ORIGINAL ARTICLE

Experimental study of thickness reduction effects on mechanical properties and spinning accuracy of aluminum 7075-O, during flow forming

Hamid R. Molladavoudi · Faramarz Djavanroodi

Abstract Flow forming technology is widely used in the production of the axisymmetric industrial parts. The advantage of flow forming process over other manufacturing methods such as press forming is use of simple tooling, reduced forming loads due to localized deformation, and enhanced mechanical and surface quality of finished parts. In this study, the effects of thickness reduction on the mechanical properties and spinning accuracy are experimentally investigated on 7075-O aluminum tube. A prototype spinning machine has been designed and manufactured. The effects of spinning accuracy, surface roughness, percentage of elongation, yield strength, and the ultimate strength as a function of thickness reduction are experimentally examined. The experimental results show that with increment of thickness reduction, the yield strength, ultimate strength, surface hardness, and crystal refining increase, and on the other hand, it has adverse effect on diameter growth, geometrical accuracy, surface roughness, and percentage elongation of spun tube.

Keywords Flow forming · Tube spinning · Aluminum 7075-O · Thickness reduction · Reduction rate · Surface roughness · Geometrical accuracy

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1 Introduction

Flow forming is an advanced eco-friendly chipless metal forming process, which employs an incremental rotary point deformation technique. Flow forming offers a remarkable increase in tensile properties due to strain hardening and provides excellent dimensional accuracy and surface finish for the formed parts. Tube spinning is suitable for the production of a hollow shape having a surface of revolution, such as tubular products and many other axisymmetric components. Flow forming has many advantages: short production runs, a variety of symmetrical shape, smaller deformation force, less investment in equipment, etc. [1–3]. Presently, the application of tube spinning is widely explored because of the usage of tubular products is increasing in the trend of light weighting [4]. It is most widely used to produce thin walled, high precision tubular products where the tubular work piece is held on to the mandrel, the material being displaced axially by one or more rollers moving axially along a mandrel, as shown in Fig. 1. There are a number of experimental and numerical studies on flow forming. Lee and Lu [5] studied the flow-forming of cylindrical tubes using a rolling mechanism. Chang et al. [6] studied spinnability of AA2024 and 7075 aluminum alloys tube. Park et al. [7] used an upper bound method to analyze the tube spinning process. Davidson et al. [8] studied the flow forming process parameters that affect the quality of flow formed al AA6061 aluminum alloy tube. They concluded that the depth of cut, the feed, the starting dimension of the preform, the starting heat-treatment condition of the preform, and the speed of the mandrel had significant role in the quality of the final product. Wong et al. [9] developed a finite element model to simulate the flow forming process. They studied the effect of roller path and geometry on the flow-forming of

Fig. 1 Schematics of forward and backward tube spinning show the relative flow of preform material
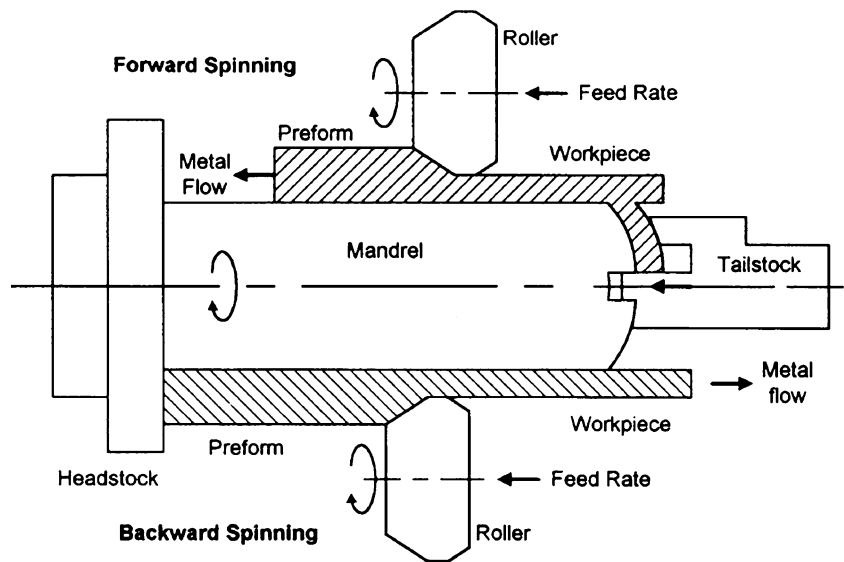
solid cylindrical components and concluded that the final dimension of the flow-formed feature depends largely on the roller geometry, feed rate, and the amount of deformation. Kemin et al. [10] performed an elasto-plastic FEM analysis to study the diametral growth in tube spinning.

