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# DEFORMATION LIMITS AND PRODUCT QUALITY IN ROTARY FORMING AND JOINING OF ALUMINUM TUBES

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## ABSTRACT

Tube forming and joining have now a lot of applications (e.g. mechanical, chemical, weaving, spinning and electronic industries). In the present work, forming and joining of commercial purity Aluminum (99.5%) tubes was investigated using a ball-ended tool on the lathe. Tests included tube end widening, tube end flanging, free (without mandrel) in-section widening, free throttling, and joining an Aluminum tube to a polymer plug. Results showed that in tube end widening, thickness distribution variation improved as the initial tube thickness increased. . In tube flanging, both the initial tube thickness and penetration distance proved to affect the success of the process and regularity of thickness. Joining of two dissimilar materials (polymer core plus Aluminum sheath) was performed successfully. A limit curve could be constructed to forecast the successful material and process variables (expressed by initial thickness and ball diameter) for specified materials, speed and feed in rotary forming. Application of such simple and inexpensive tooling to form and join Aluminum tubes is important, especially for small and medium industries. Altering the design of the tools may help to add a wide variety of applications. It was concluded that Rotary tube end widening on the lathe proved to be a quick and simple forming process. Ball diameter and tube thickness affected the success of the process. As ball diameter increases and tube thickness increases, In tube end widening and flanging, thickness distribution improved as the thickness increased. In flanging, as the thickness and the penetration distance increases, the flange diameter increases. In free section widening and throttling, both initial tube thickness and penetration distance affected the success of the process and regularity of thickness. Joining of two different materials (polymer core plus an Aluminum sheath) was performed successfully on the lathe by a ball shaped tool. Filling and thickness distribution were excellent.

***Keywords:*** Rotary forming, tube end widening, tube flanging, tube section throttling, joining of Aluminum tubes to a polymeric core

## l. An Introduction to tube forming and joining

Many processes can be used. Tube drawing involves reducing the cross section and wall thickness through a drawing die. Following the hot forming process, tubes are cold drawn using dies, plugs or mandrels to the required shape, size; from other hot forming methods include tube sinking. The tube, while passing through the die, shrinks in outer radius from the

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original radius to a final radius and the wall then thicken slightly. The final thickness of the tube depends on original diameter of the tube, the die diameter and friction between tube and die. A tapered plug is placed inside the tube. As the tube is drawn, the plug and the die act together to reduce both the outside/inside diameters of tube. Area reduction obtained was higher than that in tube sinking. Lower drawing load than fixed plug drawing. Long lengths of tubing are possible but tool design and lubrication can be very critical. Tube end widening is needed in applications such as fluid transmission pipelines. Typical techniques for producing such ends are casting, machining, forming by truncated conical plugs. Grover [1] illustrated a variety of tube forming operations including tube extrusion, tube rolling, spinning and tube stock bending, giving many examples of industrial applications. In his comprehensive guide about tube forming processes, Miller [2] explained the tube expansion, reduction, flaring, bending and grooving. Alvis and Martins [3] introduced new technologies in the forming and joining of tubes, emphasizing a series of post forming operations involving machining, crimping and welding. Compression bending was utilized for the joining of tubes to other tubes or to sheets.

Lihui et al. [4] reviewed special forming processes and associated research on light weight components based on sheet and tube materials. Ahmed et al [5] explained the occurrence of cracks and its beginning in the flange wall during the flaring process. It was suggested that work hardening during deformation encourages the possibility of initiation of wall cracks. Further deformation leads to local thinning and this continues until final splitting.

Rotary forming, in which the formed elements are rotated during forming, has many applications in industry. . Rotary forging and tube spinning could be an attractive one in producing flanges and hubs. Abdel-Rahman et a1. [6] reached widening ratios of 2.33using ball-shaped tools in rotary widening of Aluminum tubes. Some thinning was observed along the widened end. Mohamed et al. [7] obtained relatively high flanging ratios. Those were found to increase as initial tube thickness and initial tool advance increase. In the simplified analysis of circular sheels, Marciniak et a1. [8] took hole expansion, nosing and flaring as examples for their theory. In addition of getting sound products, the nature of flow in this process gives good geometrical and mechanical properties. Teng et al. [9] discussed the deformation behavior of thin-walled tube bending of an AA SA02 with internal pressure. Effect of the hydraulic pressure on section flatness, thickness variation and forming limits was discussed. Forming limits in the tube forming processes were discussed in many References. Yeh [10] developed an explicit analytical expression to compute the relation of the flaring ratio to the punch-stroke ratio in tube flanging with a conical die. The expression is useful in determining the forming limits in the flaring processes with and without friction.

