

# Using Tungsten Inert Gas Welding Equipment to Locally Heat Tubes and Achieve Inhomogeneous Thickness in Tube Sinking Processes

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**Abstract.** Tubes with non-uniform thickness are needed to even out wall thickness in draw bending and provide higher stiffness in specific directions in some applications. Tailored local heating of the tubes in tube sinking operations should reduce the local flow stresses and facilitate differential deformation along the circumference of tubes to form tubes with uneven wall thicknesses. Local heating of tubes prior to entry into the die in tube sinking is implemented in this research to form tubes with higher thickness in desired directions. Initial experiments are conducted using plasma heating by tungsten inert gas (TIG) welding equipment on EN AW 6060 AlMgSi0.5 aluminum tubes. The process window is described by varying the process temperature (weld current between 50 A and 80 A) while altering the degree of deformation, the tube diameter, and tube thickness. Tubes with no defects were formed at 50 A. Increasing the weld current led to a higher wall thickness (up to 25% thickness increase), however, high weld currents also favored the formation of surface defects, wrinkle formation, or burn-through holes depending on the process setup. The process window was larger for tubes with higher wall thickness.

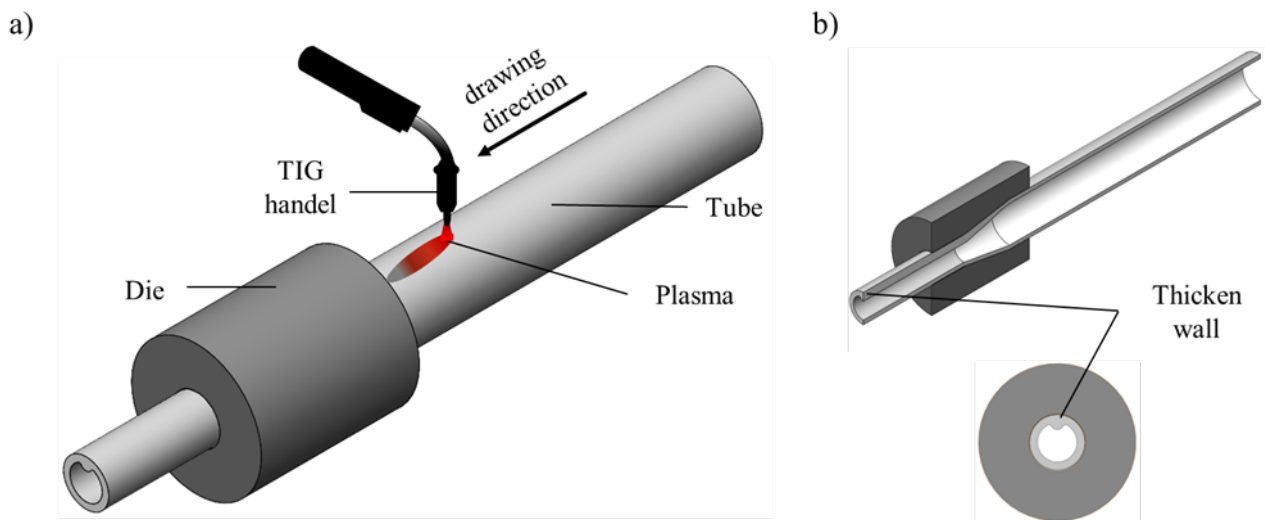
## Introduction

Tubes with uniform wall thickness are often desired to simplify design. However, tubes with non-homogenous wall thickness are required to improve bendability and stiffening in specific directions. Cracks may occur on the outer arc in tube draw bending due to excessive material thinning, while thickening and wrinkling occur in the inner arc [1]. Tubes with variable wall thickness offer the possibility to have higher wall thickness on the outer arc of the bend, thereby preventing fracture, especially for small bend radii [2]. The stiffness of mechanical components can be enhanced by increasing the thickness in desired directions while reducing thickness in other directions to reduce component weight. Guillot et al. [3] estimated that a 25% reduction in weight can be achieved by switching from designs with constant thickness to variable thickness. Weight reduction is desirable to reduce energy consumption and related CO<sub>2</sub> emissions by vehicles. Examples of tubular components that are loaded in specific directions include bicycle frame tubing, the landing gears of certain small aircraft, and tubular impact absorbers in car bumpers.