They analyzed the influences of various process parameters on the diametral growth of tubes. Hua et al. [11] performed a three-dimensional finite element analysis for analyzing the tube spinning process. Parsa et al. [12] used an explicit commercial finite element program to simulate the forward
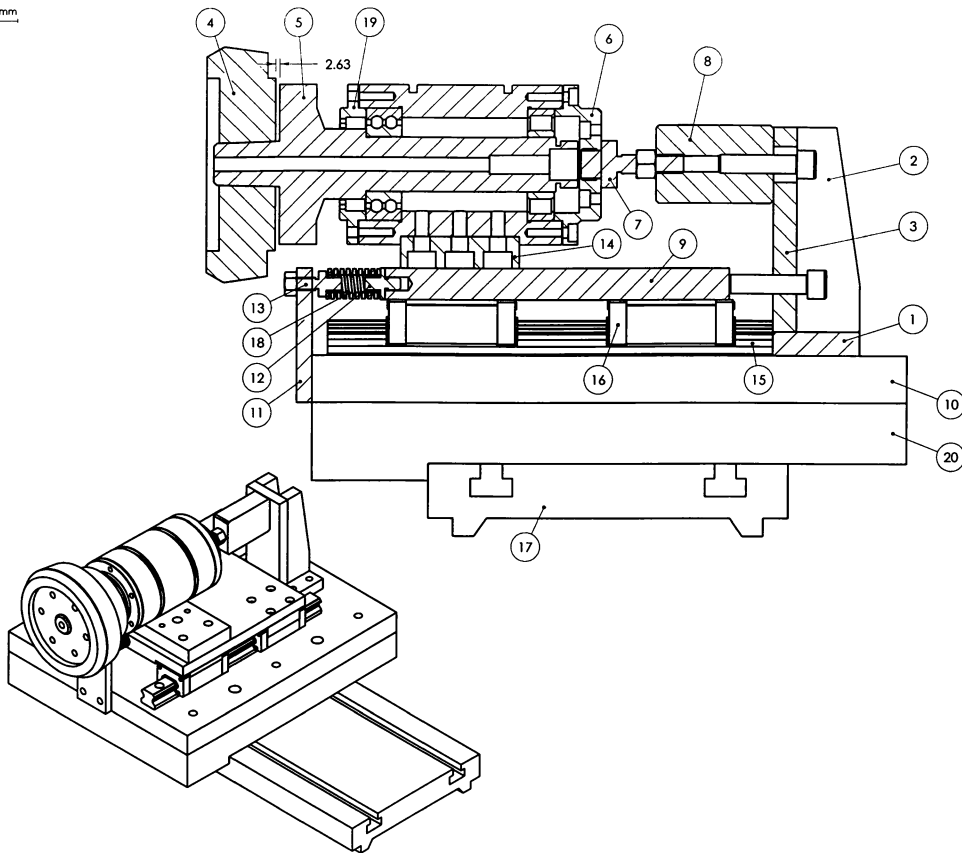
No	Part Name	Material	Qty
1	Bottom Support	ST-37	1
2	Lateral Support	ST-37	2
3	Front Support	ST-37	1
4	Forming Roller	SPK	1
5	Conic Shaft	---	1
6	Rear Housing Cover	---	1
7	Screw	ST-37	1
8	Loadcell/Stoper	DBBP	1
9	Pedestal	ST-37	1
10	Bed	ST-37	1
11	Load Plate	ST-37	1
12	Spring Holder 2	ST-37	1
13	Spring Holder 1	ST-37	1
14	Housing Support	---	1
15	Rail	HIWIN	2
16	Vagon	HIWIN	4
17	Support	---	-
18	Spring D64Y/16/044	---	1
19	Front Housing Cover	---	1
20	Bottom Plate	AL	1

Fig. 2 Sketch of NC spinning equipment: *5* spindle shaft; *4* Roller; *3* support stand; *16* linear guide; *8* stopper

flow forming of tube. They established a correlation between feed rate and axial and angular velocities.

In this work, the effects on mechanical properties, surface roughness, surface hardness, diameter growth, geometrical accuracies, and crystal refining are experimentally examined as a function of percentage thickness reduction of a circular 7075-O aluminum tube. For the experimental purpose, a prototype spinning machine has been designed and manufactured.