Kalasangiani et al. [11] used different forming limit diagrams in their FE analysis to control the formability of 304L stainless steel sheets. They concluded that increased sheet thickness led to an increase in the level of the forming limit diagram. Generally, in tube forming processes, the failure modes can be divided into wrinkling and radial cracks. Wrinkling may occur in the free flange of the blank this instability of the blank is caused by the limited ability of the material to withstand tangential stresses wrinkling limits the maximum diameter reduction that can be attained with the blank as well as the minimum sheet thickness that can be used in spinning the potential for wrinkling increases with increasing blank diameter and decreasing sheet thickness the limit is reached when wrinkles cannot be flattened in subsequent spinning passes. Radial cracks initiated by tangential compressive stress the subsequent forming passes can lead to further bending - of those wrinkles will overlap within the bent area when the process is continued this result in radial cracking of the overlapped material. In the present work, forming and joining of commercial purity Aluminum (99.5%) tubes was investigated using a ball-ended tool on the lathe. Tests included tube end widening, tube end flanging, free (without plug) in-section widening, free throttling, and joining an Aluminum tube to a polymer plug.

The main objective of the present work is to determine the forming limits and product quality in Aluminum tube forming and joining. Goals of the present paper are finding the effect of rotary forming process parameters on the forming limits and the effect of such parameters on product quality (mainly thickness distribution and surface strains) of small diameter Aluminum tubes which represent a considerable percentage in many industrial fields. The process parameters include forming tool ball diameter, entry distance and tube initial thickness. The use of a conventional lathe and a simple ball-shaped tool to achieve the forming process represent a good novelty concern in the present research work.

## 2. Experimental work

### *2.1. Tube material and machine tool used*

To investigate the tube forming and joining, commercial purity Aluminum tubes, 32 mm outer diameter and 22 mm inner diameter were supplied from the Egyptian Copper Co., Alexandria, EGYPT, in the as- received condition and machined to the required dimensions, keeping the inner diameter as 23 mm. The lathe (ZMM Bulgaria CY63 O), **Figure 1,** was used for machining the specimens and carrying out the forming experiments, a schematic for the forming processes investigated is given in **Figure 2**.


**Fig. 1.** Photos of the lathe ZMM CY63 O used

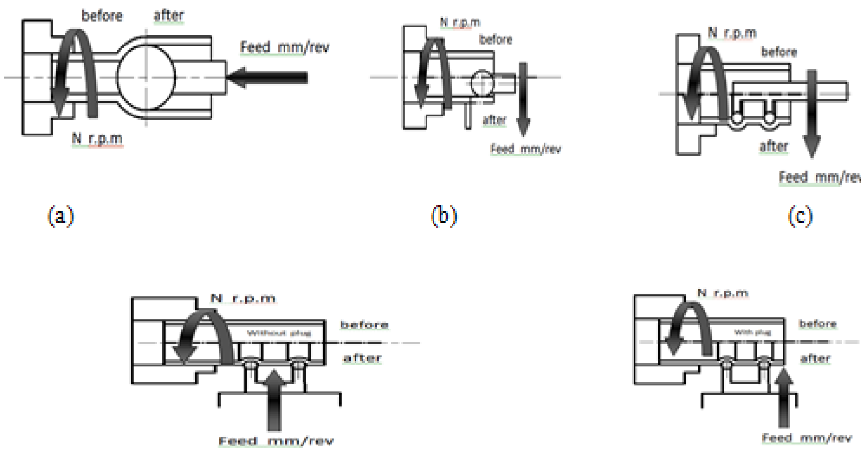



**Fig. 2. Tube forming processes used in the present work:**
a) tube end widening, b) tube end flanging, c) in-section widening,
e) section throttling and e) joining of an Al tube to a polymer plug

## 2.2. Forming tool

**Figure 3** presents a schematic assembly drawing and **Figure 4** shows a photo of the ball-ended tool used in the present investigation. Ball diameters vary according to the process. For widening experiments, the diameters were 24, 27, 28 and 30 mm. For tube end flanging, a 19 mm ball was used. For in-section widening, throttling and joining experiments, a 12 mm ball was used.

