OPTIMAL SELECTION OF MACHINE PARAMETERS IN TENSION LEVELLING OF SHEET METALS

Ibiye Roberts

Bronx Engineering Limited
Brierley Hill
West Midlands, DY5 1TX, UK
iroberts@bronx.co.uk

Diane Mynors
Department of Engineering
University of Wolverhampton
Telford Campus
Telford, TF2 9NT, UK
d.j.mynors@wlv.ac.uk

Chang Wang
Department of Engineering
University of Wolverhampton
Telford Campus
Telford, TF2 9NT, UK
c.j.wang@wlv.ac.uk

Paul Adams

Bronx Engineering Limited
Brierley Hill
West Midlands, DY5 1TX, UK
pnadams@bronx.co.uk

Kelvin Lane

Bronx Engineering Limited
Brierley Hill
West Midlands, DY5 1TX, UK
klane@bronx.co.uk

Peter Unwin

Bronx Engineering Limited
Brierley Hill
West Midlands, DY5 1TX, UK
peterunwin@bronx.co.uk

ABSTRACT

Shape correction using tension levelling has been well established over the years in the aluminium and steel industries for meeting high standard flatness requirements. The process utilises reverse bending under tension across relatively small diameter rolls to produce a resultant effect of uniformly stretched sections with minimal residual stresses across its width and thickness. This requires a controlled leveller set up. In most cases, the setting of a leveller for best results depends heavily on experience and is not fully understood. This paper presents the findings of a newly developed tension levelling predictive model. The model uses the concept of energy minimisation of the bending path of strip across the roll configuration. Field data from an industrial tension leveller were used to validate the model. The predicted tensions were within 12% of those measured. The findings provide a potential for significant energy savings of more than 30% on typical settings.

Keywords: Tension Levelling, Sheet Metal Processing, Mesh optimisation.

1 INTRODUCTION

Shape correction in the form of coil set removal, wavy edges, centre buckles and quarter buckles in metal sheets can be corrected by using a tension leveller. The tension levelling process does this by permanently and uniformly elongating sections of the sheet through a series of reverse bending cycles with the aid tension. This main difference between the tension levelling process and other sheet metal levelling processes is the permanent mid-plane elongation and stress equalisation after processing. This is achieved by using relatively small diameter work rolls and relatively large diameter anti-curvature rolls (for longbow and crossbow correction) positioned at the exit end of the tension leveller. In some cases, the anti-curvature rolls are the same size as the work rolls but with carefully set roll gaps. For the purpose of this paper, the term 'work rolls' is also used to describe the anti-curvature rolls.

The roll configuration selection and work roll gap settings (i.e. intermesh) of a tension leveller have depended largely on the experience of the machine operator and to a great extent on trial and error. This method can be exhaustive and expensive especially with the introduction into the market of thin high strength steels like DP, TRIP and HSLA steels.

The performance indices of a tension leveller are the: 1) pull tension and drag tension capacities, 2) flatness correction and residual stress elimination, and 3) tension difference across the leveller. These have economical and engineering implications. Although the flatness is the qualitative outcome, from an economical perspective, the pulling tension (i.e. exit tension) is of greatest importance, because it effectively sizes the bridle motor powers as well as energy costs in running the leveller. Minimising the exit-entry tension difference minimises power losses in the leveller and also ensures even distribution of the reaction loads across the work rolls and the framework of the tension leveller.

