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Non-axisymmetric tube spinning by offset rotation

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Abstract

A spinning method has been devised to produce an offset tube using a conventional lathe and a simple roller. By using a standard boring head in the chuck of a lathe the axis of rotation relative to the tube's axis can be modified, enabling an offset tube to be produced. Offset tubes have been produced in pure copper with varying amounts of offset and variations in key spinning parameters, including number of spinning passes, feed ratio, radial reduction and axial step per pass, and taper angle. This study has demonstrated that it is possible to produce an offset tube cheaply, without using costly and specialized spinning equipment.

Peer-review under responsibility of the scientific committee of the 17th International Conference on Metal Forming.

Keywords: Metal spinning; Non-axisymmetric; Offset tube.

1. Introduction

The technique of metal spinning has been used for many centuries to form sheets or tubes of metal into more complex shapes. Metal spinning is a process where metal is subjected to localized deformations by use of a free-spinning roller and rotation of the workpiece. There are three main types of metal spinning: conventional spinning, shear spinning and tube spinning. Conventional and shear spinning begin with a flat sheet of metal blank and deform this in the axial and radial directions to the desired profile, often making use of a mandrel to help form complex shapes. In tube spinning the blank is a metal tube, with deformation occurring mainly in the radial direction over a series of passes. This allows the production of tubes which taper from the initial tube diameter to a smaller diameter. There is not normally any mandrel used in tube spinning.

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Metal spinning is a desirable process since it requires relatively low forming forces due to the localized deformations and gives a high quality surface finish and improved mechanical strength [1] in comparison to other forming methods. Metal spinning also allows the manufacture of parts in one piece where other methods may require several parts to be joined together to create the same component. This eliminates the need for subsequent joining processes such as welding or bonding which can add impurities or weaknesses into the part as well as increasing the total cost of manufacture.

Until recently the advantages of the metal spinning process could only be utilized for parts which were rotationally symmetrical. However, as designs continue to become more complex the desire to spin parts which are non-axisymmetric has increased. Recent process advancement in manufacturing non-axisymmetric spun parts is reported by Xia et al. [2]. An offset tube is a common example of non-axisymmetric spinning where the rotational axis of the final tube is offset from the rotational axis of the initial tube, as shown in Fig. 1. This study focuses on assessing a relatively cheap and easy method to produce an offset tube using a conventional lathe as a spinning machine without using any costly and specialized equipment.

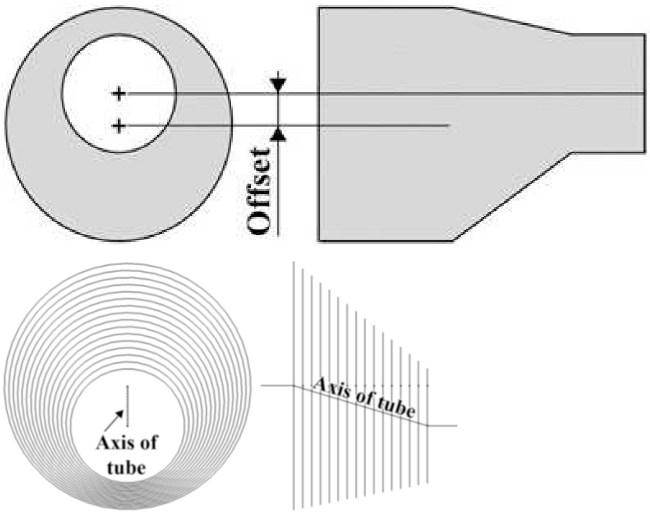

Fig. 1. Schematic of offset tube.

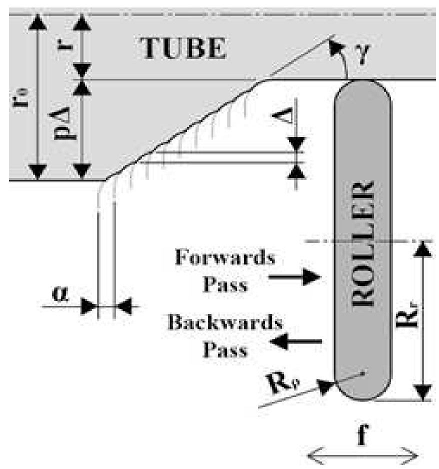

Fig. 2. Spinning parameters of offset tube.

