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Joining of EN AW 6060 Pipes by Plastic Forming

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Abstract
The article deals with an innovative, but not widely used type of joining of aluminum pipes through experiments. The joints are formed by plastic forming. The process is carried out in one step using the principle of pipe expansion, in order to bring the mating surfaces of the two pipes into a suitable position for the subsequent joining, which is created by means of plastic instability and simultaneous pressure flanging. Experimental tests were carried out with the tools designed to create most suitable joints. The length of the plastically formed pipe sections involved in the joint, the angle of the sharpened pipe ends, and the thickness of the formed joints were analyzed. One of the main goals of this study is to determine the proper joining parameters, such as tool distance or edge tapering for further investigations. As per the test results, it can be stated that the technology is suitable for joining aluminum tubes in a cost-effective way, and based on the promising strength results, further investigations will be conducted.

Keywords
innovative pipe connection, plastic instability, joining by forming

1 Introduction

There are many solutions available for connecting the ends of the pipes. Threaded, pressed, welded, brazed, or glued connections are used to connect two pipe ends (Fig. 1) [1].

Each option has advantages and disadvantages that must be considered when using them in each application.

Threaded connections (Fig. 1 (a)) use threads and screws to connect pipes. They are simple to design, easy to assemble and disassemble, and come in standard sizes. Their most important limitations are related to size, water, or gas tightness requirements. Corrosion susceptibility can also prevent the use of fixed joints when pipes and joints made of different materials are exposed to a wet environment [2].

Crimped joints (Fig. 1 (b)) make use of beads or dimples produced by reduction, swaging or electromagnetic forming. Zhang et al. [3], for example, proposed the application of rotary swaging to join tubes of different diameters, whereas Psyk et al. [4] provided a state-of-the-art review

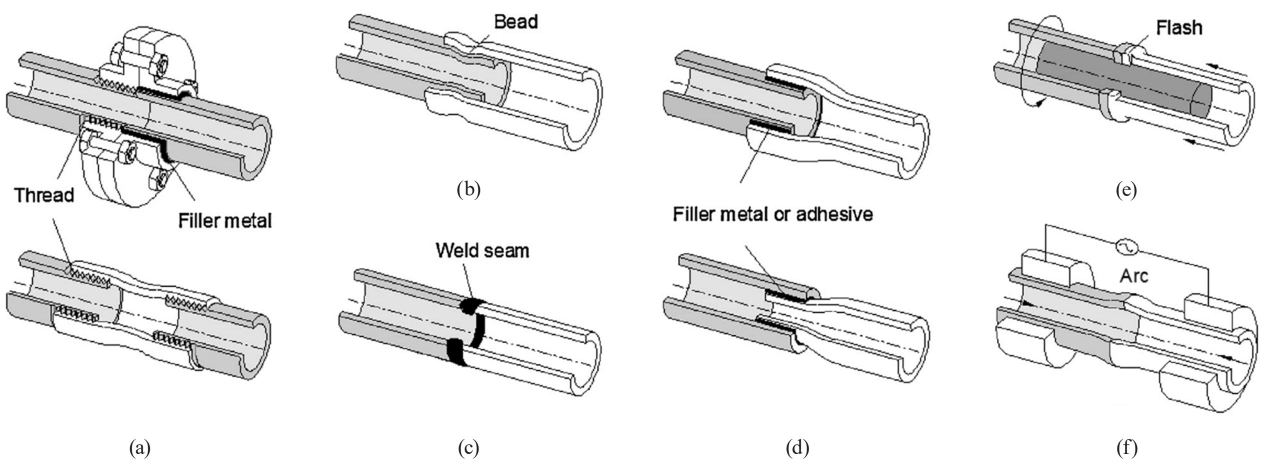

Fig. 1 Connection of two pipe ends using (a) threaded, (b) pressed, (c) welded, brazed or (d) glued (e) friction welded (f) new cold forming joints adapted from [1]

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of interference-fit and form-fit joints produced by electromagnetic forming. Pressed joints are made by reducing the cross-section. Unlike fixed joints, press joints are not limited by aesthetic requirements, standard size flanges or connections. However, they may be limited by the required pull-out force and water or gas tightness. The thickness of the two pipes to be connected must be thin, and the elasticity of the material must be sufficient to withstand large local plastic deformations without breaking.

