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Metal forming: an analysis of spinning processes

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Abstract

Spinning is frequently used for manufacturing axisymmetric shapes where press tooling might not be justified on grounds of size and production volumes. Spinning also has the possibility of producing parts that could not be deep drawn. For this paper, spinning is taken as a rotational forming process that does not set out to change the wall thickness. Both the blank and the finished product have roughly the same thickness.

The objective of changing the shape of the blank to a new desired product shape is common to spinning and deep drawing. A metal part that is drawn is limited by the ductility of the material. A part that is spun is subject to far more compressive stresses and the limit of forming may in fact be due to a buckling failure rather than a tensile failure.

Earlier authors have proposed various analyses of the spinning process. These highlight common process limitations. An analysis of spinning is presented which shows how the strains involved are quite different resulting in different spinning techniques. Results are interpreted to explain the rationale for multi-pass spinning operations.

The material used in this work was light gauge sheet aluminium (Al 99.0-Werkstoff 30205, material condition HH, 0.2% yield 110 MPa).

Keywords: Metal spinning; Conventional spinning; Shear forming; Spin forging

1. Introduction

This paper analyses a simple experimental shape produced by spinning. The chosen form was spun using a variety of different diameter blanks. The theoretical strains are considered under two idealised models. The first is a spinning process that leaves the thickness unaltered and the second a process of pure shear forming where the hoop strain is zero. With shear forming [4] or spin forging as it is termed by Kobayashi [1], the radial position of any element is unaltered. Conversely, when the radial position of any element changes significantly, it is termed conventional spinning and the objective is to maintain an unchanged wall thickness from blank to finished workpiece.

The nature of multi-pass spinning is evident from the diagram given in Fig. 1. Consider the flange after each pass, there is reduction in the outside radius implying circumferential or hoop compressive strains and radial tensile strains. It is assumed that the sheet thickness is constant.

The forming action in Fig. 1 shows that the hoop strain ε_h is compressive, the radial strain ε_r is tensile (i.e. the strain lying in a plane tangent to the sheet in a direction away from the axis of rotation) and that the thickness strain ε_z is zero.

2. Shape chosen for experimental work

A simple shape was chosen to provide a variety of forming conditions. The shape consisted of final diameter 100 mm with central section consisting of a spherical surface of radius 95 mm with a blend radius between the cylindrical and the spherical sections of 17 mm. It is a similar shape to that used in an investigation of working forces in conventional spinning [5]. A steel former to these dimensions was used but with the addition of a 20 mm central flat to allow the tailstock to clamp the blank against the former.

The strains involved in producing this part can be considered in terms of the two theoretical processes: (1) shear forming, (2) constant thickness deformation (Fig. 2).

2.1. Shear forming

In shear forming we can consider an element any distance R_n from the spinning axis (Fig. 3). In the case of the chosen

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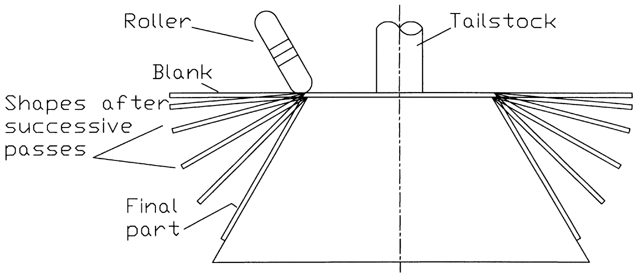

Fig. 1. Successive spinning passes.

profile the shape that the element takes in the formed part is determined by its position on the sphere or fillet radius. If α is the angle that the surface normal of this element makes with the spinning axis and t is the thickness of the blank then the thickness of the part after shear forming is $t\cos\alpha$. While shear forming the radial position of each part remains unchanged, i.e. the normal distance R_n from the axis of spinning is unchanged. It follows that the circumference of any circular element $2\pi R_n$ is also unchanged. If the circumference of any element is unchanged then the hoop strain ε_h is zero. If volume constancy is now considered it is apparent that there must be a strain in a direction perpendicular to the thickness strain. As ε_h is zero this strain must be in a radial direction so let $d\varepsilon_r$ denote this strain.