A number of studies have been carried out to investigate the tension levelling process. Many analytical models in use today are based on those described by Kinnavy (1971) for estimating the bending strain and stress parameters in permanently elongating strip. The results using this analytical model were found to be valid depending on the achieved level of conformity of strip to the work roll. Finite element methods have also been applied to simulating the tension levelling process. Huh *et al.* (2001) used the finite element method to model a three (3) roll intermeshed region of a tension leveller under a steady state condition over a strip length of 400 mm. They found that the intermesh (i.e. roll gap or roll penetration) affected the amount of strain imparted on the outer faces of the strip and that to the accuracy of the solution was affected by the size of the elements. Yoshida *et al.* (1999) also modelled tension levelling using the finite element method. In their work, they investigated two tension leveller configurations having 14 and 19 work rolls. They validated their model by comparing their predicted residual curvatures with measured curvatures of output strips. They concluded that the configuration with more rolls and a certain configuration of the exit rolls gave better flatness results. Whereas this gave the required flatness output requirements, the number of rolls is enormous because the number of strip-to-roll contacts should be kept to a minimum, firstly to reduce the possibility of roll markings and secondly because the permanent elongations of 0.3% to 1.5% associated with tension levelling can be achieved theoretically using three (3) work rolls according to Sheppard and Roberts (1972). Steinwinder *et al.* (2010) also highlighted the challenging nature of numerically simulating the tension levelling process as coupled elasto-plastic deformations occur at defined regions along the strip bending line which would require very large number of nodes and degrees of freedom in combination with highly non-linear characteristics of contact, material and geometry leading to excessive computational demand even on modern mainframe computers. With these challenges in mind, it is the opinion of the author that there is an opportunity to explore the problem with an improved analytical model.

2 MATHEMATICAL MODELLING

The model considered here assumes a constant strip curvature in which the strip is assumed to take an effective bend radius across the roll. Figure 1 gives a simple description of the analytical solution method.

The tension leveller works under the principle of permanently elongating the mid-plane of the strip equivalent to the flatness requirement (which is expressed in I-units or percentage steepness). This occurs by selectively elongating the strip at the different work rolls to produce the cumulative elongation effect. The method involves dividing the work roll configuration problem into free-body diagrams (FBD) at each work roll and establishing the equilibrium conditions while geometrically constraining the strip bend path to obtain the possible bend radii combinations. The sum of the individual FBD bend energies (i.e. strain energies in the bent sections) represents the overall system bending energy. The process of finding the possible bend radii combinations is iterative and continues in the direction of decreasing energy until there is no significant change in the total bending energy.

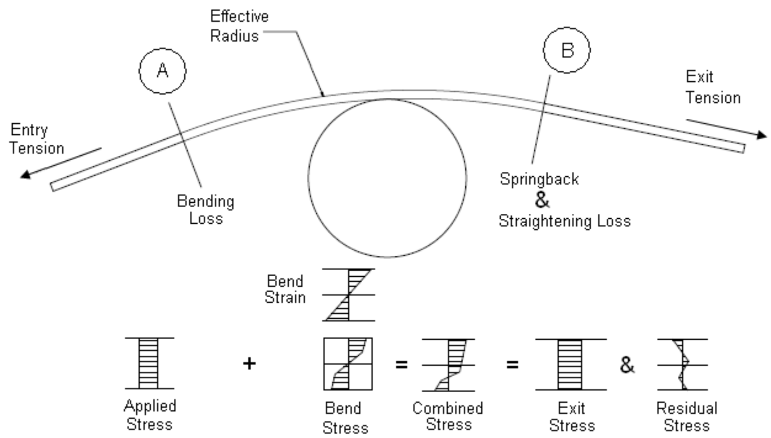

Figure 1: Stress-strain distributions across work roll

The operations performed by the mathematical model include:

1. Novel method of calculating of the bending stress and strain parameters and strain energy from the bending stress distribution, including linear strain hardening.
2. Prediction of minimum energy bend path from permissible radii combinations constrained by work roll configuration.
3. Solving the equilibrium problem of strip-roll conformity (i.e. ensuring that the external moment condition is matched by the internal bending moment)
4. Strain rate (i.e. speed effect) modification of the material yield and accumulation of tension losses (i.e. bending and straightening losses) across each work roll. The bending and straightening losses are derived from the rate of doing work to the strip as described by Marciniak *et al.* (2002).
5. Estimation of output longbow curvature and residual stress distribution in the strip across each work roll.

The model uses a 2-D plane-strain assumption and that Hertzian stresses at the strip-roll contacts are negligible. It also assumes there is no reduction in yield strength of the material during bend reversals (i.e. no Bauschinger effect).

