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ORIGINAL ARTICLE

The effect of tube material, microstructure, and heat treatment on process responses of tube hydroforming without axial force

A. Fatemi · M. R. Morovvati · F. R. Biglari

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Abstract In this paper, the influence of tube material, microstructure, and heat treatment on process responses of tube hydroforming has been studied. One of the most important parameters in performing a successful tube hydroforming process is the selection of appropriate material for tubes. In the analysis section, effective parameters for the selection of an appropriate tube material for the hydroforming process have been investigated; it was concluded that higher strain hardening exponent (*n*), elasticity modulus (*E*), and anisotropy index (*R*) can enhance formability in this process; and the effects of microstructure and heat treatment on the formability of ASTM C11000 copper and ASTM AA1050 aluminum have been investigated. Consequently, four different heat treatment processes, which had different heating temperatures and durations, were selected, in addition to different cooling methods for each of the materials. In the experimental tests, the effects of these heat treatment methods on maximum bulging height, thickness strains, and final forming pressures were scrutinized. The effects of heat treatment on copper microstructure were also studied through metallographic tests; on the other hand, the effects of microstructure on tube hydroforming process were justified. As a result of these analyses, two heat treatment methods, namely, heating to 450 and 350 °C for 15 min and cooling in water, were recommended for copper and aluminum, respectively. Using these methods and due to their consequent fine and homogenous microstructure, higher mechanical strength and increase in material formability was achieved by attaining higher thickness strain and bulging height values. Finally, after extracting the mechanical properties of the two materials and comparing them with each other, parameters of strength coefficient and strain hardening exponent were reported as two effective factors that would improve tube deformation by tube hydroforming process.

Keywords Tube hydroforming · Material selection · Heat treatment · Microstructure · Copper · Aluminum · Experimental tests · Bulging height · Thickness strain · Final forming pressure

1 Introduction

Tube hydroforming is one the most efficient methods that have been implemented by several industries in order to manufacture high-quality products. In this method, the tube is formed under inner pressure of forming fluid into the die cavity. This process, which can produce complex products that have high strength and quality in a single procedure, has replaced other processes such as welding and stamping. The application of this process in the production of automotive parts, liquid transferring network joints, and aerospace equipment is increasing. In spite of all these advantages, inappropriate selection of material and process parameters can cause defects in the parts, such as bursting, wrinkling, and buckling. Therefore, several researches were conducted to investigate the effects of different materials and parameters, like stress ratio, strain hardening exponent, anisotropy, and other material variants on tube hydroforming process.

Koc et al. [1] studied the effect of material on the tube hydroforming process and showed that an appropriate material for the tube hydroforming process should possess qualities such as high strain hardening exponent, uniformity in material deformation especially in welded tubes, and high strength coefficient. Yuan et al. [2] succeeded in producing several parts with high expansion ratio and varying cross-section in length for different materials, like aluminum and

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stainless steel, by using tube hydroforming process. They applied useful wrinkling for forming the tubes with high expansion ratio and low formability. Manabe and Amino [3] did a research about the effects of material properties and process parameters on tube hydroforming process and explained the influences of parameters, such as stress ratio, strain hardening exponent, and anisotropy, on the process. Carleer et al. [4] studied the effects of different material properties on tube hydroforming by finite element analyses. The parameters that they investigated were tube thickness, strain hardening exponent, yield strength, ultimate plastic stress, and anisotropy parameters; they also used forming limit diagram to model the failure in tube hydroforming process. Kridli et al. [5] studied the effects of strain hardening exponent and tube initial thickness on thickness distribution in the hydroformed tube by using the finite element code of ABAQUS. Lei et al. [6] used finite element simulation and Oyane's ductile fracture criterion to predict bursting in tube hydroforming of T-shaped parts. Kocanda and Sodlowska [7] identified the limits of tube hydroforming of X-shaped joints based on their material formability; in addition, they used the estimation of forming limit curves in order to determine the initiation of strain concentration and failure which were caused by bursting. Finally, in the recent research that was done by our team [8], the effects of tube thickness and inner pressure on hydroforming process responses have been studied theoretically, statistically, and experimentally. As a result of this research, a modified theoretical model has been proposed for the hydroforming process. The outputs of this result were in accordance with the statistical and experimental results.

In this paper, material parameters which are effective on tube hydroforming process have been mentioned; the effects that they produce were discussed; and based on these parameters, appropriate materials were selected. Then, the effects of microstructure and heat treatment on the formability of copper and aluminum tubes were explained in detail in order to suggest methods for improving these qualities in the tube hydroforming process. After introducing the hydroforming test and heat treatment equipment, the method of performing the tests was presented. The effect of heat treatment and copper samples microstructure were studied on tube hydroforming process responses by experimental test and metallographic investigation, and heat treatment, including heating to 450 °C for 15 min and cooling in water, was suggested for these responses. Effects of heat treatment were also studied by experimental tests on aluminum tubes, and the causes of failure in aluminum samples were also investigated. Heat treatment that includes heating to 350 °C for 15 min and cooling in water was also suggested in order to improve formability of aluminum tubes. Finally, after performing tension test on these materials and deriving their mechanical properties, the parameters of strain hardening exponent and strength coefficient were reported as two main factors for material selection.

2 Effect of material properties on process and selecting appropriate materials

Selection of appropriate materials is the main factor in a successful tube hydroforming process. A suitable material for this process should have qualities such as high elongation percentage, high strain hardening exponent, low anisotropy, high ductility, appropriate price, and availability. However, the most important factor is the strain hardening property. The higher this parameter, the better the forming properties, the more the strength against failure, and the more uniform the strain distribution will be. In order to obtain this parameter, several key factors could be used, such as strain hardening exponent (n), maximum yield stress to ultimate stress ratio $\left(\frac{\sigma_y}{\sigma_{UTS}}\right)$, total elongation percentage E_{tot}, and maximum uniform strain (ε_u). An increase in these factors results in a higher strain hardening. Strain hardening exponent (n) can precisely express strain hardening. The other important factor is elasticity modulus (E), the increase of which results in more stiffness in material and less spring back. Anisotropy shows different characteristics of a material along different directions and is measured by anisotropy index (R), which is:

$$R = \frac{\varepsilon_w = \ln(w/w_0)}{\varepsilon_w = \ln\left(\frac{t}{t_0}\right)} \tag{1}$$

Higher R value indicates that strain is higher in width rather than in thickness; therefore, material strength is higher in the thickness direction, stronger against thinning, and able to tolerate higher tensile strains [9, 10]; on the other hand, smaller R value shows that less axial displacement is required to form the tube. Rupture strength, homogeneity, and sensitivity to strain rate are the other parameters which influence the tube hydroforming process.

It was not possible to select steel or high-strength alloys as test specimens by using the current 280 MPa pump; therefore, metals that have high formability and less strength, such as aluminum and copper, were chosen. In addition, these materials have qualities like high elongation percentages, appropriate strength, and strain hardening. These materials were also the most appropriate for this research regarding cost and accessibility. As a result, ASTM C11000 copper with purity of 99.9 % and ASTM AA1050 with purity of 99.5 % were selected for the material of the tubes, and the chemical composition of these materials is presented in Table 1.

In order to extract tube material properties and their forming limits, some tests which are suitable for the hydroforming process have been recommended; the most applicable of which are simple tensile test, expansion test, cone test, and hydraulic bulge test [11].