2 Experimental work

2.1 Experimental equipment

In flow forming of tubes, the work piece is held on to the mandrel as the forming roller moves along the work piece axially to reduce the diameter. The roller travels parallel to the axis of the mandrel with a feed rate, ν, and reduces the wall thickness of the tube from the initial wall thickness, $t_\circ$, to the final thickness, t_f, not by removing material, but just by elongating it without change the inside diameter of the tube. Therefore, in order to successfully conduct the experiment, a NC lathe machine was chosen as it has the same working principles as that of a flow forming machine. A roller tool was designed and manufactured to accommodate the lathe tool post. Figure 2 shows a schematic diagram of the spinning machine. Figure 3 shows the experimental setup for the flow forming process on an NC lathe. The spinning process is preformed as follows: The preform(#1) which is held on to the mandrel (#2), is rotated by NC lathe chuck(#3), mandrel is supported by the lathe tail stock (#4) to prevent mandrel bending during spinning process, the roller tool (#5) can move in radial and axial directions by the NC lathe support. The axial feed of the roller tool is called feed rate and the radial feed of roller tool is called indented feed which will make thickness
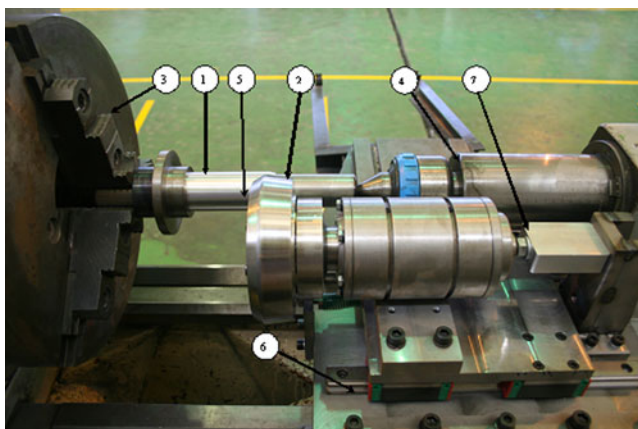

Fig. 3 Setup for flow-forming experiments on an NC lathe

Table 1 The nominal compositions of AA7075 aluminum alloy (wt.%)

Element	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti
AA 7075	0.3	0.4	1.1	0.1	2.5	0.22	5.4	0.01

reduction. One end of tube is fixed in axial direction and the other end is free in the axial direction and they are called fix and free ends respectively. For measuring axial spinning force, the roller tool is mounted on a linear guide way system (#6). A load cell can be used instead of stopper (#7), for measuring axial spinning force. In this paper, metallographic specimens were prepared from the longitudinal and transverse sections of the spun tube. Optical microscopy (OM) is used to examine the microstructure of the spun tube. The tensile test specimens are directly cut from the tube and machined to the dimensions according to the ASTM E 8-89 specification. The Vickers hardness Hv of the surface is measured by digital hardness tester. Dimension measuring is done by CMM and the surface roughness is measured by ultrasonic roughness checker.

2.2 Experimental conditions

Full annealed 7075 aluminum alloy (designated as 7075-O) was chosen as the work piece material in this study. Table 1 lists the nominal composition of AA 7075-O aluminum alloy used in this study [13]. The pre-form is a tubular blank with no tail-cup since backward tube spinning is used. During spinning, the pre-form is tightly pressed against the mandrel by the headstock. As the roller approaches the headstock, a thinning of the material occurs. Table 2 lists the experimental conditions. The configuration of the pre-form used for flow forming is shown in Fig. 4. Figure 5 shows sample flow formed tube. The percentage reduction of wall thickness is given by $RA = \frac{t_\circ - t_f}{t_\circ} \times 100$, where $t_\circ$ represents the initial wall thickness and t_f the final wall thickness as shown in Fig. 6.

Table 2 Experimental conditions of tube spinning

Material	7075-O
Mandrel speed (rpm)	280
Diameter of mandrel (mm)	40
Attack angle of roller ( )	30
Initial preform thickness (mm)	3
Feed rate (mm/rev)	0.47
Roller diameter (mm)	150
Radius of roller rounded corner (mm)	3
Thickness reduction (%)	10, 20, 30, 40, 50, 60

Section A–A
Scale 1:1
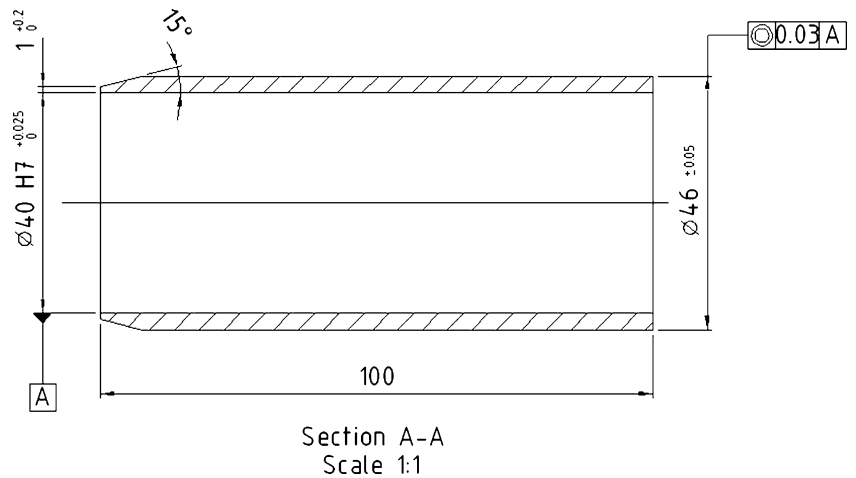
3 Results and discussions

