Available online at www.sciencedirect.com

ScienceDirect

IFAC-PapersOnLine 49-20 (2016) 244–249

Curvature control in radial-axial ring rolling ⋆

Matthew R. Arthington * Christopher J. Cleaver ** Jianglin Huang * Stephen R. Duncan *

* *Dept of Engineering Science, 17 Parks Road, Oxford, OX1 3PJ, UK (e-mail: matthew.arthington@eng.ox.ac.uk).*
** *Dept of Engineering, Cambridge, CB2 1PZ, UK*

Abstract: Radial-axial ring rolling (RARR) is an industrial forging process that produces seamless metal rings with uniform cross-section using one radial and one axial rolling stage. Conventionally, the ring products are circular and the process is tightly constrained using guide rolls for stability, and to ensure the circularity and uniformity of the ring. Recent work has shown that when guide rolls are omitted, stability can be maintained using differential speed control of the roll pairs. However, achieving uniform curvature in this unconstrained configuration was not always possible when the controller only centred the ring within the rolling mill. In addition to the regulation of constant curvature in circular rings, differential speed control in unconstrained rolling offers an opportunity to bend the ring about the mandrel to create shapes with non-uniform curvature, for example: squares, hexagons, rings with flat sections, etc. We describe a control technique for creating non-circular rings using the rolling hardware of a conventional RARR mill, machine-vision sensing and differential speed control of the rolling stages. The technique has been validated for an industrial material in numerical simulations using the finite element method and also demonstrated on a desktop-scale RARR mill using modelling clay to simulate metal at elevated process temperatures.

Keywords: Process automation, process control, sensor systems, image processing, industrial control, forging, rolling

1. INTRODUCTION

Conventional radial-axial ring rolling (RARR) of cylindrical rings is an industrial forging process that produces seamless circular rings of metal with uniform cross-section, ASM (1988). A cylindrical ring of metal is rolled repeatedly by two rolling stages so that its wall thickness reduces and its diameter increases. Figure 1 provides a schematic overview of the process; a pair of cylindrical rollers (the mandrel and the forming roll) apply compressive forces to the radial faces; another pair of conical rollers (axial rolls) apply a compressive force to the faces of the ring. The forming roll and the conical rollers are driven to rotate the ring by friction, the mandrel is driven linearly but rotates freely. Conventional RARR mills also use two additional guide rolls to apply a radial force to help keep the centre of the ring aligned with the machine and achieve constant curvature in the XY plane (hereafter referred to as curvature), as shown in Figure 1. In this paper we restrict the processing parameters to a constant axial-roll separation.

Much research on ring rolling has focused on achieving the desired outcomes in the conventional process, Allwood et al. (2005) and Allwood et al. (2004). More recently, work has been published on developing machine-vision sensing to provide feedback on the current geometrical state, Meier et al. (2010), Arthington et al. (2014). This has led to improvements in monitoring the deformation state of the ring *in-situ* and also to the novel use of RARR to produce rings with variable radial wall thickness, Arthington et al. (2015). Amongst others, Arthington et al. (2015) showed

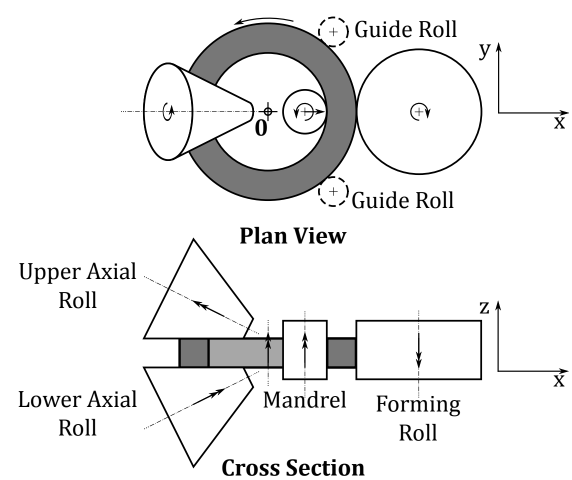

Fig. 1. A schematic diagram of the conventional RARR forging process showing the rolled ring shaded in grey. The radial roll gap is the region of the ring between the mandrel and the forming roll. The centre of the machine is taken as the origin, **0**, and is initially coincident with the axis of the ring.

⋆ This work was funded by the Engineering and Physical Sciences Research Council (EPSRC) UK.

10.1016/j.ifacol.2016.10.128

that the stabilising and centring function of the guide rolls could be replicated by controlling the relative driving speeds of the forming and axial rolls to keep the ring centred with respect to the machine, potentially removing the need for guide rolls.

Moon et al. (2008) presented a study into (radial-only) ring rolling *with* guide rolls that investigated the formation of polygonal shapes in rolled rings when the forming ratio (mandrel feed rate vs forming roll speed) exceeded a critical value. In Moon et al. (2008)'s study, these polygonal shapes were considered defects to be avoided, however non-circular rings represent a class of rolled ring products that have various applications, and the advantages of ring rolling - fast production speeds, material savings, uniform material properties, etc. - could be used to make savings in time, energy, material and labour over other production techniques.

