Numerical Analysis of Strip-Roll Conformity in Tension Levelling

I. Roberts[1,2]*, C. Wang[1)], D. Mynors[1)], P. Adams[2)], K. Lane[2)], P. Unwin[2)]

[1)] Department of Engineering and Technology, University of Wolverhampton, Telford Campus, Telford, TF2 9NT / United Kingdom; [2)] Bronx Engineering Limited, Brierley Hill, West Midlands, DY5 1TX / United Kingdom

* Corresponding author: E-mail address: Ibiye.roberts2@wlv.ac.uk; Tel.: +44 1384 26 7465

Abstract

In tension levelling, conformity of the sheet metal strip to the rolls is a necessary condition for plastic elongation to occur. Strip-roll conformity occurs over an arc of contact and is influenced by the applied tension. In describing the arc of contact of the strip around a roll, simple theoretical analyses have assumed an 'effective' radius for predicting the curvature characteristics. The plastic hinge effect that occurs around the rolls makes this very unlikely. This paper presents experimental work and finite element analysis carried out using draw-quality steel under static conditions. The influence of parameters like the applied tension, roll diameter, depth of penetration and pitch on the conformity region are presented.

Keywords: Numerical methods, Tension levelling, Conformity

Introduction

Tension levelling is used to correct shape defects in the metal strip that have been induced by upstream rolling processes as well as to alter or improve inconsistent mechanical properties within the strip. The strip material is subjected to a series of alternating bends under significant front and back line tension.

The material with defects such as wavy edges, centre buckles and cambers possess can be considered to have differential fibre lengths across the width. According to Morris et al. (2005), the process ensures equalisation of fibre lengths occurs in which the simple stretching process is augmented by bending work. From the work of Shuhua and Qing (2002), the bending work component enables desired elongations to be achieved at significantly lower strip tensions.

One necessary condition in the tension levelling process is the adherence of the strip to the work rolls. The deformation of strip around the rolls in a stretch-bending operation is an important feature in describing the conformity characteristics of the process. Controlled elasto-plastic deformations usually take place in the strip segments near the work rolls where the strip is bent and resultant plastics strains are induced according to Steinwender et al. (2010). The strip curvature characteristics are also important as they govern the stress distribution in the strip and ultimately the pulling tensions on the entry and exit ends.

Predicting the curvature of the strip around the rolls has been a challenge to researchers in the subject area. This is primarily due to the plastic hinge formation that occurs when the strip conforms to the roll and is plastically elongated. Previous theoretical analyses as stated in Li et al. (2007) have attempted to describe the curvature by using an *effective radius* with limited success. Their descriptions of the curvature characteristics do not include the influence of the arc of contact but assumes that the arc is large enough to ensure conformity.

In this paper, experimental work on studying the conformity characteristics across two rolls is presented. A three-dimensional finite element analysis model for studying the conformity characteristics of the metal strip to rolls under static conditions is also presented.

Experimental Procedure

A two-roll test jig shown in **Fig. 1** was built to provide the stretch-bend condition. The strip material used for the experiments was cold-rolled steel (EN 10130-DC01-A) used for forming and deep drawing (BSI, 2006) with a minimum yield strength of 280 MPa. The strip length, width and thickness used for the tests were 60 mm, 20 mm and 0.3 mm respectively. A calibrated load cell provided the back tension readings in the strip for various applied tensions. The strip was threaded through the rolls as shown in **Fig. 1** while the tension was applied by means of a bolt tensioning mechanism. The purpose was to study the curvature distribution across the rolls while varying the roll settings and tension in the strip under static conditions. The tests were performed in percentage steps of yield tension of the material (up to 10% yield tension).

Figure 1. Test jig

The variables in the experiment were the roll pitch, penetration and the strip tensions. The size of the roll remained constant in all test cases.

Experimental Results

The strip paths for different tensions were captured and analysed to obtain the curvature distribution for regions in the close proximity of the rolls as shown in **Fig. 2**.