Welded joints (Fig. 1 (c)) are generally used for thick-walled pipes because the pipes need to be heated to their melting point without significant distortion, warping and metallurgical changes. When choosing welded joints, the difficulties arising from the end-to-end joining of pipes made of different materials and the costs of slag removal must also be considered.

Brazed joints (Fig. 1 (d)) are a good alternative to welded joints for thin-walled pipes. They are produced by placing a filler metal – whose melting point is below the melting point of the tubes – between the opposite surfaces of the tubes and then increasing their temperature with a torch, induction coil or furnace. The molten filler flows in a capillary manner and creates a strong join between the mating surfaces of the pipes when cooled. The most important advantage of soldered joints is that they can be easily automated and efficiently used to connect pipes made of different materials or with a significant difference in wall thickness. Their most important limitations arise from the distortion caused by the heating-cooling cycle, as well as from the fact that special-purpose pipe end shapes must be made with very tight tolerances and very good surface quality.

Bonded joints are alternatives to welded and brazed joints in situations where elevated temperatures are not applicable or when dissimilar materials (such as metals and polymers) are used. Adhesive joints eliminate most of the limitations associated with other types of joining, but they require careful surface preparation with tight tolerances, and the time required for the adhesive to set must also be taken into account. Under unfavorable environmental conditions, the load bearing capacity of the bonding may decrease over time [5].

Additional solutions for connecting the ends of the pipes are the application of friction welding (Fig. 1 (e)) and butt-welding (Fig. 1 (f)) technologies [6]. In friction welding, one pipe remains stationary while the other end, placed in a chuck, rotates at high speed. The friction welding joint is created when the relatively spinning pipes are brought into contact under the influence of axial pressure, and due to the friction, temperature of the materials are increasing, therefore the ends are getting welded. During butt welding, the arc generated at the pipe ends causes local heating and softening of the material. The butt-welded joint is created even if the pipes are subjected to an axial compressive force. Both types of joints can be easily automated, but their application is limited to thick-walled pipes, as thin-walled pipes tend to buckle under typical compressive forces and temperature ranges.

Joining of sheet panels to thin-walled cylinders is also related to this research due to the forming similarities during joining for instance presented in [7, 8].

In addition to the possibilities of connecting different pipe ends, the development of new solutions is justified, which eliminates the above-mentioned difficulties and can be an effective, fast, and environmentally friendly solution. Alves et al. [1] developed a new cold forming process for connecting the ends of the pipes, which, in addition to its many beneficial properties, can be used very efficiently.

The process is carried out with one punch and two consecutive forming steps are used, as shown schematically in Fig. 2.

In the first step, the adjacent opposing surfaces are created, and in the second step, the join between these surfaces is formed through the axisymmetric plastic instability.

2 Tool design

Fig. 2 shows a new method of joining pipes that can be created by plastic instability. As can be seen from observing the open, intermediate, and closed positions of the tooling system, the joining is done in one stroke with a series of

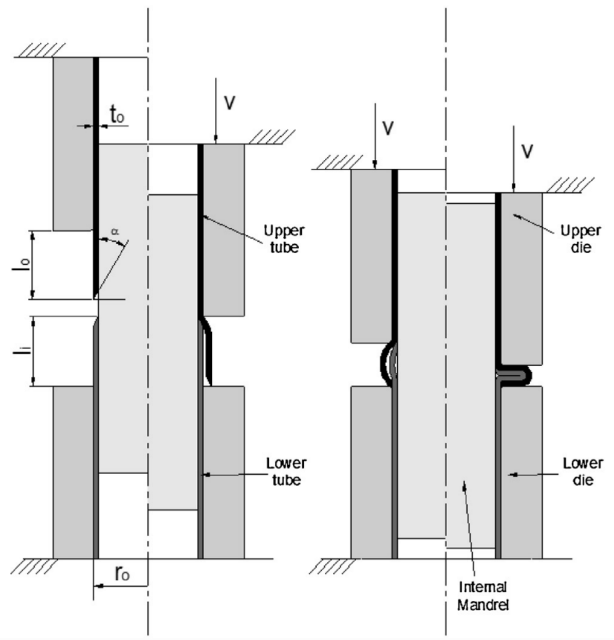


Fig. 2 Cold forming process for joining pipes adapted from [1]

two different elemental tube forming operations: expansion and pressing. Expansion is accomplished by forcing the upper tube against the tapered end of the lower tube so that the unsupported zone of the upper tube can be radially expanded, and the two tubes can slide into each other as the outer tube expands. In the first stage of the joining process, the bottom tube acts as a conical punch, and the slope of its rounded edge plays a key role in the overall feasibility of the process.

