Influence of temper rolling on tensile property of low carbon steel sheets by application of Hill 48 anisotropic yield criterion

Davoud Jafarlou\textsuperscript{a,c}, Mohsen Hassan\textsuperscript{a,b,c,*}, Noor Azizi Mardi\textsuperscript{a,c}, Erfan Zalnejhad\textsuperscript{a}

\textsuperscript{a}Department of Mechanical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia.
\textsuperscript{b}Department of Mechanical Engineering, Faculty of Engineering, Assiut University, 71516 Assiut Egypt.
\textsuperscript{c}Centre of Advanced Manufacturing and Material Processing (AMMP), University of Malaya, 50603 Kuala Lumpur, Malaysia.

Abstract

Temper rolling is a fundamental process applied in steel industries to improve the tensile properties of sheet steels by eliminating discontinuous yield behaviours. Virtually evaluating the effects of temper rolling mechanics on eliminating discontinuity is still a crucial problem due to a lack of comprehensive constitutive material models that correctly describe this elimination mechanism. In this paper, modified anisotropic constitutive model based on Hill’s 48 yield criterion are used for finite element analysis (FEA) of the temper rolling process. This model was applied for four different sheet thicknesses and the FEA results are compared with experimental results obtained directly from the production line. According to the results, the customized model that implements the modified anisotropic yielding criterion efficiently describes the tensile behaviour of low carbon steels following temper rolling, and it more accurately predicts the lower and upper yielding points than the isotropic yielding criterion. This model thus assists to facilitate the simulation, optimization and prediction of mechanical properties following temper rolling.

© 2014 The Authors. Published by Elsevier Ltd.
Selection and peer-review under responsibility of Nagoya University and Toyohashi University of Technology.

Keywords: Temper rolling; Discontinuous yield point; Anisotropic behavior; Finite element analysis.

1. Introduction

Temper rolling, also known as skin-pass rolling, represents the final forming step in the production chain of cold rolled steel to fabricate sheets with high flatness and low surface roughness. It is mainly utilized to prevent the formation of Lüder’s bands (LB) to eliminate the sharp yield point and subsequent plateaus (Roberts, 1983).

* Corresponding author. Tel.: +60-3-7967-4447; fax: +603-7967-7669.
E-mail address: mohsenegypt@um.edu.my
A sharp yield point followed by a plateau always appears in the stress-strain curve of a uniaxial tension test for annealed steels and a number of BCC materials. Sharp yield point leads to sheet surface non-uniform plastic deformation patterns called ‘stretcher-strain marks’ during stamping operations, considerably deteriorating sheet metal product quality (Pepelnjak et al., 2007).

An investigation on a wide range of steels confirmed that as a sheet passes through the roll gap, stress periodically accumulates promoting localized yielding near the surface with a tendency to disperse throughout the thickness. These plastically deformed regions generated during skin-pass rolling subsequently act as nucleation sites for diffused plastic strain propagation during post-rolling deformation. Discontinuous yielding phenomena of the skin-passed steel would thus be suppressed and a macroscopically continuous transition from elastic to plastic strain would become evident (Lake, 1985).

The effect of temper rolling on the tensile properties of low Si-Al killed sheet steel was empirically studied by Ma et al. (2009). The results indicate that yield strength initially decreased with greater thickness reduction of up to 1% and afterward increased for thickness reduction values above 1%. The outcome additionally demonstrated that the tensile strength of this type of steel increased with amplified reduction of thickness and the relation was expressed in the form of a power law.

Finite element analysis (FEA) of the yield point phenomena in temper rolling was first reported by Itoh et al. (1992), and non-uniform plastic deformation patterns appearing in mild steel sheets under tension were calculated.

Yoshida (2000) proposed the first theoretical model that describes both the yield point phenomenon and cyclic plasticity behaviour, such as the Bauschinger effect and cyclic hardening. The respective model was unable to simulate and predict actual material behaviours, such as sharp yield point.

