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THE NATIONAL STUDENT RESEARCH CONFERENCE PAPER

**EXAMINATION OF FORMING PROCESS IN JOINING STAINLESS STEEL THIN
-WALLED PIPES BY PLASTIC DEFORMATION**

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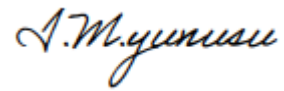
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DECLARATION OF AUTHENTICITY

I, the undersigned Idd Mohamed Yunusu, student at the Faculty of Mechanical Engineering and Informatics of the University of Miskolc, declare and certify with my signature that I have prepared this thesis myself, I have carried out the examinations described therein, unless I indicate otherwise, and I have achieved the results described myself. I used data and information only from the sources listed in the bibliography. Any part that I have taken from another source, either verbatim or in the same sense, but reworded, is clearly marked with the source.

Miskolc, 04. 11. 2024

A handwritten signature in blue ink, reading "I.M.yunusu", written over a dashed horizontal line.

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STATEMENT OF THE SUPERVISOR

I, the undersigned, **Dr. Péter Zoltán Kovács** the lecturer in the Institute of Materials Science and Technology at the University of Miskolc I consider the Scientific Student thesis (OTDK thesis) entitled **Examination of forming process in joining stainless steel thin -walled pipes by plastic deformation** as suitable for submission.

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ABSTRACT

The work is dedicated to the investigation of the forming process in joining thin-walled stainless steel pipes by application of plastic deformation. The study focuses on the possibilities of using finite element tools in modeling the forming process and determining the influencing parameters for joining the pipes.

I modeled and ran simulations of the models that demonstrate the joining process under different parameters like forming velocity, thickness of the formed joint and distance set between the top and bottom die before the forming process. Also, I performed experimental tests on stainless steel pipes to justify the formed joints from the models run from the finite element program.

Finally, the work run experiments based on the tensile tests to evaluate the mechanical properties and microscopic investigation to evaluate structural integrity of the formed joint

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1.0 INTRODUCTION

1.1 Background of the study

Thin-walled pipes find application in many industrial areas, including marine, aerospace, construction, oil and gas, food and pharmaceutical, and automotive industries [1]. Thin-walled pipes are made from different materials, including aluminum, copper, stainless steel, etc. Stainless steel materials find more application in these areas because of their excellent corrosion resistance, high strength, and durability that facilitate the manufacturing of high-performance parts or components. Different methods have been used in joining thin-walled pipes that include traditional methods like welding, threading, and brazing. The welding process is the most used method in joining stainless-steel pipes, for example, the electric arc welding (EAW) that needs special preparations of the pipe ends and specialists to perform the welding process, and it results in thermal distortion, oxidation, and residual stress on the joint [2].

In recent years, studies have tried to showcase the use of the forming process in joining pipes. Plastic deformation offers great potential to join pipes and trusses while reducing the fabrication costs, high productivity, and environmental friendliness [3]. The forming process of stainless steel thin-walled pipes is among the methods that can be applied in these industries to join pipes. Application of plastic deformation in joining pipes offers various potential advantages compared to other applied methods, including welding, such as no heat-affected zone and material degradation since it's the cold-working process. The literature review on the use of plastic deformation in joining pipes (stainless steel material) remains limited as there is no documented modeled forming process and their parameters that can be employed directly in joining the pipes. There is limited information in the suggested methods and their processes for joining the thin-walled stainless steel pipes by plastic deformation that creates the existing gap in understanding how plastic deformation principles can be applied in joining the thin-walled pipes. The forming process is also very critical in such a way it presents challenges during the process because of the materials cracking, distortion, or forming unwanted deformation. This study will focus on modeling of the process in software by determining the suitable models and parameters for joining thin-walled stainless steel pipes by plastic deformation and running experiments to justify the methods suggested [4]. The project intends to advance knowledge in plastic deformation methods, including reducing

production costs, improving the pipe joints strength, removing the need for specialists in joining the pipes, and enhancing the manufacturing processes.

1.2 Problem statement

Lack of enough information in forming process applications for joining thin-walled stainless steel pipes makes the use of plastic deformation processes difficult to implement. The forming process is very critical in such a way that it presents challenges during the process because it results in materials cracking, distortion, or forming unwanted deformation when it is not well researched. This project intends to study and develop forming models and parameters reliable for joining pipes to facilitate the high-quality joints of pipes for industrial applications.

1.3 Objectives of the study

1.3.1 Main objective

The main objective of this study is to examine by modeling the forming processes and parameters for joining thin-walled stainless steel pipes by plastic deformation.

1.3.2 Specific objectives

- a) Analyzing the factors influencing the plastic deformation process. The analysis will include the material properties, die design, forming pressure or force selection, and boundary conditions that affect the process. To run the material characterization experiment to determine the actual properties of the stainless-steel pipe material that will be used in the study.
- b) To study the possibilities of connecting thin-walled stainless steel material with plastic deformation using finite element program/tool. To create different models in the software and run their simulations to predict the behaviors of the pipes during the deformation process in consideration of different boundary conditions. Also, the study intends to analyze different forming process parameters such as die design and spacing, pipe preparation angle, forming pressure, deformation speed and come up with reliable model and parameters.
- c) To run experiments. The study intends to run experiments in the number of specimens to validate the models and parameters chosen in the real world. Several experiments will be run to join the pipes. To evaluate the mechanical properties and structural integrity of the formed joint I will run tensile tests and microstructure analysis.

2.0 LITERATURE REVIEW

2.1 Material (Stainless steel EN 1.4301) properties and application

Stainless steel material has been used in different engineering applications. Stainless steel material has different grades that consist of different alloying elements. The material EN 1.4301 falls under the category of Austenitic stainless steel Of the 300 series [5]. EN 1.4301 is equivalent to AISI 304 which has been considered as a universal solution for many applications that need corrosion resistance in aggressive environment with simple production process [6]. The following is the chemical composition by mass content in % of EN 1.4301 can be found on Table 1.

Table 1: Typical chemical composition of EN. 1.4301, mass content in % [7]

GRADE	Cr	Ni	Mn	C	Si	N	P	Fe
AISI 304 (EN 1.4301)	17.5–19.5	8–10.5	2.0	0.07	1.0	0.1	0.045	Balance

The properties of EN 1.4301 material are affected by alloying elements, impurities and heat treatment. EN 1.4301 materials consist of 17 – 19.5% of Chromium, 8 – 10.5% of nickel and less than 2% of manganese [8]. Additions of these alloying elements play a great role in the properties of this material that include high corrosion resistance and easy formability. The addition of Nickel helps in promoting austenitic microstructure and increases the ability to absorb energy, ductility and corrosion rate reduction [8]. The following are the physical properties of EN. 1.4301 materials that can be found on Table 2.

Table 2: EN 1.4301 material physical properties [7]

PROPERTY	VALUE
Density	8,000 Kg/m ³
Melting point	1450 °C
Thermal expansion	17.2 x 10 ⁻⁶ /K
Modulus of elasticity	193 GPa
Thermal conductivity	16.2 W/m.K
Electrical Resistivity	0.072x 10 ⁻⁶ Ω .m

This material finds widely engineering application due to their mechanical properties, good corrosion resistance. EN 1.4301 finds application in equipment for foodstuff industry, pharmaceutical production equipment, and oil industry, chemical and petrochemical industry [11]. Mechanical properties of EN 1.4301 can be found in Table 3 below.

Table 3: Mechanical Properties of EN 1.4301 [9,10]

Mechanical properties	Metric value	English value
Hardness, Brinell	123	123
Hardness, Knoop	138	138
Hardness, Rockwell B	70	70
Hardness, Vickers	129	129
Tensile strength, Ultimate	505 MPa	73200 psi
Tensile strength, Yield	215MPa @ strain 0.2%	31200 psi @strain 0.2%
Elongation at Break	70%	70%
Modulus of Elasticity	193 GPa	28000 ksi
Poisson's Ratio	0.29	0.29
Shear Modulus	77.0 GPa	11200 ksi
Izod Impact	150 J @temperature 105°C 150 J @temperature 210°C	111 ft-lb @temper -319°F 111 ft-lb @temper 69.8°F
Charpy Impact	352 J	240 ft-lb

2.2 Overview of pipes joints and manufacturing methods

Manufacturing processes in joining pipes ends utilize different methods and techniques that facilitate the manufacturing of joints in pipelines as shown in figure 1. These methods help in joining different pipes' thickness and material properties. Different methods and techniques have some advantages and disadvantages over joint production and the process involved.

2.2.1 Crimped joints

This type of joint is produced by the crimping process in which two tubes or metal sheet are pressed together by force using crimping tool. The process includes cutting and deburring the pipe, inserting the pipe into crimping fitting and pressing the pipes by using crimping tool. Advantages of this process include free of thermal distortion and heat, no chips and fumes produced, and no pre or post processing required [12]. Studies show crimped joints obtained

from reduction, swaging [13] that suggest the use of rotary swaging in joining pipes and electromagnetic forming [14] that showcase the form fit and interference fit produced from the electromagnetic forming. The methods involved in manufacturing crimped joints have some drawbacks, including limited in required mechanical strength and limitation in application in some pipe materials like aluminium, copper and its alloys in case of electromagnetic forming due to high electrical conductivity requirements [15].

2.2.2 Weld seam joint

These are types of joints made on the pipes by welding process. Welding is one among of the most traditional methods employed in joining parts including tubes. Welding offers both longitudinal and annular seams on the cylindrical parts. The welding process is determined by the change in phase composition and structure during the process. Welding process find difficulties in joining pipes with different material properties, small thickness and costs involved in preparation of material before and after welding [16].