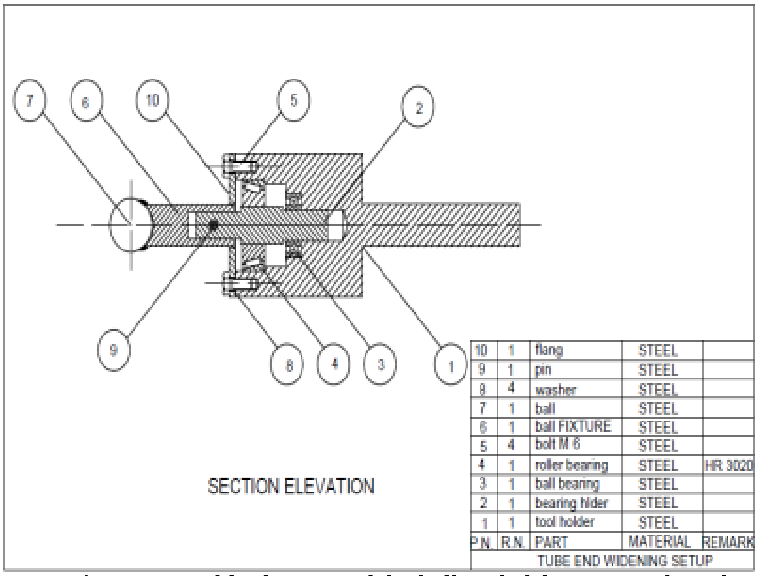



**Fig. 3.** Assembly drawing of the ball-ended forming tool used

**Fig. 4.** A photo for the assembled ball-shaped Forming Tool

## 2.3. Grid drawing and thickness strain measurements

Grid with drawn on the specimen surface into equal size (5 X 5 mm) to study the generated strains during forming processes. **Figure 5** gives a sample photo of gridded specimens before (the left side) and after (the right side) deformation in tube end widening.

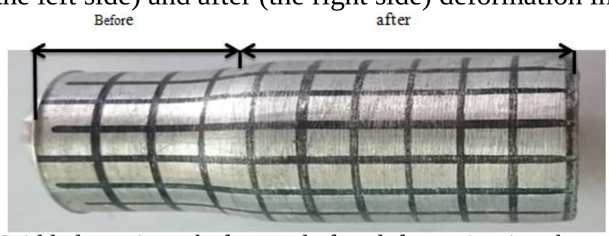



**Fig. 5.** Gridded specimen before and after deformation in tube end widening.

## 2.4. Experimental program

Details of the experimental program in the present investigation can be described as follows:

1- ***Tube end widening:*** Tubes, 32 mm outer diameter and 22 mm inner diameter were machined to 23 mm inner diameter and thickness values of 1, 1.5, 2, 2.5 and 3 mm respectively and finished with a sand paper grit size 600. Ball- ended tools had ball diameters of 24, 27, 28 and 30 mm (corresponding to widening ratios of (1.0434, 1.1739, 1.2173 and 1.3043 respectively). Widening ratios were calculated as ball diameter divided by original inner diameter of the tube. Tube rotating speed was kept constant for all experiments as 125 rpm and the feed was kept constants as 0.125 min/rev. No lubricant was used.
2- ***Tube end flanging:*** In tube end flanging, Radial movement of the flanging tool in the outward direction was utilized to form end flanges in tubes. Tubes, 32 mm outer diameter and 23 mm inner diameter were machined to 23 mm inner diameter and thickness values of 1, 1.5, 2 and 2.5 respectively and finished with a sand paper grit size 600. A unified ball-ended tool was used for all flanging experiments, having ball diameter of 16 mm. At the beginning of the experiment, tool entry distance was adjusted before the flanging and the tool was adjusted to be in contact to the inner specimen surface. Entery distances of 4.75, 9.5, 14.25 and 19 mm were tried representing 0.25, 0.5, 075 and 1.00 of the ball diameter. Maximum flanging limit was referred to as the max obtained flange diameter without the occurrence of cracking in the flange. Tube rotating speed was kept constant for all experiments as 125 rpm and the feed was kept constants as 0.125 min/rev.
3- ***Tube end in-section widening:*** In tube end in-section widening, the 12 mm diameter ball was used. Two positions were determined for the widening, pushing the ball first 6 mm in the radial direction. The center distance between the 2 widening position was 27 mm to eliminate the effect of metal stretching. Tubes, 32 mm outer diameter and 23 mm inner diameter were machined to 23 mm inner diameter and thickness values of 1, .5, and 2.5 respectively and finished with a sand paper grit size 600. Tube rotating speed was kept constant for all experiments as 125 rpm and the feed was kept constants as 0.125 min/rev. No lubricant was used.
4- ***Tube Section throttling:*** In tube throttling process, the 12 mm diameter ball was used. Two positions were determined for the widening, pushing the ball first 6 mm in the radial direction. The center distance between the 2 widening position was 24 mm to eliminate the effect of metal stretching. Tubes, 32 mm outer diameter and 23 mm inner diameter were machined to 23 mm inner diameter and thickness values of 1, .5, and 2.5 respectively and finished with a sand paper grit size 600. Tube rotating speed was kept constant for all experiments as 125 rpm and the feed was kept constants as 0.125 mm/rev. No lubricant was used.
5- ***Aluminum tube joining to a polymer core:*** In tube joining process, the 12 mm diameter ball was used. Two positions were determined for the widening, pushing the ball first 6 mm in the radial direction. The center distance between the 2 widening position was 24 mm to eliminate the effect of metal stretching. Tubes, 32 mm outer diameter and 23 mm inner diameter were machined to 23 mm inner diameter and thickness values of 1, .5, and 2.5 respectively and finished with a sand paper grit size 600. Tube rotating speed was kept constant for all experiments as 125 rpm and the feed was kept constants as 0.125 mm/rev.