3.1 Mechanical properties

Figure 7 shows the axial tensile properties of full annealed
7075 aluminum tubes with respect to various thickness
reductions. As it can be seen tube spinning increases both
yield and tensile strength of full-annealed tubes due to the
work hardening. Yield and tensile strength increment are
14% and 64% for 60% thickness reduction. Figure 8 shows
the effect of thickness reduction on percentage elongation.
As it can be seen, percentage decreases in elongation is
71%, for 60% thickness reduction.

3.2 Surface hardness

The roller tools are kept in contact with the tube in the
spinning process and the surface of formed part is
hardened. Figure 9 shows the effect of thickness reduction
on Vickers hardness Hv of the surface of formed part. The
hardness Hv increases proportionately with the increment
of thickness reduction. The deformation becomes larger as
the thickness reduction increases. Therefore, work-

hardening is strengthened. Results shows hardness is
increased up to 48% for 60% of thickness reduction.

3.3 Surface roughness

The profile of the roller tool end is a circle arc. Therefore,
the roller marks are produced on the tube surface after
spinning. Figure 10 shows the effect of thickness reduction
on roughness of tube surface for various thickness
reductions. The roughness of tube surface increases with
increment of thickness reduction, but the tendency is not
very obvious. Because the spinning force increases with the
increment of thickness reduction, the vibration of tube
becomes intensive in the spinning process, and the arc
marks by roller become greater. In addition, the friction on
tube surface by roller movement increases correspondingly
with the increment of thickness reduction. As a result, the
roughness of tube surface becomes larger.

3.4 Diameter growth

Though tube spinning has been widely used for many years
to produce a great variety of cylindrical parts with high
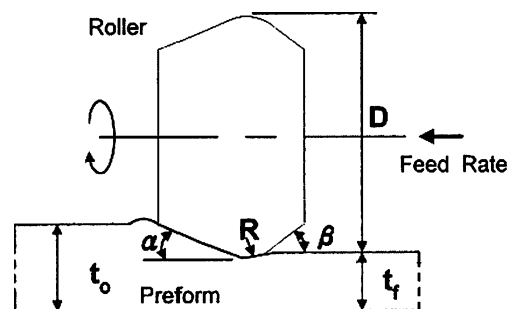

Fig. 5 Flow formed tube

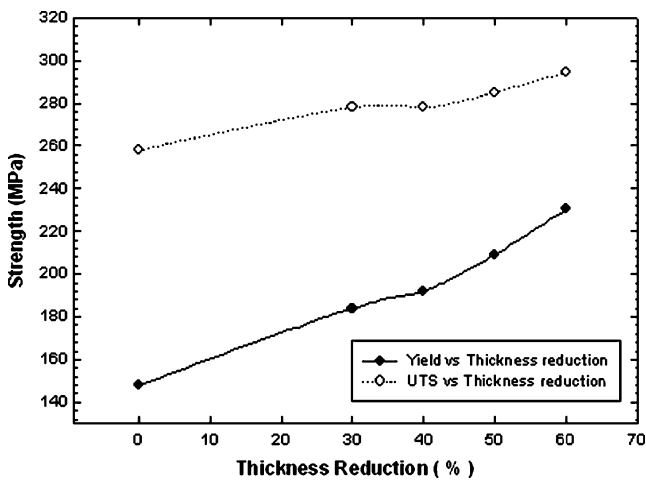**Fig. 6** Schematic thickness reduction parameters

Fig. 7 Axial tensile properties of 7075-O aluminum tubes

Fig. 9 Effect of reduction rate on hardness of tube surface

specific strength, the problem of diameter growth are still troublesome. Diameter growth is expressed by $e=D_a-D$ in which D_a is the actual inside diameter of the tube after spinning and D is the desired diameter (mandrel diameter).