Current manufacturing practice uses dedicated forming tools like oval, tapered, and stepped mandrels with variable geometries to form tubes with variable circumferential or axial thickness. The tube geometry and thickness are determined by the space between dies and mandrels. Dedicated forming tools can only form components of a specific geometry, which limits process flexibility. To increase flexibility, Bihamta et al. [4] used a position control mandrel that permits tube sinking followed by tube drawing sequences to form tubes with variable thickness in the axial direction. Negendank et al. [5] proposed using a stepped mandrel that moves in the axial direction. Jäger et al. [6] exploited the high formability of electromagnetic forming to locally alter the cross-section and thickness of tubes. Entire cross sections were altered in the study with no consideration for a specific direction. Carradó et al. [7] performed tube drawing with tilted die and mandrel angles to control eccentricity and mechanical properties. They also investigated the residual stresses, crystallographic texture, dislocation density, and control eccentricity of Cu tubes to increase part precision [8, 9].

Local heating has been implemented in forming processes to alter the geometry and improve local formability [10]. Local heating causes a reduction in the yield stress and flow stress, which leads to an alteration in the deformation mode of a workpiece since material flow is non-homogeneous. Deformation in tube sinking is due to a combination of circumferential compression and positive or negative radial strains depending on the die angle [11]. Locally heating portions of the tube circumference prior to entry into dies will cause a drop in the local flow stresses and increase material flow to the heated portion. The cross-section of tubes can be altered without the need for dedicated mandrels, thereby lowering process cost and increasing process flexibility.

Various heating methods can be used as a heat source in tube sinking with local heating. The choice of heat source is influenced by the required precision, heating time, ease of process control, and material of the tube. Laser and induction heating may offer highly precise heating but are expensive alternatives. A gas heating source is a cheaper alternative; however, it offers low precision and is ideal for heating large portions. In this study, local heating is performed using plasma heating TIG welding equipment, as shown in Fig. 1. Plasma heating has a lower cost than induction and laser heating, with higher precision compared to gas heating. The power (current) of the welding equipment is known and can be controlled to achieve desired outcomes.