Using MATLAB, the derivatives from which the curvature were obtained using the relation provided in Megson (2002):

(1)

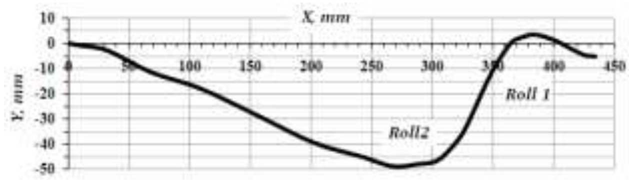

Figure 2. Strip path with no tension applied

Fig. 3 shows the curvature for the zero tension case. The peaks represent the contact regions with the rolls.

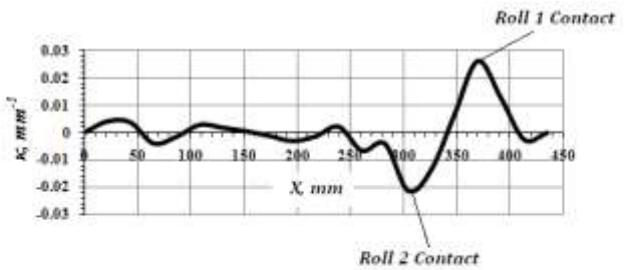

Figure 3. Curvature distribution with no applied tension

Fluctuations in strip curvature on the left hand side were clearly captured in the distribution as the strip changed from a convex bend to a concave bend (i.e. contraflexure) leading up to Roll 2. The early curvature fluctuations could also be attributed to the inherent coil set from the parent coil prior to testing.

The curvature distribution shows that $\kappa > 0.02$ at the contact regions between the strip and Rolls 1 and 2 indicating that the curvature of the strip approaches the roll curvature. The plots show a steady rise to the extreme values, implying a continuous change in the curvature for points in close proximity to the rolls. This clearly shows that the assumption of an 'effective' radius is not realistic. **Fig. 3** shows the importance of accurate prediction of the curvature in the determination of the tensions and tension drops associated with the stretch-bending process.

Applying tension causes the strip to adjust to a new equilibrium position. **Fig. 4** illustrates this clearly.

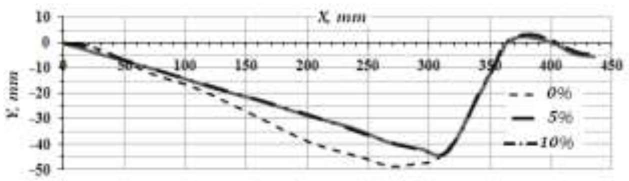

Figure 4. Tension effect on strip path

The strip path shows no significant change between the 5% and 10% tension cases due to the low flexural stiffness of the strip. The same trend was observed for different pitch settings. The results show that whereas the wrap around Roll 1 was not altered a great deal, the wrap around the higher tension Roll 2 was changed significantly with tension application.

Logically, the strip takes the path of minimum resistance and this has been shown to be the case from studies conducted by Vin 2000 involving air bending of metal sheets. A method of predicting the curvature of the strip which involved minimising the bending energy in the system was used. By implication, the stretch-bending curvature follows a path of minimum deformation energy.

Influence of Mesh Penetration. Fig. 5 and **Fig. 6** show the curvature distribution at zero tensions for various mesh penetration settings. It clearly shows that the curvature distribution is responsive to the mesh penetration.