In this research, due to the limits for material properties testing equipment, tubes were tested under different pressures in hydroforming process in order to evaluate their performance in the process. Some hydroforming tests demonstrated that copper and aluminum tubes failed in even low pressures before appropriate forming. These materials are known as naturally ductile and formable materials; therefore, their weak performance in these tests could be due to a reason other than material types. The tubes provided for the tests were produced via extrusion process and were then rolled and encircled for packing in addition to many mechanical works that were exerted on them during the sample preparation process. Thus, improper effects of thermomechanical operations on the materials' microstructure would lead to a reduction in their formability. As a result, studying the influence of microstructure on the formability of a material is essential.

3 Effect of microstructure and heat treatment on the formability of copper and aluminum tubes in the tube hydroforming process

The two main characteristics of single-phase copper are the size and shape of its grains [12, 13]. These characteristics influence tensile strength, yield strength, and ductility of copper; moreover, usually larger grain size results in hardness and strength decrease that lead to ductility improvement. Exception occurs when the tube is very thin. In this condition, an increase in grain size decreases the number of grains in thickness that decreases both mechanical strength and material ductility. On the other hand, grain shape also affects copper mechanical properties. A homogenous microstructure consisting of uniform grains with similar dimensions usually provides good formability, whereas a microstructure with stretched and nonhomogenous grains intensely decreases formability. Another effective factor is the existence of impurities in the microstructure of the tubes. The selected tubes for this research work were produced for mechanical applications; therefore, a low level of purification was used in their production and the amount of impurities is high. These impurities generate tiny and hard precipitations in grain boundaries; develop a hard and brittle microstructure; and hence, reduce material ductility.

The tubes were produced by extrusion in high temperatures that when used with mechanical forces cause grain enlargement and also stretched microstructure in the direction of the extrusion axis. Grain growth reduces mechanical strength; moreover, a decrease in the number of grains in tube thickness reduces ductility and formability. Stretched grains, longer grain boundaries, more dislocations, and their collision in addition to the presence of impurities in the precipitation in grain boundaries would all reduce tube formability. Based on these reasons, low formability of tubes in the current tube hydroforming process is due to improper microstructure, not its chemical composition; therefore, using heat treatment in order to recover microstructure eliminates the tube forming problem and changing the tube material would not be necessary.

Annealing is the heat treatment which is usually recommended for the improvement of ductility and formability [12, 13]. This process includes three steps, namely, stress relieving, recrystallization, and grain growth. In the stress relieving step, which is performed at low temperatures, residual stress that is caused by work hardening process is removed due to the displacement of dislocations and their gathering below each other. By increasing the temperature in the recrystallization step, new grains that have a microstructure similar to nondeformed grains are created. This process is initiated by generation of new nuclei in grain boundaries and slip bands and they grow until they take over all the hard-worked grain. During the two first steps of annealing, a new homogenous microstructure is developed, which improves ductility and reduces material hardness and tensile strength. The effect of different steps of annealing on hardness, tensile strength, ductility,

Table 1 Chemical composition of the tube materials: ASTM C11000 copper and ASTM AA1050 aluminum

Tube materials	Chemical substances (%)													
	Al	Cu	Fe	Mn	Si	Ti	V	Zn	P	Te	O	S	Bi	Pb
Copper ASTM C11000	–	99.9	0.0002	–	–	–	–	–	0.0003	0.001	0.04	0.0003	0.001	0.005
Aluminum ASTM AA1050	99.5	0.02	0.2	0.03	0.02	0.16	0.01	0.02	0.03	–	–	–	–	–

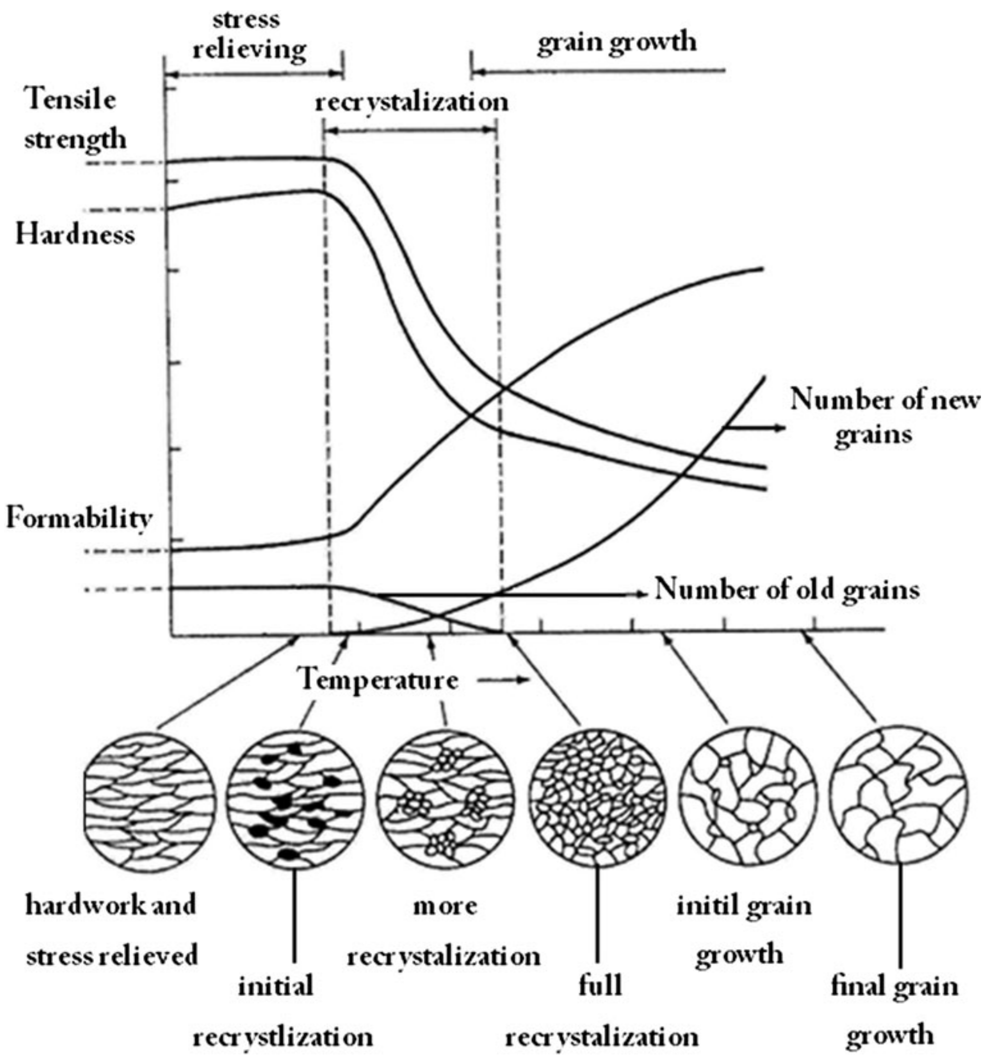


Fig. 1 Effect of different steps of annealing on hardness, tensile strength, ductility, and grain size

