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Investigation of AL/CU Bimetallic Tube Cladding Process by Severe Plastic Deformation

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Tube cladding; Ballizing; severe plastic deformation; FEM; Cu/Al bimetallic tube

Abstract
A new cladding process is proposed and implemented on a bimetallic tube of copper and aluminum. Obtaining a good mechanical bond between the tube's layers using simple setup components with low required process force and without using heating are the most distinguishing feature of this study. The objective of this paper is to study the effect of using three different spherical tipped punch diameters (21 mm, 21.6 mm, and 22 mm) on the cladding process. A spherical punch with a slightly enlarged spherical tip was pressed into the clad tube. To study the dynamical analysis of the developed process, an FE model was developed using ANSYS workbench®. The bonding of an AL6082T6 Aluminum tube (as the clad tube) to a pure copper tube (as the base tube) was studied. FE analysis results showed that increasing ball tipped punch diameter leads to an increase in the required process force, the deformation magnitude, the equivalent plastic strain, the maximum principal stress, and the maximum principal elastic strain values. The required process force was measured experimentally and by FE simulation for the three different ball tipped punch diameters. The average values of the FE process forces were found to be 21 KN, 39 KN and 48 KN respectively for the mentioned diameters, while experimentally the average forces values were found to be 13.3 KN, 33 KN and 39 KN for the mentioned diameters, respectively. A 10 KN force was required to dismantle the bimetallic tube layers using shear punch test.

1. Introduction

Nowadays, the demand for bimetallic tubes is increasingly growing. Bimetallic tubes provide a good blend of strength, corrosion resistance, heat resistance, electrical

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conductivity, high crack and wear resistance and other properties as well. Moreover, these tubes have low production costs, and possess a good weldability [1][2]. Several techniques have been developed for bimetallic tube cladding including sinking [3], spin bonding[4], stagger spinning[5], severe plastic deformation[6]and extrusion [7]. In the cladding terminology, the inner tube is called clad tube, and the outer tube the base tube. Materials used for the base tube are commonly copper, stainless steel, titanium and bronze. Those used for the clad tube are mostly carbon steel, aluminum and titanium.

AL/CU tubes are of the most common bimetallic tubes available today [3][8]. The structure of these bimetallic tubes consists of a copper base tube and an aluminum clad tube. They have many applications in nuclear engineering [5], petroleum [9], chemical and medical, food, construction, fire fighting and other fields [10]. There are commonly used in the production and transportation of oil and gas [5]. They are also employed in fabrication of structural components [5], heat exchangers [7], and refregeration [11]. So far, several methods have been proposed for fabrication of bimetallic tubes, Baghaei et al [1] propsed a mechanical tube cladding process which is claimed to be novel. A bimetallic tube consists of a stainless steel clad tube and a carbon steel base tube were produced. A shear – punch test and an optical microscope (OM) test was excuted to investigate the bonding force and the microstructre of the bonding interface respectivly. A micro-hardness test was also performed. The effect of punch diameter, nose fillet radius and punch cladding tube friction on the process was evaluated by finite element analysis.

Experimental results showed excellent bonding between tubes stronger compared to conventional thermo-haydrulic cladding. However, the used punch lacks the self- centering capability which may cause concentric deviations and faulty production. Shirzad et al.[12] employed the method of Parallel Tubular Channel Angular Pressing Process (PTCAP) to fabricate an AL/CU bimetallic tube. Effects of die angle, friction coefficient, displacement of the inner and outer layers, punch speed , and deformation ratio have been investigated. When applying Ultrasonic Vibrations on the punch it was found that increasing vibration amplitudes has a good effect on reducing force.

Li et al.[13] applied what is claimed to be a novel friction-based welding technology for the production of bimetallic tube. Microstructure evolution, bonding mechanism and mechanical properties of Al/Cu bimetallic tube have been investigated. At the reaction layer maximum hardness value was detected because of intermetallic compounds (IMC) formation. However, crack propagation paths were observed at high rotational speeds starting at 950 rpm. Moreover, the formation of intermediate transition and thick Al_2Cu layer diminishes the bonding strength of bimetallic tubes. Haghighat et al.[14] studied the bimetallic tube extrusion process analytically and numerically. Results showed good agreement between analytical and numerical outcomes. It was found that the extrusion pressure is decreased by about 20% through die rotation.

Recently, burnishing became a familiar finishing processs. several attempts have been devoted towards the utilization of ballizing technique for burnishing of internal cylinderical surface [15–18]. Fattouh[15] has carried out an experimental work to investigate the ballizing process. An experimental relationship has been developed to correlate process parameters with the maximum ballizing force. He reports that the interference value is a critical factor influencing the functional properties of the ballizing surface namely, surface finish, roundness, final diameter, and microhardness. However, lack of lubrication during the ballizing process could cause ball wear or low work piece surface finishing. Islam et al.[17] Proved that the plastic deformation in the ballizing process produces a smooth surface with favourable mechanical properties and negative residual stresses. However, lack of lubrication during the process could decrease the surface finishing quality and there is no

FE modelling for the process. Case hardening of the punch and die can be employed for increasing the surface hardness and in turn enhancing the cladding process[19][20][21].
In the present work, a cladding process was applied between two tubes, Aluminium and copper tubes are used, using spherical punch with three different spherical tip diameters. ANSYS FE simulation method was employed to investigate the joining process and the results were compared with those which obtained from the experimental study.