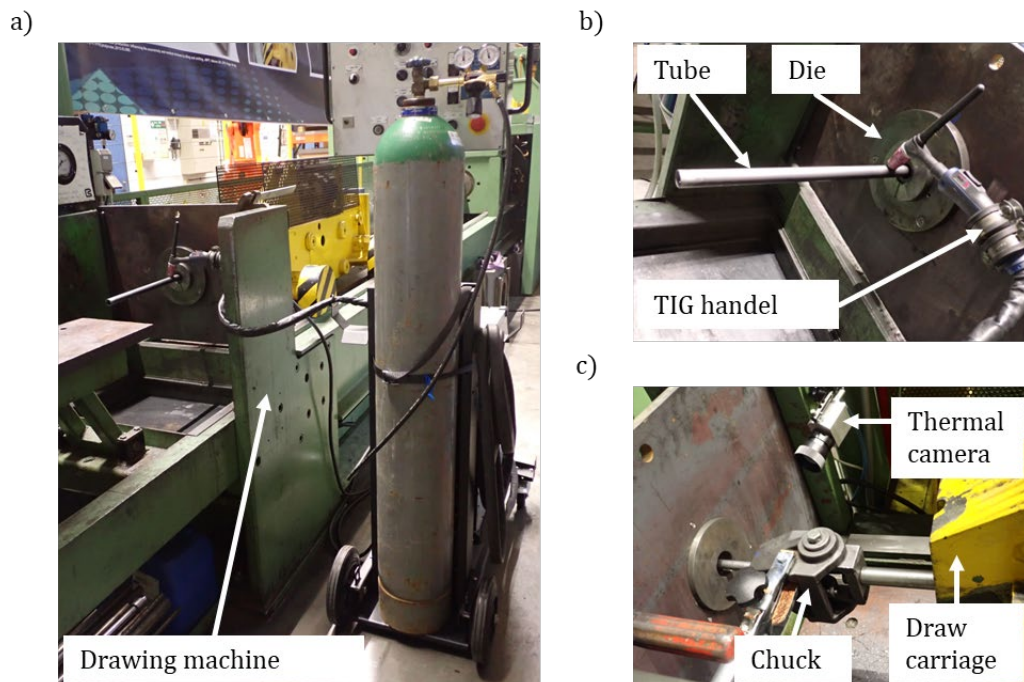


**Fig. 1.** Setup of tube sinking with induction heating.

## Materials and Methods

The experiments were conducted on EN AW 6060 AlMgSi0.5 aluminum tubes with different diameters and wall thicknesses. This aluminum alloy is known for its corrosion resistance, good surface finish, and medium strength. The aluminum tubes had 20 mm, 25 mm, and 30 mm diameters. The 20 mm and 25 mm tubes had 1 mm and 2 mm wall thicknesses, while the 30 mm tubes were only 2 mm thick. The tube diameters are reduced through dies of different sizes to represent various degrees of deformation. The 20 mm diameter tubes were reduced to 19 mm, 18 mm, and 16 mm. The 25 mm and 30 mm diameter tubes were reduced to 24 mm, 23 mm, 21 mm, and 29.2 mm, 28 mm, and 26 mm, respectively. The tubes and corresponding die diameters used in forming are presented in Table 1. Rotary swaging was performed on one end of the tubes before clamping them with the chuck used to draw the tubes through the dies, as shown in Fig. 2c. The tube was drawn at a velocity of 2 m/min, while local heating was performed at 25 mm from the opposite side of the die. Titanium 321 AC/DC TIG welding equipment made by GYS, Saint-Berthevin, France, was used as the heat source in the experiments. Given that this is the first experimental study using the novel process setup, the current was varied from 30 A to 90 A in steps of 10 A to determine the process window. The dry lubricant Molykote D-321 is used to reduce the friction between the die and tubes. The temperatures of the tubes at exit from the dies were recorded with the aid of a thermal imaging camera, OPTRIS model PI640i, and OPTRIS Pix Connect software. The camera was placed 25 cm from the die exit.

The wall thicknesses of the formed tubes were measured at 9 locations along the circumferences of the tubes using a vernier caliper. The setup of the experiments is presented in Fig. 2.



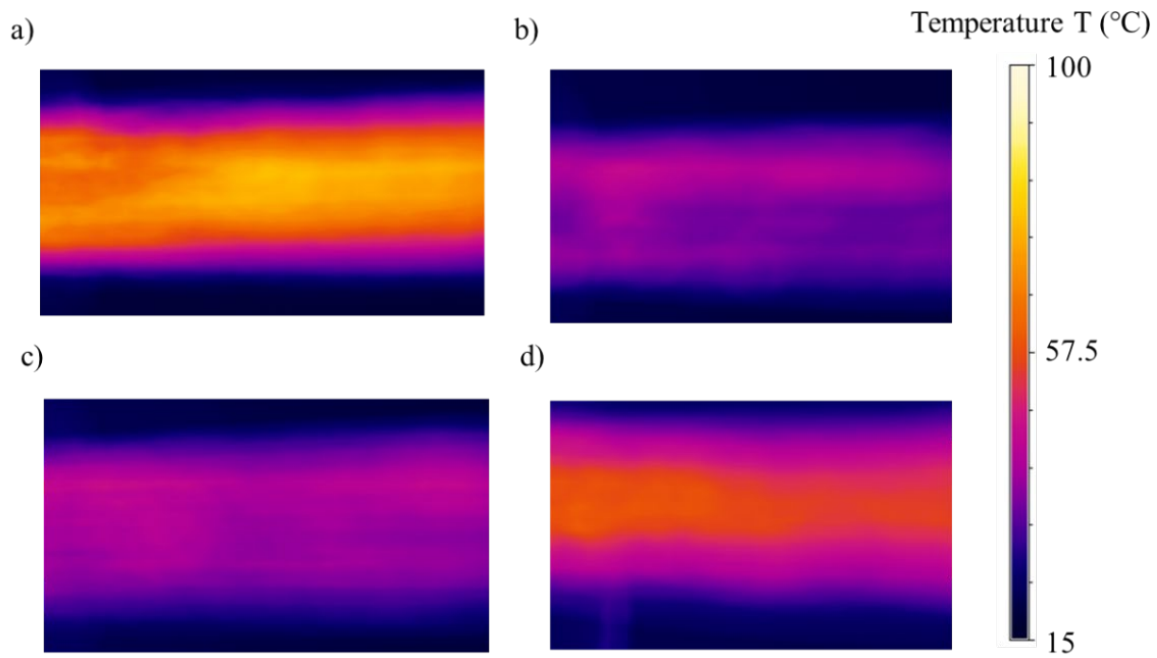
**Fig. 2.** Experimental setup of tube sinking with plasma heating.