The change in thickness is $t\cos\alpha-t$ and so the thickness strain ε_t is given by $(t\cos\alpha-t)/t$ or $\cos\alpha-1$ when simplified. Volume constancy tells us that $(1+\varepsilon_r)(1+\varepsilon_t)(1+\varepsilon_h)=1$ for engineering strains [3] but since $\varepsilon_h=0$ we can write that $(1+\varepsilon_r)(1+\varepsilon_t)=1$ and substituting for ε_t we can write that $(1+\varepsilon_r)(1+(\cos\alpha-1))=1$ and so we can solve for ε_r and we find that the corresponding perpendicular strain from volume constancy is $\varepsilon_r=(1/\cos\alpha)-1$.

2.2. Constant thickness forming

In order to evaluate the strains involved consider any arbitrary portion of the blank of radius r then the volume of this portion of the blank is $\pi r^2 t$ — (i), where t is the thickness of the blank.

Next consider the portion of the final shape that is formed by this volume of metal. Its volume is given by $\frac{2}{3}\pi((R+t)^3-R^3)(1-\cos\phi)$, where ϕ is the cone angle and R is the radius of the spherical part of the required shape, i.e. 95 mm. Since the volume of this arbitrary part is known from (i) above an equation can be solved for ϕ. The radius at the perimeter of this portion of the worked piece can be calculated as $R\sin\phi$.

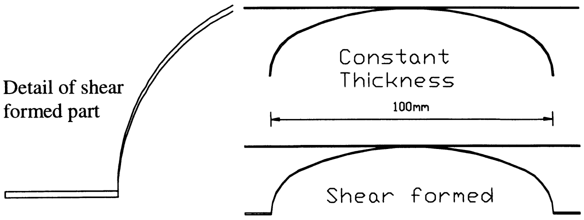

Fig. 2. Two distinct spinning processes.

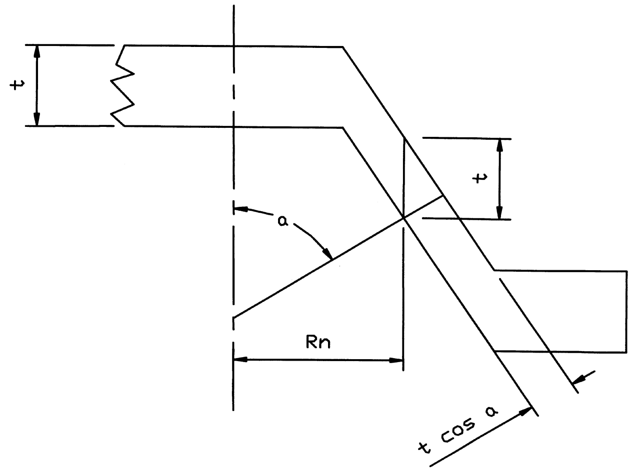

Fig. 3. Thickness reduction in shear forming.

The circumferential or hoop strain can now be considered. The original circumference is $2\pi r$, the new circumference is $2\pi R\sin\phi$ so the hoop strain is $(2\pi R\sin\phi-2\pi r)/2\pi r$ or $(R\sin\phi-r)/r$.

This is valid only for the spherical part of the worked shape, however, the strain for the part of the worked shape with radius 17 mm between the spherical and cylindrical sections can be evaluated in a similar way by considering the geometry involved. This part is toroidal in shape where R_T and r_T are the determining radii. For the chosen part these have values of $(95-17)\sin\Phi_1$ and 17, respectively, where Φ_1 is the limiting angle for the spherical portion of the part. The volume of the section of the torus between Φ_1 and Φ_2 (see Fig. 4) is

$$\Pi R_T[(r_T+t)^2-(r_T)^2](\Phi_2-\Phi_1) + \left[\frac{2\Pi((r_T+t)^3-(r_T)^3)}{3}\right](\cos\Phi_1-\cos\Phi_2)$$

The radial distance from the spinning axis is now $R_T+r_T\sin\Phi_2$ and again the radial strain can be calculated.