2. Experimental work

Fig.1 shows the setup components, (copper tube, aluminum tube, punch, and container), the inner tube and outer tube were fitted together before the cladding process and all of them were fitted into the container. All of component's dimensions as the same of FE model dimensions. A 150-ton hydraulic press machine (Tinius Olsen WILLOW GROVE, PA, U.S.A.) was used to execute the cladding process and recorded the required process force for the 21 mm, 21.6 mm and 22 mm ball punch tipped diameters as shown in Fig. 2. The setup components were fixed between upper and lower jaws of the machine and then an axial feed was given for the punch to force it laterally pressing the tubes into each other. During the manufacturing process a solid and oil lubricant of (MoS_2) were used to eliminate friction and protect surfaces from wear. Before performing this operation, it is very important to prepare surfaces, which will become the metal-to-metal interface. Punch and tubes were grinded using silicon carbide papers grit size from 300 to 4000. All surfaces must be cleaned by acetone [1] before cladding process, after that the ball tipped punch and inner layer of the clade tube should be lubricated using a (MoS_2) oil.
A shear punch test by using the setup shown in Fig.3 was performed by the 150-ton hydraulic press as shown in Fig. 4 at room temperature to ensure the bonding between the two layers of the bimetallic tube.

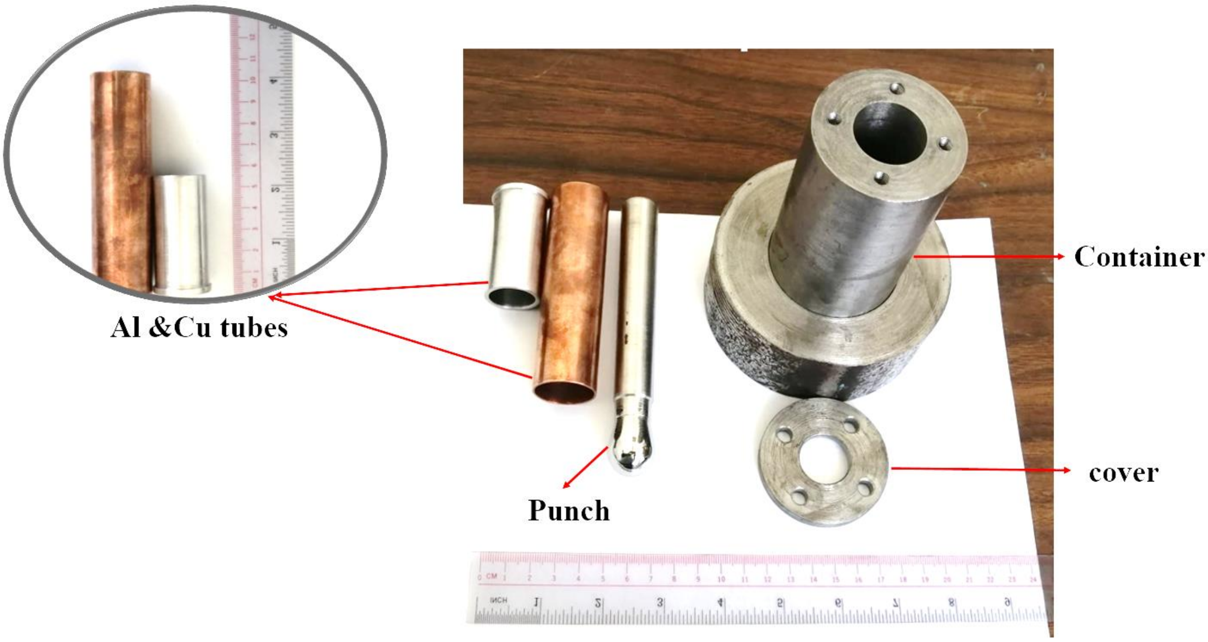

Fig. 1: Experiment setup components.

Fig. 2: Photo for experimental setup fixed on hydrulic press machine.

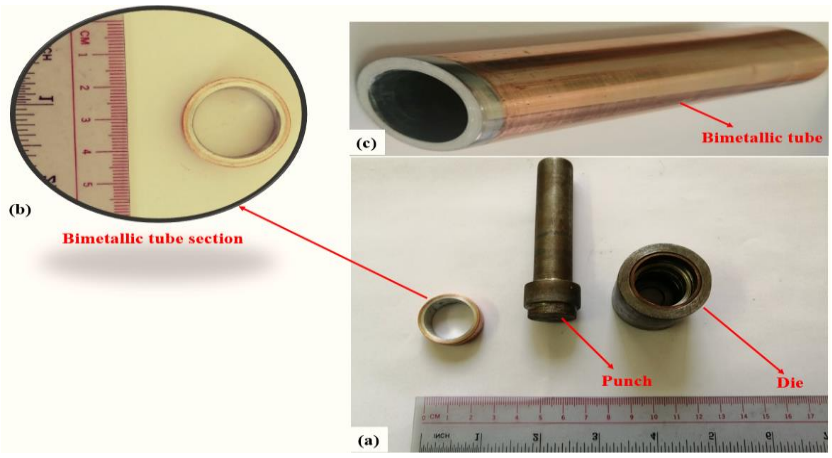

Fig. 3: (a) Setup components of shear punch test, (b) cross section of cladded tube, (c) Bimetallic tube after forming.

Fig. 4: Photo for experimental shear punch test setup fixed on hydraulic press machine.