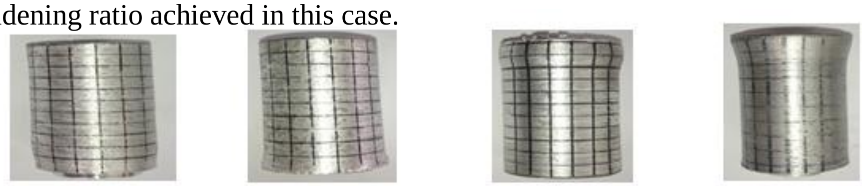
No lubricant was used. A polymer (PP) plug was machined with 2 grooves, 12 mm diameter each and introduced into the Aluminum tube. T001 was then pushed in the proper position radially to fill the machined undercut and then the process was repeated to fill the other undercut.

## 3. Results and Discussions

### *3.1. Tube end widening results*

### *3.1 1. Widening ratio of 1.0434*

**Figure 6** shows photos of deformed tubes in widening for this widening ratio. No fractures were observed for tube thickness of 1.5, 2, 2.5, 3 mm. This can be referred to the small widening ratio achieved in this case.

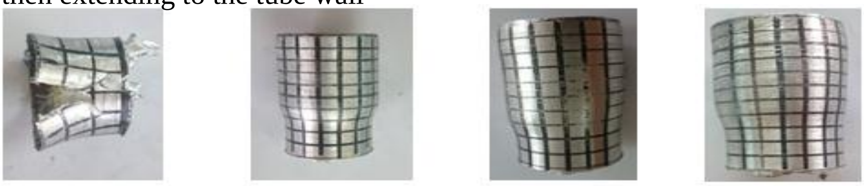


a) $t_o$= 1.5 mm b) 2mm c) 2.5 mm d) 3 mm

**Fig. 6.** Photos of end-widened tubular specimens using $D_{ball}$ of 24 mm diameter

### *3.1.2. Widening ratio of 1.1739*

**Fig**ure 7 shows photos of deformed tubes in widening for this widening ratio. No fractures were observed for different values of tube thickness except for the 1.5 mm thickness tube. A splitting occurred in this specimen beginning at the top point of the tube side and then extending to the tube wall

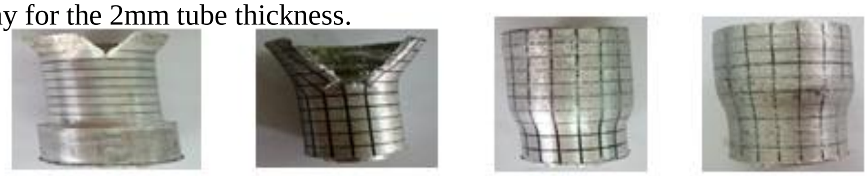


a) to=1.5mm b) t=2 mm c) t=2.5mm d) t=3mm

**Fig. 7.** Photos of end-widened tubular specimens using ball diameter of 27 mm

### *3.1.3. Widening ratio of 1.2173*

**Figure 8** shows photos of deformed tubes in widening for this widening ratio. Fractures were observed for tube thickness 1.5 mm and 2 mm. A splitting occurred in this specimen beginning at the top point of the tube side and then extending to the tube wall, in a more clear way for the 2mm tube thickness.



(a)) t=1.5mm (b)) t=2 mm (c)) t=2.5mm (d)) t=3mm

**Fig. 8.** Photos of end-widened tubular specimens using ball diameter of 28 mm

### *3.1.4. Widening ratio of 1.3043*

**Figure 9** shows photos of deformed tubes in widening for this widening ratio. Fractures were observed for tube thickness 2.5 mm. A splitting occurred in this specimen beginning at the top point of the tube side.

(a)) t=2 mm (b)) t=2.5mm (c)) t=3mm

**Fig. 9.** Photos of end-widened tubular specimens using ball diameter of 30 mm

### *3.1.5. A limit curve in widening of aluminum tubes*

**Figure 10** presents the forming limit curve in widening of commercial purity Aluminum tubes having different thickness using different ball diameters. It is clear that as the ball diameter increases, the limit tube thickness at which the crack begins increases. This can be referred to the fact that higher widening ratios require more volumes to be displaced to complete successful widening. Less volumes result in splitting of the metal and unsuccessful process. Cracks generally began at the top point, the point at which the ball is at the extreme widening ratio.