Yoshida et al. (2008) later offered the first constitutive model that describes the yield point phenomena of steels. In such model, two modes of plastic deformation are considered. First one describes the deformation at the LB front and the other is the subsequent deformation of material elements that LBs have previously passed through. These types of plastic deformation correspond to the plastic behaviour at the yield plateau as well as work hardening regions. The researchers presented two different constitutive equations for each individual mode. As a result, it was feasible to reproduce an accurate upper yield point along with the rate dependence of Lüder’s strain, both of which could not be captured by the former model. This constitutive model considers the material’s isotropic behaviour during deformation while taking into account the von Mises yield criteria as a yield function.

Many attempts have been done to formulate the effect of temper rolling on mechanical properties of steel sheets. Several of the research works identified in literature were based on empirical techniques that significantly raise process cost and time, whereas analysing and theoretically studying the sheet’s mechanical properties after temper rolling have received trivial attention. The objective of the present research work was to modify Yoshida’s model by considering the effect of anisotropy based on Hill’s 1948 quadratic yield criterion. The proposed constitutive model was applied in a FEA, after which experimental investigation were conducted to validate the results of FEA.

2. Development of Anisotropic model

Yoshida et al (2008) showed that in polycrystalline metal, during Lüder’s band (LB) propagation, plastic deformation advances rapidly only at the band front. When the LB (moving dislocation) covers the entire specimen, the deformation becomes homogeneous and the flow stress rises as the material hardens. To describe these deformations by assuming the material’s isotropic behaviours during the forming process, two different individual constitutive equations were proposed to describe the LB propagation at the band front (mode LB), and the subsequent plastic deformation with work hardening (mode WH), as follows for isotropic constitutive model:

For mode LB:

\[
\dot{\varepsilon}_{LB} = \frac{b \rho_m}{M D_{LB}} (\sigma_{eff})^n, \quad \dot{\varepsilon}^p = \frac{3\sigma'}{2\sigma_{LB}} \dot{\varepsilon}_{LB},
\]

\[
\sigma_{LB} = \sqrt{\frac{3}{2}} \sigma' : \sigma_{eff} = \left(\sigma_{LB} - Y_0\right).
\]
For mode WH:

\[
\tilde{\varepsilon}_{WH} = \frac{b p_m}{M} \left( \frac{\sigma_{eff}}{D_{WH}} \right)^n, \quad \dot{\varepsilon}^P = \frac{3(\sigma' - X)}{2\sigma_{WH}} \tilde{\varepsilon}_{WH},
\]

\[
\tilde{\sigma}_{WH} = \sqrt{\frac{3}{2}(\sigma' - X) : (\sigma' - X), \sigma_{eff} = \left\{ \tilde{\sigma}_{WH} - (Y_0 + R_y) \right\}},
\]

where \( \tilde{\varepsilon} \) is the effective plastic strain (subscripts LB and WH indicate the modes), \( \sigma' \) is the Cauchy stress deviator, \( b \) stands for the norm of the Burgers vector, \( p_m \) is the mobile dislocation density, \( M \) denotes the Taylor factor, \( D \) is shear drag stress, \( Y_0 \) indicates the initial yield stress, \( n \) is a stress sensitivity exponent, \( R_y \) is the isotropic hardening internal stress, and \( X \) denotes the kinematic hardening internal stress tensor (the back stress tensor).

To describe the kinematic hardening effect, Prager proposed the first model, in which the evolution of the kinematic variable \( X \) is collinear with the evolution of the plastic strain (Chaboche, 2008), thus:

\[
\dot{X} = \frac{2}{3} C \dot{\varepsilon}^P_{ij}.
\]

The linearity associated with the stress–strain response is rarely observed (except perhaps in the regime of significant strains). A better description is given by the model proposed initially by Frederick and Armstrong (2007) introducing a recall term, called dynamic recovery:

\[
\dot{X} = \frac{2}{3} C \dot{\varepsilon}^P_{ij} - \gamma X d\varepsilon^P, \quad (6)
\]

where \( C \) and \( \gamma \) are constants and \( d\varepsilon^P \) is the increment of the accumulative plastic strain.