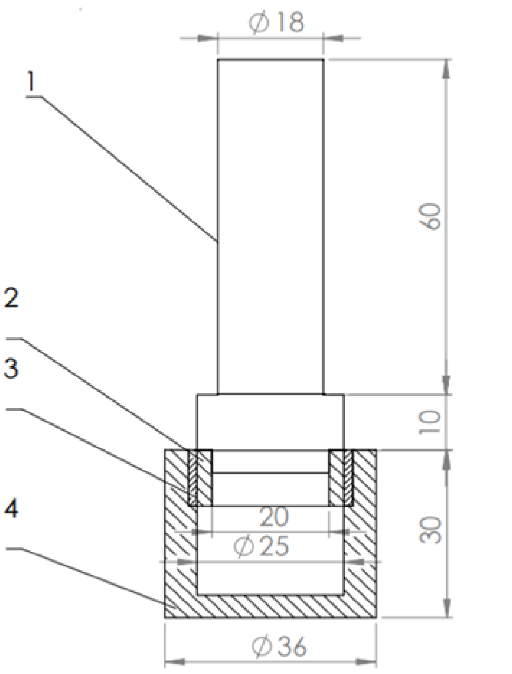

Fig. 5: Shear punch test assembly drawing.

3. Finite element (FE) model

In this research the Explicit Dynamic method was used to study the effect of changing ball diameter of the ball tipped punch on the deformation, required force and equivalent plastic strain in the cladding process. The geometry of the model consists of four components: punch, outer and inner tubes and container. Fig. 6 shows a three- dimentional FE model for the setup. Both the container and the punch were modeled as rigid parts. The copper and aluminum tubes were set as flexible parts. The model was set as temperature dependent. A specific heat of 0.890 (J/g ˚c)[22], and 0.385 (J/g ˚c) [22] were used for aluminum and copper, respectively. A frictional coefficient value of 0.05 was used between all sliding surfaces,(punch and aluminium tube, copper tube and aluminum tube, copper tube and container) [23][24][1].
Table 1 and Table 2 are used to define the mechanical properties of the used copper and aluminum tubes. Table 3 and Table 4 are used to define the chemical compositions of the same tubes. The FE model consists of 12920 elements for outer tube, 18057 elements for aluminum tube. 2 mm element size was used for aluminum and 2 mm for copper tube. Tetrahedrons method was used for meshing elements. The axial velocity value for the punch was 0.83 mm/s, the total punch stroke was 100 mm. Container was set as a fixed support. The simulation was performed at room temperature (approximately 20˚C). No heat was added for the model to promote bonding. Three different ball tipped punch diameters 21mm, 21.6mm, 22mm were used in this model. An investigation has been done to detect the values of the deformation, required force in the process, the equivalent plastic strain and the maximum principal stress and maximum principal elastic strain. The aluminum tube (ø25 mm O.D. × ø20 mm I.D.) is 6082T6 and the copper tube (ø28 mm O.D.× ø25 mm I.D.) is of pure copper. The length of copper tube is 100 mm and 50 mm for the aluminum one the aluminum tube has a shoulder of 3mm length, and 1mm thickness. The container is made from stainless steel 316 to support both tubes.

Table 1: Mechanical properties of AL 6082-T6. [25]

Material	Yield strength (MPa)	Elasticity modulus (GPa)	Poisson's ratio	Density [kg/m^3]
Aluminum alloy (6082T6)	270	72	0.33	2700

Table 2: Mechanical properties of pure copper. [26]

Material	Young's modulus(E) (GPa)	Poisson's ratio	Density [kg/m^3]	Strain hardening exponent (n)	Strength coefficient (K) (MPa)
Pure Copper	120	0.34	8900	0.31	359

Table 3: Aluminum alloy (6082-T6) chemical composition. [27]

Material	Al	Cu	Si	Fe	Mn	Mg	Zn_2	Cr	Ca	Pb	Ti_2	Sn_2
Aluminum alloy (6082T6)	96.49	0.099	1.281	0.708	0.523	0.708	0.0615	0.0141	0.0011	0.0034	0.0108	0.0173

Table 4: Pure copper chemical composition. [28]

Material	Cu	Sn	Pb	Zn	Fe
Pure Copper	99.28	0.07	0.03	0.015	0.06

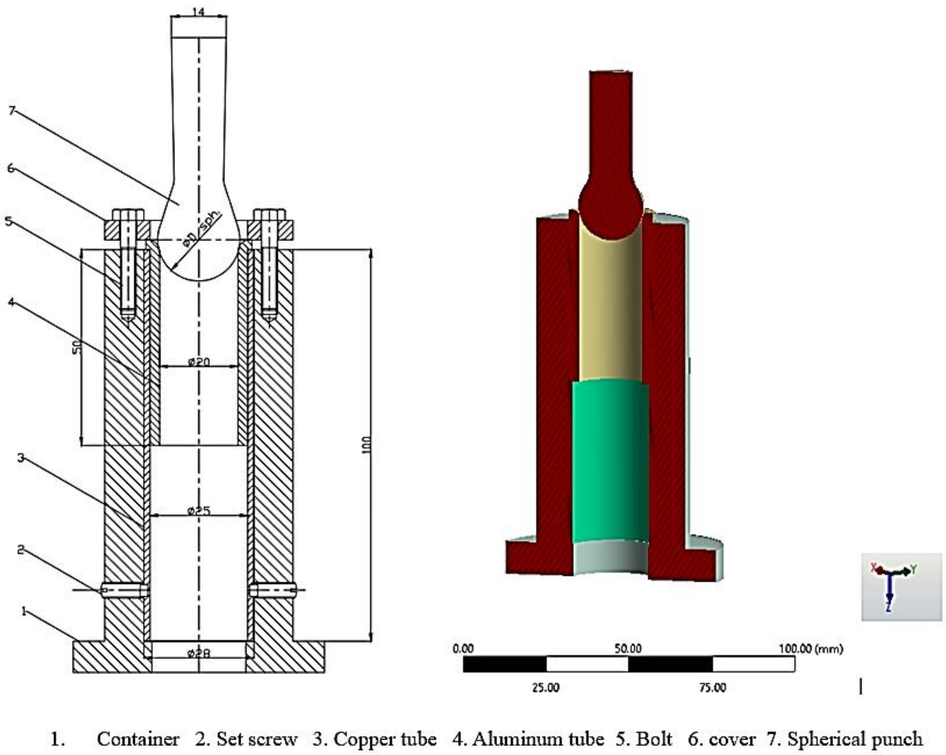

Fig. 6: Setup assembly drawing for the process, (punch have three different diameters D = 21 mm, 21.6mm and 22mm).