Fig. 5 shows the theoretical strain arising during both purely shear forming operation and during a constant thick-

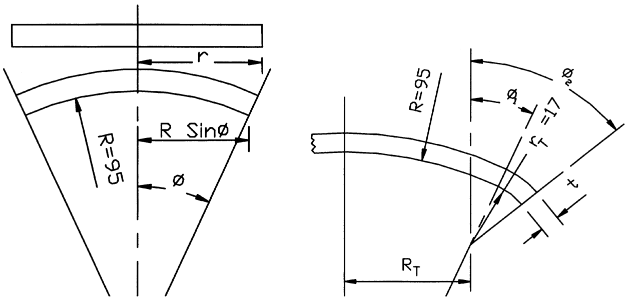

Fig. 4. Constant thickness forming.

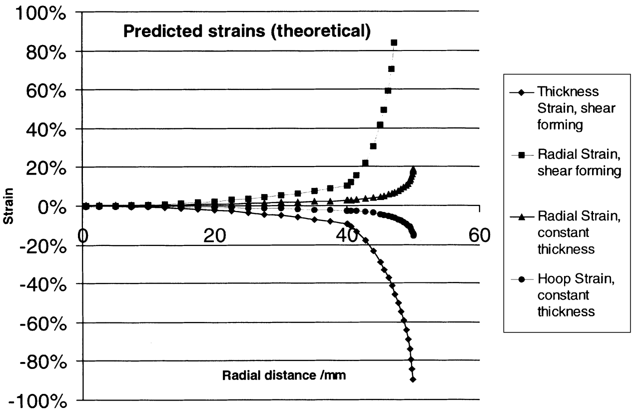

Fig. 5. Calculated strain as a function of the radial distance.

ness process. These theoretical curves can be used for comparison with experimental results.

The compressive hoop strains arising from the constant thickness calculation cannot easily be achieved in a single pass. In constant thickness spinning there is a reliance on a combination of tensile radial stress and compressive hoop stress to achieve metal flow. Buckling stresses can arise between the part of the workpiece under the roller and the undeformed flange. In practice, constant thickness spinning is a multi-pass operation.

In shear forming, however, metal flow is achieved by direct compression of the workpiece between the roller and the former. Although the absolute values for stress are larger in shear forming, a single pass is usually all that is required to produce the desired shape.

The radial position of an element in shear forming does not change, i.e. the normal distance from the axis of spinning is constant. In spite of this strain in a radial direction lying in the tangent plane can be large. It can be considered as the reciprocal of the thickness reduction. The thickness reduction is evident in detail in Fig. 2. The thickness reduces to zero when shear forming into a cylindrical shape from a flat blank is attempted. In practice the sharp corner shown in detail in Fig. 2 does not occur because of the radius of the roller. The practical result is shown in Fig. 6 where it can be seen that a definite forming limit for the sheet has been reached.

Fig. 6. Tensile failure where sheet thickness is reduced.

3. Experimental work

As previously described a spherical shape of radius 95 mm blending via a 17 mm radius into a 100 mm diameter cylinder was used for these experiments. A mild steel former having these dimensions was used. The lathe was powered by a 250 W motor, which drove the spindle at 450 rev min^{-1}. The lathe itself was a manual lathe intended for hand turning of soft materials (wood). The tool rest was adapted to provide a pivoting support for the spinning tool (Fig. 7).

Rollers of mild steel and nylon66 were used and the latter gave better results in that there was less tendency to groove the workpiece and it was therefore easier to achieve a uniform result.

Strain measurements were obtained from a pattern of circles of known size etched onto the blanks before spinning and measuring the size of these after spinning. The measurements were made using a Baty R400 optical projector.