**Table 1.** Design of experiments.

Current [A]	Initial pipe diameter $\Phi$ [mm]	Wall thickness of tube [mm]	Die size $\Phi$ [mm]		
			19	18	16
(50/60/70/80)	20	1	19	18	16
(50/60/70/80)	20	2	19	18	16
(50/60/70/80)	25	1	24	23	21
(50/60/70/80)	25	2	24	23	21
(50/60/70/80)	30	2	29.2	28	26

## Results

**Temperature.** The temperatures of the 20 mm tubes with 1 mm wall thickness drawn using the 19 mm die were measured upon exit from the die after forming, see Fig. 3. The highest temperature of about 60°C was recorded at 90 A. The temperature dropped to 56°C at 80 A and 54°C at 50 A. The maximum temperature dropped with a reduction in weld current. However, there was no linear decrease in the temperature, which can be attributed to the limits of thermal cameras in temperature measurement and the low variation of the tube temperatures formed using 50 A, 60 A, and 70 A. Determining the exit temperatures of the tubes is required to monitor and control the heat input in the process.








**Fig. 3.** Temperature of 20 mm tubes formed using the 19mm die at exit from the die.  
a) 80A. b) 70A. c) 60A d) 50A.

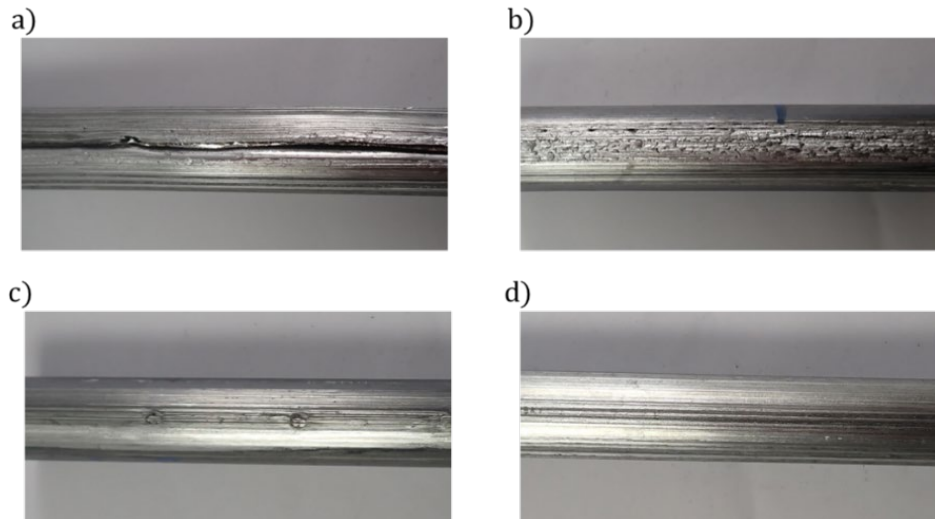
**Process window.** The process window and optimal forming conditions were determined by varying the tube diameter and thickness, degree of deformation, and weld power. Other parameters such as the distance between the weld gun and die, the gap between the weld gun and tube, and the drawing speed were constant. A short distance between the weld gun and die may lead to higher thickness variation because the material enters the die at higher temperatures and is formed at high temperatures that are associated with lower flow stress and higher formability. The gap between the weld torch and tube can only be varied within a very limited range since the weld circuit needs to be completed for welding to occur. High drawing speeds reduce the heat input per unit length of the material and result in lower formability.