In ideal conventional rolling the value of the moment required for circular ring curvature changes smoothly throughout the process. However, disturbances from sources such as variable thickness, changing contact conditions, irregular heating, material variations, and dynamic instabilities can apply unforeseen loads to the ring, resulting in non-circular curvature that may not be corrected by simply centring the ring.

In this paper, we demonstrate control of the ring curvature to create specifically shaped rings with uniform wall thickness. This technique makes ring rolling a significantly more flexible process and also offers a way to regulate circular curvature more quickly than a centring-only approach.

The curvature of the segment of ring inside the radial roll gap region is altered by instructing the axial roll pair to change its feed speed relative to the feed speed of the forming roll. This action applies a bending moment about the mandrel. Along with the compressive radial force in the radial roll gap, the applied bending moment creates a plastic hinge, where the ring exhibits a permanent change in curvature. The size of the change in curvature depends on the angle of rotation of the plastic hinge, and is controlled by prescribing the Y_c coordinate of the centre of the ring, which must be positioned by the differential speeds of the rolling stages.

The deliberate actuation of the ring curvature (using this method or otherwise) has not previously been seen in the literature. With the potential to create shaped rings using conventional RARR rolling hardware the process can be used to produce a great variety of rolled-ring products.

2. SENSING

The sensing of the ring geometry permits the controller to actuate the rolls relative to the material in the ring. In conventional ring rolling, sensors are usually limited to measuring the bulk state of the ring, such as its diameter and thickness. In this section we provide a brief overview of the sensing technique and the procedure for creating variable thickness rings; more details can be found in Arthington et al. (2014) and Arthington et al. (2015).

2.1 Measuring current state of ring geometry

The sensor used in this process is a calibrated optical camera, which is trained on the XY plane of the ring. From this vantage, the upper surface of the ring is visible against a contrasting dark background. What follows is a description of the processing that takes place for each frame acquired by the camera.

First, the inner and outer edges of the ring wall are located using standard edge detection techniques, as described in Arthington et al. (2014). Once found, geometric shape parameters for the ring can be computed. Initially, ellipses are fitted to the inner and outer edges (which are not necessarily circular), which allows an approximate measure of the ring centre, $\mathbf{c}_0$, to be obtained from the mean of their centres. The radii of the inner and outer edges, $\mathbf{r}_{i0}(\theta) = [x_{i0}(\theta), y_{i0}(\theta)]^T$ and $\mathbf{r}_{o0}(\theta) = [x_{o0}(\theta), y_{o0}(\theta)]^T$, measured from $\mathbf{c}_0$ are calculated as functions of angle from the X axis. An approximate 'midline' [1] is computed using the mean radius, $\mathbf{m}_0(\theta) = (\mathbf{r}_{i0}(\theta)+\mathbf{r}_{o0}(\theta))/2$. An improved estimate of the ring centre is then found,

$$\mathbf{c}_1 = [X_c, Y_c]^T = \overline{\mathbf{m}}_0(\theta), \tag{1}$$

the radii recalculated and a more accurate midline, $\mathbf{m}_1(\theta)$, computed using the same method.

Calculating $\mathbf{m}_1(\theta)$ in this way can only provide a true estimate of the midline when the midline is circular, but when the ring is bent an improved estimate has to be found. The method selected for calculating an updated midline position was to apply a low-pass filter to $\mathbf{m}_1(\theta)$ (necessary for the exclusion of quantisation and noise disturbances), and parametrise it as a function of its arc length, s, producing $\mathbf{m}_{s1}(s)$, calculate its normal direction, $\widehat{\mathbf{n}}(s) = \frac{d^2\mathbf{m}_{s1}/ds^2}{|d^2\mathbf{m}_{s1}/ds^2|}$ and then incrementally search along $\mathbf{m}_{s1}$ for the intersection of the normal with the inner and outer edges to find $\mathbf{r}_{si}(s)$ and $\mathbf{r}_{so}(s)$. The updated midline coordinate was then calculated as $\mathbf{m}(s) = (\mathbf{r}_{si}(s)+\mathbf{r}_{so}(s))/2$ and thickness taken as $T_s(s) = |(\mathbf{r}_{so}(s)-\mathbf{r}_{si}(s))|$.

A single point of material in the initially-uniform wall of the ring was selected to be the origin, corresponding to $s = 0$. A radial marker was applied to the ring's upper surface here. Other markers of a different colour were applied to the ring in an evenly-spaced radial spoke pattern on the initial ring, as shown in Figure 2. The markers were used to locate regularly-spaced fixed points of material in the circumference of the ring. The tangential centres of the markers were identified by looking for changes in hue and brightness along $\mathbf{m}$. The markers were drawn radially and used sparingly (12 here) so that they were visible even after large deformations of the wall.

Integrating the thickness along the arc length calculated the volume as a function of arc length (assuming constant axial height), $v(s) = \int_0^s T_s(\tau)d\tau$ and allowed the curvature, κ, (described in Section 2.2) to be calculated as a function of volume fraction, $v_f = v/V_{total}$, around the circumference instead of arc length. This provided $\kappa(v_f)$ for comparison with its targeted values in the final ring state, no matter the current ring diameter and thickness

[1] The midline is the closed curve running along the centre of the ring wall, equidistant between the inner and outer edges.