There are currently several different methods of non-axisymmetric metal spinning. These can be categorized as having either a rotating or non-rotating workpiece. Xia et al. [3] and Sekiguchi et al. [4] use rotating workpieces in non-axisymmetric conventional spinning. Xia et al use a profile driving technique where the workpiece is fastened to a platform which is free to move in the plane of rotation of the part and is connected to a profile driving part which spins at the same rotational speed as the workpiece. As the profiled part rotates it drives the platform in the appropriate direction to form the desired shape. Sekiguchi et al. [4] use a more sophisticated computer controlled approach to create shapes on a curved axis in conventional spinning. This approach not only allows products with circular cross sections to be achieved but also products with polygonal cross sections. Although the actual machinery required is not discussed, it is clear that this method is likely to involve using very expensive and complex machinery. No record of the use of oscillating rollers to create offset tubes has been found but there is no reason why, with the correct machinery, an offset tube cannot be produced using this method.

Irie and Ota [5] use rotating rollers to produce offset and oblique (where the rotational axis of the final tube is at an angle to the rotational axis of the initial tube) tubes. With this method the rollers oscillate in sync with their rotation, allowing non-circular cross sections to be created. Irie and Ota [5] use computer controlled rollers giving good flexibility of part design and easy adjustments but disadvantages is the complexity of the machinery required. Firstly, power (electrical or hydraulic) must be provided to the rollers which are not a straight forward issue since the rollers are in a rotating frame. Secondly, since the rollers must oscillate in sync with their rotation they are likely to be moving very quickly. This means that they must be controlled very rapidly and precisely, but even with this there may be problems with syncing the radial motion of the rollers with their rotation. If a slower rotational speed was used to lessen this problem then the manufacturing time of the part would increase proportionally. While this method has the advantage of being extremely flexible in the product specifications it requires a very complex and therefore expensive machine to perform the process. This method is patented meaning that only this particular machine can use this exact method.

A different approach to rotating rollers is used by Xia et al. [6]. A commercial machine, known as the HGPX-WSM CNC Spinning Machine is used to provide the experimental data in their studies. All that is known about this machine is that it translates the workpiece in both the axial and transverse directions. This has the effect of changing the center of rotation of the part, thus allowing offset tubes to be manufactured without the need to oscillate the rollers in the radial direction. This seems like the most sensible method when using rotating rollers, since there are no issues with synchronization. In effect this method simplifies one oscillatory motion into two much simpler linear motions. There are, however complexities in this design since the rollers still need to move in the radial direction to reduce the diameter of the tube and are still in a rotating frame. This could possibly be done by a manual adjustment after each pass if a cheaper solution was required.

In this paper, a spinning method has been devised to produce an offset tube by offsetting the tube's axis from the axis of rotation using a conventional lathe and a simple roller. By using a standard boring head in the chuck of a lathe the axis of rotation relative to the tube can be modified, enabling an offset tube to be produced in pure copper with varying amounts of offset. Effect of variations in key spinning parameters, including number of spinning passes, feed ratio, radial reduction per pass and axial step per pass and taper angle, on the deviation between the desired geometry and the actual geometry is investigated and its limitations are discussed.

2. Spinning of an offset tube by offset rotation

2.1. Spinning parameters

In tube spinning parts are formed in a number of passes, with the roller being set at a reduced radial position before each new pass. Passes define the axial movement of the roller along the tube and there are two different types of passes. A forwards pass is defined as where the roller moves from a chosen position close to the chuck, towards (and past) the free end of the tube, while a backwards pass is the reverse of a forwards pass. Forwards passes have the effect of thinning the material, due to the material flowing in the same direction as the roller, towards the free end of the tube. Backwards passes thicken the material, due to the material being restricted from flowing towards the free end of the tube since the rollers motion is towards the chuck. It is usual to use forwards and backwards passes alternatively to achieve a roughly constant thickness throughout the whole tube. This means that to some extent it is possible to control the thickness of the tube by using different combinations of forwards and backwards passes. However, as Ando and Karino [7] and Xia et al. [8] have reported, the axial thickness distribution in tube spinning is far from trivial.