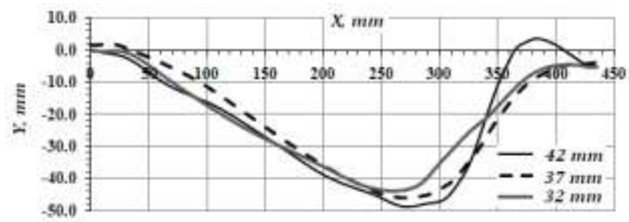

Figure 5. Effect of mesh penetration on strip path

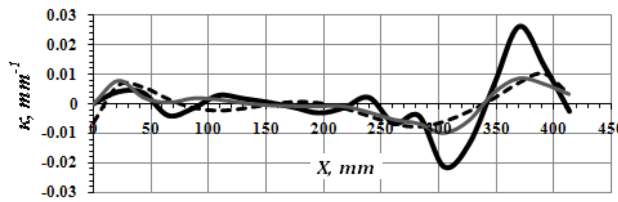

Figure 6. Effect of penetration on curvature

Fig. 5 shows an increase in the steepness of the strip path between the rolls as the mesh increases. In all the cases considered, the curvature changed continuously around the roll supporting the earlier finding. The curvature distribution in **Fig. 6** shows that as the penetration decreases, the curvature around the rolls relaxes.

Influence of Roll Pitch. To prevent the occurrence of mismatch between the rolls, the mesh penetration was set to 27 mm for this study. **Fig. 7** and **Fig. 8** show the strip paths and curvature distribution for various roll pitches. The results show that the roll pitch has an effect on the curvature distribution.

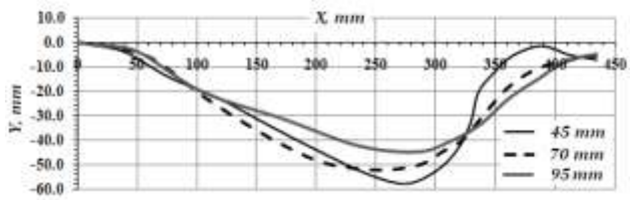

Figure 7. Influence of pitch on strip path

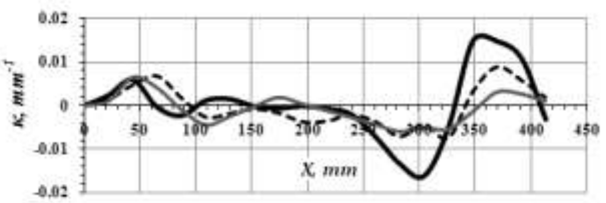

Figure 8. Influence of pitch on curvature

Increasing the pitch relaxes the curvature of the strip around the roll. It can be seen from **Fig. 8** that the closely spaced roll significantly increased the strip curvature. This supports industry practice where the rolls are closely spaced to cause the bend radius in the proximity of the rolls to be forced below the elastic limit radius over an extensive distance around the roll, hence utilising much of the bending work.

Effect of parameters on size of conformity region. The wrap-around contact lengths on the strip were measured at the end of the tests (i.e. after 10% yield tension loading) to study the influence of the various settings. **Fig. 9** shows that the penetration has a significant effect on the arc of contact. The results show that as the penetration increases, the arc of contact about both rolls also increases steadily. The results also show a decrease in the contact length with increasing pitch. It is interesting to note the reversal of contact behaviour around Roll 1 and Roll 2. The noticeable drop in the wrap length with pitch observed from 45 mm to 70 mm was a direct consequence of the physical constraints of the test jig. A slight decrease from the 70 mm to 95 mm pitch cases in the wrap lengths around Roll 1 and Roll 2, which is a more representative trend.

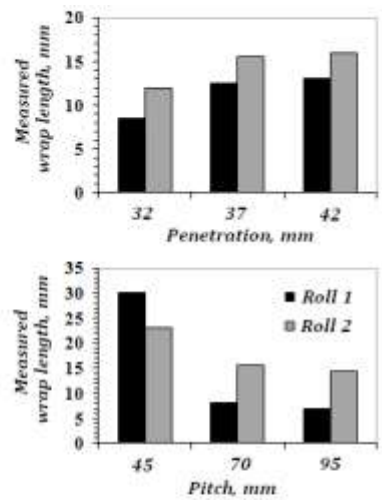

Figure 9. Influence of pitch on contact length

The results show that increasing the pitch and decreasing the mesh would cause a reduction in the wrap length.

From the foregoing, it could be said that to maximise conformity around the roll, a low pitch and a high penetration would be required. However, practical experience shows that a number of undesirable downstream effects may result. While the pitch is limited by machine design and roll selection, a high mesh penetration results in significant crossbow in the strip as a result of the residual stresses that remain in the strip outer surface after levelling (Ginzburg and Ballas, 2000).