As soon as the unsupported height l0 of the upper pipe comes into contact, the pipe expansion process is completed by the lower tool. The expansion is replaced by plastic instability, i.e., the tubes non-linearly buckle, and the joint is achieved by simultaneous pressure flanging of the two tubes.

The schematic representation of the tool system (Fig. 2) enables the identification of the main operating parameters of the process:

- the initial unsupported height of the upper tube is l_0, which expands radially,
- the initial unsupported height l_1 of the lower pipe, which behaves as a conical mandrel in the first stage of the process,
- and α is the angle of tapering angle the pipe ends.

The question is how the joints and joining process is affected by different initial conditions of tools and tubes. The upper and lower tools were designed for the specified reference radius r_0 of the pipes to be tested, the mandrel for the specified wall thickness t_0 of the pipes to be joined.

3 Experimental studies

The tools used for the experiments were designed based on previously conducted FEA simulation with a similar type of aluminum. The previous study focuses on the different angles and distances of the set up. The applied tubes were considered the commercially available tube diameters and wall thicknesses, and the load bearing capacity of the applied testing machine is also taken into consideration during the design phase, since the further research activity would deal with steel connections, which leads to a well-defined maximum joining and destructive load. A more detailed description can be read about the pre-design phase in [9].

3.1 Material characterization

In this study EN AW 6060 type of aluminum were used. The chemical composition and the mechanical properties of the applied material can be seen in Tables 1 and 2. The flow properties of the aluminum can be seen in Fig. 3.

Table 1 Chemical composition of EN AW 6060 in m/m%

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti
0.45	0.19	0.006	0.044	0.38	0.007	0.011	0.013

Table 2 Mechanical properties of EN AW 6060

$R_{p0.2}$ [MPa]	R_m [MPa]	A_{50} [%]	HB
171.6	221.5	9.2	73

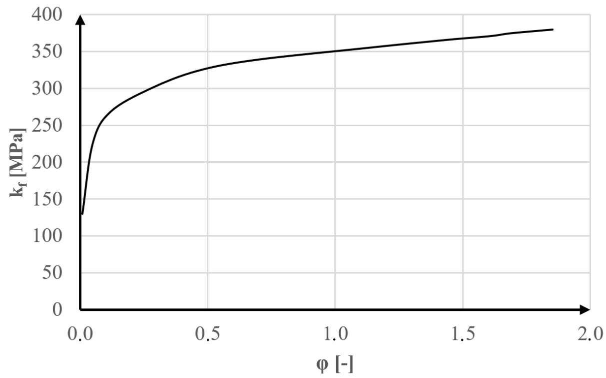


Fig. 3 Flow curve of EN AW 6060

In order to determine the flow curve Watts-Ford test was conducted. Further numerical studies will be performed to analyze the material flow and stress, strain distribution of the tubes during the tests.

3.2 Tool design

The first step for the experimental tests was to prepare the tools. The tool need of the process is two clamping device which are holding the tubes, and a mandrel which is supporting the inner surfaces of the tubes during the forming to eliminate unwanted buckling modes. The tools have to be hold by two connector elements which are supporting the parts in the testing rig. These elements were also designed and manufactured for the tests. The drawings of the parts of the tools and their main dimensions are shown in Fig. 4, and the completed pieces are shown in Fig. 5.

The parts of the joining tool made by 42CrMo4 type of steel. The geometric size of the pipes is determined by commercially available size. The tested pipes typically had a length of l_{CS} = 100 mm, an outer diameter of d = 30 mm, and a wall thickness of t = 1.5 mm.

The tool system was installed in an electro-hydraulic testing machine type MTS250, where the mechanical characterization of the material was also performed previously (Fig. 6). The crosshead speed of the testing machine was set to 120 mm/min (2 mm/s).

The Fig. 7 is shown a joining curve, which can be divided into six phases.