During a pass, the roller is fed in the axial direction at a constant velocity, often expressed in terms of a distance per revolution of the tube. This is known as the feed ratio and the value of this greatly affects the surface finish of the spun part along with the amount of thinning/thickening which occurs. Table 1 shows the spinning parameters used in this study, illustrated in Fig. 2. The taper angle of the spun part can be determined by the radial reduction and axial step used at each pass as shown in Fig. 2, $\gamma = tan^{-1}(\Delta/\alpha)$.

Table 1. Spinning parameters of offset tube.

Symbol	Quantity	Units
f	feed ratio	mm/rev
p	number of passes	-
r	final tube radius	mm
r_0	initial tube radius	mm
t_0	initial tube thickness	mm
x	axial distance	mm
D	maximum deviation	mm
R_r	roller radius	mm
R_ρ	roller nose radius	mm
α	axial step per pass	mm
γ	taper angle	degrees
γ'	effective taper angle	degrees
δ	offset amount per pass	mm
θ	rotational angle of chuck	degrees
Δ	radial reduction per pass	mm
Δ'	effective radial reduction	mm

2.2. Spinning an offset tube

For an offset tube any cross section of the tube in the axial plane is circular and therefore lies on its own axis, as shown in Fig. 1. Therefore by rotating the tube about each cross sections axis it is possible to recreate the geometry of an offset tube. By offsetting the axis of the original tube in relation to the axis of rotation it is possible to rotate the tube about the axis of any cross section of an offset tube. Furthermore, since tube spinning is an incremental forming process, a desired overall offset can be achieved by adjusting the value of offset after each pass of the roller. As the number of passes is increased, the produced tube will approach the geometry of an ideal offset tube although this is also dependent on the value of radial reduction per pass used. If the roller were to be positioned at a fixed radial position during a pass and assuming that the roller is always contacting the tube, a perfect circle must be created about the rotational axis of the tube.

Given the desired part is non-axisymmetric and the roller is at a fixed radial position during a pass, the instantaneous radial reduction of the tube must vary with its rotational angle. It is desirable to calculate this variation since the radial reduction has a direct effect on the forming forces experienced by the roller.

Fig. 3 shows an exaggerated view of a pass during offset tube spinning. The larger circle represents the existing geometry of the tube whereas the smaller circle represents the intended geometry of the tube after a pass of the roller. The tube is rotated about the center of the smaller circle. By considering the distances shown in Fig. 3, the effective radial reduction at a given pass number for any rotational angle of the chuck and any value of offset and radial reduction per pass can be determined

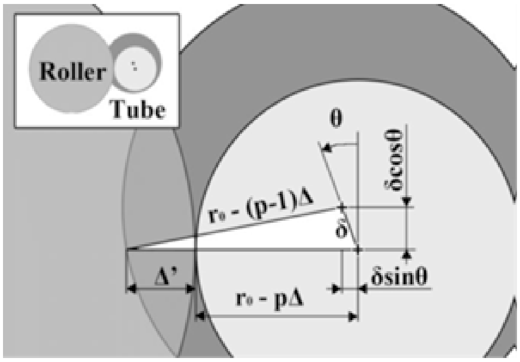

Fig. 3. Distances during offset tube spinning.

$$\Delta' = \sqrt{[r_0 - (p-1)\Delta]^2 - (\delta\cos\theta)^2} - \delta\sin\theta - (r_0 - p\Delta). \quad (1)$$

Fig. 4 shows that at low values of offset the effective radial reduction is well represented by a sine curve. However, as the value of offset is increased, the effective radial reduction at 0° and 180° is decreased. At first glance this may appear counter intuitive, since there is no horizontal component of the offset acting to move the tube towards or away from the roller one may expect the effective radial reduction to be equal to the radial reduction per pass. However, since there is a vertical component of offset acting at these positions the tube will move up or down in relation to the rollers axis, therefore leading to a lower value of effective radial reduction. As the tube is rotated, this effect decreases since the vertical component of the offset is decreased, meaning that the effective radial reduction converges to a sine curve when the rotation reaches 90° or 270°. It is noted that Fig. 4 shows an exaggerated scenario where the radius of the tube is being reduced to half its original radius in one pass and in practice the deviation from a sine wave is likely to be relatively small.