It is important to note that the plastic elongation is not just limited to the conformity region but also the regions where the strip has been forced below its elastic limit radius. Furthermore, the level of conformity governs the amount of bending energy in the strip because it is a function of the wrap length and the bend radius. The changing radii around the rolls, which have been shown to be the case, determine the bending moment distribution and hence the tension drops (i.e. bending losses) across these plastic elongation zones (Marciniak et al., 2002).

Numerical Model

A finite element analysis study was carried out using ANSYS. The model consists of two-half rolls and a strip. An elasto-plastic linear isotropic hardening model using von Mises criterion and an associative flow rule was used for all materials. The strip was modelled using 3-D shell elements (SHELL 281) while the rolls were modelled using solid elements (SOLID 185). 3-D contact and target elements were employed to model the interaction between the strip and the roll and were assumed to be frictionless. **Fig. 10** shows the finite element model. The experimental conditions were simulated: (1) addition of mesh penetration, and (2) incremental addition of tensile load up to 10% of the yield tension. Geometric specification, material properties were set similar to the experiments. The boundary conditions were applied in a representative manner to the experiments. The simulation model did not take into account heat losses due to plastic work.

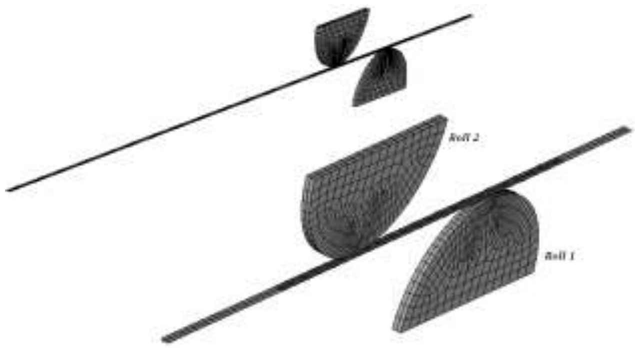

Figure 10. Finite element model

Simulation Results

Stress and Strain Distribution. Fig. 11 shows the stress and strain distributions after addition of mesh penetration for the 70 mm pitch case. The strain results obtained showed a resultant membrane plastic elongation of 0.035% around Roll 1 while the region around Roll 2 remained largely in the elastic regime. Discounting end effects, the predicted maximum stress in the strip around

Roll 1 exceeded the yield strength, indicating some degree of strain hardening.

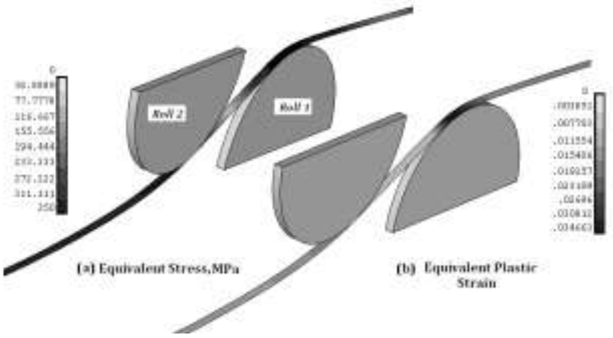

Figure 11. (a) von Mises Stress, and (b) Equivalent strain distribution

Curvature Distribution and Comparison with Experiments.

Comparison of the simulation model curvature distribution and that obtained in the experiments is shown in **Fig. 12**. It shows strong similarities in the behaviour of the strip around the rolls. However, the simulation model predicts a lower exit curvature than the experiments, which could be attributed to the numerical model assumptions.

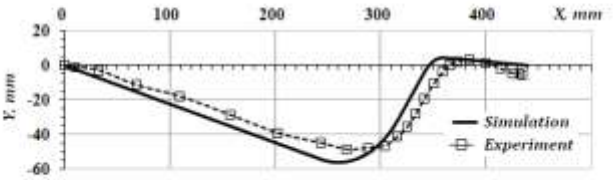

Figure 12. Strip path under zero tension

Fig. 13 shows the strip path under applied tension. The path for the 10% yield tension is similar to that obtained earlier in the experiment.