TIG welding of the aluminum tubes can be performed at different currents based on the blank thickness. However, the high temperatures in welding cause microstructural changes and reduced strength. The temperature in tube sinking with local heating should permit forming in the warm to hot temperature range, which has high formability but with little alteration of microstructure. As a result, the process current was increased from 30 A to 90 A in steps of 10 A to determine the influence of the current on wall thickness and tube geometry in the first trial experiments, see Table 2. Visual inspection was used to classify the tubes based on the appearance of the tube surface. Good refers to tubes without surface defects, surface refers to tubes with some surface defects, wrinkling represents tubes with more pronounced surface defects and hole refers to tubes with burn-through holes. The tube diameter before drawing, wall thickness, and degree of deformation are maintained at a constant value. Only the current (heat input) is altered in these investigations.

**Table 2.** Current variation in tube drawing with local heating (initial trials).

Tube diameter (mm)	Wall thickness (mm)	Exit diameter (mm)	Current (A)	Results
20	1.0	19	90	Hole 
20	1.0	19	80	Wrinkling 
20	1.0	19	70	Wrinkling 
20	1.0	19	60	Surface 
20	1.0	19	50	Good 
20	1.0	19	40	No heat
20	1.0	19	30	No heat

The pictures of the formed tubes are presented in Fig. 4. The results of the first trials reveal that at the highest current of 90 A, excess heat caused the formation of burn-through holes, as shown in Fig. 4a. Tubes could be formed at lower currents of 80 A and 70 A, however, wrinkles and very poor surface quality were observed on these parts, see Fig. 4b. The tube formed at 60 A had improved surface quality but was still not acceptable for most applications. The best results were achieved for the tubes formed at 50 A, as the surface quality did not degrade due to heating. For the low currents (40 A and 30 A), no heat was generated by the welding equipment.