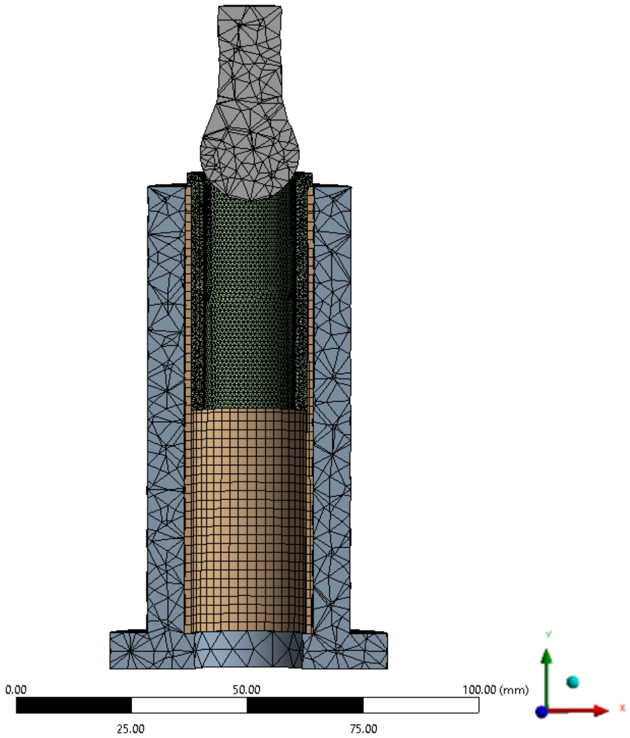

Fig. 7: FEM ANSYS Model for the cladding process setup.

3. Results & Discussion

In this part, the effect of changing ball tipped punch diameter on process energy requirements and the interface bonding between the base and the cladded tube materials for the cladding process was explored, experimentally and FE simulation. Results are summarized in Table 6 and Table 7.

3.1 Load measurement comparison between FE and experimental model

By using the different sizes of the ball tipped punch (21 mm, 21.6 mm, and 22 mm) the required force for the cladding process was measured experimentally and then it was compared to that was obtained from the FE model, the results were summarized in Table 5.
As shown from the previous results Figs. 8-10 and Table 5, there are a good agreement between the FE and experimental results. The average values of the punching forces for the studied cladding process are 21 kN, 39 kN, and 48 kN from the FE simulation using 21 mm, 21.6 mm, and 22 mm ball-tipped punch diameters, respectively. While, from the experimental study, the average values of the punching forces are 13.3 kN, 33 kN, and 39 kN using 21 mm, 21.6 mm, and 22 mm ball-tipped punch diameters, respectively. The results showed that the required forming force was increased with the ball diameter of the ball tipped punch increasement due to the plastic deformation incidence.
As it is clear from the previous results, Figs. 8-10, the values of the experimental forces are lower than those of the FE at the same ball-tipped punch diameter. This can be interpreted due to the lubricant used during the experiment which reduced the friction between the punch and the tubes. Following the cladding process the shear test results presented in Fig. 11 were derived from the disassembly process between the two tubes. It was revealed from the shear punch test that the average value of the force required to move the pipe is equal to

10 KN for the cladded tubes. This gives a good indication on the strong bonding between the cladded tubes.

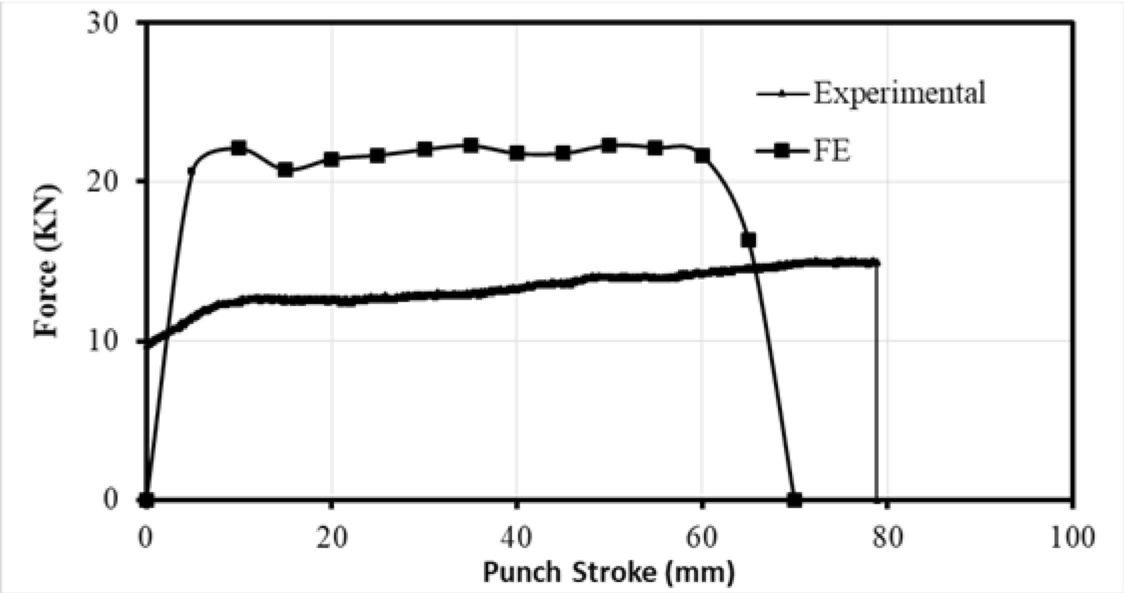

Fig. 8: Comparison between the experimental and the FE required process force for the 21 mm ball tipped punch diameter.