A variety of different diameter blanks was used. The part shown in Fig. 8 was spun from a blank of 136 mm. The flange was too strong to allow the part to be easily formed. However, parts spun from smaller blanks presented no difficulty in being deformed to a fully spun condition but

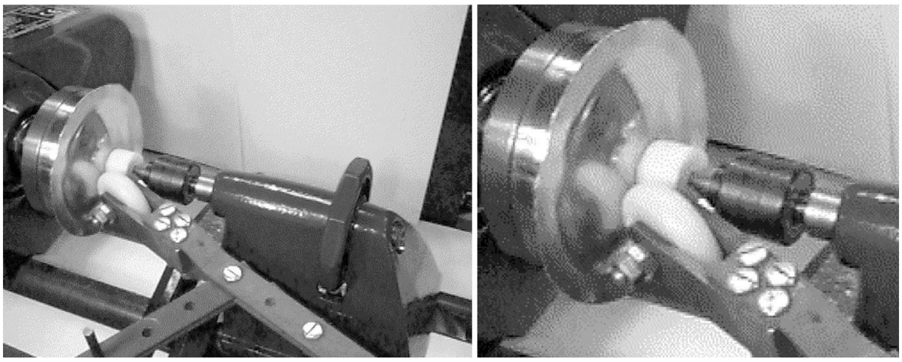

Fig. 7. The rig used for spinning 0.5 mm sheet metal.

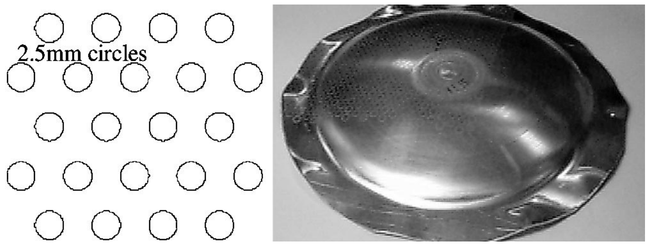

Fig. 8. The pattern used and an etched part.

they did not extend around all of the 17 mm radius to the cylindrical part where some difficulty might be expected. A size of 115 mm diameter was chosen for further investigation.

Two specific conditions of spun part were examined. The first being a single pass spinning operation on a 115 mm diameter blank, and the second a fully formed part produced from the same size blank. Fig. 9 shows the profiles achieved for each component.

Fig. 10 shows the measured strain compared to the theoretical curves presented earlier in Fig. 5. It can be seen that there is significant radial strain. Nearer to the centre the radial strain is close to the theoretical values for shear forming but it decreases to a value less than the theoretical predicted strain for constant thickness spinning as the distance from the centre increases. The magnitude of hoop strain remains close to the theoretical value for constant thickness spinning but the observed strains do not mirror each other thus implying that there is some thickness strain. Unfortunately, due to the small sheet thickness used it was difficult to measure the thickness strain accurately.

The strains arising after a single roller pass are shown in Fig. 11. It can be seen that both hoop and radial strains are positive, i.e. there is both axial and radial stretching. However, the radial strain is significantly larger than the hoop strain and in fact it follows the theoretical shear forming radial strain curve along its middle section, i.e. at radial distances between 20 and 35 mm. This suggests that the first pass in a conventional spinning operation is very much a