With considering the anisotropic plastic deformation behaviour of the steel during forming process with proper yield criteria (Hill’s 1948), Eqs. (1) to (4) are modified in following form:

For mode (LB):

\[
\tilde{\varepsilon}_{LB} = \frac{b p_m}{M} \left( \frac{\sigma_{eff}}{D_{LB}} \right)^n, \quad \dot{\varepsilon}^P = \frac{c : \sigma'}{\sqrt{c : \sigma' : \sigma'}} \tilde{\varepsilon}_{LB},
\]

\[
\tilde{\sigma}_{LB} = f(c : \sigma' : \sigma'), \sigma_{eff} = \left\{ \tilde{\sigma}_{LB} - Y_0 \right\}.
\]

For mode WH:

\[
\tilde{\varepsilon}_{WH} = \frac{b p_m}{M} \left( \frac{\sigma_{eff}}{D_{WH}} \right)^n, \quad \dot{\varepsilon}^P = \frac{c^* : (\sigma' - X)}{\sqrt{c^* : (\sigma' - X) : (\sigma' - X)}} \tilde{\varepsilon}_{WH},
\]

\[
\tilde{\sigma}_{WH} = f(c^* : (\sigma' - X) : (\sigma' - X) - R_y), \sigma_{eff} = \left\{ \tilde{\sigma}_{WH} - (Y_0 + R_y) \right\}.
\]

In Eqs. (7) to (10), \( c \) describes the initial anisotropy in state of zero plastic strain, \( c^* \) describes anisotropy depending on the present state of plastic strain. In the model for mode LB, the kinematic hardening is neglected since the deformation at LB front is characterized by the rapid multiplication of dislocations rather than the dislocation interactions which cause the Bauschinger effect.

3. FE-model and simulation procedure

In order to investigate the influence of temper rolling on removing the discontinuity of a yielding region in low-carbon steel based on the newly modified model, the scope of FEA was organized in three different phases for four different sheet thicknesses. First, mechanical properties of the target steel were evaluated experimentally and numerically to observe the discontinuous yield phenomena. At the second phase, for each thickness FEA of temper
rolling were carried out by consideration of isotropic and anisotropic models. Finally at the third phase, following temper rolling by consideration of residual stresses, equivalent plastic strain and mesh configuration, the tensile tests were performed numerically and experimentally to obtain the specimen’s mechanical properties.

FEA was carried out with the Abaqus 6.11 explicit elasto-plastic package. The FEA mesh configuration for the sheet was constructed with 5890 nodes and 4392 eight-node brick elements, with reduced integration and hour-glassing control. Brick element application takes into account the sheet as a 3D domain, which is a more realistic approach to process modelling. To increase process sensitivity four elements were considered in thickness direction. Arbitrary Lagrangian Eulerian adaptive meshing was applied in all simulation steps in order to maintain high mesh quality throughout analysis. In addition, the mass scaling feature was utilized to facilitate computational time reduction. The rollers in this simulation were deemed as a rigid body. The coefficient of friction at the interfaces between the blank and rollers was 0.15.

Number of tensile tests before temper annealing in accordance to the ASTM Standard E8 were performed to determine the mechanical properties of steel sheet (SAE1008). The tensile test results were summarized in Table 1.

### Table 1: Mechanical properties measured for the SAE 1008 sheets.

| Thickness (mm) | $\sigma_y$ (MPa) | $\sigma_{UTS}$ (MPa) | $E$ (GPa) | $\rho$ (Kg/m³) | $n$ | $R_{00}$ | $R_{45}$ | $R_{90}$ |
|----------------|-----------------|---------------------|----------|---------------|---|---------|---------|---------|
| 0.83           | 227.23          | 313.76              | 211.2    | 0.29          | 7850 | 0.22   | 1.21    | 1.49    | 1.72    |
| 1.03           | 277.9           | 332.57              | 227.8    | 0.3           | 7850 | 0.194  | 1.43    | 1.52    | 1.66    |
| 1.43           | 266.81          | 331.52              | 225.6    | 0.3           | 7850 | 0.252  | 1.32    | 1.39    | 1.80    |
| 1.46           | 235.06          | 334.2               | 230.3    | 0.3           | 7850 | 0.194  | 1.30    | 1.44    | 1.75    |

Anisotropic yield behaviour is modelled through the use of yield stress ratios, $R_{ij}$. In the case of anisotropic yield the yield ratios are defined with respect to a reference yield stress, $\sigma^0$ (given for the metal plasticity definition), such that if $\sigma_{ij}$ is applied as the only nonzero stress, the corresponding yield stress is $R_{ij}\sigma^0$.