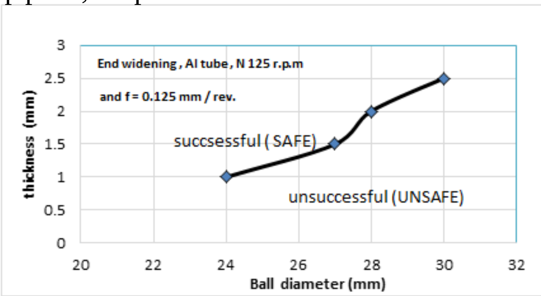



**Fig. 10.** The limit curve in widening of commercial purity Aluminum

## *3.2. Tube end flanging results*

### *3.2.1. Flanging of 1 mm thickness tubes*

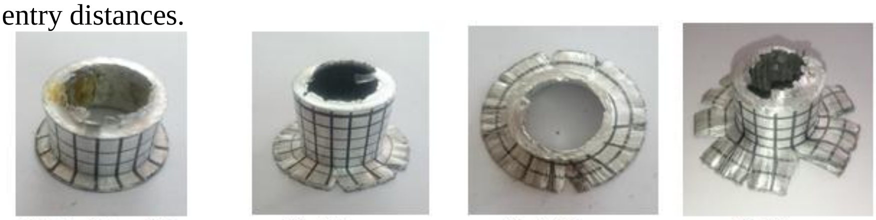
For entry distance of 4.75 and 9.5 mm, specimens were formed successfully in flanging for the present thickness. At an entry distance of 14.25 mm a split crack was noticed in the deformed flange and as the entry distance was increased to 19 mm, many splits were noticed in the flange, propagating to the tube body itself. **Figure 11** shows photos of flanged A1 tubes 1 mm thickness for varying entry distances.

Entry distance 4.75 mm (b) 9.5 mm, (c) 14.25 mm (d) 19 mm

**Fig. 11**. Photos of flanged Aluminum tubes having 1 mm thickness for varying entry distances of the 19 mm forming ball

### *3.2.2. Flanging of 1.5 mm thickness tubes*

Only for entry distance of 4.75, the process was successfully performed. Increasing the entry distance resulted in the appearance of splits in the flange, increasing number as the distance increases. **Figure 12** shows photos of flanged Al tubes having 1 mm thickness for varying entry distances.

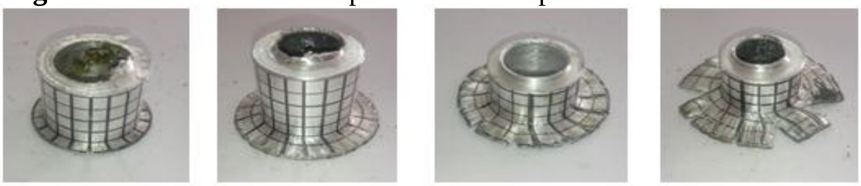


(a) Entry distance 4.75 mm (b) 9.5 mm, (c) 14.25 mm (d) 19 mm

**Fig. 12.** Photos of flanged Aluminum tubes having 1.5 mm thickness for varying entry distance of the 19 mm forming ball

### *3.2.3. Flanging of 2 mm and 2.5 thickness tubes*

For entry distances of 4.75 and 9.5 mm successful specimens were obtained. As the entry distance was increased, splits appeared to a varying degree of severity decreasing as the tube thickness increases. This can be referred to the increase in displaced volume in this case. **Figures 13 and 14** show the photos of such specimens.



a) Entry distance 4.75 mm (b) 9.5 mm, (c) 14.25 mm (d) 19 mm

**Fig. 13.** Photos of flanged tubes, 2 mm thickness for varying entry distances

a) Entry distance 4.75 mm (b) 9.5 mm, (c) 14.25 mm (d) 19 mm

**Fig. 14.** Photos of flanged Al tubes, 2.5 mm thick for varying entry distances

### *3.2.4. Effect of original tube thickness on the maximum flange diameter*

**Figure 15** presents the influence of the initial tube thickness on the maximum flange diameter obtained in the flanging process for different entry distances. It is clear that increasing the tube thickness has led to an increase in the flange thickness due to the increase in displaced volume in this case. Also as the entry distance increases, the flange diameter increases.