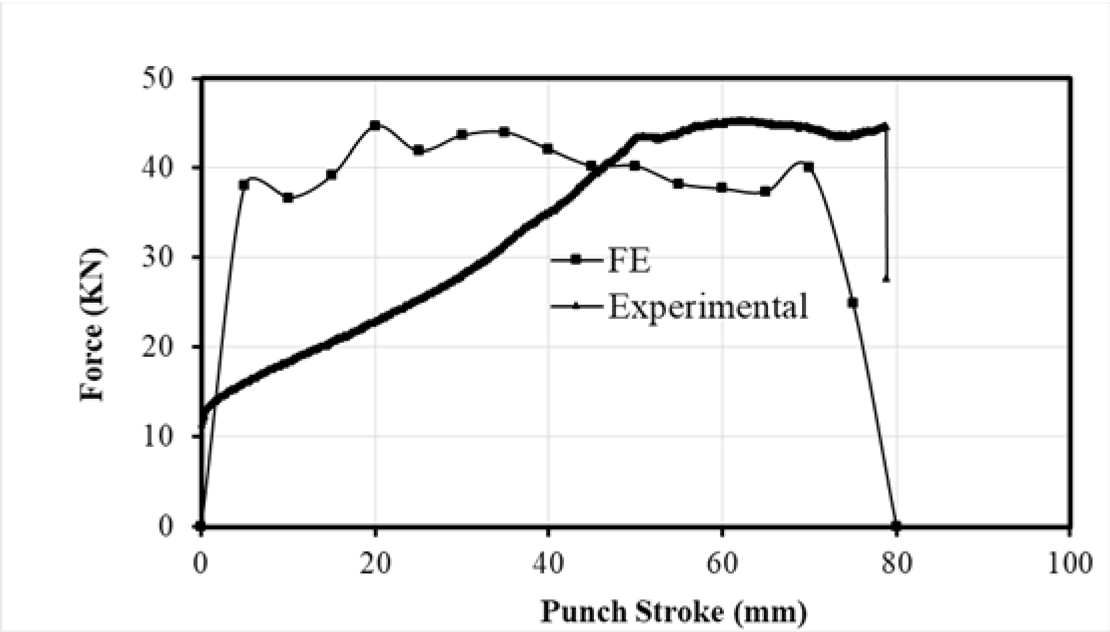

Fig. 9: Comparison between the experimental and the FE required process force for the 21.6 mm ball tipped punch diameter.

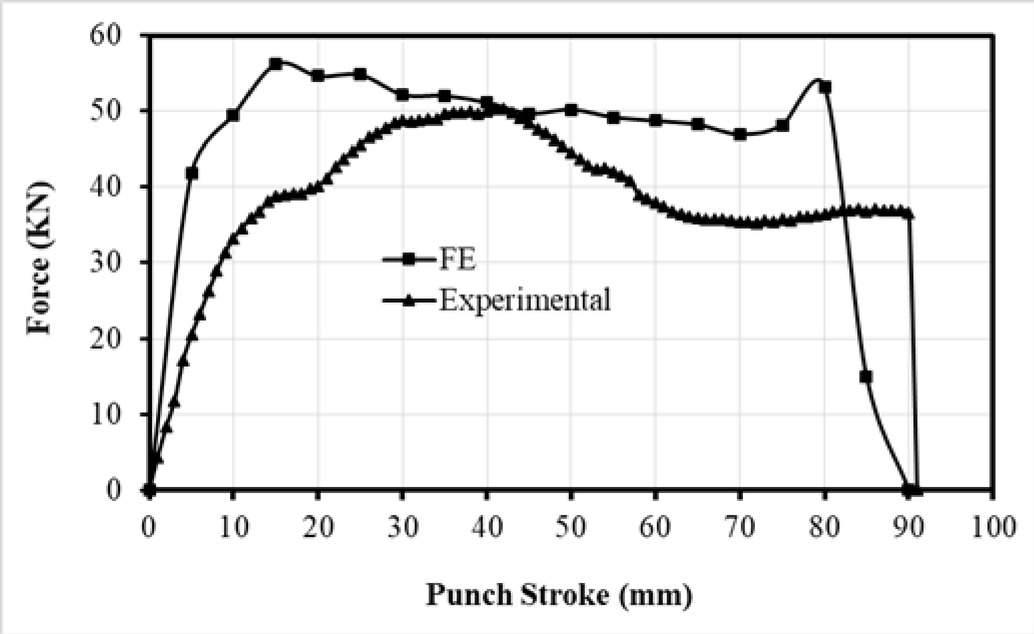

Fig. 10: Comparison between the experimental and the FE required process force for the 22 mm ball tipped punch diameter.