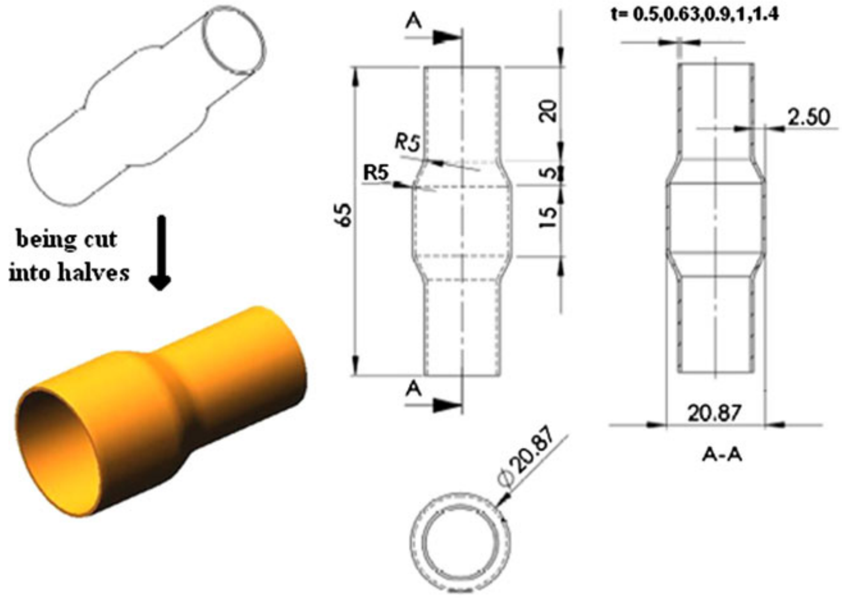


Fig. 2 Hydroformed axisymmetric part, used as 5/8-in. reduction joint after being cut into halves and the geometry of the final workpiece

Table 2 Different types of heat treatment processes for copper and aluminum tubes

Heat treatment type	Heating temperature (°C)	Duration of heating in the furnace (min)	Method of cooling	Tube material
Type A	450	15	Cooling in water	Copper
Type B	350			
Type C	350	30	Cooling in furnace	
Type D	450			
Type E	350	15	Cooling in water	Aluminum
Type F	250			
Type G	250	30	Cooling in furnace	
Type H	350			

and grain size is illustrated in Fig. 1. In the third step, any increase in grain size reduces formability and increases strength unexpectedly due to the low thickness of the tubes, which is not suitable. As a result, this step should be eliminated to provide a homogenous microstructure with fine grains that leads to high mechanical properties and appropriate ductility and formability; therefore, two processes of normalizing or quenching which contains cooling by air or water are recommended. On the other hand, the quenching process has two inverse attributes against copper alloys and divides them into two categories: quench hardening and quench softening alloys [9]. Copper with a high level of purity is usually softened under the quenching process and improves its ductility and formability. Consequently, heat treatment, including heating in a furnace for stress relieving and recrystallization and then cooling in water, is suggested to improve microstructure and mechanical properties of copper and aluminum tubes. The effects of heating temperature and duration and cooling method on the formability of copper and aluminum tubes were studied in the next sections.

4 Experimental tests

In order to investigate the effects of material, microstructure, and heat treatment, the tube hydroforming process for producing an axisymmetric part is shown in Fig. 2. The tests were performed on a set of aluminum and copper samples

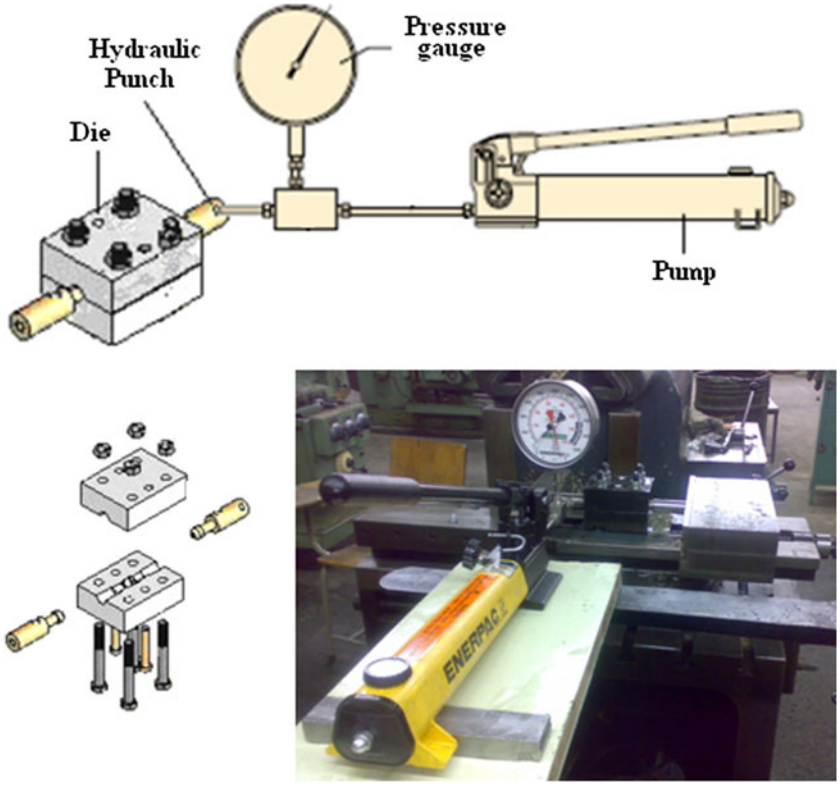


Fig. 3 Experimental test setup and the tube hydroforming die (enlarged view)

Fig. 4 Sequences of experimental tube hydroforming tests

with the initial length of 73 mm with different heat treatment processes. In order to improve the microstructure, four different types of heat treatment processes for each copper and aluminum tube were considered, which are shown in Table 2.

After heat treatment, sections of copper tubes with and without heat treatment were tested to study their microstructure by metallographic test. In order to carry out tube hydroforming tests, hydroforming die setup and pressure exertion and controlling and transferring equipment were prepared and assembled, which are shown in Fig. 3. After the test sample preparation process, samples were located in the die, as shown Fig. 3. Then, by mechanical chuck force, the hydraulic punches sealed both ends of the tube, and after closing the upper part of the die, the die was completely clamped. Finally, by exerting inner pressure, forming of the tube was performed. The pressure was increased until die filling or failure occurrence. This procedure is presented in Fig. 4.

Table 3 Experimental tests and their results on copper tubes with different thicknesses and heat treatment methods

Part number	Initial tube thickness (mm)	Bursting pressure (MPa)	Minimum final thickness (mm)	Maximum thickness strain (%)	Maximum bulging radius (mm)	Heat treatment type
7	0.50	10	0.36	28	8.85	No heat treatment
18	0.63	18	0.43	32	8.88	
30	0.90	21	0.58	35	9.33	
36	1	28	0.6	40	9.98	
6	0.50	11	0.37	26	9.85	Type D
17	0.63	19	0.45	28	9.93	
29	0.90	24	0.61	32	9.76	
9	1	50	0.7	30	10.5	
5	0.50	13	0.36	28	9.88	Type C
16	0.63	21	0.43	31	10.37	
26	0.90	45	0.65	28	10.5	
33	1	74	0.7	30	10.5	
4	0.50	16	0.35	30	10.29	Type B
14	0.63	34	0.47	25	10.5	
27	0.90	60	0.65	28	10.5	
34	1	80	0.7	30	10.5	
3	0.50	44	0.36	28	10.5	Type A
15	0.63	56	0.47	25	10.5	
28	0.90	72	0.64	28	10.5	
35	1	93	0.7	30	10.5	

