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ACHIEVABLE GEOMETRIES IN FLEXIBLE RADIAL PROFILE RING ROLLING

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Summary

Flexible radial profile ring rolling is a novel metal forming process that could potentially offer increased material yield and reduced downstream machining costs, without expensive part-specific tooling. A different approach is taken to previous experimental studies into the process, classifying three key flow patterns observed in the outer and inner profiling of a ring of intended L-shaped cross-section: axial flow and uniform/non-uniform circumferential flow. The axial height ratio of thick to thin sections and the ring aspect ratio are shown to be key factors determining which of these flow patterns occur. The trends in these factors suggest that the range of final geometries achievable by simple flexible radial profile ring rolling is limited due to undesirable non-uniform flow.

1. Introduction

Ring rolling is a bulk metal forming process that typically generates large (1-5m diameter) metal rings for engineering applications such as aerospace, energy conversion and oil and gas extraction industries. The process conventionally creates metal rings with a rectangular cross-section, unless a 'profiled' tool set is generated to suit each application.

Thus, in numerous low-volume ring rolling applications when producing a profiled tool is uneconomical a rectangular ring is made and machined to the final geometry. This results in considerable yield losses – the difference between input material and material in the finished product - and additional machining costs. Ideally, with a single set of 'universal' tools, it would be possible to convert rectangular/ barrelled metal ring preforms into a wide range of radially profiled rings.

A plausible – but as yet unproven - process is for a moving narrow inner mandrel or outer forming roll tool to incrementally generate a profile on the inner or outer radial surface.

2. Literature on Flexible Ring Rolling

2.1 (Inflexible) Profile Ring Rolling

A typical radial-axial ring rolling machine is shown in **Fig. 1**. A thick-walled ring 'preform' is thinned in the 'radial roll bite', between a powered forming roll and idly rotating inner mandrel. Two guide rolls centre and stabilize the ring. A second pair of tools, the lower and upper axial rolls, control the ring's axial height.

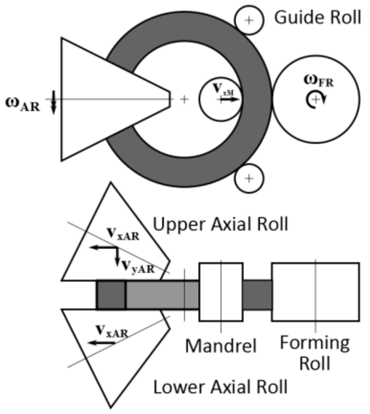

Fig. 1 Radial-Axial Ring Rolling Machine

This machine set-up can be used to generate a non-rectangular shaped ring cross-section if part-specific shaped tooling is used. Inner radial profiles require a shaped mandrel, while outer radial profiles require a shaped forming roll and guide rolls.

A comprehensive experimental study into profile ring rolling at University of Manchester Institute of Science and Technology, UK showed that profile filling – the extent to which the cross-section of the workpiece is changed by the profiled tool - requires internal axial flow of material from the radial section that is thinned the most into the section that is thinned the least. However, this is not guaranteed to occur [1].

The study concluded that in some cases adequate profile filling could only be achieved by starting with ring preforms that are initially shaped. Furthermore, in some applications a set of intermediate profiled tools were needed.

Similar conclusions were drawn by Marczinksi [3] in a discussion of industrial practice in 1980s; and in FEM simulation studies such as [4]. The need for intermediate tooling in generating thin-walled rings such as aero engine casings is also emphasised in the context of reducing yield losses in the industry [5].

2.2 Flexible Radial Profile Rolling

The part specific tooling required for profile ring rolling can be prohibitively expensive to develop for low-volume applications. This motivated work into flexible, or incremental, radial profile ring rolling.

An experimental flexible machine to process wax rings was developed at RWTH Aachen, Germany. **Fig. 2** shows this machine, with an inner mandrel that can move axially (vertically) and thus thin sections of the ring incrementally.

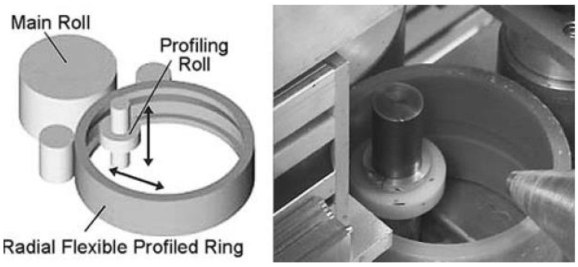

Fig. 2 Flexible Radial Profile Machine [6]

Because the tool acts on a small section of an otherwise unconstrained ring, there is an even greater range of possible material flow patterns than in conventional profile rolling. An empirical model for material flow was developed by Tiedemann [6], predicting the geometrical outcome of a simple tool movement. However, crucially this does not seem to have been 'inverted' to a) determine the tool movements required to achieve a certain shape and b) map out the range of shapes that can actually be achieved with this tooling set-up.