Temper rolling process were performed with two-high mill machine, with working roll diameter of 535.59 mm with maximum and minimum deviation of $4\times10^{-4}$ mm and $-9\times10^{-4}$ mm respectively. The temper rolling operating conditions are listed in Table 2 and directly applied on FE-model.

### Table 2: Temper rolling operating conditions.

| Entry thickness (mm) | Exit thickness (mm) | Roll force (kN) | Un-coiler force (kN) | Re-coiler force (kN) | Mill speed (mpm) |
|---------------------|---------------------|-----------------|----------------------|----------------------|------------------|
| 0.83                | 0.8                 | 2800            | 25                   | 45                   | 371.67-403.19    |
| 1.03                | 1                   | 3000            | 30                   | 50                   | 371.67-403.19    |
| 1.43                | 1.42                | 3000            | 50                   | 70                   | 371.67-403.19    |
| 1.49                | 1.46                | 3000            | 50                   | 70                   | 371.67-403.19    |

Mesh configuration, boundary conditions and load cases for uniaxial tests and temper rolling process are depicted in Fig. 1. The first load case is skin pass rolling process parameters while the second load case is for uniaxial test which was performed before and after temper rolling.

![Fig. 1. FE model and boundary conditions of (a) rolling process, (b) tensile test.](image-url)
4. Results and discussion

The FE-simulation of temper rolling process for the sheets with initial thickness of 0.83, 1, 1.03, 1.43 and 1.49 mm based on the material properties (Table 1) and operating condition (Table 2) with respect to isotropic and anisotropic constitutive equations (section 2) and simulation conditions (section 3) was carried out to reach the final thicknesses of 0.8, 1, 1.42 and 1.46 mm.

FEA results of uniaxial tension test at quasi static conditions (strain rate of roughly $10^{-3}\text{s}^{-1}$) for as-received steel sheets (before temper annealing) are depicted in Fig. 2-a to 2-d in blue line. A sharp yield point and a subsequent abrupt yield drop, followed by a work hardening zone for all tested thicknesses are obvious. This phenomenon is a consequence of rapid dislocation multiplication and stress dependence of dislocation velocity. Specifically for the metal with BCC structure and annealed steels, the dislocation locking mechanism affects the rapid multiplication in the initial yielding stage. The numerical results depicted in Fig. 2 validate Shioya et al. (1976) and Yoshida et al. (2008) constitutive models.

The FEA results after temper annealing prove that the anisotropic constitutive model can predict the behavior of steel more accurately and very close to experimental results in comparison with the isotropic constitutive model, particularly with respect to yielding point and ultimate tensile stress. The simulation results for the anisotropic case are more accurate; however the deviation between simulation results in the anisotropic and isotropic cases is less than 5%. This difference is magnified and shown as an example in the inset ellipse in Fig 2-b for a thickness of 1.03 mm. This deviation is same for other thicknesses and show the same error level. As can be clearly seen from Fig. 2-a to 2-d, the Lauder’s bands completely disappeared owing to the implementation of the modified anisotropic model. The practical tension test results are in acceptable agreement with the numerical results.

![Fig. 2. FEA and experimental results of tension tests before and after temper rolling for thicknesses of (a) 0.83, (b) 1.03, (c) 1.43, (d) 1.49 mm.](image)

Acceptable correlations between numerical and experimental data were obtained for the samples after temper rolling. The results confirm the aptitude of temper rolling to lower the yield point and remove discontinuity. The
FE simulation outcome does not indicate a significant difference in which whether the anisotropic or isotropic combined hardening model is considered, since both models can successfully predict the elimination of Lüder’s bands. The results were summarized in Table 3.