2.2.3 Threaded joint

These are kind of joints that employ threads and screws to connect tubes [17]. These kinds of joints find application in many areas that do not need special treatment because they are easier to design, easier to assemble and disassemble. These kinds of joints have limitations in areas that need air tightness joint, and which are not exposed to wet environment when pipes and joints are of dissimilar materials.

2.2.4 Filler metal or adhesive joint

These joints use brazing and adhesive bonding for joining two parts (pipes). These kinds of joints are produced by using a filler material which has a small melting point compared to the joined pipes. These joints are not good for application in high temperature environments and in joining dissimilar materials due to differences in thermal expansion rate and mechanical strength. These joints face also distortion during heating cooling cycle which can change the shape of the joint [18].

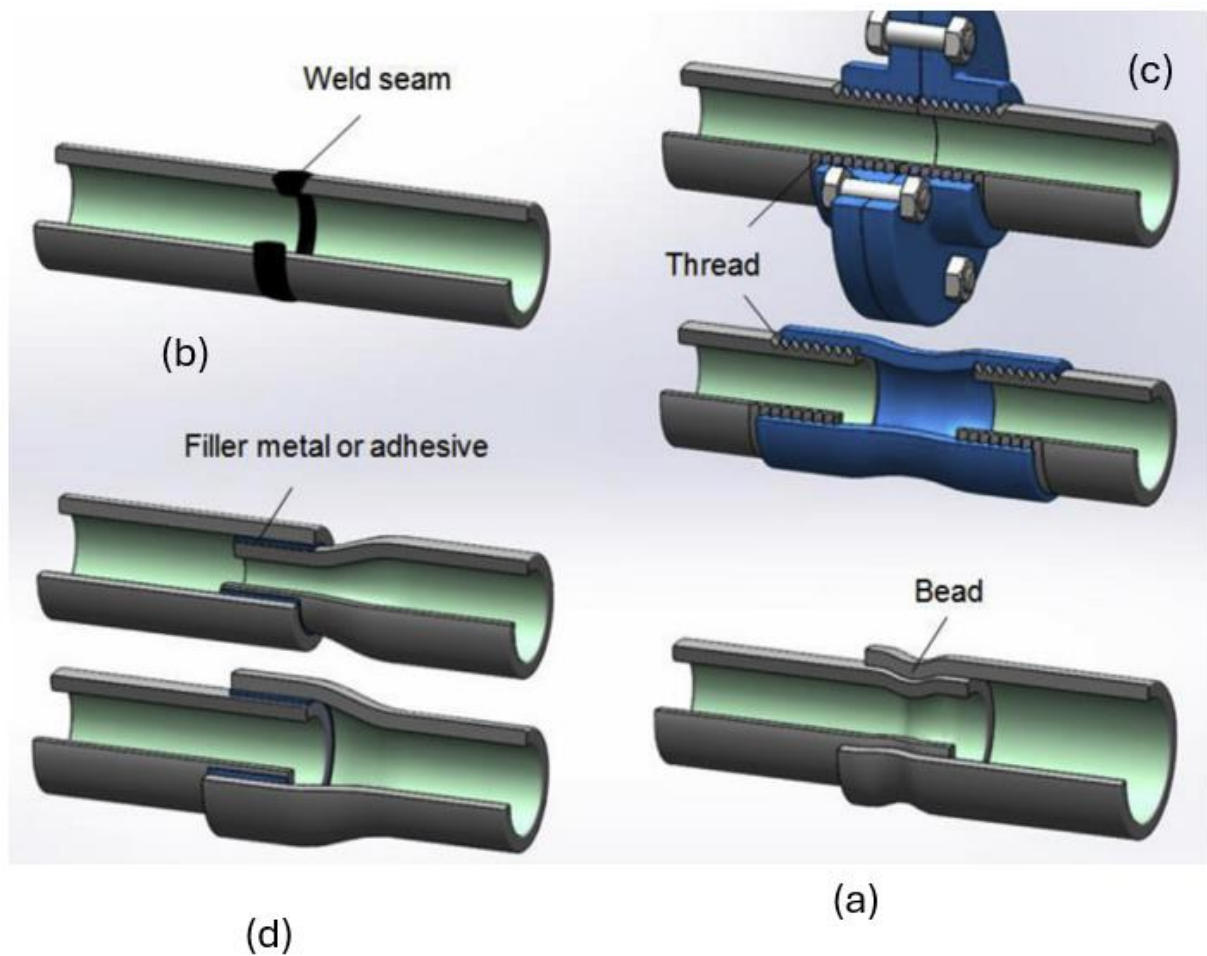


Figure 1: Types of convectional joints (a) crimped joint, (b) welded joint, (c) threaded joint, (d) filler metal/adhesive joint [15]

2.3 Plastic deformation in joining parts

Mostly plastic deformation has been used in forming processes to produce different mechanical parts with various shapes. Currently, plastic deformation can be used in joining parts without external heat application. The processes involved in joining parts by plastic deformation can be termed metallurgical joining process and mechanical joining process. The process works by using force which exceeds the yield strength of the material that results to permanent deformation of the parts. Metallurgical joining processes include friction stir welding, resistance welding, friction welding, cold welding by rolling, extrusion, forging etc. mechanical joining includes self-pierce riveting, mechanical clinching, joining by forming e.g. hydroforming, electromagnetic forming or incremental forming, and fastening e.g. hemming, seaming and staking.

2.3.1 Metallurgical joining process

In metallurgical joining process, the interface between joining parts is broken by plastic deformation leaving the clean surface that join by high interfacial pressure. The joining parts are always heated internally by interfacial slipping [19]. Methods involved here can join a range of materials including dissimilar material. For example, cold pressure welding is carried out at ambient temperature in which dissimilar material like Al-Cu, Al-Ti can be joined [20]. Most of the methods under metallurgical joining processes need surface preparation of joining parts that can be done by mechanical cleaning or chemical cleaning [21], [22]. Studies suggest that normal pressure on the weld interface has an influence on the weld strength [23]. Drawbacks of cold pressure welding include less preference in joining large components, high stress environments and in metals with oxide layers. This method makes it difficult to implement efficiently in joining tubes.

Friction stir welding uses friction and plastic deformation in which materials of the joining parts on the interface are heated by friction and then mechanical force is applied to cause plastic deformation for bonding [24]. Different techniques have been developed for this method that include rotary, orbital and linear friction welding process. This welding process finds application in many areas like automobiles, buildings, industries, transportation for example joining of aluminum material by spot welding in automobile. This method also encounters some limitations in joining pipes that includes some difficulties with curved surfaces and high equipment cost.

2.3.2 Mechanical joining process

In mechanical joining processes only the pressure and interlocking are used without heat application during parts joining. In this process, the contacting surface of the joining parts are not bonded hence no need for the high temperature or breaking the oxide layers on the joining surfaces. Joining dissimilar materials that have different melting points creates a challenge in using methods like resistance spot welding, for example joining aluminum and high strength steel. Methods like self-pierce riveting and mechanical clinching are used. In self-pierce riveting, parts especially sheet metals are pieced with a rivet skirt without a pre-drilled hole through the upper sheet to lower sheet and flaring it to form an interlock as shown in figure 2. This technique is mostly used to join parts (sheets) of aluminum, coated steel, copper and sandwich materials [25]. Some limitations with this method include less control of pipe deformation, limitations to curved surfaces, high costs and material thickness limitations.

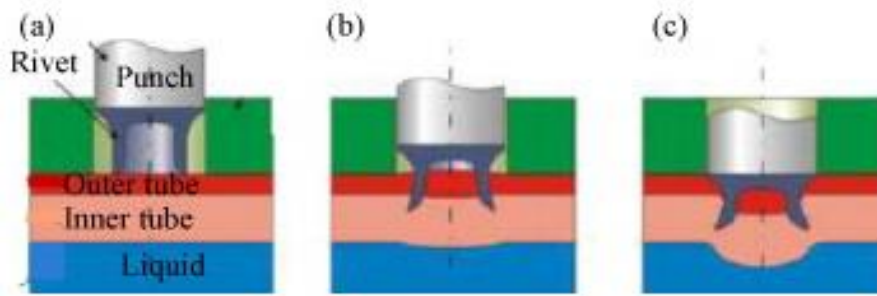


Figure 2: Self-pierce riveting tubes (a) start, (b) driving through outer tube, (c) formation of interlocking [26]

Mechanical clinching, parts (sheets) are joined by hemming with a punch and die without using rivet. Forming the two joining parts and form interlock by controlling the plastic deformation of the sheets, preventing excessive thinning of the upper sheet at the neck and fracture of either sheet as indicated in figure 3. Methods under mechanical joining processes have some drawbacks like large joining force is required, formation of bulges and indents in joints, and access required from both sides of joints with punch and die. This method is less practical in joining pipes as it cannot meet the requirements in areas that need pressure, air tightness and sealing.