2.3 Novel Set-Ups To Influence Material Flow

Research is ongoing into novel machine set-ups to improve shaping. Three-roll cross-rolling has been investigated at Wuhan University of Technology, China. In this process, a thick-walled ring is formed between an outer forming roll and two outer 'passive rolls' opposite. Good filling of a deep outer radial groove was achieved; the passive rolls appear to enable the internal axial flow required for profile filling by preventing circumferential flow [7].

Research into cylindrical ring rolling has shown that it is possible to constrain a ring with a solid sleeve around its circumference, allowing only axial material flow (perpendicular to the conventional 'rolling direction'). This method led to improved filling of an inner profile [8].

The promotion of axial flow has also been investigated at Dresden University of Technology, Germany. In this technique, outer profiles are incrementally created on long, tubular rings [9]. A small section of tube is thinned radially by a profiled tool, and since circumferential flow is prevented by the rest of the workpiece the material flows axially.

However, none of these methods could be considered flexible: it is necessary to develop specific tooling for each new part.

2.4 Research Gap

As yet, no solution exists for reliably generating shaped profiles from non-shaped blanks without part specific tooling.

The basis for this solution could lie in an understanding of the flow patterns observed in flexible radial ring rolling, allowing us to determine the range of ring geometries that are achievable.

3 Flow Patterns in Flexible Radial Profile Ring Rolling

In order to understand the response of a ring workpiece to incremental radial thinning, an experimental study was carried out on a model ring rolling machine at University of Cambridge, UK; **Fig. 3**. The machine was developed to investigate the effect of novel machine set-ups on achievable ring geometries [10].

Fig. 3 Flexible Ring Rolling Machine

The results from a chosen sub-set of these experiments in which L-shaped profiles were targeted (see **Fig. 4a**) are discussed in this paper. This type of profile resulted in an interesting range of flow patterns, which are summarised further below. It is thought to be representative of some industrially relevant parts such as weld-neck flanges.

The model material plasticine, a proprietary oil-clay mixture, was used for the experiments. It has been widely used in prediction of flow patterns in metalworking since it has a similar stress-strain flow curve to engineering metals (distinct yield, strain rate hardening) e.g. [11].

Ring preforms were prepared in a mould; two sizes were developed representative of a 'thick' and 'thin' walled ring, with differing ratio of axial height to wall thickness, β, see **Fig. 4c**.

Six experiments were carried out on each size of preform. Each ring was partially indented by the mandrel to approximately 50% of its original thickness (γ) over 25, 50, or 75% of its original axial height (α), on both the outer or inner surface i.e. outer and inner profiling.

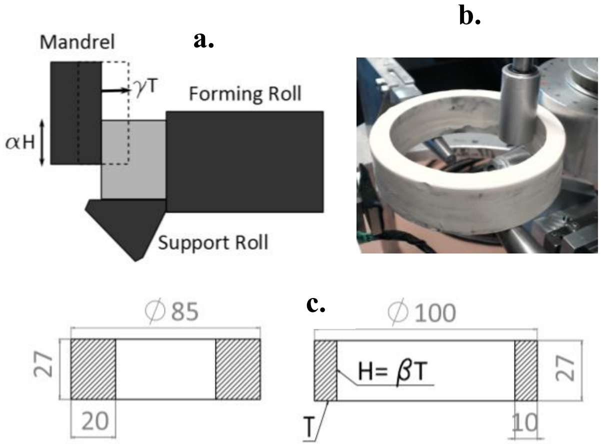

Fig. 4 a. Toolpath Parameters (inner profiling) **b.** Experimental Set-Up **c.** Preform Geometry

3.1 Flow Patterns Observed

Three main flow patterns were observable within the results: axial flow, non-uniform and uniform circumferential flow.

Fig. 5a shows the cross-section of a ring that has principally undergone axial material flow. In this experiment on a thick-walled preform, the outer forming roll tool acted over 50% of the ring's initial height (α=50%).

The ring has mostly grown in height, and hardly at all circumferentially, indicating that axial material flow was dominant. It appears that the bottom section of the ring was sufficiently large that it remained almost rigid; it was not possible for the action of the tool to achieve sufficient hoop stress in this region for circumferential yield.

The second flow pattern, non-uniform circumferential flow, is shown in **Fig. 5b**. In this, an inner profile was generated with α=50%, but on a *thin-walled* preform. The ring appears almost conical, with the upper section growing in circumference, and the lower section less-so, leading to a 'bent' cross-section. There must have been sufficient tensile hoop stress developed in the lower section to allow it to be partially stretched and bent, allowing the upper section to flow in the rolling direction (and slightly axially).