The flow of particles beneath the roller has two components; axial and circumferential. Diameter growth is a function of material flow in the axial direction compare to circumferential direction which is determined by coefficient ξ. Figure 11 shows the aspect of contact between the blank and the roller in backward tube spinning. The X axis coincides with the anti-rotational direction of the blank and Z axis coincides with the axis of the tube. The material coming into the clearance between the roller and the mandrel with the velocity V_o in the rotational direction of the blank is forced to flow in the direction of the Z axis, while the other part of the metal flows in the rotational direction of the blank with velocity V_x [14]. The volume of the metal flow in the Z direction is given by parameter "ξ".
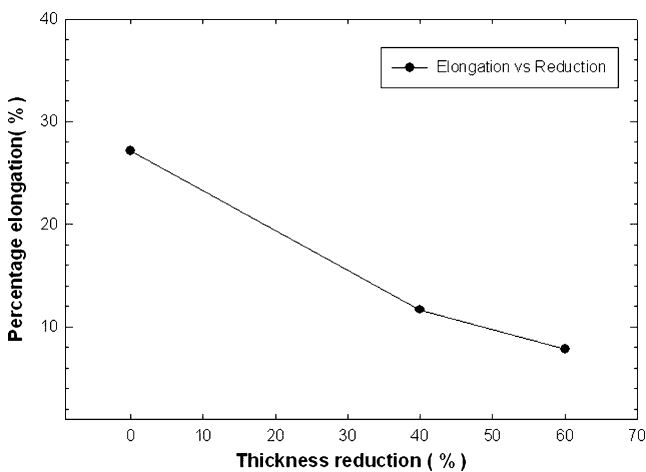
In the backward tube spinning, in order to maintain the steady of deformation and keeping the volume $A_3{}'$ of the wave, ahead of the roller, material should flow in the same and opposite direction of the motion of the roller. Therefore in order to maintain the steady flow of metal in the direction of "Z" axis, the following equation must be satisfied [14]:

$$\xi A_\circ{}' = A_3{}' \tag{1}$$

$$A_\circ{}' = A_1{}' - B_\circ{}' \tag{2}$$

$$A_1{}' = \left\{\Delta Z_\circ^2 (\tan\alpha + \tan\gamma) + \left(t_\circ{}' + t_1 - 2t - Z_1\tan\alpha\right)Z_1\right\}/2 \tag{3}$$

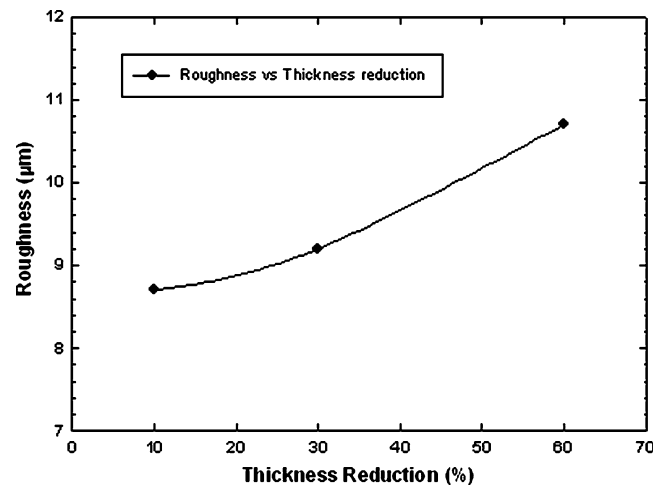Fig. 8 Effect of reduction rate on percentage elongation
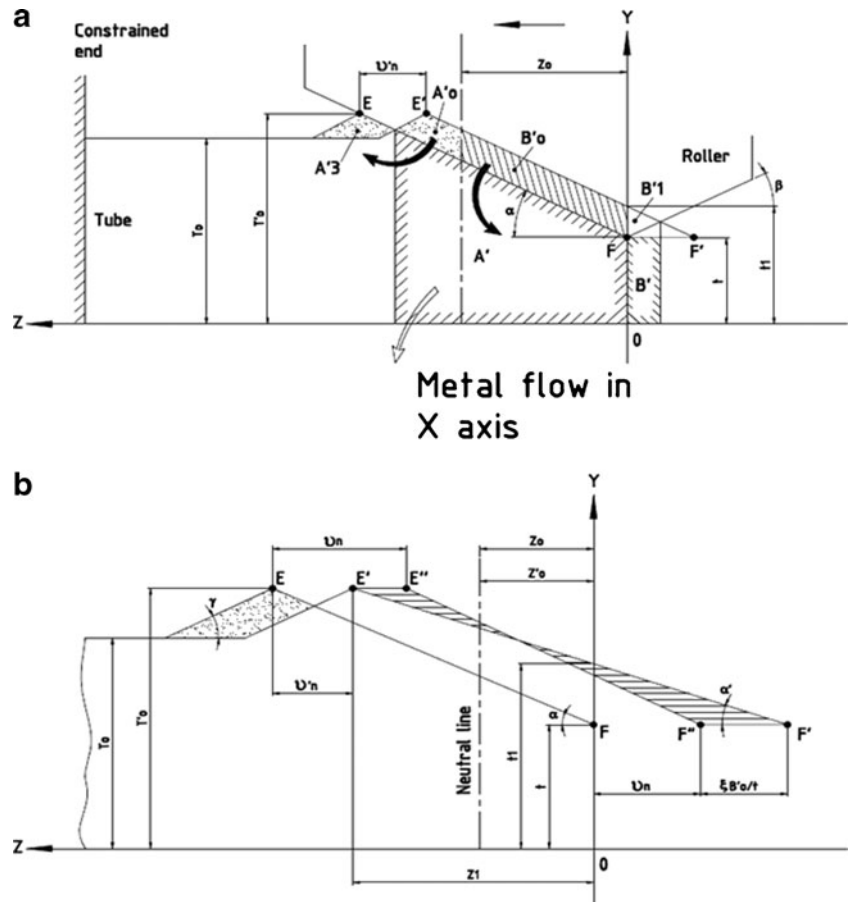