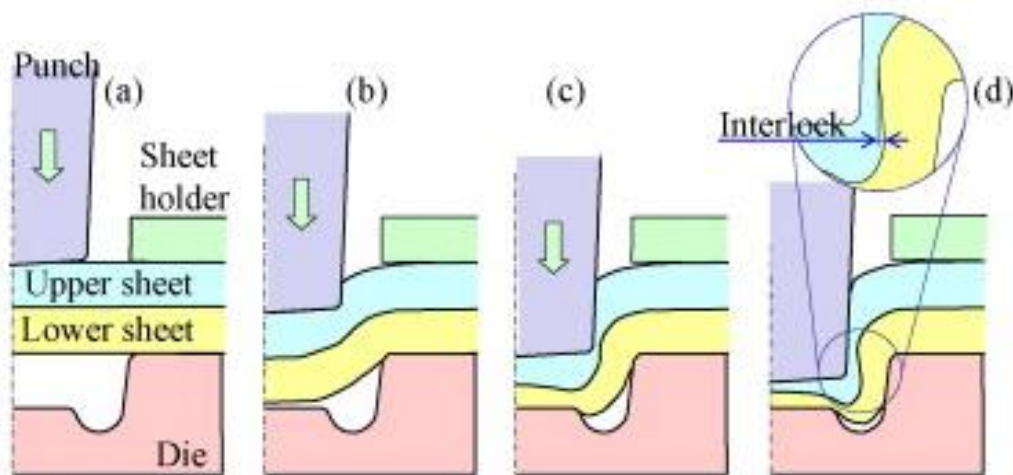


Figure 3: Joining of sheets by mechanical clinching. (a) Start, (b) bulging, (c) compression and (d) formation of interlock. [27]

2.3.3 Joining by forming

The forming process comprises of different methods that can be used in joining parts such as forging, extrusion, sheet metal forming and tube forming. Application of forming process in joining parts is achieved using plastic deformation [28]. Joints can be achieved in tubular

parts by compression or expansion of the joined workpieces. In forming we can achieve different joints such as interference-fit joint based on difference of elastic recovery of joining workpieces [29]. Form-fit joints based on the additional geometrical elements [30]. Methods like die-less hydroforming use a pressurized hydraulic fluid to join workpieces in which a ring is aligned coaxially with the tube and hydro-probe set inside the inner joining workpiece.

Some studies have been performed in this area of joining pipes by forming process with the help of plastic instability. Kovacs showed in his paper how EN AW 6060 pipe can be joined, and he developed a way for joining the pipes [31]. Also, his findings suggest the best pipe end angle preparation is 20° for smooth joining process of the pipes. Also, the study done by Carlos, et.al suggest the name of the joint made on two tubes at room temperature by forming as tubular lap joint [15]. Joining pipes by this kind of method tries to solve the limitations offered by many methods as mentioned above.

2.4 Modeling forming processes methods and software's

Joining pipes by plastic instability can be modeled in finite element tools before running experiments. Studies show various software can be used in modeling and simulation in engineering with mostly two FE tools that can model forming and joining process in case of pipe joining by plastic deformation. These FE tools are Simufact forming and DEFORM.

Simufact forming is among the specialized FE tools for comprehensive process simulation, multistage processes and material behavior. This tool provides also an opportunity and option for calculation of welding processes [32]. Simufact forming covers the spectrum of working with forming processes such as rolling, forging and sheet metal forming [33].

DEFORM is another FE tool designed for manufacturing processes involving plastic instability. It provides both 2D and 3D simulation options for extrusion, bending and mechanical joining [34]. The software also offers material flow and forming analysis in which it is easier to predict how material will behave during the joining process. It's also possible to simulate the tool and die design with this FE tool that can be used during the experiment. The program works in such a way that five components are fed in the program as shown in figure 4 that include.

- Die design (Top and bottom die)
- Joining workpieces (Top and bottom pipes)

- An insert

The materials for the workpiece are specified in the program and boundary conditions are set. Then, simulation is run to simulate the joining process of the pipes. During the first step the upper pipe is pressed and forced against the end of the bottom pipe which is chamfered at an angle to expand and produce overlap between the joining pipe ends surfaces. At this point the bottom pipe tapered end acts as a tapered punch and the depth of insertion can be controlled by the distance available between them. On the second step, it involves axisymmetric compression beading leading to plastic instability of the two joining pipes subjected to axial compression and results in locking between their adjacent surfaces [15]. The insert used during the process is to ensure the compression beads are formed outward and maintain the inner diameters of the joining pipes.

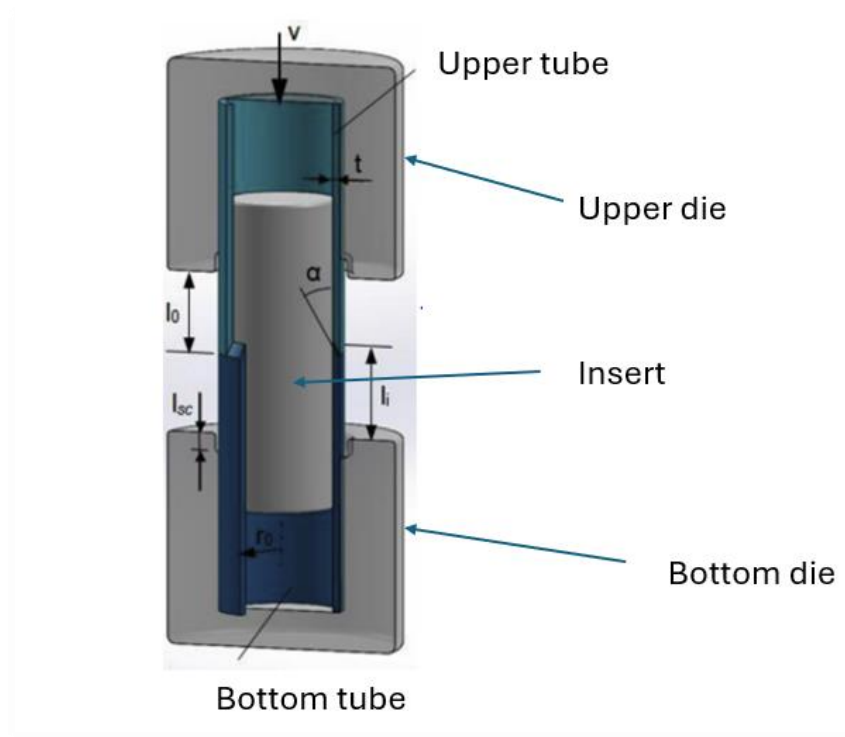


Figure 4: Joining process of two pipes by plastic deformation. [15]

3. METHODOLOGY

3.1 Research design

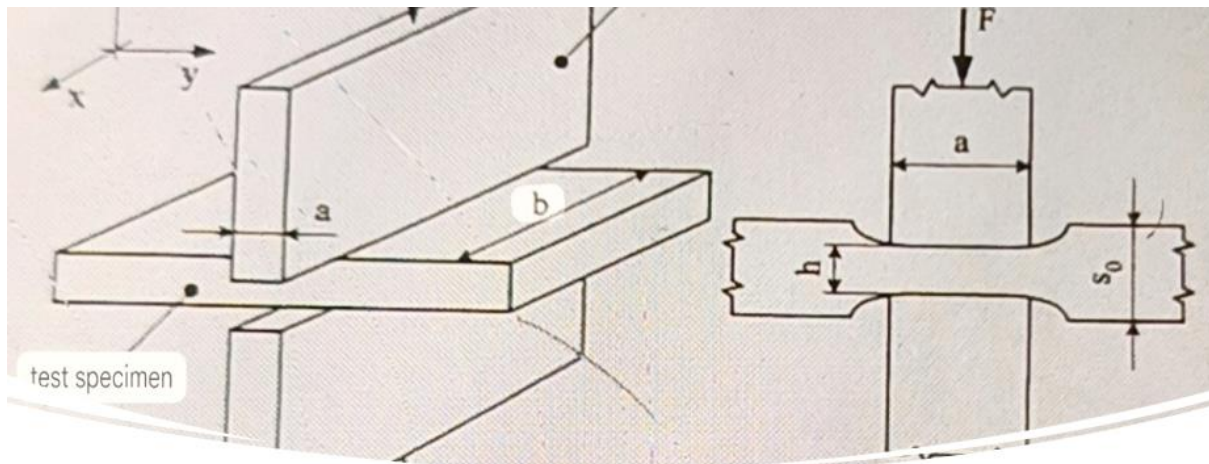
The study will start with the material characterization for determining the material properties. The modeling and experiments will be run on the workpiece, which is EN 1.4301 (TP 304L) pipe of 30 mm x 1.5 mm thickness. Running the material flow experiment by using the MTS machine to determine the actual properties of the stainless-steel pipe material that will be used in the study. Designing the experiment set up in the DEFORM that includes the die design, insert, and joining pipes. Insert the material properties, set the different boundary conditions that will be tested, and run the simulation. Choosing the best models and parameters for testing in experiments.

The study will run experiments in the number of specimens to validate the models and parameters chosen in the real world. Several experiments will be run to join the pipes and form joints. The study will run tensile tests and virtual tests to evaluate the shape, mechanical strength, durability, and reliability of the joints compared to the joints made by other methods.

3.2 Materials and tools used

3.2.1 Materials characterization

The study was carried out on EN 1.4301 HEAT N.0538901 tubes with an outer diameter of 30mm and a wall thickness of 1.5mm. A piece of material was cut 50mm length to determine the material flowability by the compaction of a flat specimen by deformation (Watts-Ford method as shown in figure (5)). The equipment's that was used is Bernardo MBS 300DG for cutting a workpiece, and MTS for compaction to determine the material flowability. The operations were as indicated in figure 6 below.