3 RESULTS AND ANALYSIS

The mathematical model was validated against data collected from an operating Bronx Tension Leveller installed in a high speed coil-to-coil inspection line at JSW Steel Limited, India. Entry and exit tension data were obtained for steel thicknesses ranging from 0.5 mm to 1.2 mm for permanent elongations of 0.2% to 0.5% and speeds of up to 300 metres/min. The yield strengths ranged from 180 MPa to 250 MPa. A plastic tangent modulus was derived from the true stress-strain curves for the steel materials for strain values from 0.2% to 1% and was used to model the linear strain hardening behaviour.

The work roll configuration is shown in Figure 2. The tension leveller under consideration comprises eight (8) work rolls, but for purposes of clarity, only the four (4) active rolls are shown.

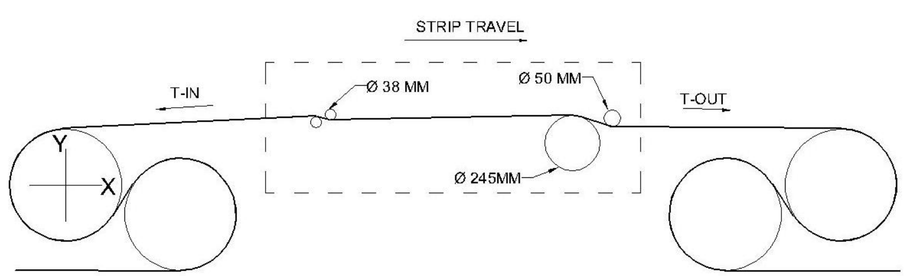

Figure 2: Tension leveller 4-roll configuration

Figure 3 shows a plot of the pull and drag tensions for 0.5 mm thick steel sheet for various target permanent elongations. It shows a positive agreement in the variation of the entry and exit tensions for various thicknesses between the mathematical model and those measured. The model predictions were compared with the collected data for the various elongation settings and work roll configuration and roll gaps. The predicted results were within 4% and 12% of those measured for the entry and exit tensions respectively.