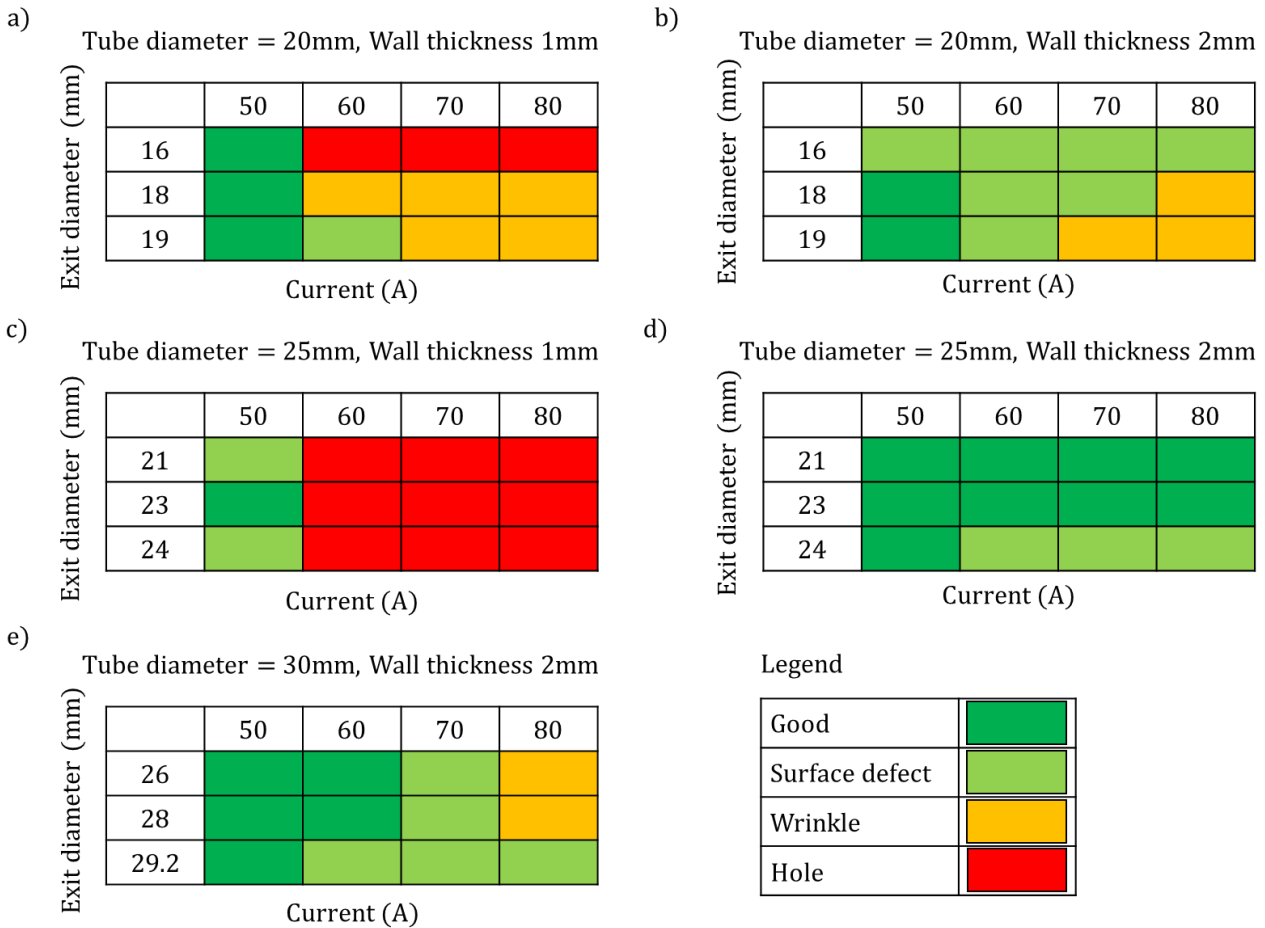


**Fig. 4.** Effects of input current on surface quality in the tube sinking process.

- a) Burn-through at 90 A. b) Very rough surface and wrinkle formation at 80 A and 70 A.  
c) Rough surface at 60A. d) Good surface at 50 A.

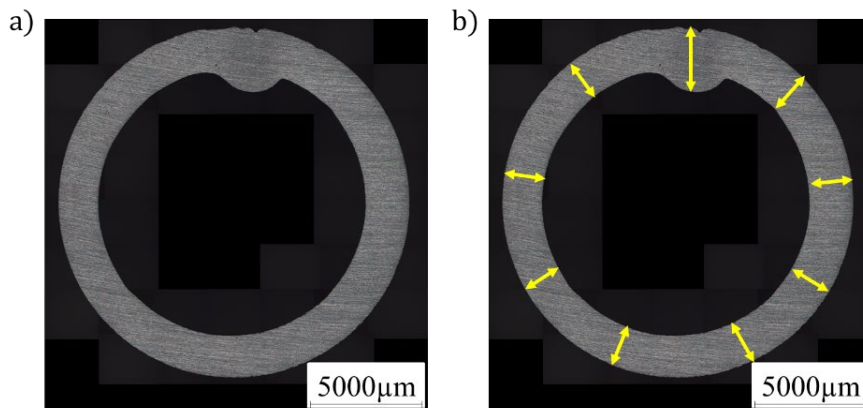
More experiments were performed over a range of parameters to establish the process window. The tubes were successfully formed at currents between 50 A and 80 A depending on the process setting. The 20 mm diameter tubes with a wall thickness of 1 mm required 50 A to successfully form tubes, see Fig. 5a. At higher currents, the 16 mm diameter tubes had burn-through holes. The rest of the tubes formed at 60 A, 70 A, and 80 A had surface defects or wrinkles. The 20 mm diameter tubes with a thickness of 2 mm had no defects when formed using 50 A current and 18 mm and 19 mm dies. However, at higher currents, either surface defects or wrinkles were observed, as seen in Fig. 5b. The 25 mm diameter tubes with a wall thickness of 1 mm formed at 50 A had surface defects except for the 23 mm diameter tube, which had a good appearance. All the tubes formed at 60 A, 70 A, and 80 A had holes, as shown in Fig. 5c. At a higher thickness of 2 mm, the 25 mm tubes were formed in a wide range of current and die diameters, as shown in Fig. 5d. Only the tubes formed to 24 mm diameters heated at 60 A, 70 A, and 80 A had surface defects. The 30 mm tubes with 2 mm thickness had no surface defects at 50 A and 60 A except for the tube formed to 29.2 mm diameter heated using the 60 A heat source, see Fig. 5e. All the tubes formed using 70 A had surface defects. At 80 A, tubes formed to 26 mm and 28 mm diameters had wrinkles, while the 29.2 mm tube had surface defects.