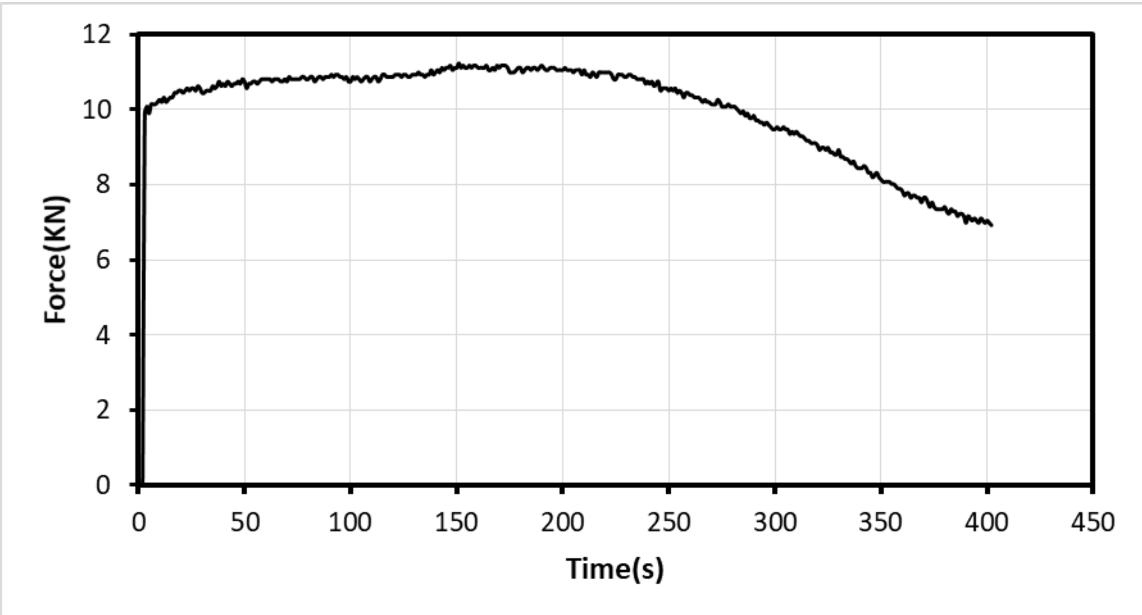

Fig. 11: Force vs. time for shear punch test.

Table 5: Comparison between FE and Experimental process force value.

Ball tipped punch diameter (mm)	FE Force (KN)	Experimental Force (KN)
21 mm	21	13.3
21.6 mm	39	33
22 mm	48	39

3.2 Deformation

Figs. 12-14 show the deformation values for the three different ball diameters of the ball-tipped punch: 21, 21.6, and 22 mms, respectively.

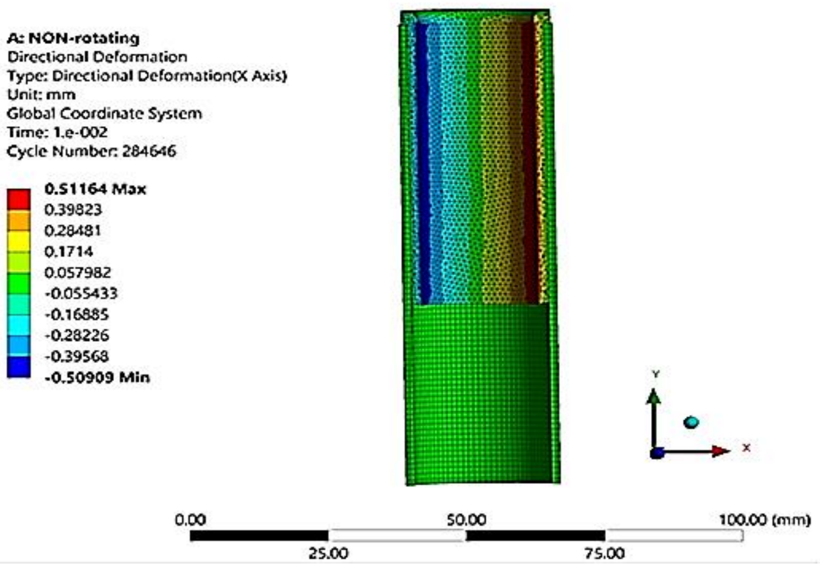

Fig. 12: Radial plastic deformation at the end of punch stroke, punch diameter = 21mm

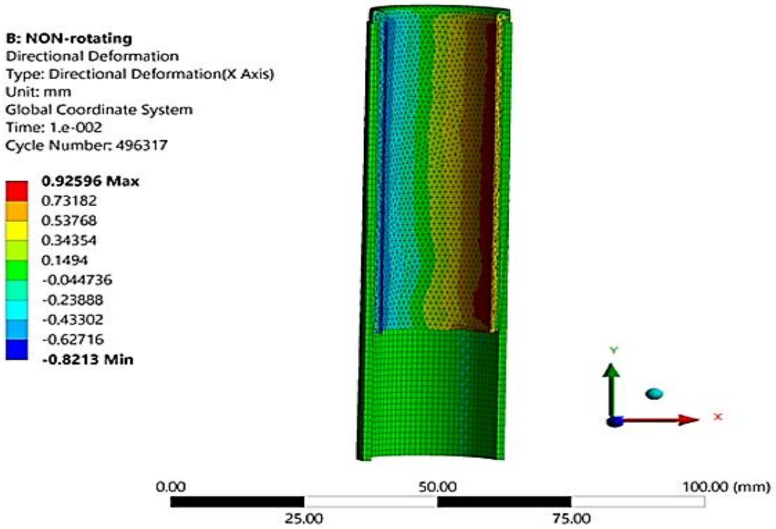

Fig. 13: Radial plastic deformation at the end of punch stroke, punch diameter = 21.6 mm.