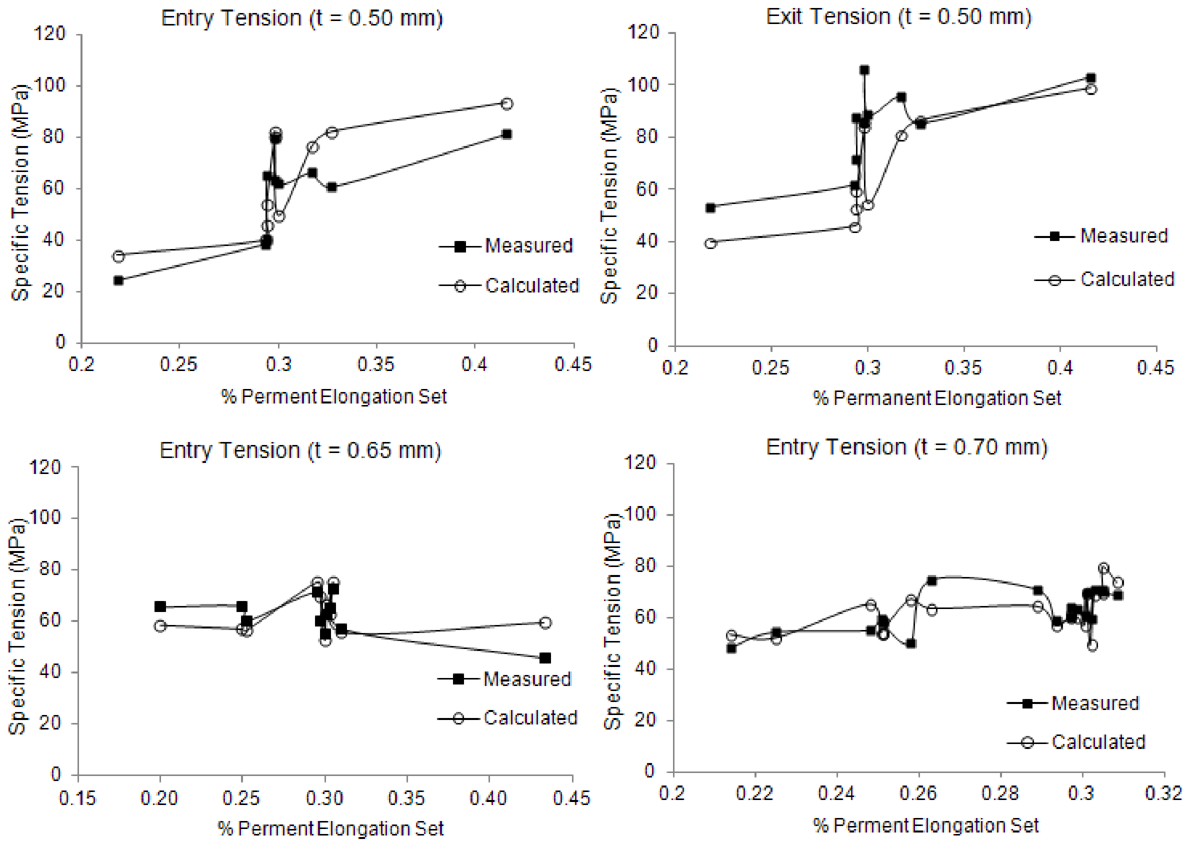

Figure 3: Comparison of model predictions and measurements

4 CURVATIRE CHARACTERISTICS AND MESH OPTIMISATION

Using the mathematical model, a curvature distribution along the X-direction from the X-Y coordinate system (shown in Figure 2) can be plotted. Figure 4 shows the curvature distribution for a typical leveller setting for 0.5 mm thick material. It can be seen that the curvature peaks occur in rectangular steps over the roll locations. This is representative of the effective radius method used, even though the strip may make a line contact across the roll width. An earlier study by Roberts *et al.* (2011) suggests a parabolic curvature variation across the work rolls. For the mesh setting in consideration, it can be seen that the last work roll, which is expected to function as an anti-curvature is actually the most active in the configuration. This goes against the tension levelling principle, where it is expected that the greatest amount of permanent strain is imparted by the first work roll pair.

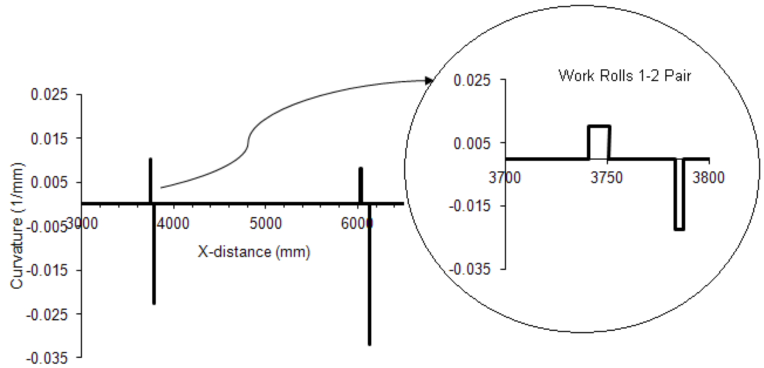

Figure 4: Curvature variation across length of tension leveller

Figure 5 shows the variation of the total bending energy per unit width with the mesh settings for the two work roll pairs. It can be seen that the system energy is proportional to the amount of intermesh. The bend energy, however, is inversely proportional to the applied tension. A high tension has the effect of decreasing the bending moment for a given bend radius. It also causes the strip to conform to the work rolls over a short length of strip (i.e. forces the strip curvature to match that of the work roll) resulting in a low bend energy condition, while a low tension may not cause full conformity and the strip to bend over a large bend length resulting (i.e. high bend energy). The energy minimisation method of setting the tension leveller is therefore a trade-off solution between the pull and drag tensions, the output flatness and the tension difference. A solution that minimises the pulling tension and the tension difference across the leveller, while maintaining flatness and a relatively low bending energy represents an optimal solution.