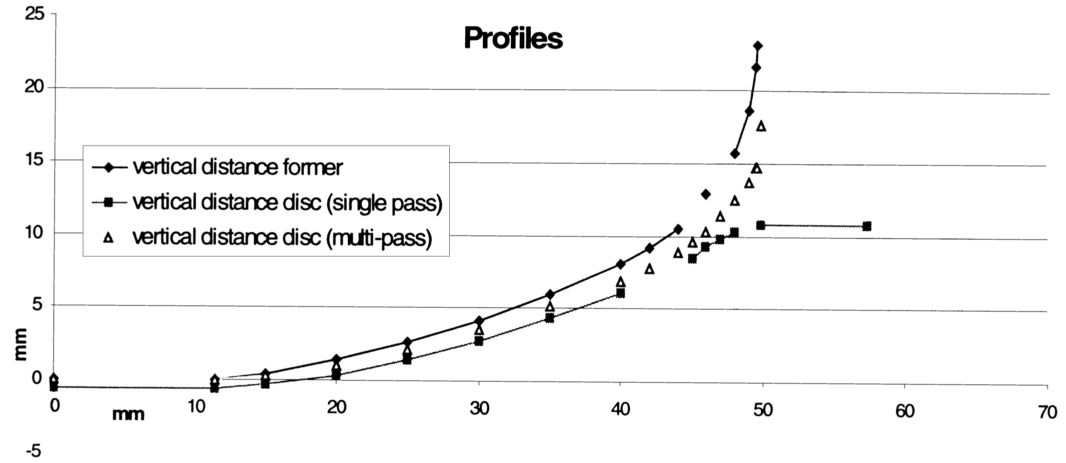

Fig. 9. A comparison of the profiles achieved with single and multi-pass spinning.

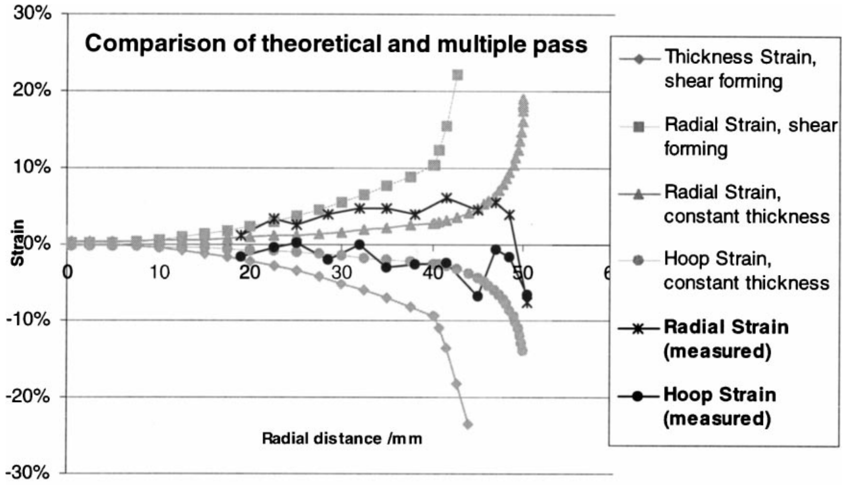

Fig. 10. Graph of strains arising after a multi-pass spinning operation.

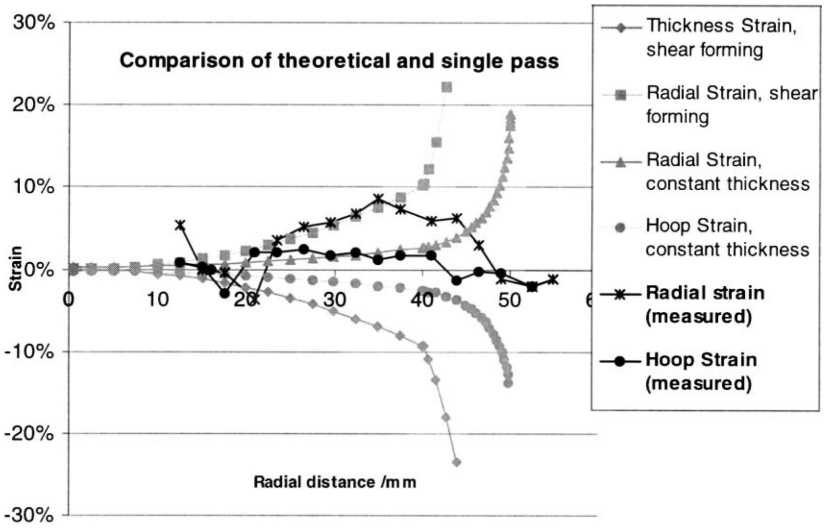

Fig. 11. Graph of strains arising from a single pass.

shear forming process. Compressive strains in the hoop direction are developed in subsequent passes.