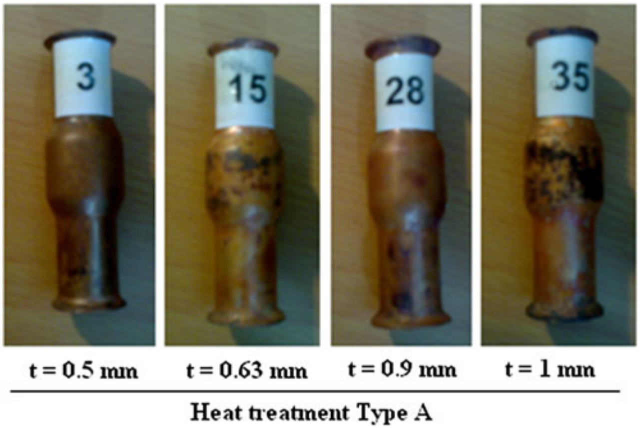


Fig. 5 Hydroformed copper tubes of different thicknesses with "type A" heat treatment in experimental tests

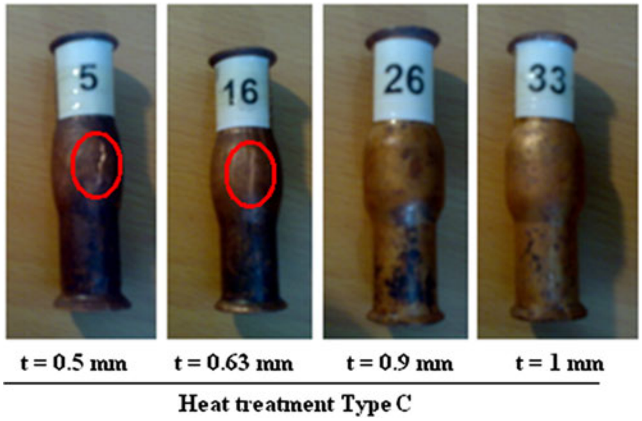


Fig. 7 Hydroformed copper tubes of different thicknesses with "type C" heat treatment in experimental tests

5 Results of experimental tests

Tube hydroforming tests on copper tubes with four different heat treatment methods in different thicknesses were performed until failure occurs or die fills fully by using equations derived from theoretical studies in our previous survey [8]. Table 3 shows the experimental tests and their results which were done on copper tubes with different thicknesses and heat treatment methods. As demonstrated in Fig. 5, all the tubes that had "type A" heat treatment were able to complete the process successfully. Figure 6 shows the tubes with "type B" heat treatment in which all of the tubes had a proper performance in the process, except the tube with the thickness of 0.5 mm. In Fig. 7, hydroformed tubes with "type C" heat treatment is illustrated and shows that failure has occurred in tubes with thicknesses of 0.5 and 0.63 mm. Figure 8 shows parts with "type D" heat treatment. In these tests, all tubes except the thickest one failed during the process due to improper heat treatment method. Finally, in Fig. 9, the last tests which were performed on copper tubes without heat treatment are shown. All of these test samples burst during the process before the completion of bulging due to unsuitable microstructure and mechanical properties. It is obvious that the tubes with higher thicknesses and with more appropriate heat treatment were not prone to any defect during the hydroforming process.

Figure 10 shows the effect of the heat treatment method on maximum bulging height. The maximum bulging height occurs for the specimens with "type A" heat treatment. The tubes with this heat treatment method were able to complete bulging and calibration stages in all thicknesses. Samples with "type B" heat treatment also showed good formability. In higher thicknesses, they have completed the process without any defect. However, in samples with thickness of 0.5 mm, failure happened in the tube when reaching the bulging radius of 10.29 mm. As it was anticipated, shortening of heating duration and cooling the tubes in the water improved tube formability. In "type C" heat treatment, samples with thicknesses of 0.5 and 0.63 mm all failed before completion of bulging. In "type D" heat treatment, samples

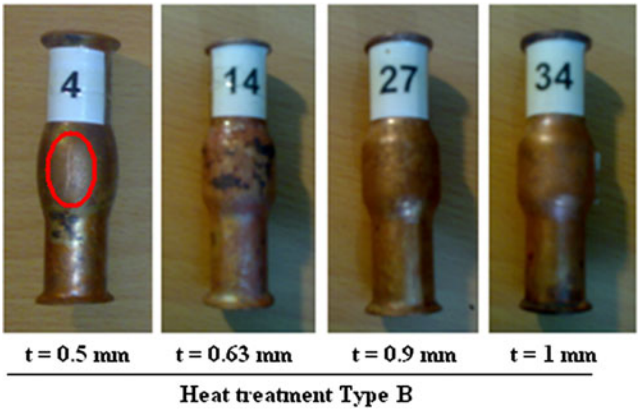


Fig. 6 Hydroformed copper tubes of different thicknesses with "type B" heat treatment in experimental tests

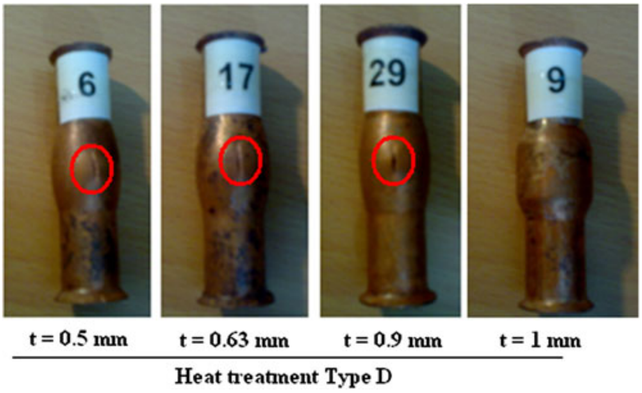


Fig. 8 Hydroformed copper tubes of different thicknesses with "type D" heat treatment in experimental tests

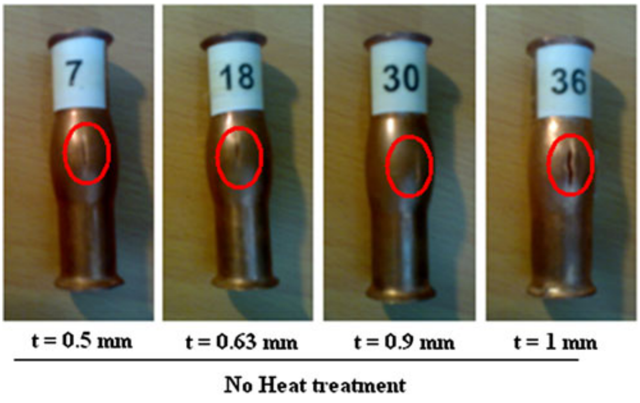


Fig. 9 Hydroformed copper tubes of different thicknesses without heat treatment in experimental tests

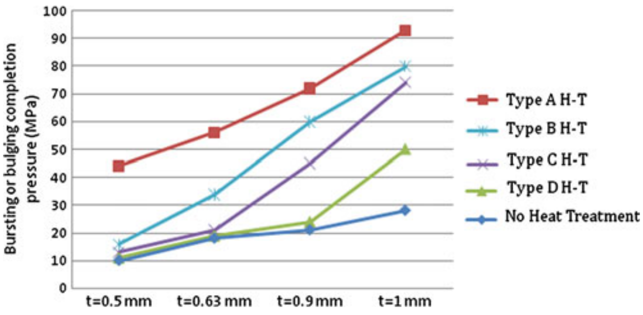


Fig. 11 Effect of heat treatment on final forming pressure or bursting pressure of copper tubes with different thicknesses in experimental tests

of all thicknesses, except the tube with 1 mm thickness, burst before completion of bulging. In samples without heat treatment, all the samples also burst before completion of the process. Therefore, “type A” heat treatment is more suitable for hydroforming of copper tubes. Furthermore, increase in tube thickness reduces the negative effect of improper grain size growth during heat treatment. The best evidence for this is that, for the tubes with a thickness of 0.5 mm, all the processes resulted in failure except for “type A” heat treatment, while for tubes with the thickness of 1 mm, only in the tubes without heat treatment which possess a nonhomogenous and stretched microstructure failure has occurred. In these tests, any increase in thickness caused an increase in bulging height. This shows that the effect of thickness in the tube hydroforming process is indispensible.

