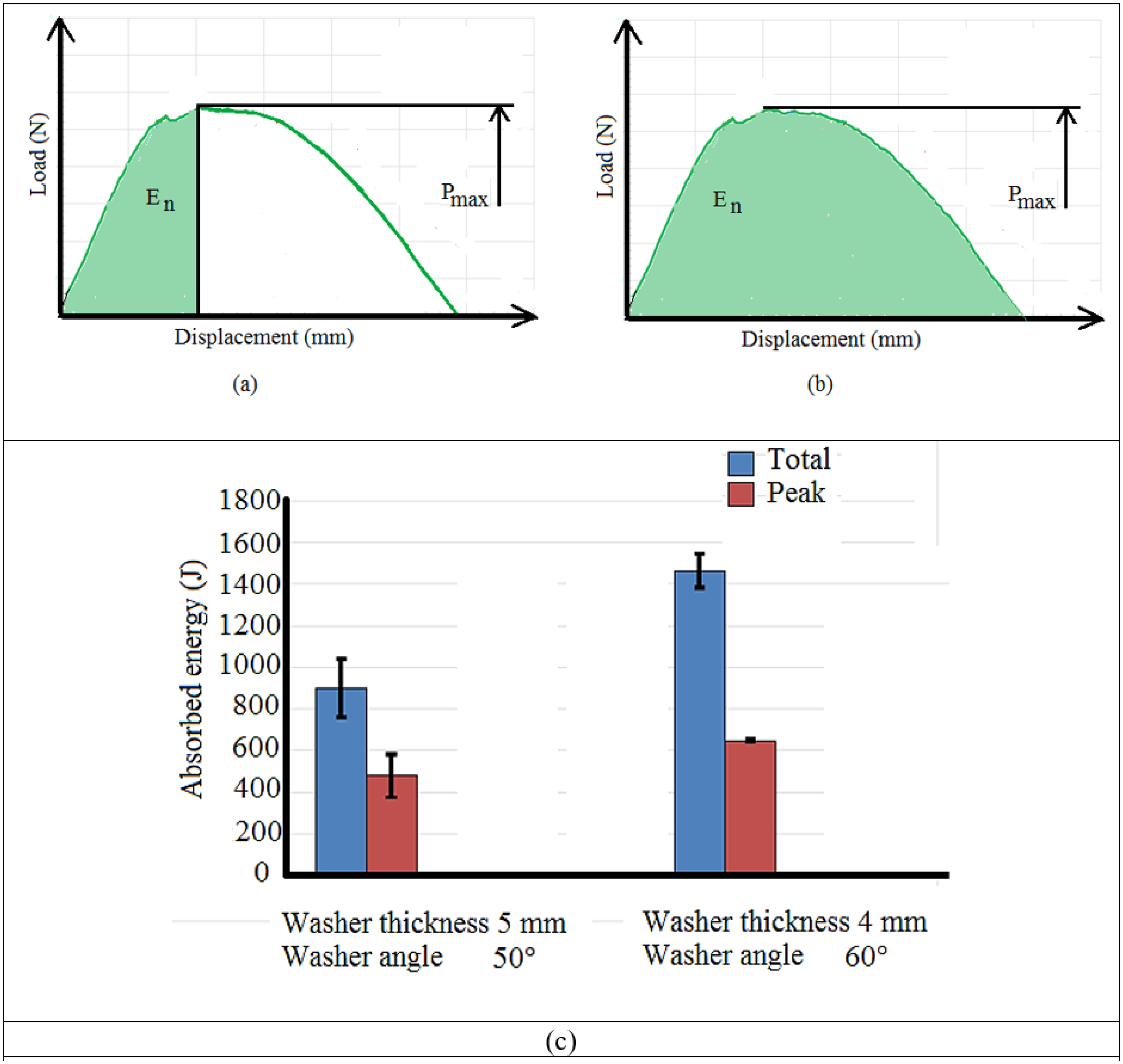


Figure 17

Energy absorption (a) up to peak load (b) at the end of complete failure (c) two different pull-out tests