In general, the experiments revealed that the components with no defects were formed at 50 A, as higher energy inputs caused surface defects, wrinkle formation, or burn-through. Increasing the wall thickness reduced the presence of defects, which can be explained by the ability of the higher tube thickness to absorb heat. The formability increases at higher wall thicknesses.



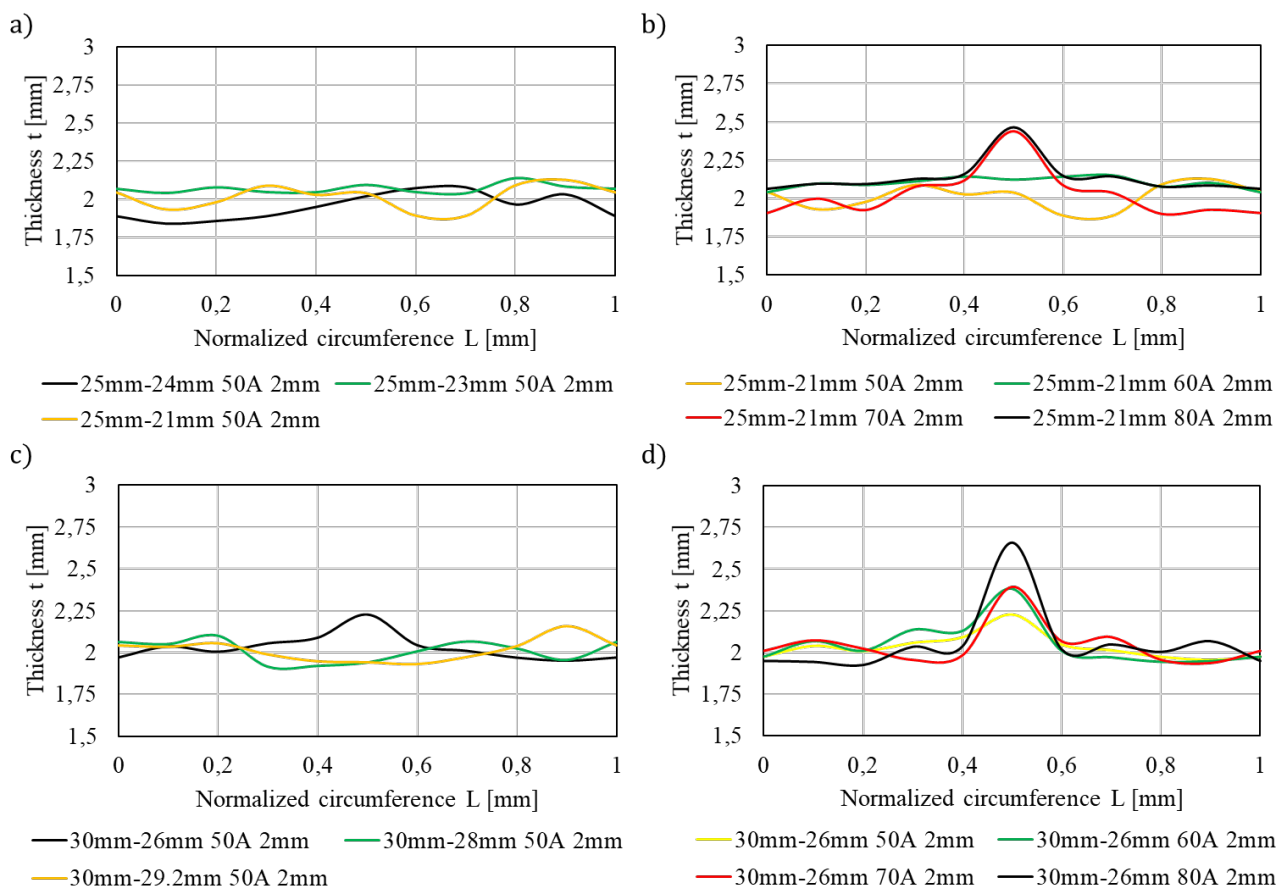
**Fig. 5.** Results of tube drawing with local heating. a) 20 mm diameter tubes with 1 mm wall thickness. b) 20 mm diameter tubes with 2 mm wall thickness. c) 25 mm diameter tubes with 1 mm wall thickness. d) 25 mm diameter tubes with 2 mm wall thickness. e) 30 mm diameter tubes with 2 mm wall thickness.