In Fig. 11, the effect of the heat treatment process on the required final forming pressure or bursting pressure is studied. In this diagram, tubes with “type A” heat treatment were able to bear the highest pressures for a successful forming process. In “type B” heat treatment, only the tubes with the thickness of 0.5 mm burst in low pressures and the other tubes deformed well. In “type C” and “type D” heat treatments that were subjected to longer duration of heating and cooling in the furnace, the formability was reduced and tubes failed especially those with less thickness. Tubes without heat treatment were not able to bear high pressures and failed after a small amount of bulging. This diagram also demonstrates that “type A” is the best heat treatment method among other types. In addition, any increase in thickness and heat treatment improvement provides the possibility of using wider pressure tolerances and a better forming process.

Another important result is that all failures due to improper heat treatment occurred in a pressure lower than yield pressure and after a small deformation. This can be related to low formability and critical thickness strain that are due to large grains and small number of grains in the thickness of these tubes. This could be a consequence of inadequate stress relieving and weak microstructure recovery.

In Fig. 12, the maximum thickness strain versus tube thicknesses in different heat treatment methods is plotted. Conical columns that present the thickness strain in nonheat-treated tubes show that an increase in tube thickness improves the capacity of thickness strain before bursting. In addition, comparison of thickness strains for tubes which have a thickness of 0.5 mm with different heat treatment methods shows that tubes with

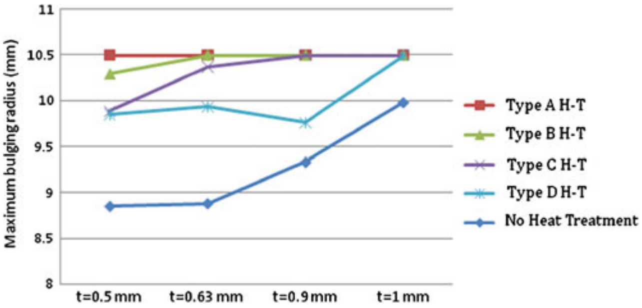


Fig. 10 Effect of heat treatment method on maximum bulging height of copper tubes with different thicknesses in experimental tests

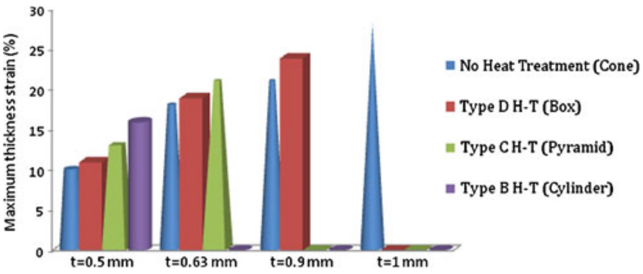
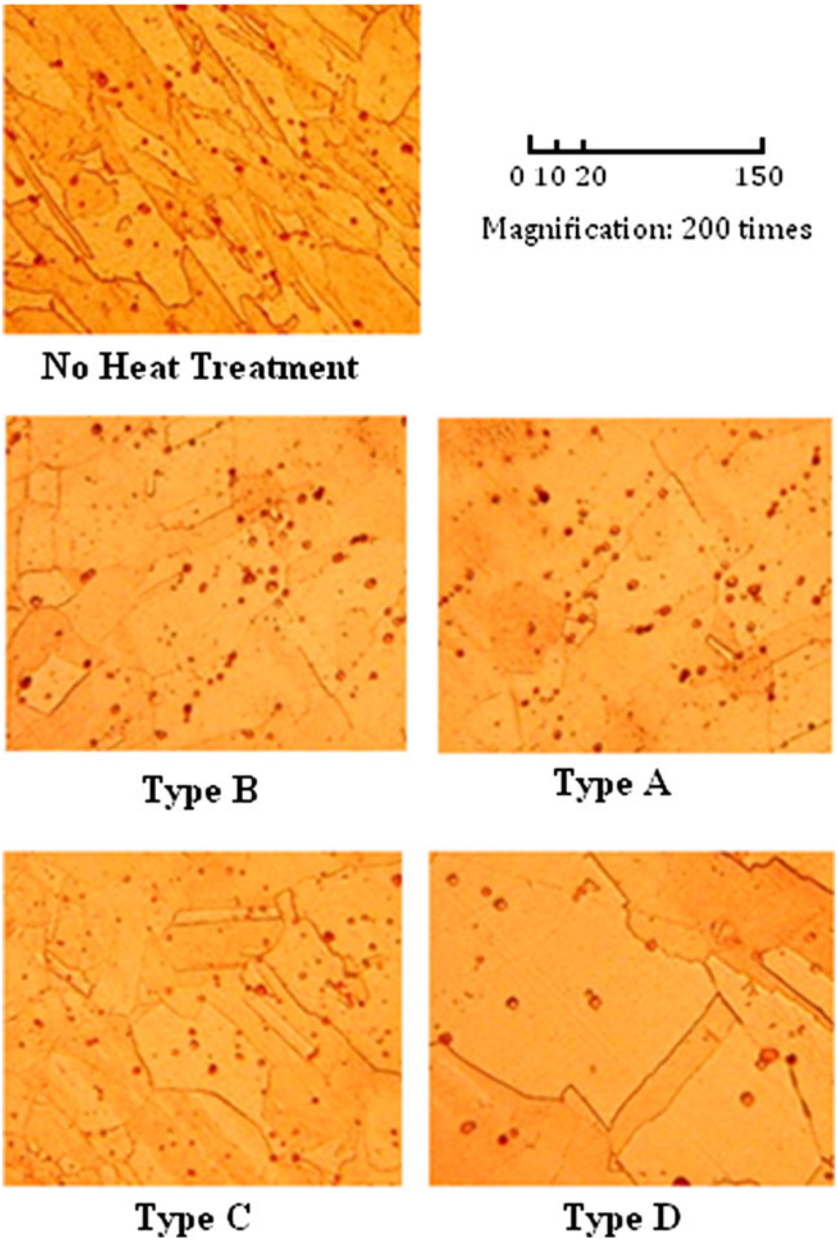


Fig. 12 Effect of different heat treatment methods on maximum thickness strain for copper tubes with different thicknesses in experimental tests

Fig. 13 Metallographic images from copper tubes with different heat treatments with magnification of 500 times and approximate dimension of grains