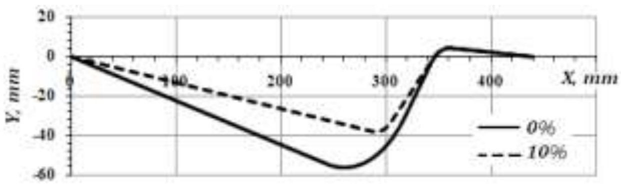

Figure 13. Simulation prediction of tension on strip path

Discussion

The experimental findings from this work agree with finite element analyses studies of a tension leveller by Steinwender et al. (2010). They showed a similar distribution where the curvature peaked leading up to work rolls. The curvature was then found to reduce with increasing distance away from the rolls up to a point of inflexion (given by the intercept on the horizontal axis) at a distance between the centres of the rolls. The occurrence of single distinct peak points in the strip curvature distribution at the strip-roll contact region represented a line contact along the width of the strip, whereas the occurrence of a rounded peak in the distribution represented an area of contact where the work roll radius and the bend radius of the strip coincide. The curvature distribution plots observed in this work do not exhibit sharp peaks, but show smooth variations leading up to a maximum curvature value.

As the strip meanders through the rolls, it does so in constantly changing radii. The region of plastic elongation is not only limited to the zone of conformity, but to regions around the rolls where the bending strain exceeds the yield strain. The radius below which plastic elongation starts to occur in bending is referred to as the limiting elastic radius and is dependent on the yield strength of the strip as stated in Marciniak et al. (2002).

Conclusion

Experimental investigations of the curvature characteristics in a static stretch-bending process of draw-quality steel have been presented. The following conclusions can be drawn:

- The curvature of the strip is constantly changing around the vicinity of the rolls
- Increasing the mesh penetration increased the curvature around the rolls
- Decreasing the pitch increased the curvature around the rolls
- A balance between increasing penetration and decreasing pitch would be desired to maximise strip-roll conformity as well as suitable downstream properties.

A finite element model also corroborated the experimental findings on the curvature distribution for the mesh penetration and applied tension. The proposed numerical model can represent the typical bend-stretching process. This model would be used in future work to obtain reduced mathematical relationships between the process parameters and the physical attributes of the conformity region.

References

BSI (2006). BS EN 10130: 2006 - Cold rolled low carbon steel flat products for cold forming Technical delivery conditions, British Standards International.

Ginzburg, V. B. and Ballas, R., 2000. Fundamentals of Flat Rolling Manufacturing Engineering and Materials Processing, CRC Press.

Li, S.-z., Yin, Y.-d., Xu, J., Hou, J.-m. and Yoon, J., 2007. Numerical simulation of continuous tension leveling process of thin strip steel and its application, Journal of Iron and Steel Research, International, 14, p. 8-13.

Marciniak, Z., Duncan, J. L. and Hu, S. J., 2002. Mechanics of Sheet Metal Forming, 2nd Edition, Butterworth Heinemann.

Megson, T. H. G., 2002. Structural and Stress Analysis, Butterworth Heinemann.

Morris, J. W., Hardy, S. J. and Thomas, J. T., 2005. Effects of tension levelling process parameters on cold rolled strip characteristics using a designed factorial analysis

approach, Ironmaking and Steelmaking, 32, p. 443-448.
Shuhua, L. and Qing, L. T., 2002. Research for the Theory of Stretch-Bend, Metallurgical Equipment, 132, p. 8-13.
Steinwender, L., Kainz, A., Krimpelstätter, K. and Zeman, K., 2010. Computational analysis of the curvature distribution and power losses of metal strip in tension levellers, IOP Conference Series: Materials Science and Engineering, 10, p. doi:10.1088/1757-899X/10/1/012135.
Vin, L. J. D., 2000. Curvature prediction in air bending of metal sheet, Journal of Materials Processing Technology, 100, p. 257-261.