Effect of temper rolling on tensile properties of C–Mn steels

X. Fang, Z. Fan, B. Ralph, P. Evans, and R. Underhill

The tensile properties of two C–Mn steels TR1 (Fe ± 0.135C± 0.66Mn) and TR2 (Fe ± 0.019C± 0.18Mn) under different temper rolling conditions were investigated. It was found that the lower yield strength and ultimate tensile strength of steels TR1 and TR2 which were temper rolled at different reductions can be expressed by the following formula, \( \sigma = \sigma_0 + K \varepsilon_{eq} \), where \( \sigma \) is the strength after temper rolling; \( \sigma_0 \) is the strength without temper rolling; \( \varepsilon_{eq} \) is the equivalent strain of the temper rolling reduction; \( K \) is a constant. The uniform elongation and the total elongation of these two steels which have been temper rolled at different reductions (or equivalent plastic strains) are those of samples without temper rolling subtracted from their equivalent plastic strains. The work hardening exponents of temper rolled samples can be predicted using the tensile curves of the samples which have not been temper rolled. Very good agreement between the experimental results and the calculated data was obtained.

Introduction

Temper rolling (also called skin passing) is a process to produce good flatness and low surface roughness in sheet samples in order to achieve a high ‘glossiness’ in the finished product after painting. A small reduction is usually employed to satisfy the size requirements of steel sheets in order not to change the mechanical properties too much. Sometimes a larger reduction is also used to remove the yield point effect in the tensile curve so as to ensure that stretcher strain markings are not formed on pressing. It also has been found that a larger skin pass reduction results in higher surface roughness. No matter what reduction is used it always influences the mechanical properties of steel sheets to a degree. A higher reduction results in more influence on mechanical properties. If the reduction is chosen to be too high, it will deteriorate the tensile properties. Therefore, choosing an appropriate reduction is very important in the temper rolling processing. For good prediction of the mechanical properties of temper rolled samples it is beneficial to choose an appropriate reduction for temper rolling.

In the literature, there have been publications on the prediction of the plastic deformation of steels during temper rolling, the modelling of the roughness transfer and flatness correction, the effect of the temper rolling on the \( \tau \) value and the fluting resistance of steel sheets, and the yield point phenomena. However, very little effort has been devoted to the relationship between the temper rolling reduction and the tensile properties such as yield strength, ultimate tensile strength, uniform and total elongations, and work hardening exponent.

Low carbon–manganese steel sheets are widely used in the automotive industry. Steels based on Fe–0.135C–0.66Mn and Fe–0.019C–0.18Mn were chosen primarily because they are two typical commercial carbon–manganese steels with quite different C and Mn concentrations. Investigation of the effect of temper rolling on the mechanical properties of these two steels is beneficial as they are representative of other steels with similar compositions. In this paper the effect of the reduction in thickness by temper rolling on tensile properties has been investigated and the work hardening exponents of samples with different amounts of temper rolling have been predicted using the tensile curves of samples which had not been temper rolled. Very good agreement between experimental results and the calculated data was obtained.

Experimental procedure

The two commercial C–Mn steel sheets used in this work were supplied by Corus R, D&T, Welsh Technology Centre. Their chemical compositions are given in Table 1. The thickness values of these two steels (TR1 and TR2) were 2.0 and 0.7 mm respectively. These two steels were used to investigate the effects of temper rolling on tensile properties and one of them (TR1) was used to compare the calculated and experimental results of the \( \tau \) values.

The temper rolling was conducted using a Hille 100 rolling mill. The as received and temper rolled samples were cut along the rolling direction to produce flat testpieces 25 mm in width and 240 mm in length for tensile tests. All the specimens were machined to give an 80 mm gauge length. Tensile testing was conducted in a Zwick 1474 machine with an initial strain rate of \( 7.4 \times 10^{-4} \) s\(^{-1} \).

Results and discussion

YIELD STRENGTH AND ULTIMATE TENSILE STRENGTH

After temper rolling there is no external load on the steel sheets and only macro plastic strain remains. This plastic strain is caused by temper rolling and will be described using tensile curves in this paper, and it is called ‘equivalent plastic strain’. The reduction of temper rolling \( R \) and the

Table 1 Chemical composition of steels, wt-%

<table>
<thead>
<tr>
<th>Steel</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Al(_{tot})</th>
<th>N</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>TR1</td>
<td>0.135</td>
<td>0.019</td>
<td>0.66</td>
<td>0.02</td>
<td>0.012</td>
<td>0.042</td>
<td>0.0055</td>
<td>Bal.</td>
</tr>
<tr>
<td>TR2</td>
<td>0.019</td>
<td>0.003</td>
<td>0.18</td>
<td>0.014</td>
<td>0.039</td>
<td>0.047</td>
<td>0.0023</td>
<td>Bal.</td>
</tr>
</tbody>
</table>
equivalent plastic strain $\varepsilon$ are related by the following