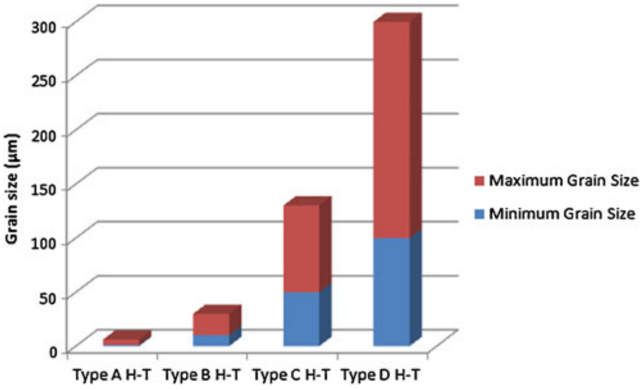


Fig. 14 Effect of heat treatment method on the copper tube grain size

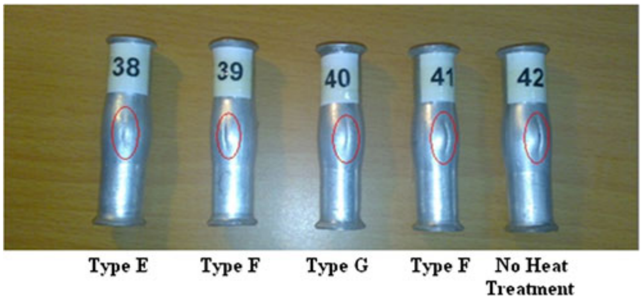


Fig. 15 Hydroformed aluminum tubes with different heat treatments in experimental tests

Table 4 Experimental tests and their results on aluminum tubes with different thicknesses and heat treatment methods

Part number	Initial tube thickness (mm)	Bursting pressure (MPa)	Minimum final thickness (mm)	Maximum thickness strain (%)	Maximum bulging radius (mm)	Heat treatment type
38	1.4	12	0.56	60	9.41	Type E
39	1.4	11	0.6	57	9.31	Type F
40	1.4	10	0.62	56	9.22	Type G
41	1.4	10	0.63	55	9.17	Type H
42	1.4	10	0.62	56	9.22	No heat treatment

"type A" heat treatment did not fail under inner pressure; moreover, the tubes with "type B" heat treatment could also deform to higher thickness strains before rupture.

Several metallographic tests were carried out to study the effect of various types of heat treatment methods on the microstructure of specimens. Various metallographic photos with the magnification factor of 500 were taken from the test samples which are shown in Fig. 13. In Fig. 13, the microstructure of copper tubes without heat treatment is composed of grains which were stretched in the direction of force exertion during the extrusion process. This structure revealed a low formability due to nonhomogeneity in microstructure, improper grain boundaries distribution, and presence of several obstacles in the dislocation path. However, after heat treatment by stress relieving and recrystallization, a new homogeneous and uniform microstructure was generated.

Figure 14 illustrates the effect of heat treatment method on the copper tube grain size. A grain average size of 100 to 200 μm has been identified for "type C" and "type D", which means that, in the thickness of 0.5 to 1 mm of the tubes, only five grains would exist. Therefore, a high degree of rigidity is expected through the thickness and a decrease in formability of the tubes. But in the tubes with "type A" and "type B" heat treatments, fine grains and homogenous microstructure were developed and demonstrated a high strength and a well-accepted formability. These fine grains are produced as a result of water quenching.

The other part of the experimental tests was performed on aluminum tubes which had a thickness of 1.4 mm and an outer diameter of 15.87 mm (Fig. 15). In these tests, tube hydroforming processes were carried out on aluminum tubes with four different kinds of heat treatment and the nonheat-treated tubes until failure or complete die filling occurred, as shown in Table 4. As Fig. 18 shows the samples produced in the tests, all of the aluminum samples burst during the process, which bears two important results. First, the tubes burst when passing the elastic section and with a small deformation. Bursting occurred in the opposite side of the curvature of the tubes before sample preparation. Aluminum stiffness grows fast due to cold work exertion and it might be the reason for these failures. Heat treatment also did not improve aluminum formability that much; this can be related to the presence of impurities and hard phases in aluminum composition that prevented dislocation displacements.

Figure 16 demonstrates the influence of heat treatment methods on maximum bulging radius of aluminum tubes. By reducing the heating duration, increasing its temperature, and cooling them in water, it is possible to reach larger bulging radii. However, it was not possible to complete the bulging process in any of the aluminum samples.

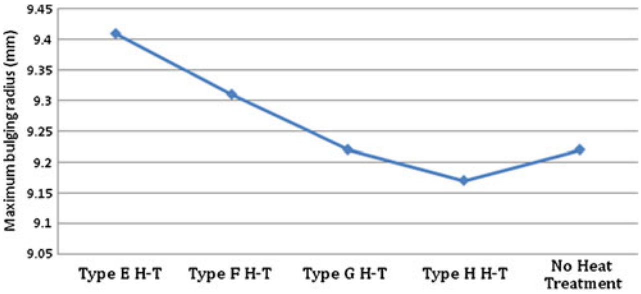


Fig. 16 Effect of heat treatment methods on maximum bulging radius of aluminum tubes in experimental tests

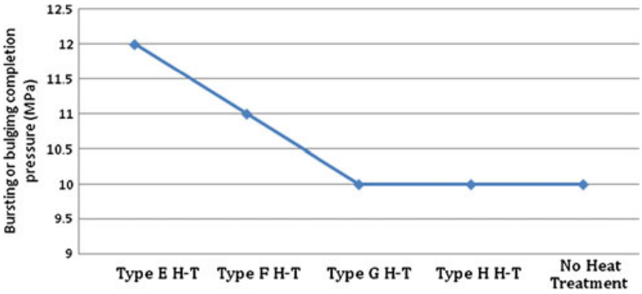


Fig. 17 Effect of heat treatment methods on final forming pressure or bursting pressure of aluminum tubes in experimental tests

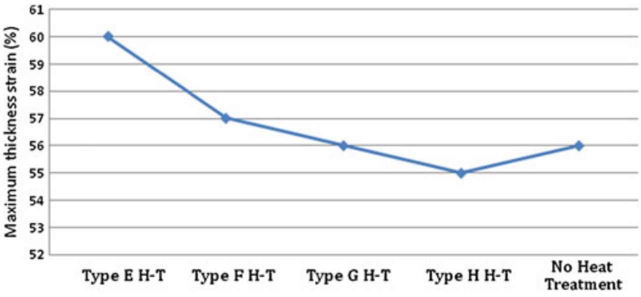


Fig. 18 Effect of heat treatment method on maximum thickness strain of aluminum tubes in experimental tests

Figure 17 shows the effect of heat treatment methods on final pressure in hydroforming of aluminum tubes as well. Tubes with “type E” heat treatment experienced higher pressures during the process; therefore, this was chosen as the best heat treatment for these materials. As can be inferred, heat-treated tubes which were cooled in the furnace were able to bear lower pressures than the ones which were cooled in water. In these tubes, no stress relief was performed and grain growth also worsened the forming conditions. A similar inference can be viewed in the investigation of the effect of heat treatment method on maximum thickness strain in Fig. 18. The “type E” and “type F” heat treatments show a better performance, i.e., after stress relieving and recrystallization, letting the grains remain fine and improving the formability of the aluminum tubes. Therefore, proper heating temperature, duration, and cooling of aluminum tubes in water improve the formability of the tubes.