- a – Pressing tool thickness
- b – Length of the workpiece 50mm
- F – Force applied by MTS machine
- h – Final thickness of workpiece
- s_0 – Original thickness

Figure 5: Watts-Ford method



Figure 6: MTS operations and data recording for material characterization

The obtained data were analyzed by using the following formular (i) and (ii) below to plot the flow curve of the material. (Analyzed data from TMS 250 Machine).

$$\text{Forming strength, } k_f = \frac{\sqrt{3}}{2} \frac{F}{ab} \dots \dots \dots (i)$$

$$\text{Comparative strain, } \phi = \frac{2}{\sqrt{3}} \ln \frac{s_0}{h} \dots \dots \dots (ii)$$

Table 4: MTS compaction data based on watts-Ford method

b (mm)	a (mm)	ho (mm)	F (kN)	h (mm)	φ	Kf (N/mm2)
49.82	3	1.5	89.09396	1.36	0.113138	516.24
49.82	3	1.5	125.0999	1.35	0.12166	724.87
49.83	3	1.5	150.6023	1.32	0.147609	872.47
49.93	3	1.5	163.019	1.23	0.229151	942.51
49.98	3	1.5	174.6743	1.17	0.286898	1008.9
50	3	1.5	186.4653	1.13	0.327066	1076.6
50.04	3	1.5	197.9413	1.07	0.390065	1141.9
50.08	3	1.5	207.9163	1.02	0.445325	1198.5
50.15	3	1.5	217.6767	0.97	0.503362	1253
50.2	3	1.5	221.5177	0.92	0.564472	1273.8
50.24	2	1.5	152.081	0.87	0.628997	1310.8
50.28	2	1.5	160.6594	0.8	0.725855	1383.6
50.34	2	1.5	161.5787	0.64	0.983519	1389.9
50.38	2	1.5	161.9988	0.58	1.097188	1392.4
50.38	2	1.5	163.1648	0.55	1.158513	1402.4

Figure 7 below shows the material flow curve of EN 1.4301 and the material properties obtained were fed into the DEFORM 2D – 3D tool for modeling the joining process of the pipes.

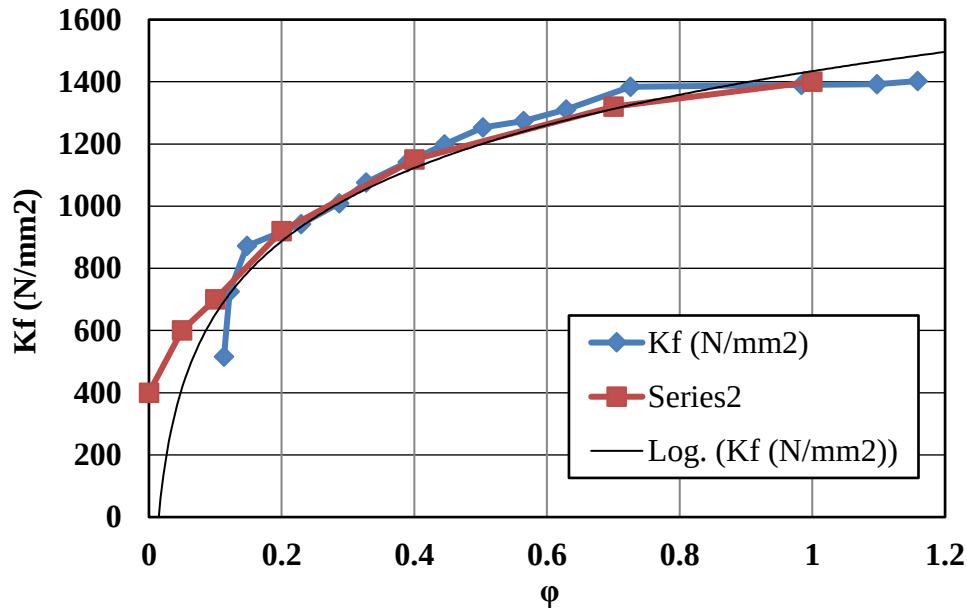


Figure 7: Flow curve of EN 1.4301

3.2.2 Tool design

Before performing the experiments, the tools to be used in the process were developed. Tools were developed based on the forming process to join the pipes. The overall requirement of the forming tool of this forming process was designing tools and the insert that support the inner surfaces of the pipes during forming process. The dies must provide the connecting options to the testing rig of the MTS 250 machine. The forming tool for this process as indicated in figure 8 was modified and fabricated for running experiments in which tolerance was maintained between ± 0.01 to ± 0.03 with surface roughness set between Ra 0.2 to $0.6\mu\text{m}$

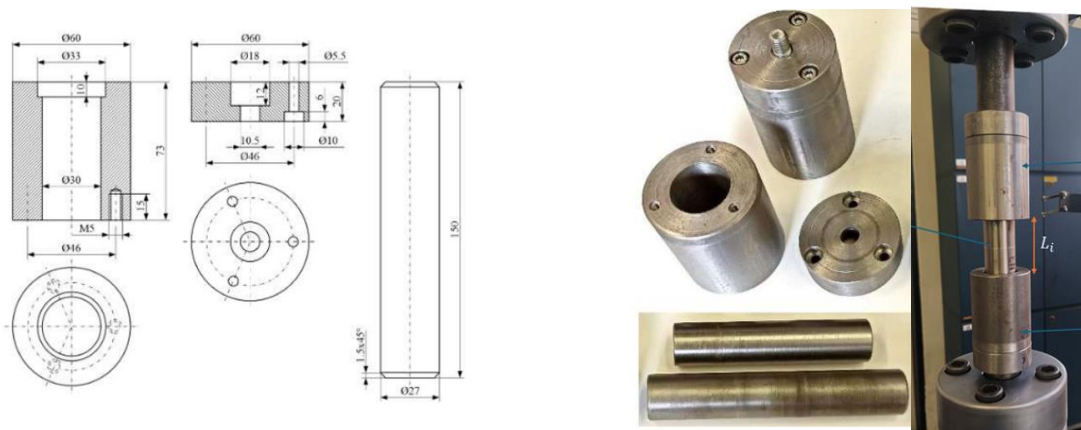


Figure 8: 2D drawings of the tools and the manufactured tool elements

3. 3 Finite element modeling

3.3.1 Parameters

There were several parameters required to be modeled in the FE tool. Parameters included thickness of the joint formed, initial gap set between the joining pipes die tool, pipes end chamfered angle and forming without an insert.

From the study done by Kovacs, it suggests that 20° chamfered angle on the pipe end is the best angle for best results although other literature suggest any angle between and up to 75° can be used and provide better results with small difference. For optimum and small initial gap force requirement to start the expansion. The modeling and experiments will be run on the specimen with end chamfered angle of 20°.

Other parameter is the initial gap set between the joining pipes die tool (L_i). For this project model will try to simulate the results of $L_i = 30\text{ mm}, 40\text{ mm}, 50\text{ mm}, 60\text{ mm}, \text{ and } 70\text{ mm}$. From the simulation results, the experiments will be conducted on the die gap distance that provided best results.

Another parameter will be running the forming process with the chosen model without an insert to know how the joint will be without use of the insert.

The last parameter is the thickness of the joint formed. The experiments will be run on the chosen die gap distance and see the results on the joint of 5mm, 7mm, and 9mm thickness. Other joint thickness can be considered after the deform simulation is done.

3.3.2 DEFORM 2D-3D modeling

The simulations were run on the Finite element tool after feeding the tool designed, materials specified of the workpiece, and boundary conditions. Boundary conditions that were set during the simulation involved, die tool and an insert are rigid, meaning they will not deform during the process. The workpiece (pipes) was assigned plastic properties. The upper die is the only part of the tool moving downward while pressing the top pipe workpiece and it was set on the translation speed of 5mm/s. simulation control was set with the number of simulation steps to 230. Inter-object relation of all the parts were set defining the contact relationship of every part to each other and defining the contact friction of coulomb 0.1 as shown in figure 9 below.

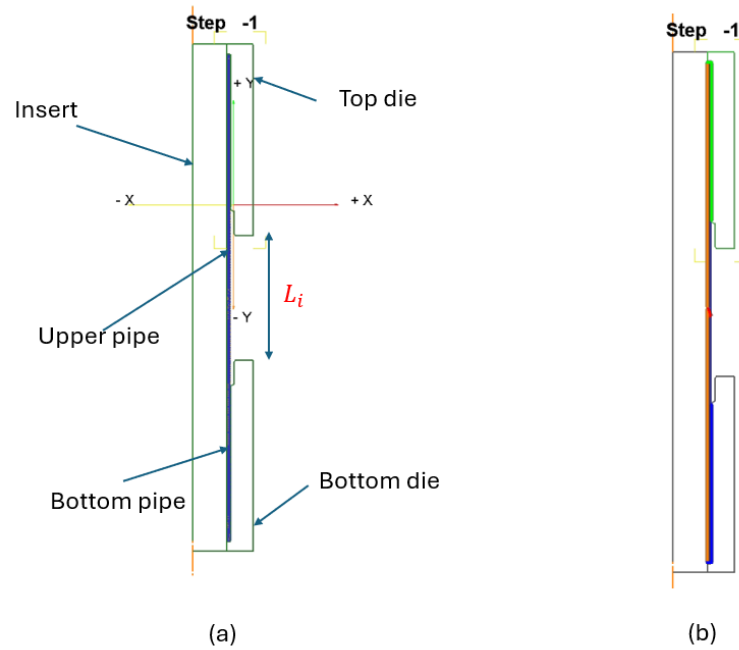


Figure 9: (a) set up of the simulation (b) Contact relation of the parts (inter-object relation)

The following are the simulations results of the forming process

The forming tool was set at the distance of 30 mm between them and pressed for forming, the joint was recorded at the thickness of 5.0504 mm after 125 steps, 7.0077 mm after 115 steps and 9.0058 mm after 105 steps as shown in figure 10.