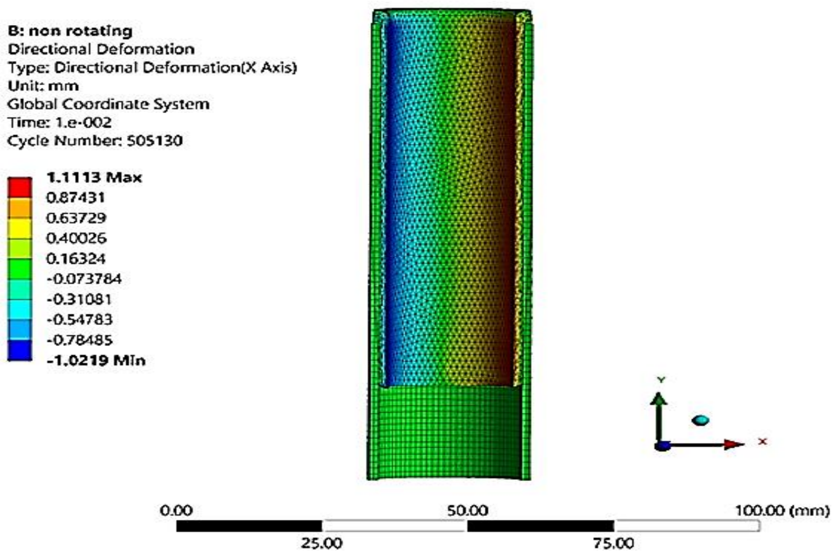

Fig. 14: Radial plastic deformation at the end of punch stroke, punch diameter = 22 mm.

Results show, in Figs. 12-14, that the radial plastic deformation was increased by increasing the ball tipped-punch diameter. The directional deformation values for the 21 mm, 21.6 mm and 22 mm ball-tipped punch diamters were 0.5 mm, 0.8 and 1 mm, respectively. During cladding process, material piled-up along the tube due to plastic flow. The plastic flow of material during cladding process contaied a displacement of tube material along radial and axial directions. The displacement of tube material along radial direction depended on the spherical-punch diameter. The piled-up material is influenced by the pressure and the work hardening property of material [29]. One of the most important benefits of the bimetallic tube forming with spherical-tipped punch is the low required force and the simplicity of the setup comparing with other techniques such as technique used by Matthew[23].

3.3 Equivalent Plastic Strain

Figs. 15 - 17, Showed the bimetallic tube plastic lateral strain for the three different ball tipped punch diameters 21 mm, 21.6 mm, 22 mm.

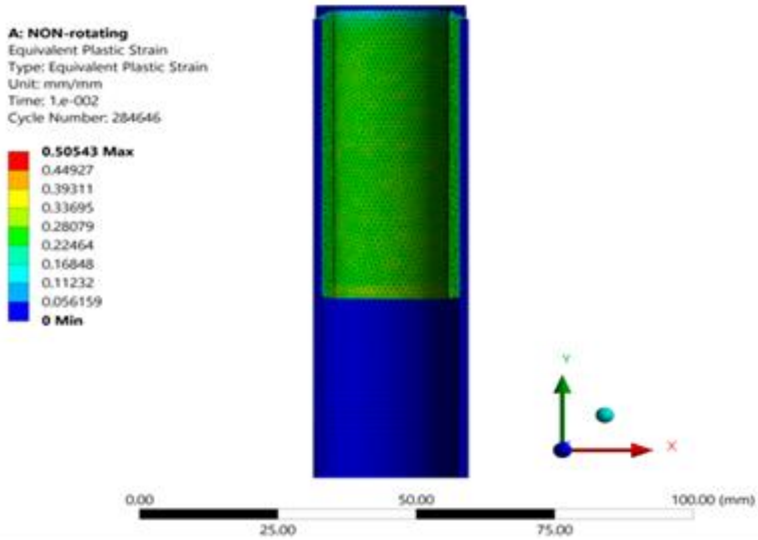

Fig. 15: Equivalent Plastic Strain vs. punch stroke with ball tipped punch diameter 21mm.

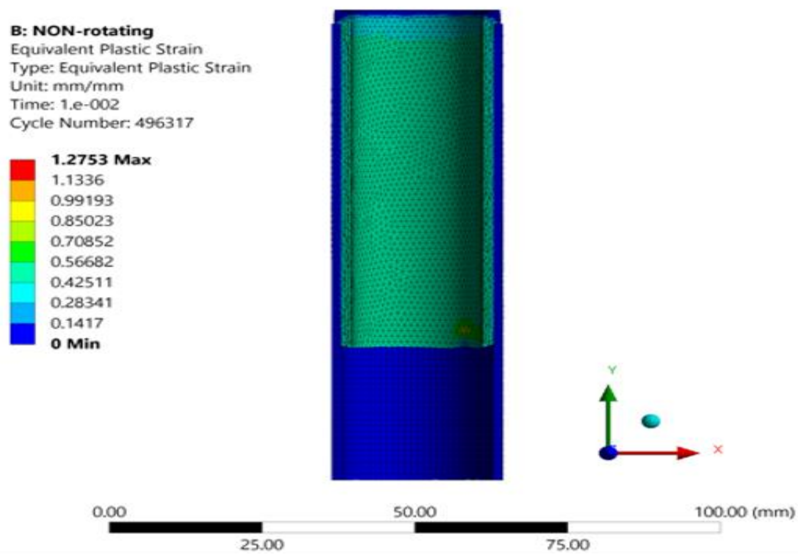

Fig. 16: Equivalent Plastic Strain vs. punch stroke with ball tipped punch diameter 21.6 mm.