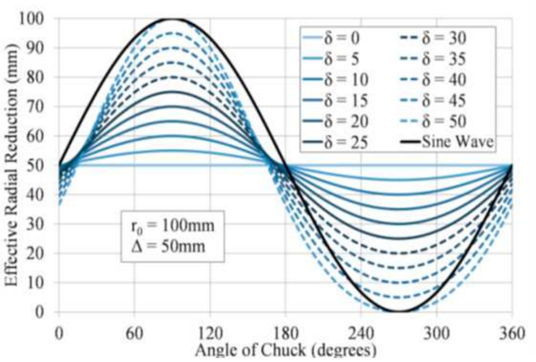

Fig. 4. Effective radial reduction for different offsets.

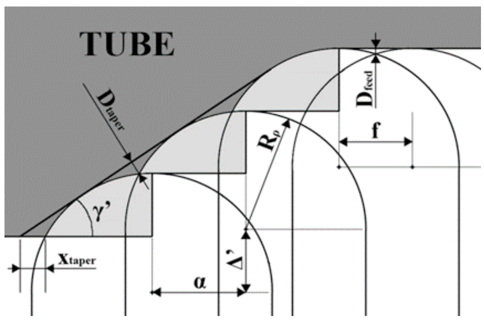

Fig. 5. Deviations in tube spinning.

2.3. Geometrical accuracy

Due to the incremental nature of tube spinning a deviation between the desired geometry and the actual geometry will always exist in the tapered section of the part. The size of this deviation depends on the feed ratio, roller nose radius, effective radial reduction and axial step per pass. As shown in Fig. 5 the deviation on final tube due to feed ratio, D_{feed}, the maximum deviation from desired profile on tapered section, D_{taper}, and the axial shift of tapered section, x_{taper}, can be calculated by

$$D_{feed} = R_p - \sqrt{R_p^2 - \left(\frac{f^2}{4}\right)}, \tag{2}$$

$$D_{taper} = R_p - \sqrt{R_p^2 - \left(\frac{\alpha^2 + \Delta'^2}{4}\right)}, \tag{3}$$

$$x_{taper} = \frac{\alpha\left[R_p\left(\frac{\alpha}{\sqrt{\alpha^2 + \Delta'^2}} - 1\right) + \Delta'\right]}{\Delta'}. \tag{4}$$

3. Spinning test equipment and procedure

All spinning was conducted on a Dean Smith & Grace Type 17 lathe with digital positioning display. The roller and roller holder were designed and two angular contact bearings were used to support the roller on an M10 bolt which bolted through the roller holder. The roller had a radius of 30 mm and a nose radius of 5 mm and it was positioned in the tool post of the lathe. The initial outer diameter of the tube made of pure copper was 28.6 mm and the inner diameter was 25.4 mm, giving a wall thickness of 1.6 mm. Both axisymmetric and offset tube spinning tests were conducted. For offset tube spinning, a boring head with a 25.4 mm tool bore was used to hold the tube. This allowed adjustments of offset to one thousandth of an inch (approximately 0.025 mm). The set up used during offset tube spinning can be seen in Fig. 6. All tests were conducted at a chuck rotational speed of 54 rpm.

When carrying out offset tube spinning tests, it should firstly ensure there is zero offset on the boring head when position the roller so that the roller is just contacting the tube in the radial direction, then apply the chosen offset per pass to the boring head from its current position. After the rotation of the chuck started, feed the roller the chosen radial reduction inwards from its current position, then start the axial feed of the roller away from the chuck in a forwards pass. The following backwards pass, in the axial feed of the roller towards the chuck, follows the similar steps. The above procedure is repeated until the desired number of passes has been reached.