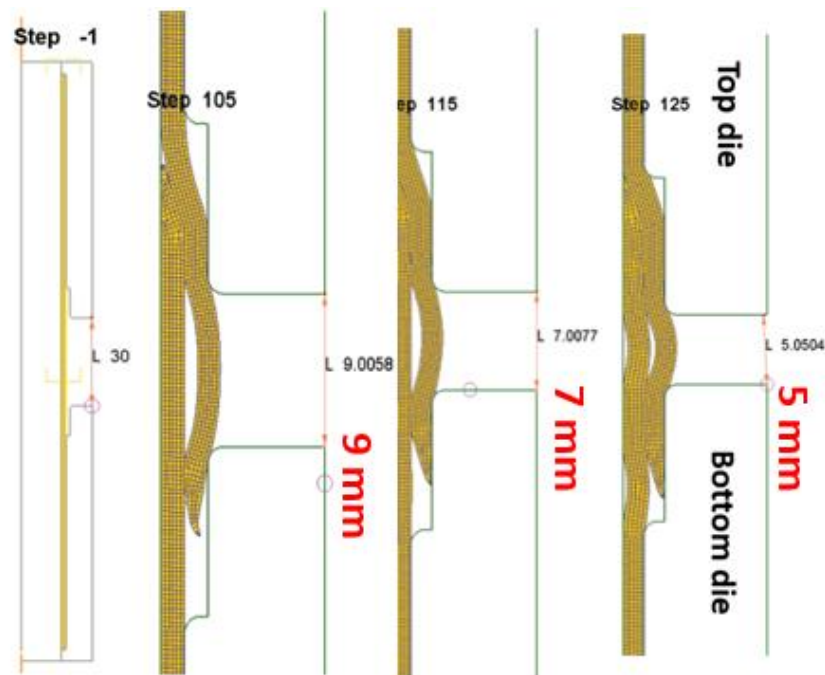


Figure 10: joints formed by the initial die distance of 30 mm

The forming tool was set at the distance of 50 mm between them and pressed for forming, the joint was recorded at the thickness of joint of 5.0865 mm after 227 steps, 7.19625 mm after 215 steps and 9.00751 mm after 206 steps as shown in figure 11.

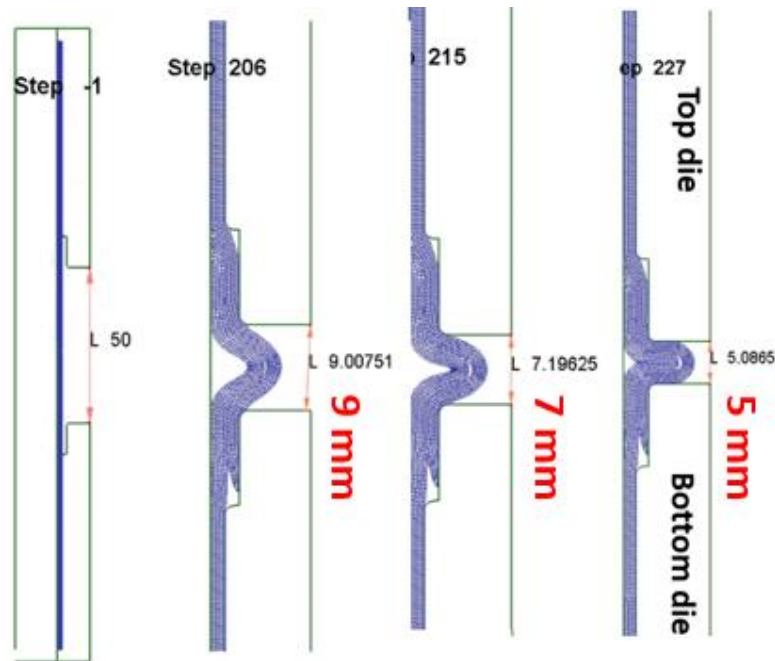


Figure 11: Joint of 5 mm, 7 mm and 9 mm formed by the initial die distance of 50 mm

The forming tool was set at the distance of 60 mm between them and pressed for forming, the joint was recorded at the thickness of 3.23257mm after 287 steps, 4.0041 mm after 283 steps, 5.1159mm after 276 steps, 7.13876mm after 265 steps and 8.13876mm after 260 steps as shown in figure 12.

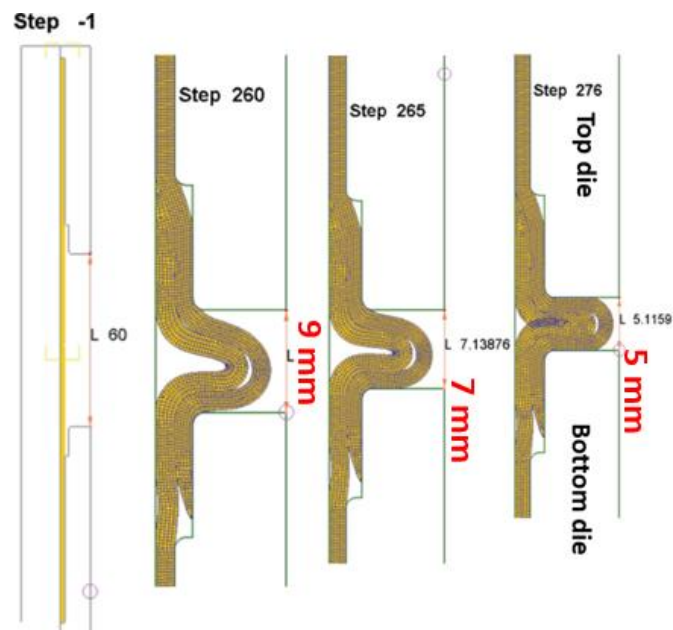


Figure 12: Joints formed by the initial die distance of 60mm

The forming tool was set at the distance of 70 mm between them and pressed for forming, the joint was recorded at the thickness of 5.01219 mm after 332 steps, 7.01mm after 320 steps, 9.0058 mm after 308 steps and 4.82008 mm after 333 steps as shown in figure 13.

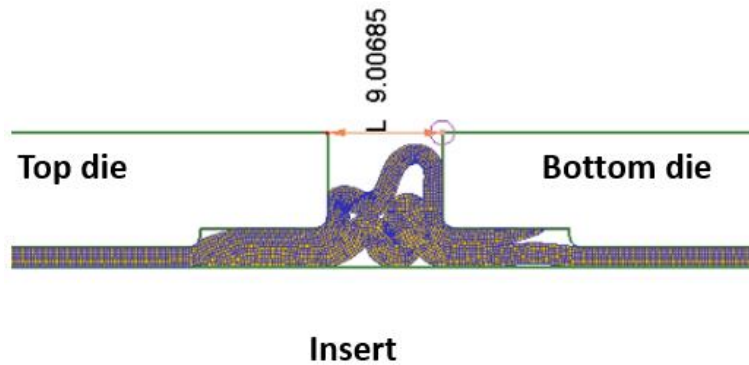


Figure 13: Joints formed by the initial die distance of 70 mm

The forming tool was set at the distance of 50mm in between, the insert was not used, and the tool was pressed for forming, the joint was recorded at the thickness of 3.91508mm after 231 steps, and 7.11507mm after 215 steps as shown in figure 14.

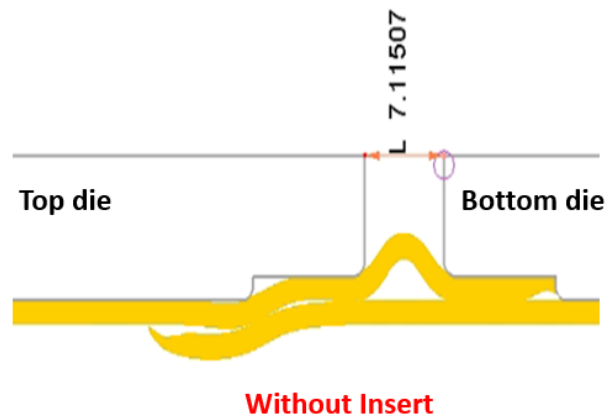


Figure 14: Joints formed by the initial die distance of 50 mm without using an insert

3.4 Experimental work.

3.4.1 Introduction

The investigation was performed on thin-walled EN 1.4301 pipes with outer diameter of 30mm, length of 100mm and wall thickness of 1.5mm. The forming tool was installed in the electrohydraulic testing machine (MTS 250) for running the joining process of EN 1.4301 thin-walled pipes as shown in figure 16 below. The model run on DEFORM 2D-3D was used as a baseline in running experiments. Data for the 5.0865 mm joint simulation was fed to the computer system of the MTS 250.

- Crosshead speed of the testing machine set to be 2 mm/s

- Final thickness joint 6mm
- Preparation made on the pipes ends 20° chamfered angle
- Starting initial gap of the joining pipes 50 mm

The pipe was cut into pipe pieces of 100mm length and preparation on the ends of the pipes was done. A chamfer angle of 20° was cut on the outside surface of one pipe and on the inside surface of the other pipe as shown on figure 15.