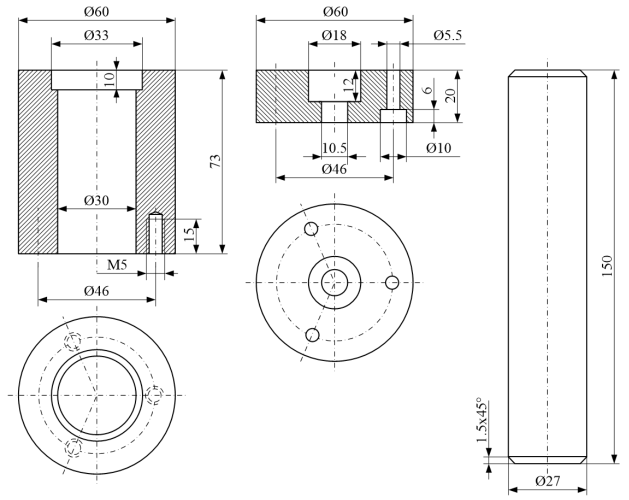


Fig. 4 Drawings of the parts of the tool for pipe joints (a) clamping head, (b) connector, (c) mandrel

Fig. 5 Manufactured parts

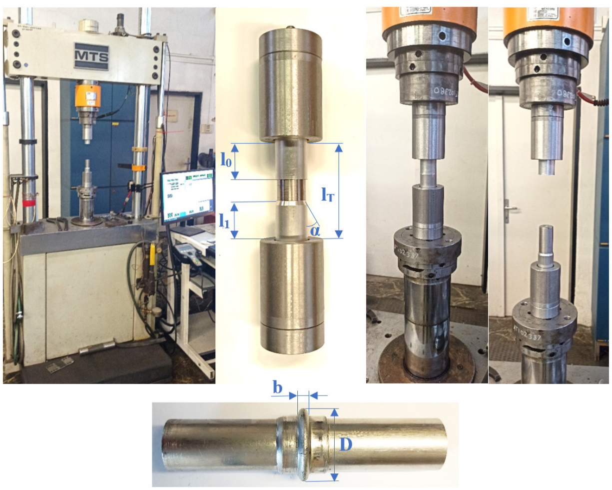


Fig. 6 The testing equipment with a tool designed to create joints

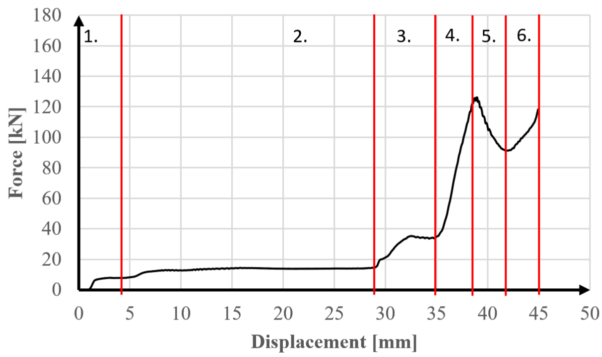


Fig. 7 Force-displacement diagram for joining (test specimen 2)

The phase 1. is the initial contact and the outer tube's initial expanding phase. The phase 2. is the continuous tube expansion phase. This phase is similar to the traditional tube expansion process [9]; however, the expanding tool in this case is the inner tube in contrast to the tube expansion process. In the phase 3. the so-called plastic instability is getting into the joining process. The plastic instabilities are discussed in [10, 11]. The phase 4. is the continuous bulging, where both the tubes formed, and the flange is formed. In the last two phases (5. and 6.) the flange forming into the final form, and the forming force is getting higher due to the plane compression of the contacted tube sections.

The effect of distance in between the tools, as well as the effect of the tapering were analyzed. During the inter-tool distances (l_T), the pipe sections (l_0, l_1) protruding from the tool were of equal length (20 mm, 25 mm, and 35 mm, respectively). The literature [1] recommends 20° edges at the ends of the pipes, however based on the equations presented in [12] the effect of the angle could be varied from roughly in between 15–75° without high affection on the forming force, therefore experimentally analyzing this theorem is necessary, lower or higher values would increase the forming force in extremely, which is unfavorable.

3.3 Experimental work

During the pipe joints, edges of $\alpha = 20°$, 40° and 60° were formed on the ends of the pipes. During the analysis of the effect of the examined parameters, the thickness of the joints created (the distance between the tools at the end of forming) was set to $b = 5$ mm (Fig. 6). The thickness of the joints (b) was also examined, the applied thicknesses are the following: 5 mm, 7 mm and 9 mm, respectively. The series of experiments can be seen in Table 3.