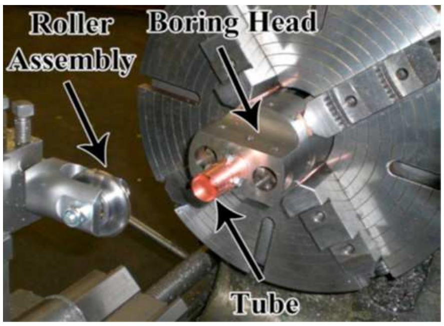

Fig. 6. Offset tube spinning test set up.

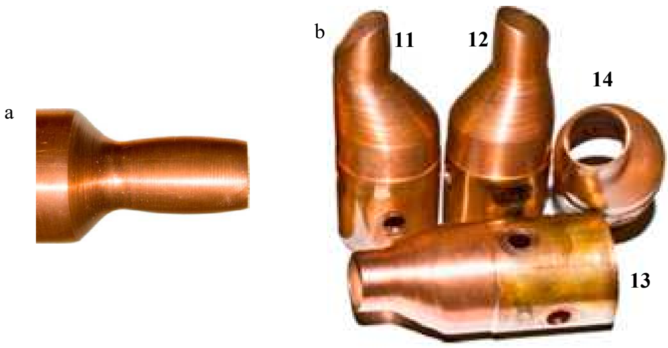

Fig. 7. (a) Axisymmetric spun tube; (b) offset spun tubes.

4. Results and discussion

4.1. Axisymmetric tube spinning

Since metal spinning on a lathe is not common and the roller and roller holder were bespoke designs, six axisymmetric tube tests were first carried out to test the equipment. Spinning parameters and final radius results (taken at its maximum value) are listed in Table 2. Firstly, it can be seen that the final radius of all samples is greater than the theoretical value ($r_{theory} = r_0 - p\Delta$). From Fig. 7 it can also be seen that the radius varies with the axial position on the tube, creating a barrelling effect. It is noted that this effect is least prominent on sample 1 which has the lowest radial reduction per pass and the shallowest taper angle. The effect is also less significant on sample 3 where the final tube was subjected to a feed ratio of 0.36 mm/rev over 2 passes at the final radial position of the roller. Since the forming forces are likely to be lower with less radial reduction per pass and a slower feed ratio, this leads to the conclusion that higher forming forces lead to a greater error between the intended and actual final radii. The smaller radius at the end of the tapered section is most likely due to the procedure used, since the rotation of the chuck was not stopped during the process and the roller spent a considerable amount of time at the end of the tapered section between passes when the radial feed of the roller was being adjusted. The reduction in radius towards the free end of the tube appears to indicate that the forming forces decrease significantly as one approaches the free end. This is a sensible assumption since at the free end there is less material constraining the working section. The axial starting position for sample 6 was 20 mm from the tubes free end and all other tests had an axial starting position of 26 mm from the tubes free end. Therefore sample 6 had a slightly smaller deviation than that of sample 2 with a shallower taper angle. The higher radii in the center section could be due to either the roller assembly being deflected away from the tube during spinning, or the tube deflecting away from the roller whilst it is spinning. To solve this, 3 rollers opposing each other would be needed, thus spreading the force over 3 roller assemblies and producing no resultant force on the tube in axisymmetric spinning. This is a widely used method in metal tube spinning, but adds a certain degree of complexity in the process.

Table 2. Axisymmetric tube spinning test results.

No.	f (mm/rev)	Δ (mm)	α (mm)	p	γ (°)	$r_{actual} - r_{theory}$ (mm)
1	0.71	0.25	1.0	29	14.0	**0.55**
2	0.71	0.50	1.0	17	26.6	1.7
3	1.42/0.36	0.50	1.0	15	26.6	**1.25**
4*	1.42	0.50	0.5	14	45.0	N/A
5*	0.71	0.50	0.5	14	45.0	N/A
6	0.71	0.50	0.5	15	45.0	1.6

**Samples 4 and 5 failed at the end of the tapered section during the 15th pass.*

Using Eqs. (2) and (3) and the spinning parameters which will give the most significant deviations, the maximum deviations due to the feed ratio and in the tapered region can be calculated as 0.051 and 0.031 mm respectively. Since the lowest actual deviation from the intended geometry is 0.55 mm (sample 1) it is clear that there are issues which far outweigh the deviations predicted using Eqs. (2) and (3) and therefore more detailed measurements of these deviations would be irrelevant. However, it is worth noting that a feed ratio of 0.71 mm/rev produced an acceptable surface finish whereas at a feed ratio of 1.42 mm/rev there were very pronounced grooves in the tube surface.