After the determination of appropriate microstructure and heat treatment for copper and aluminum tubes, tensile tests were conducted on the tube materials to obtain mechanical properties. In order to perform these tests, samples with the length of 300 mm were prepared according to the ASTM E8-04 standard. A set of standard mandrels were made and put at the two ends of the tubes, and then tensile tests were performed. Stress–strain diagrams were obtained for copper tubes with “type A” heat treatment and aluminum tubes with “type E” heat treatment, as illustrated in Figs. 19 and 20. In these figures, a logarithmic relationship between true stress and strain has been approximated with the aid of linear regression where *y* refers to logarithmic true stress and *x* refers to logarithmic true strain. The coefficient of determination R^2 was also reported for both diagrams. The mechanical properties of these materials were also obtained from these diagrams and are presented in Tables 5 and 6. By comparing the strength coefficients and strain hardening exponents of these two materials which are demonstrated in Fig. 21, it can be understood that these values are much higher in copper in comparison with aluminum. As a result, the more appropriate formability and higher capacity of tolerating strains and forming pressures of the copper tubes in the tube hydroforming process can be consequences of

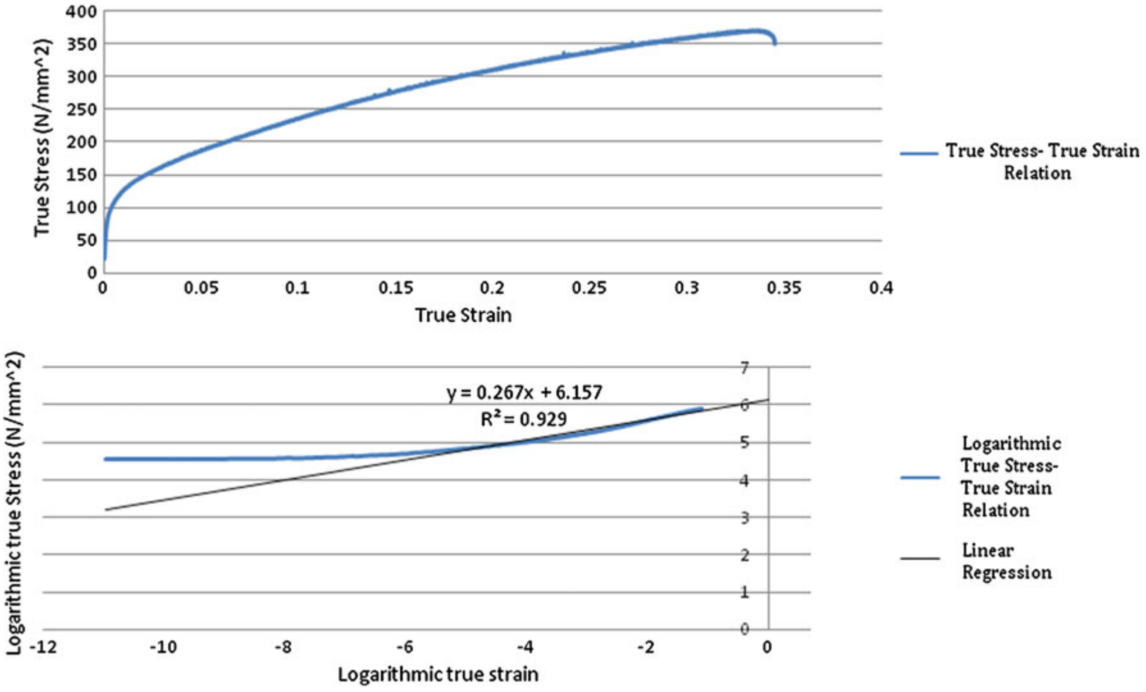


Fig. 19 Stress–strain diagram in normal and logarithmic scales for copper ASTM C11000 driven from tensile tests

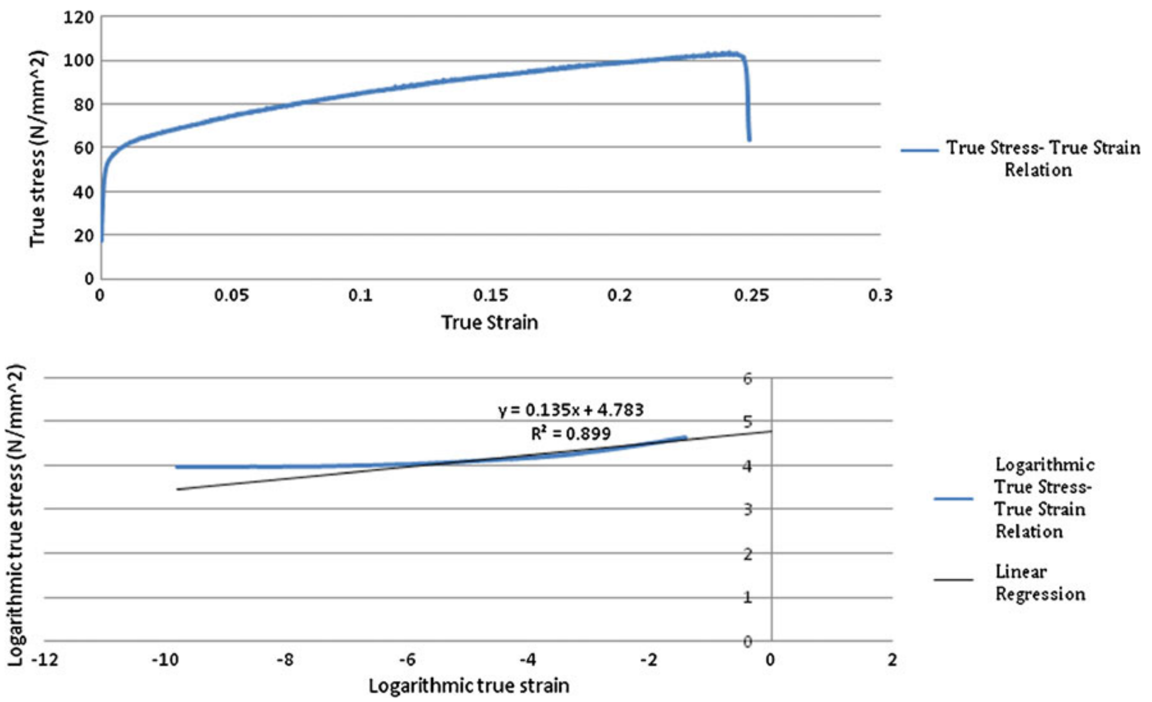


Fig. 20 Stress–strain diagram in normal and logarithmic scales for aluminum ASTM AA1050 driven from tensile tests

higher strength coefficient and strain hardening exponent of the copper.

As another research on this subject, strength coefficients and strain hardening exponents of copper and aluminum tubes with different heat treatment methods derived from tensile tests were compared. As can be observed in Fig. 22, copper tubes with "type A" heat treatment demonstrate higher *K* and *n* values accompanied with better formability, and with a reduction in these two values, a weaker performance is seen in the hydroforming tests. Experiments on aluminum tubes in Fig. 23 show the same result. Tubes with "type E" heat treatment have higher strength coefficients, strain hardening exponents, and better formability compared to aluminum tubes with improper heat treatment and microstructure. Therefore, these two parameters can be the main factors for the selection of the proper material and heat treatment type for the tube hydroforming process.