4. Rationale for multi-pass spinning

It can be observed that there are a number of distinct stages in the production of a part using multi-pass spinning.

The first stage is when the roller comes into contact with the spinning disc or blank the disc is bent elastically as a cantilever. This is the approach stage of the first pass and is illustrated in Fig. 12. (The roller was brought into contact with a non-rotating blank for the purposes of this figure.)

The second stage creates the initial doming of the blank. It can be considered that the bending, as in Fig. 12, has reached the plastic limit and so a permanent deflection of the blank from its original flat stage is achieved as it is rotated under the action of a traversing roller. In fact there are two different mechanisms of plastic deflection. On the outer part of the blank the mechanism is the bending, as in Fig. 12, reaching the plastic limit. An analysis of this deformation was proposed [5] in order to provide a theoretical basis for the spinning forces involved. On the central part of the blank, i.e. close to the region clamped by the tailstock, plastic deformation occurs in a local area without the plastic bending of the blank [5]. Fig. 13 shows this mechanism. This cross-section shows the roller deflecting the workpiece into contact with the former. In fact a deformation of this nature can take place during several roller passes before the workpiece contacts the former.

The third stage is after the blank has achieved some depth. In this state the workpiece has become much stiffer and can react with much larger roller forces while it is not yet in contact with the mandrill or former during most of the roller pass. As soon as it is no longer flat it has far greater stiffness to resist the deflection mode illustrated in Fig. 12. Controlled deforming of the dome can now take place by a series of roller passes.

While this is a useful insight into what happens during the spinning process it is still very much a three-dimensional problem. The workpiece is being held by the tailstock and ultimately working forces have to be carried through this clamped area until the situation of Fig. 13 arises when the workpiece is touching the former and transmitting roller forces directly to the former.

While many texts admit that there are no laws defined which place the process variables in a clearly defined mathematical relationship, work such as [6] has developed

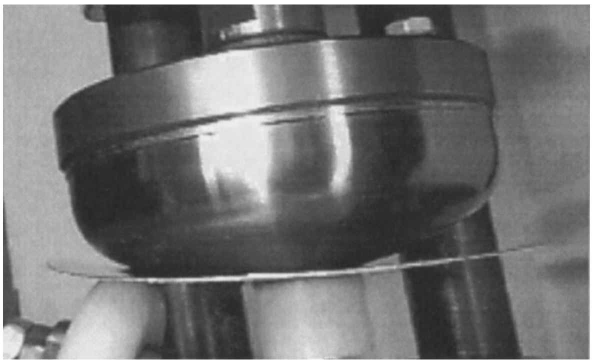

Fig. 12. Initial elastic deformation.

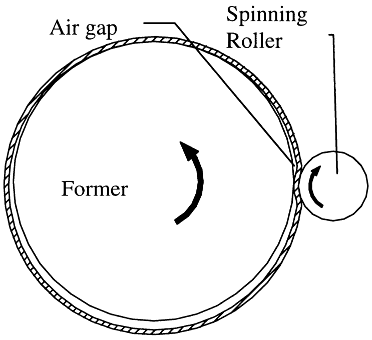

Fig. 13. Deformation in spinning after [2].

a thorough practical guide to spinning and the various process parameters involved.

Means of optimizing parameters such as processing time, accuracy of size shape and surface finish are well developed. Extensive publications and patents by Prof. Schwager of Forschungsgesellschaft Umformtechnik Stuttgart on the subject remain a little inaccessible to the authors being entirely published in the German language. Nonetheless, it is hoped that the investigation presented adds some insight to the process. Ref. [7] provides a very useful introduction to a large volume of material which is published mainly in the German language.

5. Conclusions

1. Calculations show that for conventional spinning the strains involved are much less than for shear forming.
2. Experiments show that there is some degree of shear forming involved in the first roller pass of conventional spinning.
3. Further modelling of the deformation modes and associated regions of plastic strain could usefully complement an approach to the problem using the finite element method where a relatively large overhead in computing time is involved in modelling incremental forming processes.

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