Assuming a nominal taper angle of 26.6° and that the offset value per pass cannot be greater than the radial reduction per pass, the absolute maximum taper angle achievable in offset tube spinning can be calculated as 45°. Since an axisymmetric tube has been spun with a constant taper angle of 45° it is deduced that it should be possible to produce an offset tube with a nominal taper angle of 26.6° and an offset value of up to the radial reduction.

4.2 Offset tube spinning

Initial testing using the boring head in the chuck with zero offset highlighted that the holding mechanism of the tube was far from ideal since the tube visibly moved during the spinning process. To reduce the forming forces the copper was heated for 2-3 minutes using a butane gas torch until its surface became dark brown in color. From Constable [9] and Miley [10] it can be estimated that the copper was heated to a temperature of around 400°C. Heat was applied a total of 4 times during the spinning process of a tube; prior to any spinning and after the 5th, 9th and 13th passes. In an attempt to evaluate the effect of heating, sample 14 was turned down to a wall thickness of 1 mm and after annealing and cooling was formed cold. Table 3 shows the spinning parameters and results of these tests. All tests were conducted at a chuck rotational speed of 54rpm, axial step of 1 mm per pass, radial reduction of 0.5 mm per pass, feed ratio of 0.71 mm/rev and had 15 passes.

From Table 3 it can be seen that (as in the axisymmetric tube tests) the final tube radius is larger than intended, although samples 7 and 12 show significantly less error (r_{actual} - r_{theory}) than the other samples. The lower error on sample 7 is most likely due to the tube being heated to a higher temperature since it was the first test using heat and it was unknown how much heat was needed to soften the material sufficiently. The lower error on sample 12 is due to the final tube being passed by the roller an extra 4 times at the final radius setting and with a lower feed ratio of 0.18 mm/rev.

Table 3. Offset tube spinning test results.

No.	r_0 (mm)	t_0 (mm)	r_{actual} - r_{theory} (mm)	δ (mm)	$p\delta_{actual}$ (mm)	$p\delta_{actual}$ - $p\delta_{theory}$ (mm)
7	13.65	1.10	**0.525**	0.20	3.50	0.45
8	13.70	1.15	1.050	0.25	4.75	0.94
9	13.90	1.35	1.225	0.30	4.90	0.33
10	13.90	1.35	1.025	0.35	6.15	0.82
11	13.95	1.40	0.850	0.40	7.50	1.40
12*	13.95	1.40	**0.400**	0.20	4.35	1.30
13**	13.95	1.40	1.100	0.20	3.70	0.65
14	13.55	1.00	1.050	0.20	3.85	0.80

** After the 15 passes, sample 12 was subjected to 4 passes (two backwards, two forwards) with a feed ratio of 0.18 mm/rev at the rollers final radial position. **Sample 13 was spun with only backwards passes.*

All samples measure a greater offset than intended, as presented in the final column of Table 3. Fig. 8 shows that the actual total offset is roughly proportional to the theoretical total offset. This suggests a systematic error in the adjustment of the offset on the boring head. It was noted that when adjusting the boring head there was always some backlash in the threads, making it extremely difficult to offset the head a precise value. It is also possible that the position of the boring head was shifted during spinning since the mechanism is not designed to take large loads. This could have led to the backlash in the threads being present when later adjusting the offset.