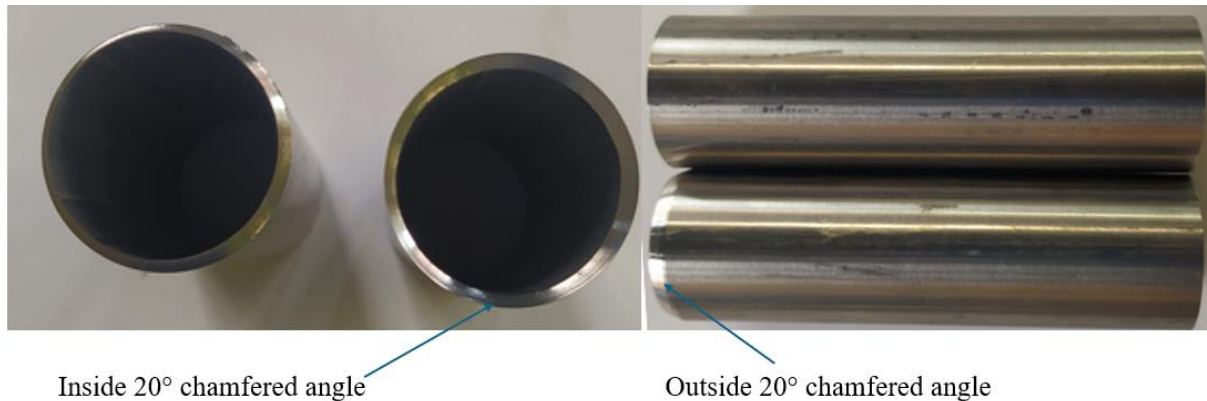


Figure 15: End pipes 20° chamfered angle preparation

At this stage, we fabricated the forming tool and mounted it in the MTS 250 machine for joining the pipes. The figure 16 shows the joining process experiment setup. The joining process followed the following steps.

- Experiment setup, I fixed the forming tool on the MTS 250 machine test rig by using bolts. I applied lubricant in the parts and mount pipe specimens in the forming tool and ensured alignment between them to prevent uneven deformation during the joining process.
- Compression process, I applied force on the upper die of the forming tool to induce plastic deformation at the pipe interface. At this step, monitoring of force and displacement data was done and recorded for further evaluation of deformation behaviour and joint formation.
- Initial joint assessment, I examined the formed joint for alignment, absence of defects and presence of uniformity by visual inspection and measurement tools like vernier calliper with the intention of understanding the thickness of the pipe joint formed.

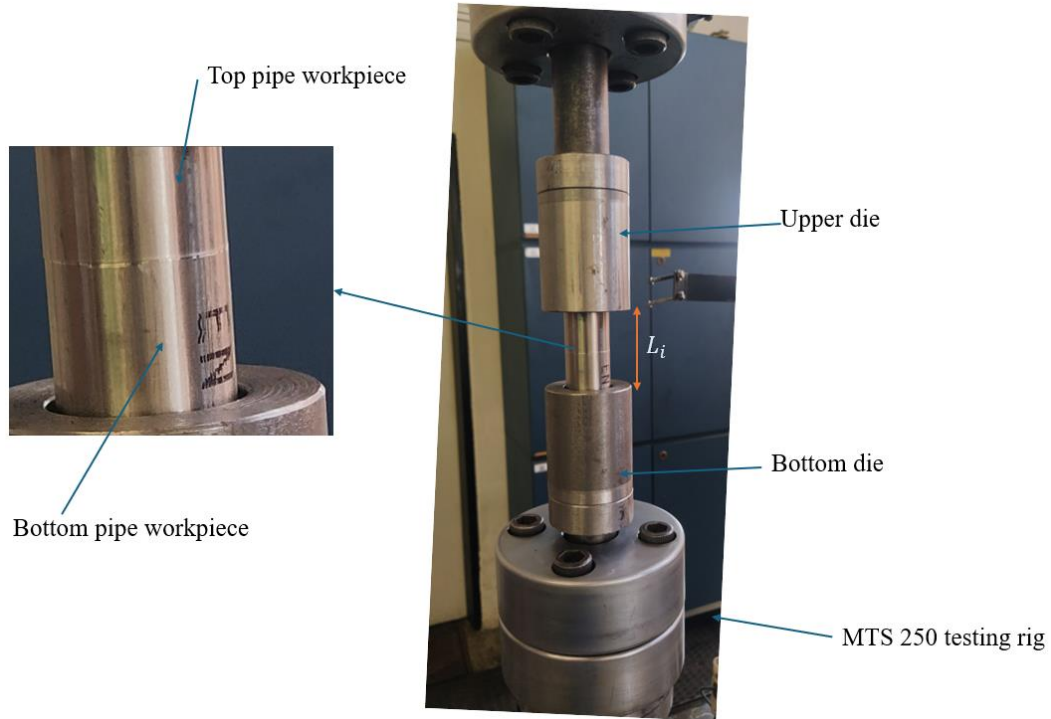


Figure 16: Setup of the experiment

3.4.2 Joint formed

During the experimental work, lubricant was applied on the internal surfaces of the pipes and the process of joining pipes was recorded and data from MTS 250 was saved. I performed a joining process in 4 pipe pairs in which 4 pipe joints were obtained. Joint 1 and 2 showed a 6 mm joint where pipe joints 3 and 4 measured to 8 mm thickness refer to the figure 17. The analysis on the relationship between the compression force during the forming process and the axial displacement of the workpiece was done as indicated in figure 18 below.



Figure 17: Joints of 6 mm and 8 mm thickness formed at 50 mm die gap distance

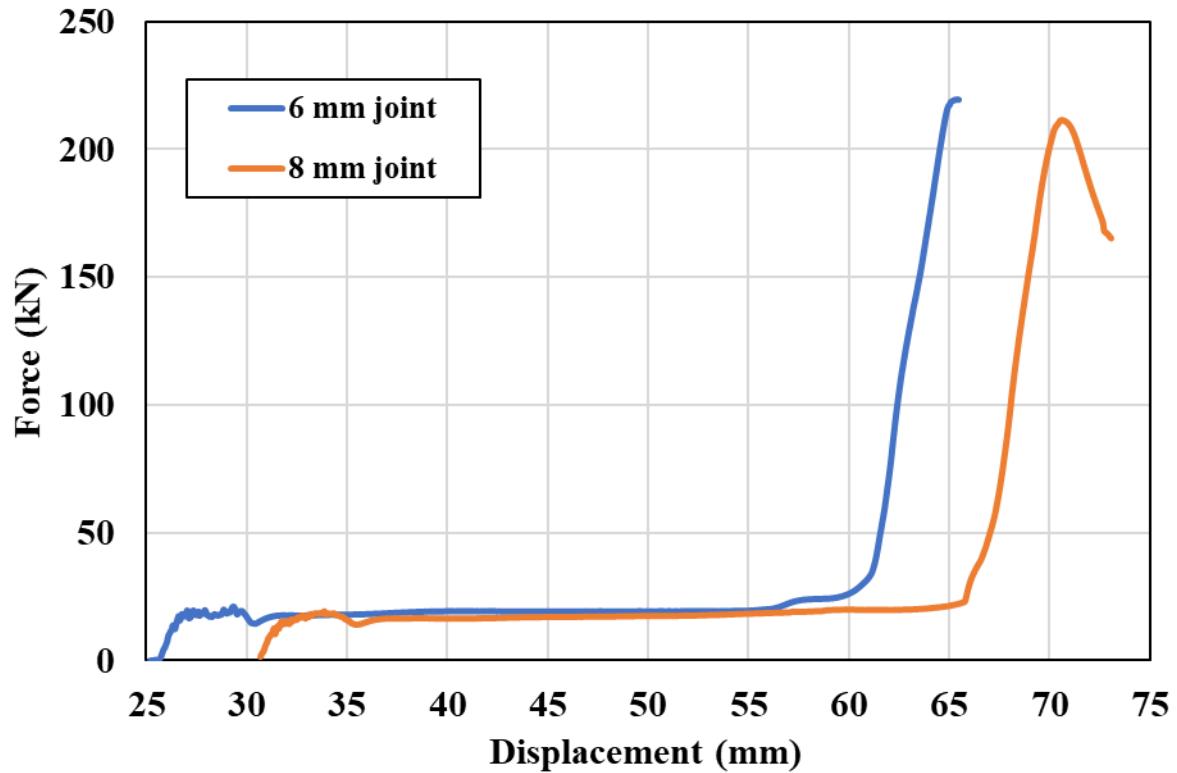


Figure 18: Force – displacement diagram variation during the forming process for 6 mm and 8 mm joint

3.4.3 Tensile test

The tensile test was done on the joint of 5.8mm by using MTS 250 machine and results were recorded for analysis. The following was the setting of the experiment.

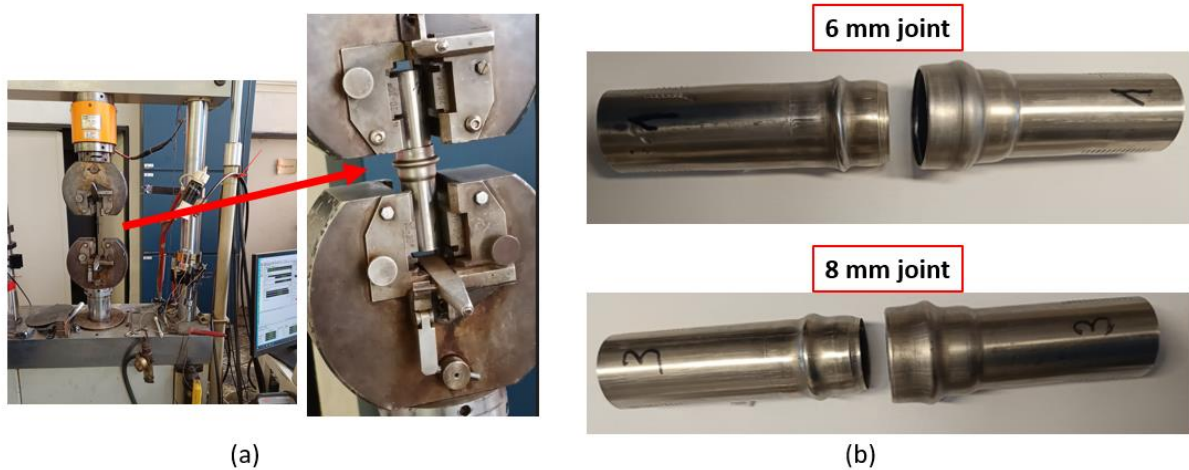


Figure 19: (a) Tensile test setup, (b) Sample 1 & 3 after tensile test

4.0 RESULTS AND DISCUSSION

4.1 simulation results (Load prediction)

From the model's simulation in DEFORM 2D-3D, the best parameters that showed best results was the model set with the die distance between of 50mm and 60mm as indicated in figure 9 and 12. The following is the simulation result of load prediction during the forming process for the model set with the die distance gap of 50mm as shown in the figure below 20.