Fig. 10 Effect of thickness reduction on roughness of tube surface

Fig. 11 **a**, **b** Metal flow between the blank and the roller in backward tube spinning [14]

$$B_{\circ}{}' = \{2t_1 - 2t + Z_{\circ}(\tan \alpha\,' - \tan \alpha)\}Z_{\circ}/2 \qquad (4)$$

$$A_3{}' = (t_{\circ}{}' - t_{\circ})v_n{}' - \Delta Z_{\circ}v_n{}'\tan \gamma/2 \qquad (5)$$

$$v_n = v/n_{\circ} \qquad (6)$$

$$v_n{}' = (t_{\circ}{}' - t)\cot \alpha - Z_1 \qquad (7)$$

$$Z_1 = (t_{\circ}{}' - t_1)\cot \alpha\,' \qquad (8)$$

Where n_{o} is the number of rollers used in the process, v_n is the apparent feed of the roller, $v_n{}'$ is the actual feed of the roller. When the value of ξ is small, the material flow in the circumferential direction increases and then, the fit between the finished part and the mandrel will be loose [14]. In other words, the higher the ξ value, the better the diameter control, and the smaller the ξ value, the greater the diameter growth [14, 15]. The relationship between calculated coefficient ξ and reduction rate is shown in Fig. 12. It is clear that decreasing of ξ is associated with the increasing of reduction rate (R_{o}) as well as with the decreasing of feed rate (ν) and the angle of the roller α. As shown in Fig. 13, with the increase of reduction rate, the diameter growth of work piece increases. It is in consequence of decreasing ξ by increasing reduction rate. Therefore, decreasing the reduction rate increases ξ value and helps to avoid diameter growth. Also, it is clear that the diameter growth on the free side of tube is more than the fixed side; this is because the free side must travel freely over the mandrel and is, therefore, susceptible to bell-mouthing and distortion [16].

3.5 Thickness variation

Figure 14 shows the effect of thickness reduction on thickness variation of tube wall. As shown in Fig. 14, with the increase of the reduction rate of wall thickness, there are small increases in the thickness variation. It is deduced that with increasing reduction rate, resistance to material flow increases correspondingly and thus causes wall thickness changing between thick and thin.
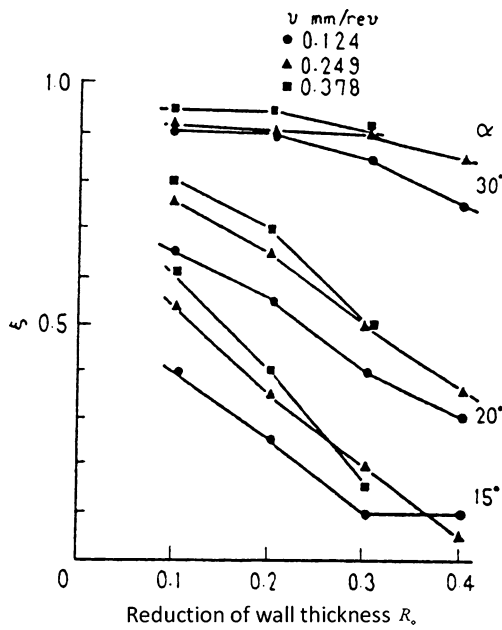
Fig. 12 Relationship between coefficient ξ and reduction rate [14]