| Mechanical properties | Experimental results | Simulation results |
|-----------------------|----------------------|--------------------|
| Initial thickness (t₀) | 0.83 1.03 1.43 1.49  | 0.83 1.03 1.43 1.49 |
| Yield point           | Pass Pass Pass Pass  | Pass Pass Pass Pass |
| σₚ₁ (MPa)             | 172.3 172.7 176 177.3 | 164.6 165.2 170.9 171 |
| σₚₙ₁ (MPa)            | 315.3 314.8 315.5 316.4 | 298.8 302.9 306.9 309.8 |
| σₚ₂ (MPa)             | 172.3 172.7 176 177.3 | 171.4 173.1 174.4 174.5 |
| σₚₙ₂ (MPa)            | 315.3 314.8 315.5 316.4 | 314 313.9 314.8 314.5 |
| E (GPa)               | 174.9 150.2 180 247.8 | 175.8 195.4 177.5 241.5 |
| n                     | 0.21 0.21 0.21 0.2    | 0.22 0.21 0.2 0.25   |
| A₀ %                  | 21.97 21.47 20.73 19.94 | 21.75 21.5 22.19 21.9 |

* : FE-Simulation based on isotropic constitutive model.
** : FE-simulation based on anisotropic constitutive model.

5. Conclusion

Steel sheet temper rolling is conducted to eliminate the discontinuous yield point behavior and decrease the high yield value caused by the Lüder’s bands effect. In this research the effects of temper rolling on yield point behavior of steel SAE1008 sheets were studied by consideration of isotropic constitutive model and the modified anisotropic constitutive model based on Yoshida’s model. Results showed, both constitutive models successfully predicted the mechanics of the temper rolling process and generated the tensile properties of rolled sheets. The models were also validated by conducting the uniaxial tensile tests on steel sheets which were obtained directly from the production line. A comparison between the results revealed that the proposed anisotropic constitutive model is able to simulate the elimination of Lüder’s bands more accurately than the isotropic constitutive model. From an engineering point of view, the isotropic hardening model is still acceptable since the difference in error between the two models is below 5%. However, from an academic perspective, the modified anisotropic model helps facilitate the simulation, optimization and prediction of the mechanical properties of temper rolled low-carbon steel.

Acknowledgment

The authors would like to acknowledge the support given by University of Malaya and the Ministry of Higher Education, Malaysia with the university research grant (UMRG) grant number of RP021B-13AET.

References

Chaboche, J.L., 2008. A review of some plasticity and viscoplasticity constitutive theories. International Journal of Plasticity, 24, 1642-1693.
Frederick, C.O., Armstrong, P.J., 2007. A mathematical representation of the multiaxial Bauschinger effect. Materials at High Temperatures, 24(1), 1-26.
Itoh, M., Yoshida, F., Yamashita, Y., Ohmori, M., 1992. FEM analysis for non-uniform yielding processes in mild steel plates under stretching. JSME International Journal, 1(35), 70-77.
Lake, J.S.H., 1985. Control of discontinuous yielding by temper rolling. Journal of Mechanical Working Technology, 12(1), 35-66.
Ma, Q.L., Wang, D.C., Liu, H.M., Lu, H.M., 2009. Effect of temper rolling on tensile properties of low-Si Al-Killed sheet steel. Journal of Iron and Steel Research, International 16(3), 64-67.
Pepelnjak, T., Barisic, B., 2007. Analysis and elimination of the stretcher strains on TH415 tinplate rings in the stamping process. Journal of Materials Processing Technology, 186(1-3), 111-119.
Roberts, W.L., 1983. Cold Rolling of Steels. Marcel Dekker, Inc., New York.
Shiroya, T., Shiroti, J., 1976. Elastic-plastic analysis of the yield process in mild steel. Journal of the Mechanics and Physics of Solids. 24 187-204.
Yoshida, F., 2000. A constitutive model of cyclic plasticity. International Journal of Plasticity, 16, 359-380.
Yoshida, F., Kaneda, Y., Yamamoto, S., 2008. A plasticity model describing yield-point phenomena of steels and its application to FE simulation of temper rolling. International Journal of Plasticity, 24, 1792-1818.