In Fig. 8 can be seen the manufactured joints with respect to the outer diameter (D) of the protruded zones.

Table 3 Test series parameters

Speciment ID	l_{CS}, mm	l_0, mm	l_1, mm	l_T, mm	α, °	b, mm
1	95	20	20	40	20	5
2	100	25	25	50	20	5
3	100	35	35	70	20	5
4	100	25	25	50	40	5
5	100	25	25	50	60	5
6	100	25	25	50	20	7
7	100	25	25	50	20	9

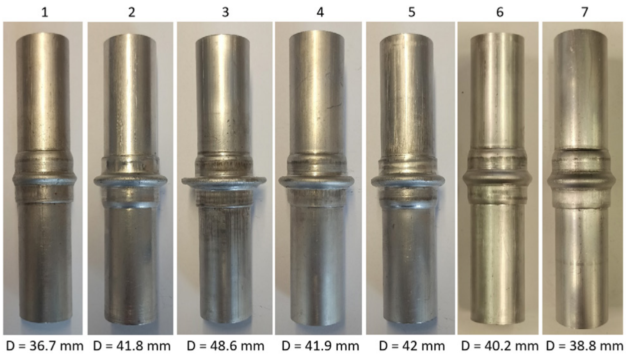


Fig. 8 Joints made with tools

The examination of the quality of the joints was carried out by examining the force-displacement diagrams recorded during the forming process. Fig. 7 shows the force values measured during the tapering angle of 100 mm long pipes with a 20° taper as a function of displacement. During the joining process, l_0 and l_1 were equally set to 25 mm, and the thickness of the joint created was 5 mm.

The first trials were conducted to examine the distance between the tools. The examined distances are 40 mm (l_0 and l_1 = 20 mm), 50 mm (l_0 and l_1 = 25 mm) and 70 mm (l_0 and l_1 = 35 mm), respectively. The joint thickness was set to 5 mm, considering the plate thickness, and a 20° chamfer was applied at the ends of the pipes according to the literature. Fig. 9 shows the force-displacement values registered during the forming.

It can be seen from the diagram that the properly formed joints are highly depends on the distance of the tools. If the distance between the tools is small (40 mm), then the form-locking cannot be formed. In contrast, if it the distance of the tools is large, excessive force is needed to form the joint (70 mm). A tool distance of 50 mm seems to be the most proper distance from the forming force point of view, therefore in further experiments the 50 mm was set up.

Fig. 10 shows the force-displacement diagrams of the experiments with different edges (α = 20°, 40° and 60°, respectively).

The measured force-displacement curves differ according to the degree of tapering angle. The force requirement for expansion is seems to be preferable at the chamfer of 20°, since the smallest force is needed to start the expansion. The larger the angle, the greater the chance of an unsuccessful/poor joint.

Analyzing the thickness of the formed joints (b), we created a larger thickness. The thickness we used was increased to b = 7 mm in order to reduce the formed edge.

During the analysis of the formed joints, sections were also made of joints with a joint thickness of 5 mm and 7 mm (Fig. 11) in order to be able to examine the material flow occurring in the formed joint.

Tensile tests were conducted to investigate the joint strength of the pipe joints with different thicknesses investigated. In order to avoid indentation when gripping the ends of the joined pipes, special inserts were made to support the internal surfaces of the pipes. The strength of the joints was investigated at joint thicknesses of b = 5 mm, b = 7 mm, and b = 9 mm. These results can be seen in Fig. 12.

The measured maximum force of 26.4 kN for the 5 mm thick joint, 38.3 kN for the 7 mm thick joint, and 19.7 kN for the 9 mm thick joint. At the joint thickness of 9 mm, the inner tube slipped out from the outer tube. From the obtained results, it can be seen that a lower joint strength can