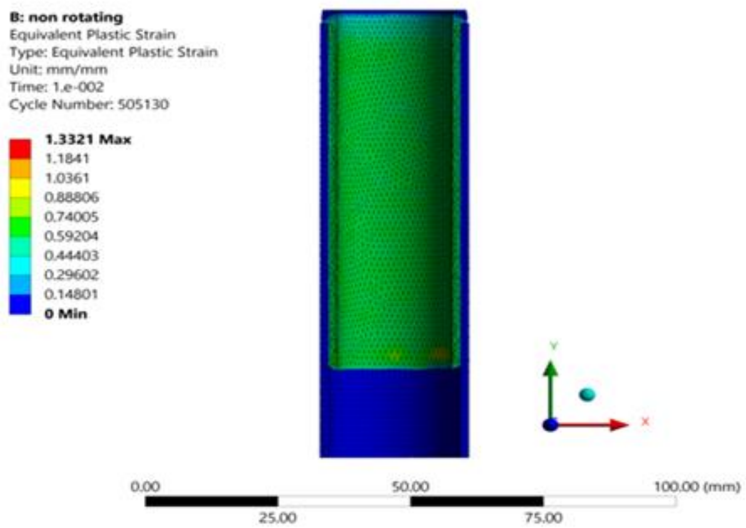

Fig. 17: Equivalent Plastic Strain vs. punch stroke with ball tipped punch diameter 22 mm.

As shown in Figs. 15- 17, the equivalent plastic strain in the lateral direction tends to increase as the ball diameter of the ball tipped punch increases. The equivalent plastic strain values at the process increased from (0.5 to 1.3) for the various the ball diameter of the ball tipped punch. The maximum value for deformation, force, and equivalent plastic strain for the process were summarized in Table 6.

Table 6: the maximum value for deformation, force and equivalent plastic strain for the process using FE.

Maximum deformation (mm)			Maximum force (KN)			Equivalent plastic strain		
Punch diameter (mm)			Punch diameter (mm)			Punch diameter (mm)		
21	21.6	22	21	21.6	22	21	21.6	22
0.5	0.8	1	21	39	48	0.5	1.2	1.3

3.4 Maximum principal stress and maximum principal elastic strain

Table 7: Values of maximum principal stress and maximum principal elastic strain for the two cases using the different ball tipped punch diameters, (21mm, 21.6mm, and 22mm). From Table 7 the results show that an increase in the ball-tipped punch diameter leads to an increase in the maximum principal stress and the maximum principal elastic strain.

Table 7: Values of maximum principal stress and maximum principal elastic strain.

Punch diameter (mm)	21	21.6	22
Max principal stress (MPa)	633	1070	1161
Max principal elastic strain	0.015	0.068	0.092

4. Conclusions

In this study a new method was used for producing bimetallic tube based on severe plastic deformation. A three ball-tipped punch diameters were used for detect the effect of changing the ball diameter of the ball-tipped punch on the process.

It was observed that an increase of the ball diameter of the ball tipped punch leads to an increase in the deformation magnitude, the Equivalent Plastic Strain, the required process force, the maximum principal stress, and the maximum principal elastic strain values. The experimental verification indicated a good agreement with the FE model process force. For the 21 mm, 21.6 mm and 22 mm ball-tipped punch's diameters, the FE process average values of forces were found to be 21 KN, 39KN and 48 KN respectively, while the experimental average of the required process forces were found to be 13.3 KN, 33 KN and 39 KN for the 21 mm 21.6 mm and 22 mm ball-tipped punch's diameters, respectively. A shear punch test indicated that the average value of the required force to disassemble the two cladded tubes is equal to 10 KN. Good bonding between the two materials was achived by applying this method.

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التحقق من عملية تجليد أنابيب مزدوجة الجدار من مواد النحاس والألومنيوم بواسطة التشكل البلاستيكي اللدن

الملخص العربي:

في هذا البحث تم اقتراح عملية تصنيع جديدة لتجليد الأنابيب حيث يتم من خلالها الضغط بواسطة مكبس ذو مقدمة كروية يتحرك بإزاحة معينة في الطبقة الداخلية للأنبوب ثنائي المعدن. تم عمل محاكاة للنموذج وتجارب عملية باستخدام ثلاثة أقطار مختلفة للمكبس (21 مم، 21.6 مم و22 مم) لدراسة تأثير زيادة قطر المكبس ذو المقدمه الكروية على تشوه الأنبوب المعدني وقوة التشكيل المتطلبة لإتمام العملية والانفعال البلاستيكي الناتج من العملية. لاستكشاف العملية تم انشاء نموذج محاكاة بالعناصر المحدودة باستخدام برنامج ANSYS workbench® بطريقة التحليل (EXPLICT DYNAMIC) حيث تم عمل محاكاة لعملية وصل أنبوب من الألومنيوم (6082T6) (كطبقة داخلية) بأنبوب من النحاس النقي (كطبقة خارجية).

عن طريق المحاكاة تم اكتشاف أنه مع زيادة قطر المكبس يزداد مقدار القوة المتطلبة لإجراء العملية وكذلك مقدار التشكل والانفعال. تم عمل تحقق عملي للعملية لقياس القوة اللازمة لإتمام العملية باستخدام مكبس ذو مقدمة كروية للثلاثة أقطار 21مم و21.6 مم و22مم وأظهرت الدراسة توافق جيد بين النتائج النظرية والعملية. حيث كان متوسط قيم القوة اللازمة لإتمام العملية نظريا تكافئ 21كيلو نيوتن و39كيلو نيوتن و48 كيلو نيوتن على التوالي لأقطار المكبس المذكورة، في حين أنه أظهرت الدراسة العملية أن متوسط قيم القوي المتطلبة لإتمام العملية تكافئ 13.3 كيلو نيوتن و33كيلونيوتن و39 كيلو نيوتن على التوالي لنفس أقطار المكبس المستخدمة.

كما تم عمل اختبار القص للعينة بعد التصنيع لاختبار قوة الالتصاق بين الأنبوبتين وأظهرت الدراسة أن متوسط قيمة القوة المطلوبة لفصل الانبوبتين 10 كيلو نيوتن. تتميز هذه العملية ببساطة التصميم، التكلفة المنخفضة، قوة التشكيل المنخفضة وعدم وجود تشوه في شكل الأنبوب الخارجي بعد إجراء العملية.