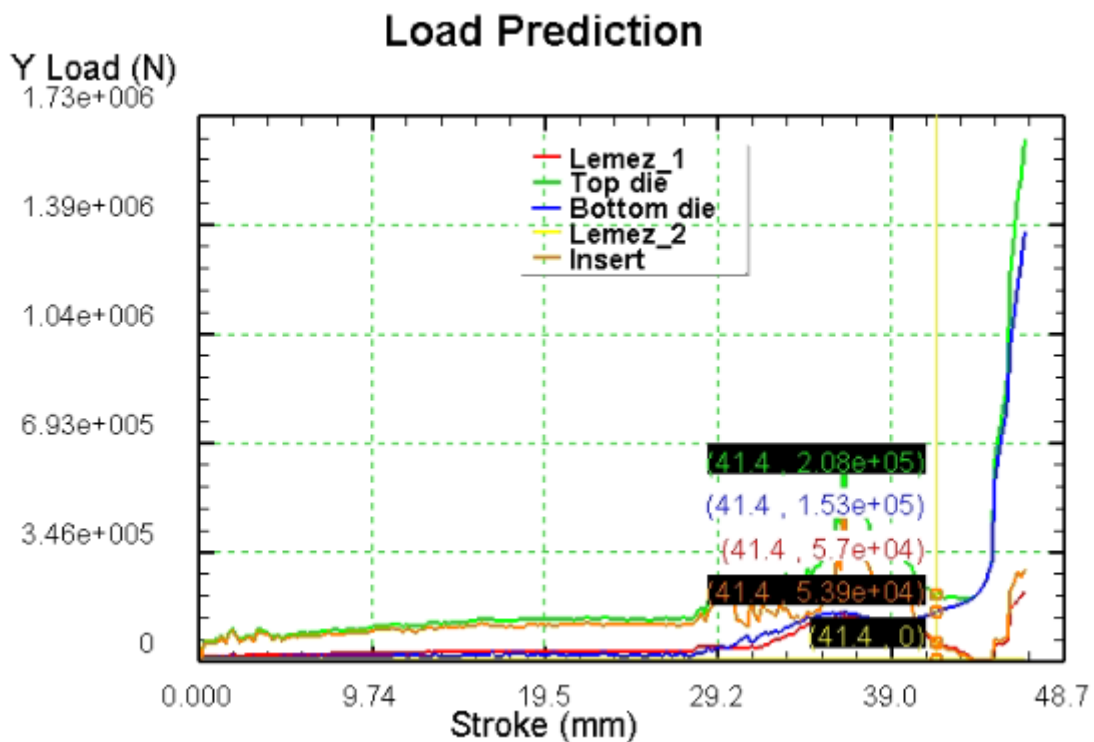


Figure 20: Load prediction during the forming process at die initial distance of 50mm

From the figure 16 above it shows during the forming process around $183.35 \times 10^5 N$ is required.

4.2 Experimental results

4.2.1 Joining process

Experimental results show the best result of forming process in joining the thin-walled pipes by plastic deformation results to 6 mm and 8 mm joints by using the initial die gap distance of 50mm for the fed data of 5 mm and 7 mm thickness joints respectively from the simulation, 20° chamfered angle of the tubes end, and using an insert during the process as portrayed in figure 16.

The maximum recorded forming force as recorded in figure 17 is around 220kN, which can deform the EN 1.4301 pipes without breaking the material.

4.2.2 Tensile test

Tensile test results as shown in figure 21 show that the 6 mm joint can withstand the force of around 72 kN and 8 mm joint can withstand a force of around 52 kN

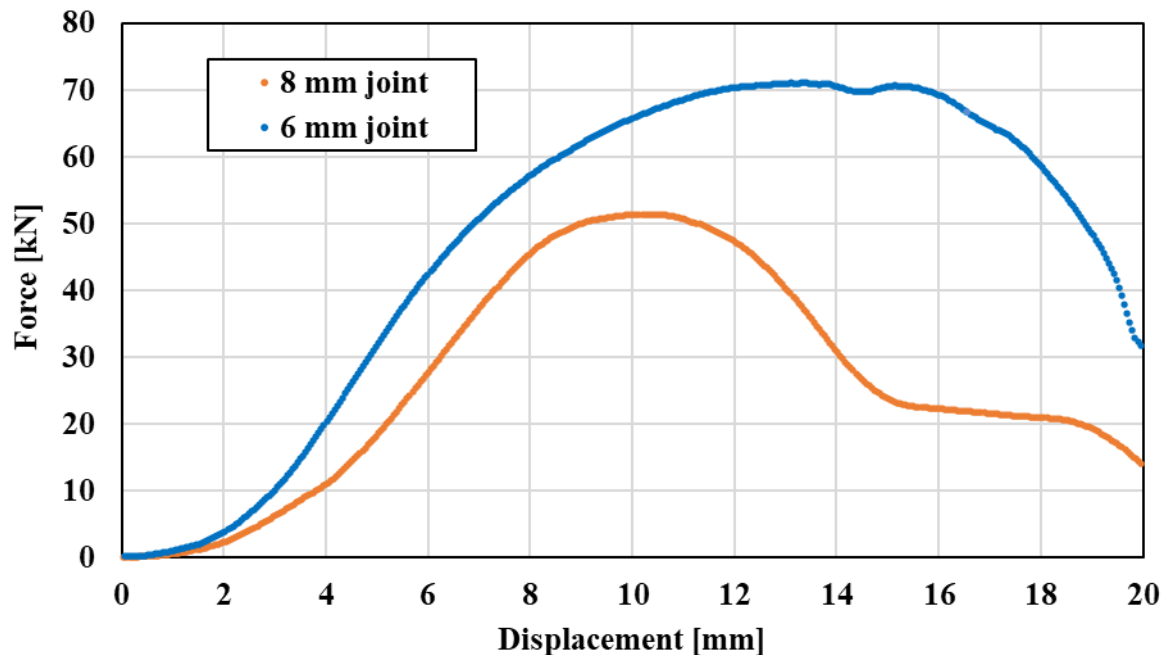


Figure 21: Tensile test (Force – displacement diagram) for 6 mm and 8 mm joints

4.2.3 Microscopic investigation of pipe joint

The microstructure analysis was necessary to analyze the tightness of the joining surface of the pipes and compare them with the sections of the simulations results. The microstructure section was performed by cutting specimen 1 and 4 joints and analyzing their sections by using visual microscope by 2 mm magnification after etching. The following were the results as compared to simulation pipe section result as shown in figure 22.

The result shows that the pipe joint appears to be consistent with no thinning and the comparison between the results obtained from the experiment and simulation look alike with the existing of a small gap between the joining pipes.

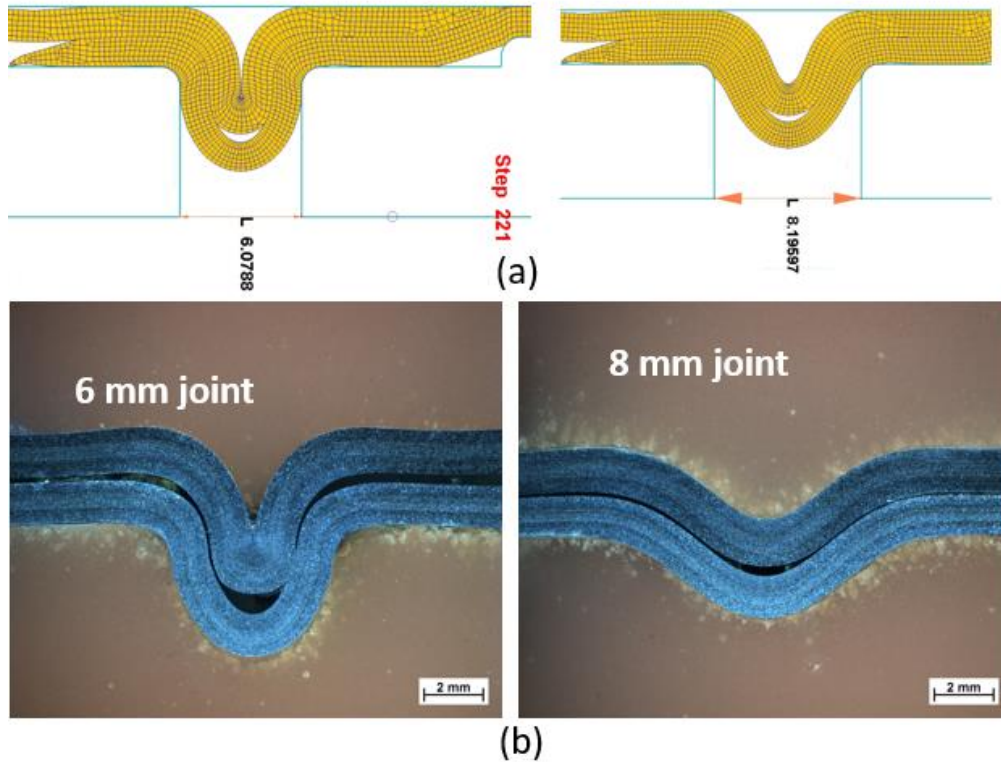


Figure 22: Pipe microstructure section results (a) from simulation (b) from microscopic investigation

4.3 Conclusion

This proposed method of joining pipes provides a simple way and is effective compared to the most traditional solutions like welded joints, brazed joints, and threaded joints. The numerical solutions show the impact of parameters over the joint formed, as when one parameter is changed, it changes and affects the final joint formed. The study achieved 6 mm and 8 mm pipe joints from the experiment that demonstrated the possibility of using this technique in industrial applications. More experiments are expected to be done, including microstructure analysis under high magnification to observe grain boundaries and phases and to determine the hardening of the formed joints. More experiments on tensile tests will be run for different thicknesses of formed joints and compare their results with the mechanical properties of the same joints made from other methods like welding.