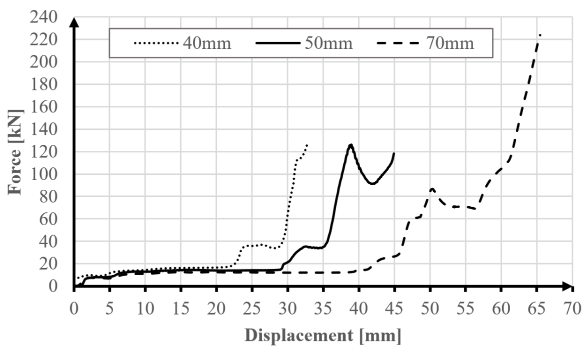


Fig. 9 Connections for different lT values

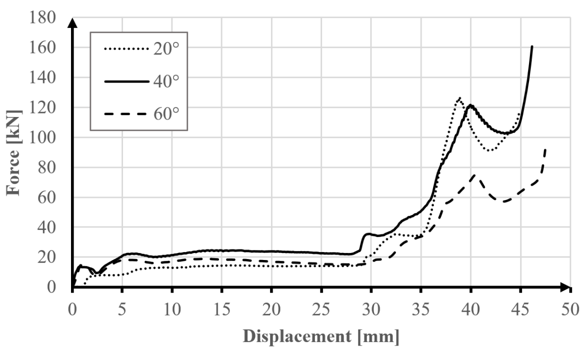
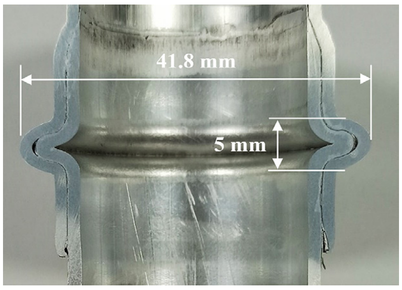
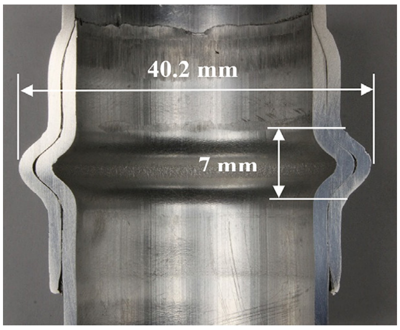


Fig. 10 Effect of tapering angle on the force-displacement diagram



(a)



(b)

Fig. 11 Cross-section of prepared joints (a) at a joint thickness of 5 mm (b) at a joint thickness of 7 mm

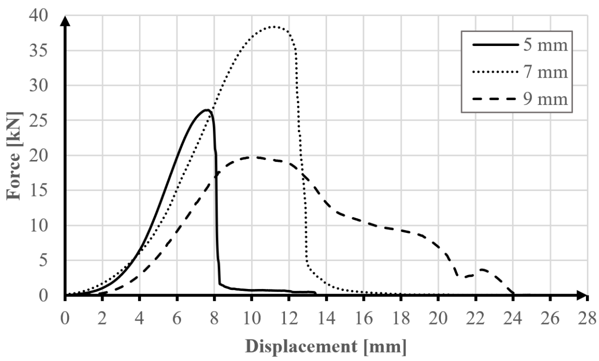


Fig. 12 Tensile test results for different *b* values

be achieved with a joint thickness of 5 mm, while a greater joint strength can be achieved with a joint thickness of 7 mm. When examining the cases of 5 and 7 mm, it can be observed that their tensile diagrams show similar characteristics, while the 9 mm one is much flatter. For this reason, if we only focus on the 5 and 7 mm joint, then not only the strength of the joint is authoritative, but also the displacement until failure, which can be said to be significant.

However, joints are not only exposed to tensile stress, but also to twisting, bending and other effects, such as pressure caused by liquids. Therefore, it is not possible to clearly state which thickness is the most suitable. Additional tests are required to qualify joints of different thicknesses.

4 Conclusion

The new proposed jointing procedure enables a simple and effective replacement of existing solutions based on the use of fixed, pressed, welded, brazed, or glued joints. We have successfully produced a tool set consisting of simple elements, with the help of which we created pipe joints in one step using pipe expansion and simultaneous pressure flanging. During the tests, the effects of the length of the plastically formed pipe sections involved in the joint, the angle of the tapering pipe ends, and the change in the thickness of the formed joints were analyzed. In addition to the force-displacement diagrams of the production processes, the first tensile tests were also carried out, which already provide predictions regarding the strength of the joints for further research.

As a conclusion, for further investigations the applied tool distance is 50 mm and the edge tapering of the joints is 20°, the thickness of the joints is 5 mm based on the presented results.

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