Finally, (**Fig. 5c**) shows uniform tangential flow, for an inner profile with α=75%. The ring cross-section remains square as originally intended. This seems to be possible because: a) sufficient material is able to flow internally axially from the top to bottom sections, and b) sufficient hoop stress is developed for it to yield circumferentially.

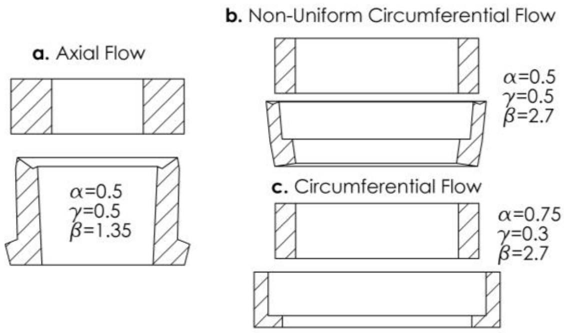

Fig. 5 Flow Patterns Observed. **a.** Axial **b.** Non-Uniform and **c.** Uniform Circumferential

3.2 Analytical Modelling and Simulation to Predict Flow Patterns

Predictions into when a particular flow pattern will occur were made by an upper bound approach, and also inferred from a finite element method (FEM) study of inner profiling.

In the upper bound approach an idealised rigid-plastic velocity field was made for each flow pattern. It was assumed that the velocity field requiring the least work input (plastic work, shear at discontinuities, and friction at the rolls) will be indicative of the real flow pattern.

Fig. 7a shows the results of this upper bound approach by plotting the mode with least work for discretized ratios of β and α.

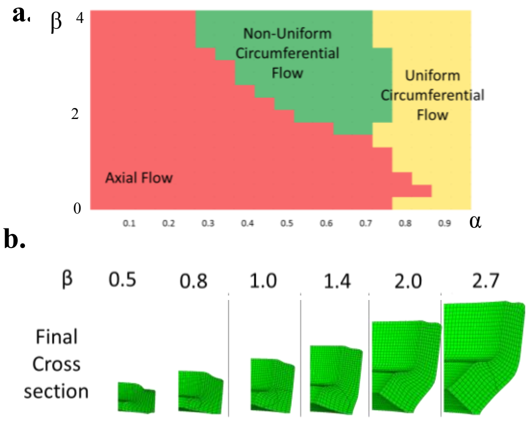

Fig. 7 Prediction of flow patterns: **a.** Upper Bound Map, **b.** FEM simulation

If the tool acts over a small section of the ring (small α), axial flow is predicted. For large α, uniform circumferential flow is predicted. For intermediate values of α, the ring height to thickness ratio, β, becomes important: thinner walled rings (large β) are predicted to show non-uniform circumferential growth.

A parametric study was made into the effect of varying the ratio β for α=50%, using a series of 3D FEM simulations. The simulations were carried out in ABAQUS, with the explicit solver. The simulation suggests a transition from axial growth to non-uniform circumferential growth, as shown in **Fig. 7b**. This is broadly consistent with the experimental results and upper bound analysis prediction.

4. Achievable Geometries

An illustrative evaluation is now made into the range of achievable geometries from such a process. An operating window approach is used, for L-shapes with a final (not initial) geometry ratio, A = 0.5, varying B, and C: see **Fig. 8.**

There is potential to make use of axial flow by first rolling to the required outer radius and then shaping the ring upwards. This strategy is limited to relatively low aspect ratio rings (B<1.5-2); and there is a probable upper limit on the variation in thickness (e.g. C>0.75).

For large B, although the non-uniform circumferential flow mode appears to generate rings with unacceptable conicity, it might be possible to make use of this flow pattern by first acting on the surface of the ring that is to be thinned most, and then acting on the bottom section so as to correct for the conical shape. However, this approach is unlikely to achieve high profile filling (C>0.2-0.4), and would require careful control of the order and amount of indentation on each pass.

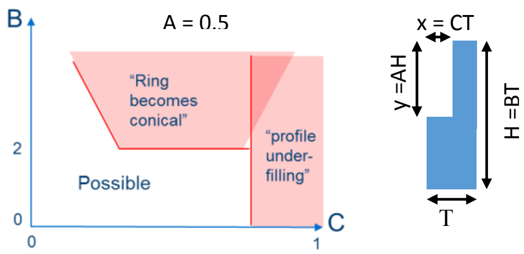

Fig. 8 Operating Window for L-Shapes

4. Discussion and Conclusions

This paper set out to find out if a ring rolling process for making shaped rings with flexible tooling was possible. Such a process could potentially reduce yield losses and downstream machining costs in low-volume applications.

The research described here takes a step forward in the understanding and classification of flow patterns observed in a candidate process.

It appears that achievable geometries from such a process is limited. Considerable scope remains to extend this work by considering different target geometries, and crucially, how different toolpaths and additional tooling can increase the range of achievable geometries.

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