As a conclusion, for future work, further investigations will be made to cover the project objectives and provide an industrial framework for applications that will include a simple way of joining a long pipe without using an insert, joining dissimilar material pipes, and demonstrating the application of elevated temperature of the forming tools on the efficiency of the joining process.

REFERENCES

- [1] Baddoo, N. R. (2008). Stainless steel in construction: A review of research, applications, challenges and opportunities. *Journal of Constructional Steel Research*, 64(11), 1199–1206. <https://doi.org/10.1016/j.jcsr.2008.07.011>
- [2] Sharma, S. K., & Maheshwari, S. (2017). A review on welding of high strength oil and gas pipeline steels. In *Journal of Natural Gas Science and Engineering* (Vol. 38, pp. 203–217). Elsevier B.V. <https://doi.org/10.1016/j.jngse.2016.12.039>
- [3] Mori, K. I., Bay, N., Fratini, L., Micari, F., & Tekkaya, A. E. (2013). Joining by plastic deformation. *CIRP Annals - Manufacturing Technology*, 62(2), 673–694. <https://doi.org/10.1016/j.cirp.2013.05.004>
- [4] Groche, P., Wohletz, S., Brenneis, M., Pabst, C., & Resch, F. (2014). Joining by forming - A review on joint mechanisms, applications and future trends. *Journal of Materials Processing Technology*, 214(10), 1972–1994. <https://doi.org/10.1016/j.jmatprotec.2013.12.022>
- [5] Santacreu, P. O., Glez, J. C., Chinouilh, G., & Fröhlich, T. (2006). Behaviour model of austenitic stainless steels for automotive structural parts. *Steel Research International*, 77(9–10), 686–691. <https://doi.org/10.1002/srin.200606448>
- [6] Mithieux, J. D., Kostoj, V., Chassagne, F., & Charles, J. (2008). New stainless steel solutions as economic alternatives to classical 1.4301 austenitic grades. *Steel Research International*, 79(6), 449–454. <https://doi.org/10.1002/srin.200806152>
- [7] Material data sheet 1.4301 – 304, Thyssenkrupp Materials (UK) Ltd accessed through <https://ucpcdn.thyssenkrupp.com/legacy/UCPthyssenkruppBAMXUK/assets/files/material-data-sheets/stainless-steel/stainless-steel-1.4301-304.pdf>. at 22/08/2024 (12:4pm)
- [8] Harsch, D., Fischer, P., Berisha, B., Heingartner, J., Renkci, Y., & Hora, P. (2018). Considering fluctuations of material properties, stainless steel 1.4301, on manufacturability of kitchen sinks. *IOP Conference Series: Materials Science and Engineering*, 418(1). <https://doi.org/10.1088/1757-899X/418/1/012113>
- [9] Metals Handbook, Vol.1 - Properties and Selection: Irons, Steels, and High-Performance Alloys, ASM International 10th Ed. 1990.
- [10] Metals Handbook, Howard E. Boyer and Timothy L. Gall, Eds., American Society for Metals, Materials Park, OH, 1985.
- [11] Talonen, J., Nenonen, P., Pape, G., & Hänninen, H. (n.d.). *Effect of Strain Rate on the Strain-Induced gamma arrow alpha prime-Martensite Transformation and Mechanical Properties of Austenitic Stainless Steels*.

- [12] Wróbel, N., Rejek, M., & Krolczyk, G. (2017). Testing of crimp connections made on a prototype stand. *E3S Web of Conferences*, 19. <https://doi.org/10.1051/e3sconf/20171903029>.
- [13] Zhang, Q., Jin, K., & Mu, D. (2014). Tube/tube joining technology by using rotary swaging forming method. *Journal of Materials Processing Technology*, 214(10), 2085–2094. <https://doi.org/10.1016/j.jmatprotec.2014.02.002>
- [14] Psyk, V., Risch, D., Kinsey, B. L., Tekkaya, A. E., & Kleiner, M. (2011). Electromagnetic forming - A review. *Journal of Materials Processing Technology*, 211(5), 787–829. <https://doi.org/10.1016/j.jmatprotec.2010.12.012>
- [15] Silva, C. M. A., Nielsen, C. v., Alves, L. M., & Martins, P. A. F. (2015). Environmentally friendly joining of tubes by their ends. *Journal of Cleaner Production*, 87(1), 777–786. <https://doi.org/10.1016/j.jclepro.2014.10.022>
- [16] Ivanov, A. Y., Sulyagin, R. v., Orlov, V. v., & Kruglova, A. A. (2011). Structure and properties of weld joints in X80, X90, and K70 pipe steel. *Steel in Translation*, 41(7), 611–616. <https://doi.org/10.3103/S0967091211070047>
- [17] Ji, H., Li, Y., Huang, X., Dong, S., Li, Y., & Xiao, W. (2023). Study on formability of duplex steel expansion pipe and its threaded joints. *Measurement: Journal of the International Measurement Confederation*, 206. <https://doi.org/10.1016/j.measurement.2022.112308>
- [18] Grund, T., Gester, A., Wagner, G., Habisch, S., & Mayr, P. (2018). Arc brazing of aluminium, aluminium matrix composites and stainless steel in dissimilar joints. *Metals*, 8(3). <https://doi.org/10.3390/met8030166>.
- [19] Kalpakjian S, Schmid SR (2010) Manufacturing Engineering & Technology, 6th ed. Prentice Hall: 900–920.
- [20] Milner DR, Rowe GW. Fundamentals of Solid-Phase Welding. *Metallurgical Reviews*. 1962;7(1):433-480. doi:10.1179/mtlr.1962.7.1.433
- [21] Clemensen, C., Juelstorp, O., & Bay, N. (1986). Cold welding. Part 3: Influence of surface preparation on bond strength.
- [22] Milner, D.R. and Vaidyanath, L.R., 1960. Significance of surface preparation in cold pressure welding. *Met Constr Br Weld J*, 7, pp.1-6.
- [23] Tabata, T., Masaki, S., & Azekura, K. (1989). Bond criterion in cold pressure welding of aluminium. *Materials Science and Technology (United Kingdom)*, 5(4), 377–381. <https://doi.org/10.1179/mst.1989.5.4.377>
- [24] Vairis, A., & Frost, M. (1998). High frequency linear friction welding of a titanium alloy. In *WEAR* (Vol. 217).

- [25] Pickin, C. G., Young, K., & Tuersley, I. (2007). Joining of lightweight sandwich sheets to aluminium using self-pierce riveting. *Materials and Design*, 28(8), 2361–2365. <https://doi.org/10.1016/j.matdes.2006.08.003>
- [26] Kato, T., Abe, Y., & Mori, K. (2008). Plastic joining of dissimilar material of high tensile strength steel and aluminium alloy sheets. *Welding International*, 22(9), 575–581. <https://doi.org/10.1080/09507110802410361>
- [27] Nong, N., Keju, O., Yu, Z., Zhiyuan, Q., Changcheng, T., & Feipeng, L. (2003). Research on press joining technology for automotive metallic sheets. *Journal of Materials Processing Technology*, 137(1-3 SPEC), 159–163. [https://doi.org/10.1016/S0924-0136\(02\)01083-X](https://doi.org/10.1016/S0924-0136(02)01083-X)
- [28] Grote, K. H., & Hefazi, H. (Eds.). (2021). *Springer handbook of mechanical engineering*. Springer Nature.
- [29] *Fundamentals of Angular Joining by Means of Hydroforming*. (n.d.).
- [30] Weddeling, C., Woodward, S. T., Marré, M., Nellesen, J., Psyk, V., Tekkaya, A. E., & Tillmann, W. (2011). Influence of groove characteristics on strength of form-fit joints. *Journal of Materials Processing Technology*, 211(5), 925-935.
- [31] Kovács, P. Z. "Joining of EN AW 6060 Pipes by Plastic Forming", *Periodica Polytechnica Mechanical Engineering*, 68(1), pp. 31–37, 2024. <https://doi.org/10.3311/PPme.23005>
- [32] Bauer, A., Manurung, Y. H. P., Sprungk, J., Graf, M., Awiszus, B., & Prajadhiana, K. (2019). Investigation on forming–welding process chain for DC04 tube manufacturing using experiment and FEM simulation. *International Journal of Advanced Manufacturing Technology*, 102(5–8), 2399–2408. <https://doi.org/10.1007/s00170-019-03320-1>
- [33] Al-Maqdi, S., Qudeiri, J. A., & Ziout, A. (n.d.). *Optimization of Flat Rolling Process through a Simulation Approach Using Simufact Forming*.
- [34] Obiko, J. O., Mwema, F. M., & Bodunrin, M. O. (2019). Finite element simulation of X20CrMoV121 steel billet forging process using the Deform 3D software. *SN Applied Sciences*, 1(9). <https://doi.org/10.1007/s42452-019-1087-y>