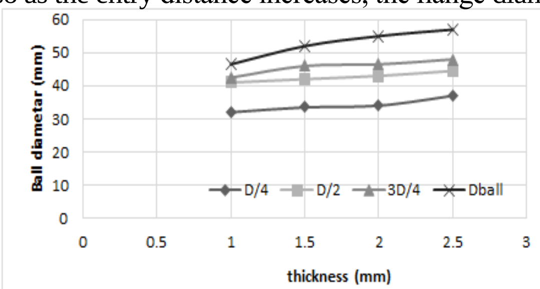
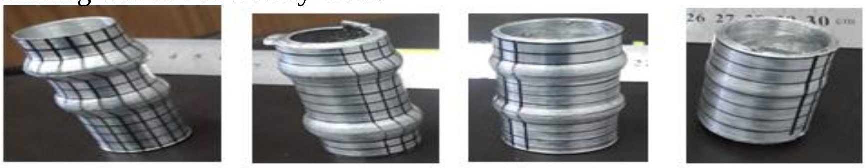



**Fig. 15.** Flange diameter vs. tube thickness in Flanging ($D_{ball}$ =19 mm, N =125 rpm and f= 0.125 mm/rev)

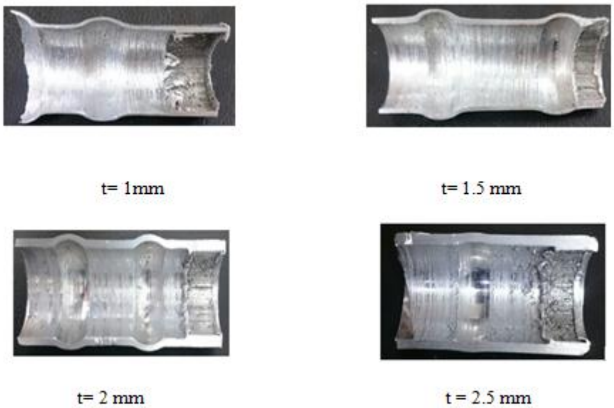
### 3.3. Tube end in-Section widening results

**Figure 16** presents photos of the deformed specimens for different thickness values. All specimens were successful and no cracking was observed. **Figure 17** shows photos of sliced sections of the deformed specimens and also Thickness distribution along section length for different specimens in section .widening. The uniformity of thickness appears to be clearer as the tube thickness increases. However, the effect of initial tube thickness on the wall thinning was not obviously clear.

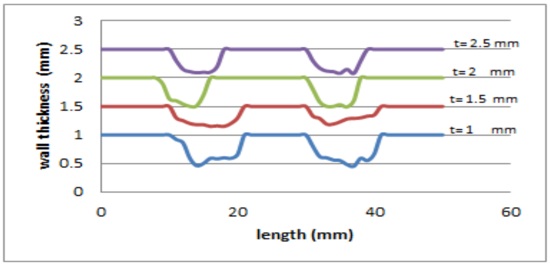


(a) t = 1mm, (b) t = 1.5 mm (c) t = 2 mm, (d) t = 2.5 mm
D ball = 12 mm, N = 125 rpm, f =0.125 mm/rev.

**Fig. 16.** Photos of the in-section widened specimens




a- Photos of wall sections in section widened specimens




b- Thickness distribution along widened section

**Fig. 17.** a) Photos and b) thickness distribution plots along section length for different specimens in section widening

### 3.4. Tube Section throttling results

**Figure 18** presents photos of the throttled specimens for different thickness values. All specimens were successful and no cracking was observed**. Figure 19** shows photos of sliced sections of the throttled specimens and also thickness distribution along section length» for different specimens in section widening. The uniformity of thickness appears to be clear as the tube thickness increases. In the same time, the amount of thinning along the tube length appears to be larger as the initial thickness decreases. This can be referred to the ease of throttling in this case. For example, a thinning of 12% only was noticed for 3 mm tube thickness, while it was about 33% for 1 mm tube thickness.

t= 1mm t= 1.5 mm t= 2 mm t = 2.5 mm t = 3 mm t= 3.5 mm

**Fig. 18.** Photos of the throttled specimens

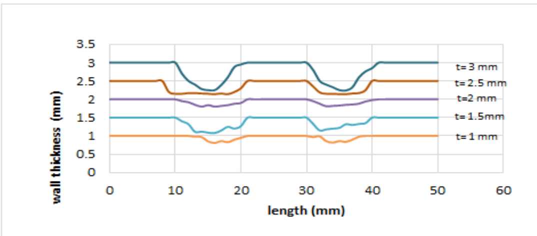
t= 1 mm

t= 1.5 mm

t= 2 mm

t= 2.5 mm

a- Photos of wall sections in throttling reduction.




(b)

b- Thickness distribution along section length for different specimens in throttling reduction.

**Fig. 19.** Photos and plots of thickness distribution along section length for different specimens in throttling reduction**.**

## *3.5. Aluminum tube joining to a polymer core results*

**Figure 20** Shows photos of the Joining of Aluminum tubes having various initial thicknesses to shaped Fiber (PP) plugs. . All specimens were successful and no cracking was observed. **Figure 21** shows wall sections in joining of Aluminum tube to shaped polymer plug.  Excellent filling of the Aluminum in the PP plug grooves was noticed for all thickness values. This simple method proved to be a suitable means to form permanent joint between different materials (Aluminum tube and polymeric core material).