Fig. 14 Effect of reduction rate on thickness variation

3.6 Roundness

Figure 15 shows the effect of thickness reduction on spun tube roundness. The higher the (ξ) value, the more material will tend to flow in the axial direction, rather than in the circumferential direction [14]. Under this condition, the circularity (Roundness) of tube is well kept, where as a small ratio of (ξ) leads to geometrical inaccuracies [15]. As shown in Fig. 15, with the increase of reduction rate, roundness of tube decreases. It is in consequence of decreasing ξ by increasing reduction rate. Also it is obvious
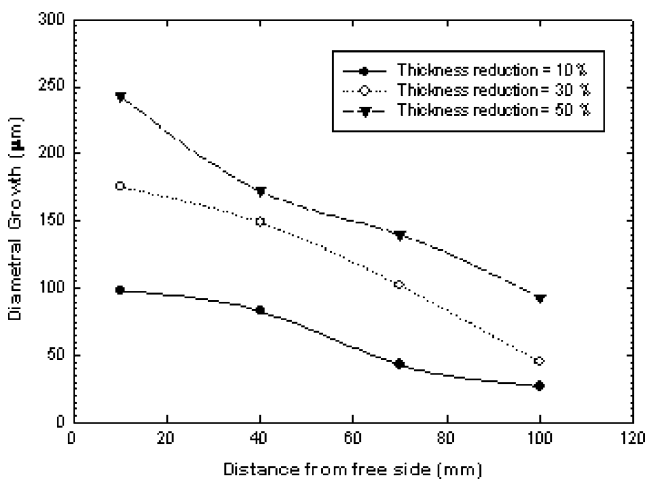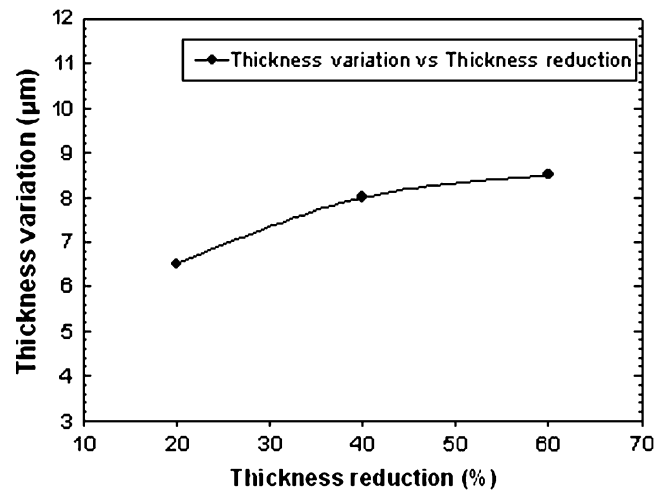
that roundness on the free side is larger than fixed side. Therefore, decreasing the reduction rate increases ξ value and helps to avoid geometrical inaccuracies.