**Thickness variation.** The wall thickness of the 20 mm tube formed to 16 mm with a 2 mm initial wall thickness and heated using the 80A current is shown in Fig. 6. There is a significant increase in the tube thickness along the circumference in the heated zone. The outer surface is wavy along the thickened portion of the circumference, which reveals the presence of surface defects. The thicknesses of the tubes are measured at 9 points along the circumference of the tube, as indicated in Fig. 6b.



**Fig. 6.** a) Tube with inhomogeneous wall thickness. b) Points used to measure wall thickness.

The wall thickness of the 25 mm and 30 mm tubes with 2 mm wall thickness formed to different degrees are presented in Fig. 7. These results are presented because the tubes with the best appearances were formed in these test conditions, and there were no burn-through holes. Reducing the tube diameter at different levels (degrees of deformation) has minimal influence on the wall thickness and eccentricity in general, as revealed in Fig. 7a and Fig. 7c. The tube diameter was reduced from 25 mm to 21 mm, 23 mm, and 24 mm in Fig. 7a and from 30 mm to 26 mm, 28 mm, and 29.2 mm in Fig. 7c. However, the 30 mm tube reduced to 26 mm had a high thickness of 2.25 mm in the heated portion. This may be because, although the process temperature for the 50 A is low, the degree of deformation is high, and the high flow stress causes local thickening. Increasing the current (temperature) leads to an increase in wall thickening. Local heating had a minimal effect on the thickness of the 25 mm diameter tubes formed to 21 mm at 50 A and 60 A. At higher currents (70 A and 80 A), the thickness increased because of high temperatures at the same degree of deformation. The 30 mm diameter tubes reduced to 26 mm diameter revealed an increase in wall thickness, see Fig. 7d.



**Fig. 7.** Thickness variation in tube sinking with local heating. a) Tubes with 25 mm diameter reduced to 24 mm, 23 mm, and 21 mm. b) Tubes with 25 mm diameter reduced to 21 mm using different currents. c) Tubes with 30 mm diameter reduced to 26 mm, 28 mm, and 29.2 mm. b) Tubes with 30 mm diameter reduced to 26 mm using different currents.

## Discussion

Increasing the current of the TIG heat source leads to an increase in the temperature of the tube. This agrees with the high temperature recorded in the tube drawing experiment at 80 A compared to the lower currents, see Fig. 3. Heating leads to thermal softening and a drop in the local flow stress. Thermal softening causes the material to flow more easily to the high-temperature region indicated by the local thickening in the heated zone. This agrees with the change in the wall thickness along the heated part of the tube circumference observed in Fig. 6. High temperatures correlate with increased formability, as demonstrated by the high wall thickness for the tubes formed at the high

currents for the 25 mm and 30 mm tube diameters in Fig. 7. However, thermal softening also causes surface defects (wavy surface) due to the friction between the die and tube. Increasing the wall thickness provides more material to be heated and formed, which accounts for the higher formability of the thicker tubes. Forming using dies with small diameters increased the degree of deformation and local thickening of the tube as highlighted in Fig. 7c, however, its influence is lower than the influence of weld current on formability. By controlling other parameters such as the distance between the weld gun and die, heat source distance, and drawing speed, ideal process temperatures that allow thickening of the tube without a reduction in surface quality can be achieved.

A major hindrance of the TIG heat source is the fact that a threshold current is required for heating to occur, eliminating the possibility of performing heating at lower temperatures than that needed to create the electric arc. In addition, the heating zone is mainly controlled by the size of the fixed tungsten filament and not the distance from the heat source to the tube, thereby reducing control over the size of the heated zone. In future research, the heat source will be altered to overcome these hindrances.

### Conclusions

- Local heating in tube sinking by a TIG welding gun resulted in thickening of the walls of the tubes. An increase in wall thickness of over 25% was achieved for some process setups.
- The current had the most significant effect on the resulting wall thickness. Higher currents resulted in increased wall thickness. However, current below 40 A could not be used to heat the tubes.
- The process window in tube sinking local heating is mainly controlled by the tube thickness and input current. Burn-through holes and other defects are easily formed in the drawing of tubes with thin walls. Increasing the tube thickness leads to higher formability.

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