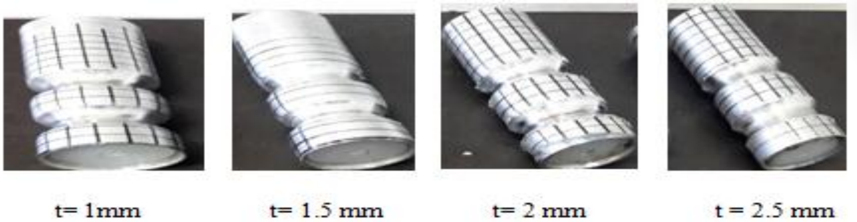



**Fig. 20.** Joining of Aluminum tubes to shaped polymeric (PP) plug

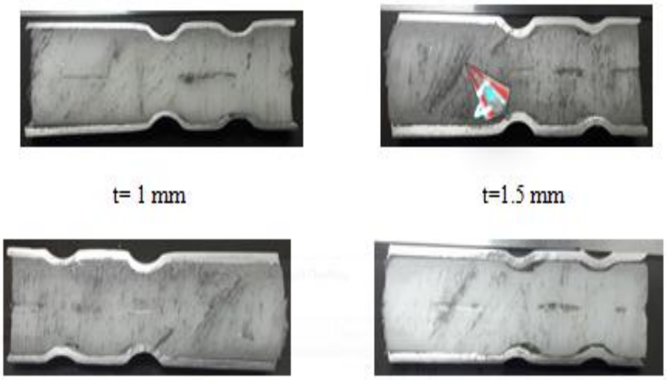
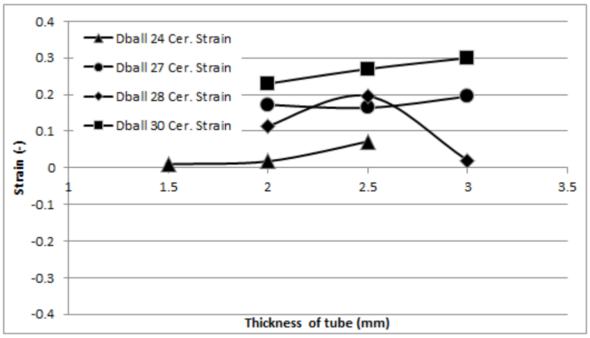



**Fig. 21.** wall sections in Joining to shaped Fiber plugs

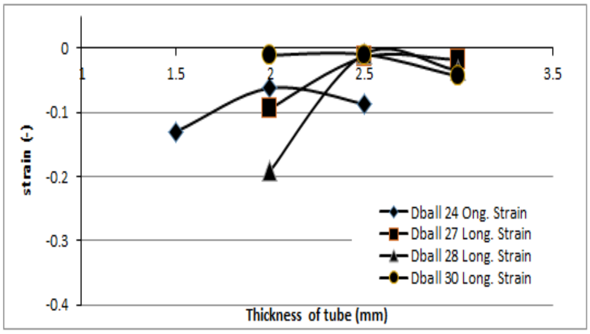
### *3.6. Surface strains of formed specimens*

In the widening process, **Figure 22** presents the relationships between the strain in the longitudinal and circumferential directions for different initial tube thickness values. Tensile strains in the circumferential direction tend to increase as the initial tube thickness increases. Longitudinal strains were compressive, but no clear effect of the initial tube thickness could be found. In the in-section widening process**, Figure 23** presents the relationships between the strain in the longitudinal and circumferential directions for different initial tube thickness values. Both strains were tensile due to the nature of the process. Longitudinal strain was increased (from 0.15 to 0.35) as the initial tube thickness increased, while circumferential strain was decreased as the initial tube thickness (from 0.2 to 0.025). In spite of the different between the two processes, one of them being widening by contact of the terminal diameter and the other being with contact of the inner diameter in one part and then increasing the contact area until the final intended profile, the analogy is strongly presented.

For tube end flanging experiments, **Figure 24** presents the relationship between local circumferential and longitudinal strains with varying the initial tube thickness for different entrance distances... It is clear that as entrance distance increases, the circumferential strain increases while the longitudinal strain decreases. Longitudinal strains were compressive (from -0.1 to -0.4) while circumferential strains were tensile (from 0.2 to 0.8).




a) Variation of the circumferential strains




b) Variation of the longitudinal strains in widening experiments

**Fig. 22.** Relationships between the strain in the longitudinal and circumferential directions for different initial tube thickness values