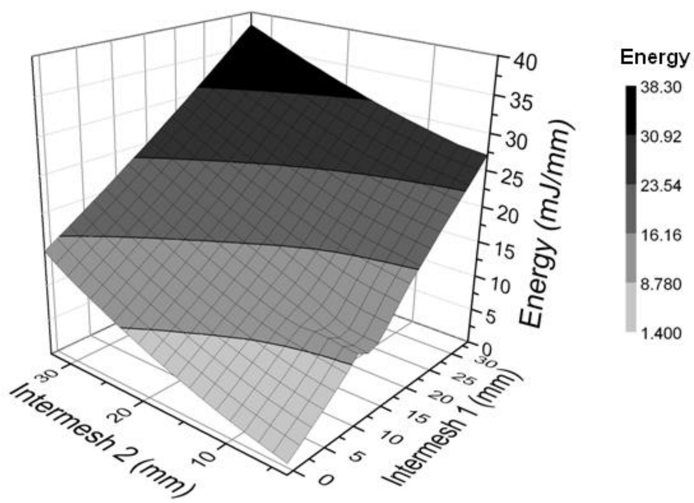

Figure 5: Energy variation with roll mesh settings

Manually calculating the optimal roll gap settings for a tension leveller of known work roll configuration (i.e. fixed roll sizes and pitches) can be laborious and exhaustive. The mathematical model includes a solution algorithm that solves the problem mix comprising of the total bend energy, tension difference and exit tension. The optimal mesh selection solution is performed by stepping through the possible roll gap combinations, with each refinement tending towards a lower system energy solution. Whereas the task of finding an optimal setting using manual calculation methods could take many hours of laborious repetitive calculations, the model described in this work calculates the optimal setting for an 8-work roll leveller in just a few minutes.

Figure 6(a) compares the curvature characteristics for the optimised setting for the same settings as Figure 4. It shows that the optimal setting is also one that ensures the first roll pair is the most active. Figure 6(b) shows the cumulative permanent elongation path as the strip travels through the tension leveller. The preferred setting would strain the strip at the first pair and attempt to eliminate the residual stresses at the exit end of the leveller. The optimal setting shows a significant reduction in the entry and exit stresses of at least $0.14\sigma_y$ or a 36% reduction in bridle tensions.

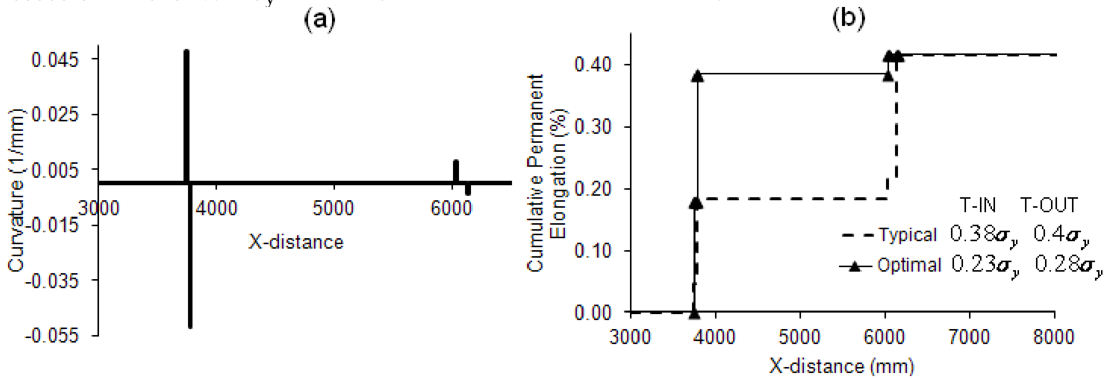

Figure 6: (a) Curvature variation, (b) Cumulative elongation path

From an economical perspective, a 10% reduction in exit pulling tension for a similar line run condition results in a proportional reduction in the bridle power requirements. This could improve the specification of bridles and motor powers at an early design stage or a net energy saving in site operations and improved longevity of tension levellers.

5 CONCLUSION

A mathematical model for predicting tension leveller mesh settings based on minimisation of bending energies has been presented. The predicted tensions were found to be within 12% of those obtained from an industrial tension leveller. This work highlights the importance of correct leveller setting. The model predictions show potential reductions in bridle tensions of more than 30% from typical operating levels. Due to its flexibility, the developed model has the potential to be used in parametric studies of roll configurations (i.e. diameters, pitches and roll gaps) for optimally designing industrial tension levellers.

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