Table 5 Mechanical properties for copper ASTM C11000

Yield stress, σ_y (MPa)	94.5
Ultimate tensile strength, σ_{UTS} (MPa)	370
Ultimate tensile friction strain, ε (%)	31
Coefficient, μ	0.36
Hardness (HV)	65
Elasticity modulus, E (GPa)	115
Density, ρ (g/cm^3)	8.9
Poisson's ratio, v	0.32
Strength coefficient, K (MPa)	472
Strain hardening coefficient, n	0.267
Tube initial thickness, t_0 (mm)	Variant
Tube initial diameter, d_0 (mm)	15.87

6 Conclusion

The effect of tube material, microstructure, and heat treatment on process responses of tube hydroforming has been studied in this paper. Based on the findings, it has been concluded that:

- The appropriate heat treatment method for copper tubes with the material standard of ASTM C11000 and the purity of 99.9 % would be heating to the temperature of

Table 6 Mechanical properties for aluminum ASTM AA 1050

Yield Stress, σ_y (MPα)	54	Density, ρ (g/cm3)	2.7
Ultimate Tensile Strength, σ_{UTS} (MPα)	105	Poisson's Ratio, υ	0.3
Ultimate Tensile strain, ε (%)	28	Strength Coefficient, K (MPα)	119.5
Friction Coefficient, μ	0.4	Strain hardening Coefficient, n	0.135
Hardness (HV)	52	Tube Initial Thickness, t_0 (mm)	1.4
Elasticity Modulus, E (GPα)	69	Tube initial diameter, d_0 (mm)	15.87

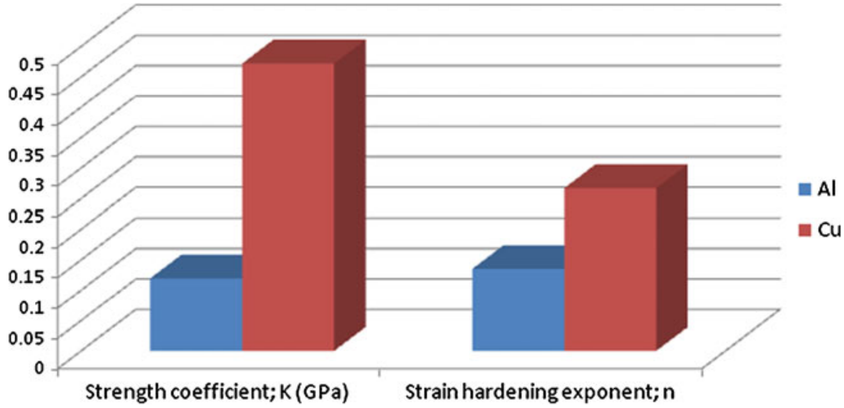


Fig. 21 Comparison of strength coefficients and strain hardening exponents of the applied aluminum and copper tubes

450 °C for 15 min and then cooling in water. A similar heat treatment to the temperature of 350 °C is also suitable for aluminum tubes that have the material standard of ASTM AA1050 and the purity of 99.5 %.

- Using this heat treatment has resulted in a homogenous microstructure and reduces grain size up to 10 times. This fine and homogenous microstructure demonstrates higher mechanical strength and an increase in material formability.
- Using the appropriate heat treatment can increase maximum bulging height up to 16 % in a copper tube with 0.5 mm thickness, whereas this increase is lower for thicker tubes (about 5 %), which shows that improper heat treatment has less undesired effects on tubes with higher thickness.
- The maximum pressure that a tube can endure in the hydroforming process rises by means of a better heat treatment. It also causes thickness strains to promote up to 40 % for a copper tube with the thickness of 0.5 mm. Moreover, any increase in thickness reduces the undesirable effect of heat treatment and it would be possible to attain higher inner pressure and thickness strains.

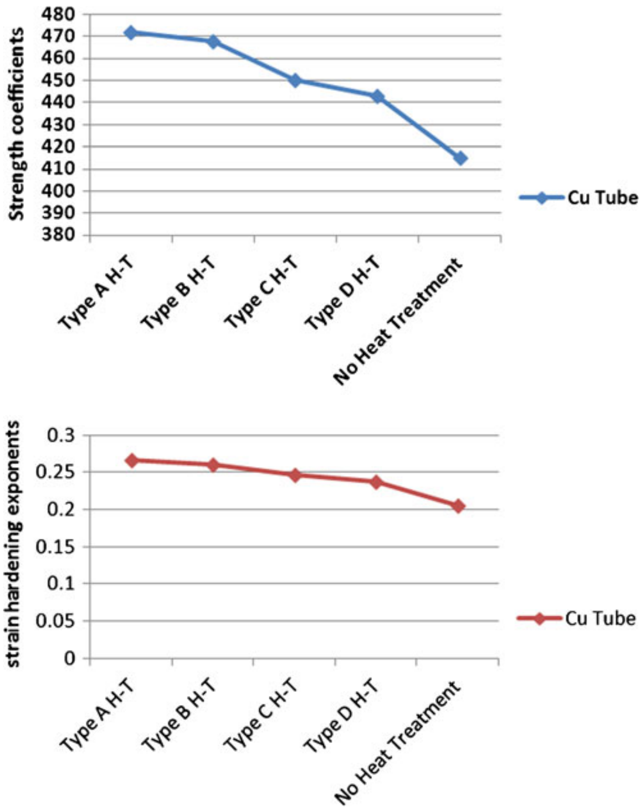


Fig. 22 Strength coefficients and strain hardening exponents of copper tubes with different heat treatment methods

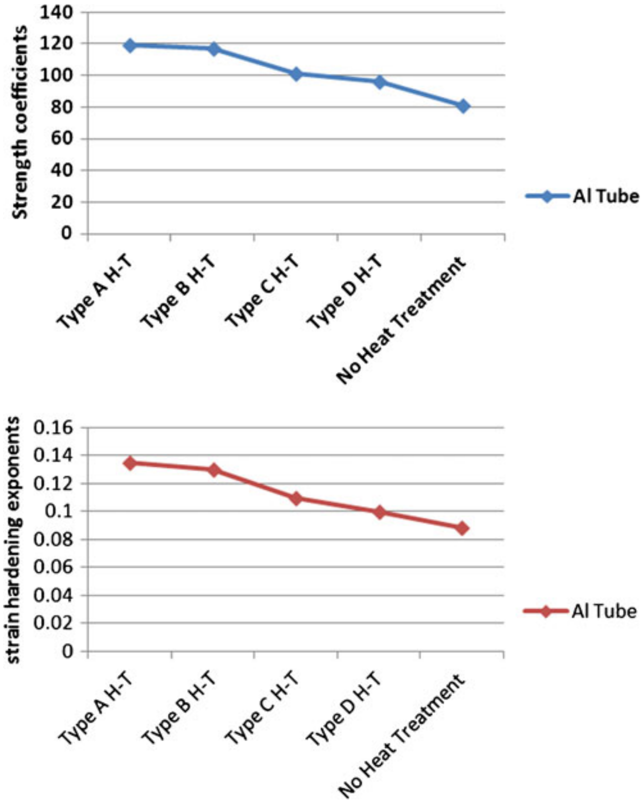


Fig. 23 Strength coefficients and strain hardening exponents of aluminum tubes with different heat treatment methods

- Higher strain hardening exponent and strength coefficient have a positive effect on the formability of materials in the tube hydroforming process. The better performance of copper in this process supports this hypothesis; therefore, these two parameters can be used for the selection of proper materials for the tube hydroforming process. On the other hand, using a heat treatment type which increases these two parameters in a material could enhance the material's performance in the hydroforming process.

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