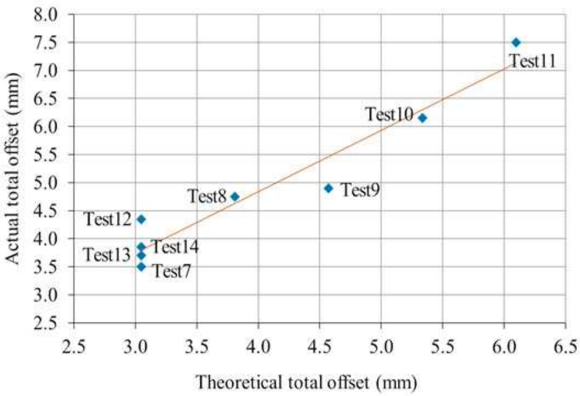

Fig. 8. Theoretical total offset vs. actual total offset.

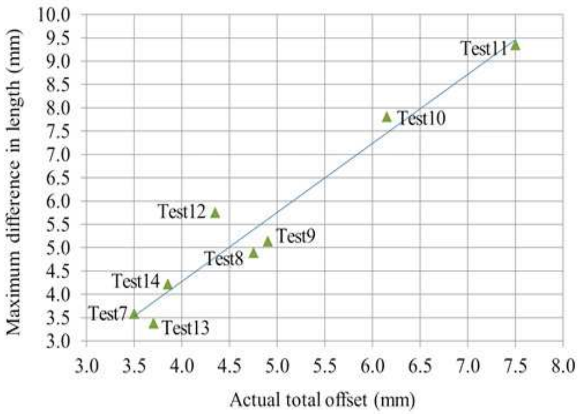

Fig. 9. Max difference in length vs. actual total offset.

Fig. 7(b) shows a selection of the offset tubes produced. It can be seen that sample 11 is very close to the maximum achievable offset (since at θ = 270° its profile is almost straight) shown in Fig. 4. All tubes have an acceptable surface finish but the surface finish on sample 12 is extremely good due to the extra passes with a lower feed ratio. In Fig. 7(b), it can also be seen that the ends of the tubes are not perpendicular to their axes. This is due to the effective radial reduction changing around the circumference of the tube as explained in Section 2. Since the tube is being deformed by varying amounts around its circumference this leads to the axial deformation also changing around the circumference. It is believed that this axial deformation is directly related to the effective radial reduction and therefore also to the amount of offset used. Fig.9 shows the difference in axial length between the shortest and tallest sections of the tubes against the actual total offset produced. It can be seen that the difference in length of the tubes around their circumference is strongly affected by the amount of offset used in an approximately linear relationship. It is noted that samples 12-14 were spun with different parameters to the rest of the samples and therefore could be neglected when drawing any conclusions to the exact relationship. The thickness of the tube is also believed to change around the circumference of the tube and with knowledge of the thickness distribution a more accurate relationship between the amount of offset and the difference in length of the tube could be obtained.

With the current equipment the desired offset value is difficult to achieve in practice due to limitations in the accuracy of the boring head. In addition to this, the diameter of the final tube was seen to vary along its length, meaning the dimensional accuracy of the part was compromised. In the future, work should be conducted on assessing the forming forces during the spinning process [11], which will allow a more robust alternative to the boring head to be designed. This will enable a more accurate offset to be achieved along with being able to hold the tube sufficiently secure without the need to heat or reduce the wall thickness in order to reduce forming forces. There is also scope for measuring the thickness distribution on the spun part both along its length and around its circumference. Another area of improvement would be to use 3 opposing rollers as opposed to the single roller used in this study. This would greatly reduce the resultant force on the tube and should increase the dimensional accuracy of the final part. The use of 3 rollers would also allow the part to be formed much quicker, since a feed ratio 3 times as fast would give a similar surface finish to that achieved with a single roller and normal feed ratio.

5. Conclusions

A spinning method has been devised to produce an offset tube using a conventional lathe and a simple roller. The analysis of the deviations between the desired geometry and the actual geometry suggests a systematic error in the adjustment of the offset on the boring head because the position of the boring head is shifted during spinning since the holding mechanism is not designed to take large loads. A more robust alternative to the boring head should be designed to enable a more accurate offset to be achieved. This work has demonstrated that it is possible to produce an offset tube without using any specialised equipment, offering cost advantages in manufacturing spun offset tubes for potential applications.

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