3.7 Crystal refining

Figure 16a–f shows the microstructure of spun surfaces for fully annealed and after 20%, 30%, 40%, 50%, and 60% thickness reduction, respectively. As shown in Fig. 16, with the increase of the thickness reduction which results in larger degree of deformation, crystals refined further. The axial roller traveling direction is shown by arrow in the figures.
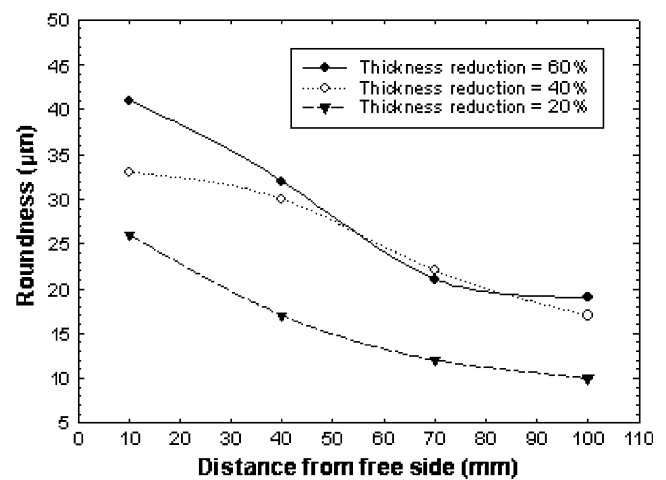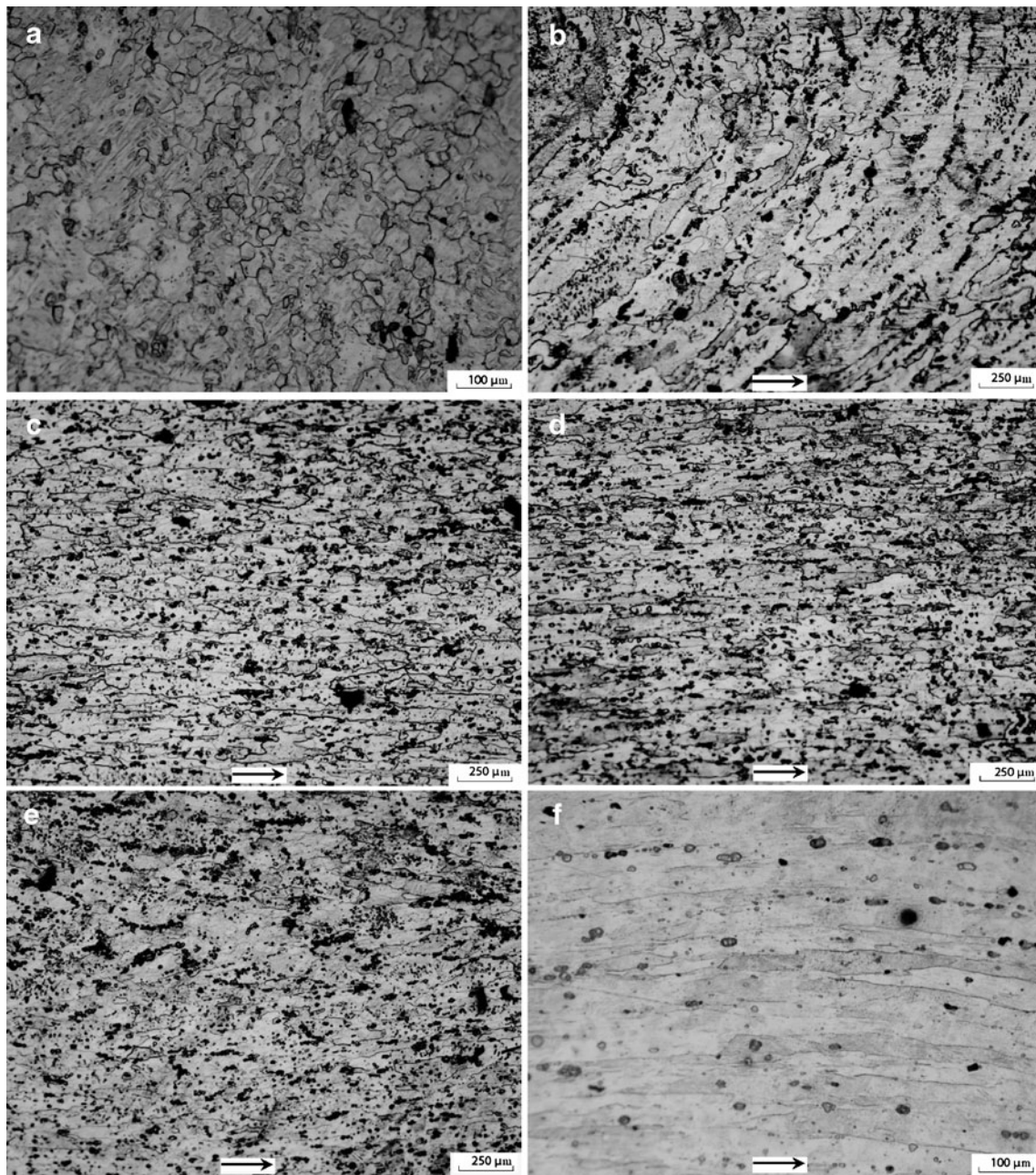

Fig. 13 Effect of reduction rate on diameter growth

Fig. 15 Effect of reduction rate on geometrical inaccuracies

Fig. 16 a Microstructure of full annealed 7075 aluminum alloy, **b** 20% thickness reduction, **c** 30% thickness reduction, **d** 40% thickness reduction, **e** 50% thickness reduction, **f** 60% thickness reduction

4 Conclusions

The effects of thickness reduction on the forming properties of spun tube have been examined in this study. Based on the above examination, the following conclusions can be drawn:

1. The roughness of tube surface increases with increment of thickness reduction.
2. The hardness is increased up to 48% for 60% of thickness reduction.

3. The geometrical accuracy becomes worse with the increment of thickness reduction.
4. The diameter growth increases with increment of thickness reduction.
5. Increase of the thickness reduction results in crystals refinement.
6. Increase of the reduction rate of wall thickness results small increase in thickness variation.
7. Yield and tensile strength increment are 14% and 64% for 60% thickness reduction. And percentage

elongation decreases up to 71%, for 60% thickness reduction.

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