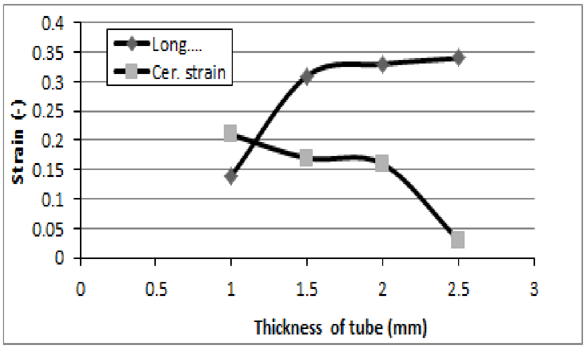



**Fig. 23.** Variation of the circumferential and longitudinal strains during in-section widening experiments

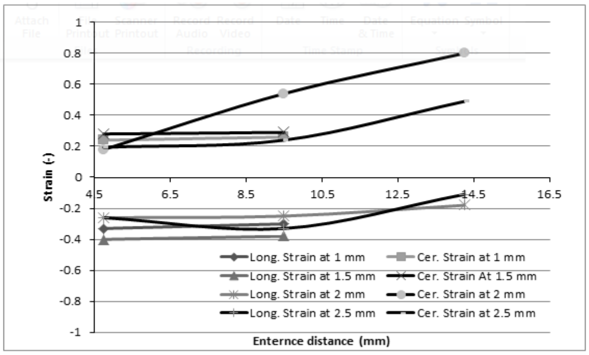



**Fig. 24.** Variation of the circumferential and longitudinal strains during in-section flanging experiments

## 4. Conclusions

From the results obtained, the flowing conclusions can be drawn:

1- Rotary tube end widening on the lathe proved to be a quick and simple forming process. Ball diameter and tube thickness are affected the success of the process. As ball diameter increases and tube thickness increases, in tube end widening, thickness distribution (variation) in proved as to increases due to the larger volume displaced.
2- In tube flanging, the thickness and the penetration distance proved to affect the success of the forming process. As to and the penetration distance increases, the flange diameter increases. This can be referred to the process of a larger volume of metal formed. Also to increases, the process was successful.
3- In free section widening and throttling, both initial tube thickness and penetration distance affected the success of the process and regularity of thickness.
4- Joining of two different materials (polymer core plus an Aluminum sheath) was performed successfully on the lathe by a ball shaped tool. Filling and thickness distribution were excellent.

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# حدود التشكيل و جودة المنتج فى عمليات التشكيل الدوار والوصل لانابيب من الالومنيوم

**الملخص العربى**

تدخل عمليات التشكيل والوصل لانابيب الالومنيوه فى انتاج العديد من الاجزاء المستعمله فى تطبيقات صناعيه متنوعه (كمثال: الصناعات الميكانيكيه و كيميائيه والغزل والنسج و الالكترونيه). فى هذا البحث تمت دراسه حدود التشكيل و نوعيه المنتج فى عمليات التشكيل الدوار لنهايات الانابيب وايضا عمليه وصل انبوبه من الالومنيوم التجارى (نقاوه 99.5%) مع قلب من ماده بلاستيكيه. وقد تمت عمليات التشكيل والوصل بادوات تشكيل ذات نهايه كرويه على مخرطه الزنبه. وقد شملت الاختبارات عميات توسيع نهايات الانابيب و تكوين فلانشه فى تهايه الانبوبه و توسيع وتضييق موضعيين فى قطاع الانبوبه. كما شملت تشكيل وصله دائمه عباره عن انبوبه الومنيوم (كغشاء خارجى) مع قلب (شاقه) من ماده يلاستيكيه.

وقد اظهرت النتائج انه فى حاله عمليات توسيع نهايات الانابيب يزداد انتظام سمك الجزء المتشكل مع زياده السمك الاولى للانبوبه قبل التشكيل وانه فى حاله عمليه تشكيل الفلانشات يؤثر سمك الانبوبه الاولى اضافه الى مسافه الاختراق على نوعيه المنتج من حيث انتظام السمك و نجاح العمليه نفسها. وثبت انتظام السمك والملء فى عمليتى التوسيع والتضييق الموضعيتين. وايضا ثبت نجاح عمليه الوصل من حيث انتظام السمك والملء فى الجزء المشكل. وقد امكن رسم منحنى لحدود التشكيل يفيد فى تحديد نجاح العمليه من عدمه لظروف تشكيل دوار محدده فى مدى السرعات والتغذيات المحدد وايضا قطر نهايه أدوات التشكيل.

وفى المجال التطبيقى يرى الباحثان ان تطبيق تلك التقنيه البسيطه و غير المكلفه فى تشكيل ووصل نهايات الانابيب مفيد للصناعات الصغيره والمتوسطه التى لا تملك فى الغالب ماكينات تشكيل انابيب متقدمه. و يمكن بتغيير بسيط فى هندسه اداه التشكيل توسيع مدى المنتجات وبالتالى التطبيقات المتاحه. كما ان خريطه حدود التشكيل مفيده للانابيب الالومنيوم وظروف التشكيل المحدده و تفيد فى تحديد نجاح العمليه من عدمه.