$$
\varepsilon = R (1 - R) \tag{1}
$$

The lower yield strength and ultimate tensile strength of steels TR1 and TR2 under different equivalent plastic strains are plotted in Fig. 1. Within this range of equivalent plastic strain the yield strength of steel TR1 decreased linearly with an increase in the equivalent plastic strain (Fig. 1). It had decreased by about 10 MPa when the equivalent strain increased to about 1-3%. However, when the equivalent strain had increased from 1-56 to 4-3% (the reduction increased from 1-54 to 4-13%) the proof strength of steel TR1 at 0-2% plastic strain increased linearly with increase in the equivalent plastic strain. The $\sigma_{0.2}$ increased about 15% to 385 MPa when the equivalent plastic strain increased to 4-3%. Similarly the lower yield strength of steel TR2 also decreased linearly with the equivalent plastic strain. The correlation between the lower yield strength and the equivalent plastic strain of steels TR1 and TR2 could be expressed as follows

steel TR1

$$
\sigma_y (\text{MPa}) = - 5.8 \varepsilon_{eq} (\%) + 328.9 \tag{2}
$$

steel TR2

$$
\sigma_y (\text{MPa}) = - 9.4 \varepsilon_{eq} (\%) + 309.2 \tag{3}
$$

where $\sigma_y$ is the lower yield point and $\varepsilon_{eq}$ is the equivalent strain of temper rolling reduction.

The second term on the right hand side of equation (2) is 328.9 MPa which is quite close to the average lower yield strength (332.7 MPa) of steel TR1 without temper rolling. Similarly the second term on the right hand side of equation (3) is 309.2 MPa, which is also close to the average lower yield strength (316-9 MPa) of the samples which have not been temper rolled. Therefore, the relationship between the lower yield strength and equivalent plastic strain of steels TR1 and TR2 can be expressed as follows

$$
\sigma_y = \sigma_{0.2} + K_1 \varepsilon_{eq}(\%) \tag{4}
$$

where $K_1$ is a constant.

For steels TR1 and TR2 $K_1$ is $-5.8$ and $-9.4$ MPa respectively. The variation of the lower yield strength with the equivalent plastic strain or reduction depends on the yield point elongation. The sample with the higher yield point elongation required a higher reduction to remove the yield point. The higher the yield point elongation $\varepsilon_{YPE}$ the larger the constant $K_1$. The constants $K_1$ of steels TR1 and TR2 are about twice their yield point elongation in each case. Thus the lower yield point strength and equivalent strain could have the following relationship

$$
\sigma_y = \sigma_{0.2} - 2\varepsilon_{YPE}(\%) - \varepsilon_{eq}(\%) \tag{5}
$$

Because the amount of reduction was not high enough to produce enough data for the relationship between the proof strength and equivalent plastic strain the case of steel TR2, only a relationship concerning steel TR1 was obtained

$$
\sigma_{0.2} (\text{MPa}) = 24.6 \varepsilon_{eq}(\%) + 276.5 \tag{6}
$$

where $\sigma_{0.2}$ is the proof strength at 0.2% plastic strain.

When steel sheets are temper rolled with a reduction $R$, an equivalent plastic strain $\varepsilon$ along the temper rolling direction is induced. If this plastic strain is described using a tensile curve (Fig. 2), the stress goes up from point O to point A and down to point O'. When the equivalent plastic strain is high enough the external stress will go from point O' to point B. The higher the equivalent plastic strain the higher the proof stress $\sigma_{0.2}$. Therefore, the proof strength increases with an increase in the equivalent plastic strain. The coefficient of the first term on the right hand side of equation (6) is 24.6 MPa which mainly depends on the work hardening exponent of that part of the flow curve. If the work hardening exponent is higher, i.e. the stress increases rapidly with an increase in strain, this coefficient should be larger. The second term on the right hand side of equation (6) is 276.5 MPa, which should mainly be affected by the lower yield point and yield point elongation.

It was found that the ultimate tensile strengths of steels TR1 and TR2 increased linearly when the equivalent plastic strain was raised. The following relationships were obtained

steel TR1

$$
\sigma_{UTS} (\text{MPa}) = 4.6 \varepsilon_{eq}(\%) + 446.9 \tag{7}
$$

steel TR2

$$
\sigma_{UTS} (\text{MPa}) = 6.2 \varepsilon_{eq}(\%) + 380.2 \tag{8}
$$

where $\sigma_{UTS}$ is the ultimate tensile strength.

The second terms on the right hand side of equations (7) and (8) are 446.9 and 380.2 MPa respectively, which are very close to the average ultimate tensile strengths 443.7 and 377.8 MPa of steels TR1 and TR2 respectively. Therefore the relationship between the ultimate tensile strength and equivalent plastic strain can be expressed as follows

$$
\sigma_{UTS} = \sigma_{0.2} + K_2 \varepsilon_{eq}(\%) \tag{9}
$$

where $\sigma_{UTS}$ is the ultimate tensile strength by temper rolling, $\sigma_{0.2}$ is the ultimate tensile strength without temper rolling, and $K_2$ is a constant.
3 Effect of temper rolling on uniform elongation $e_u$ and total elongation $e_t$ of steels TR1 and TR2

The values of constant $K_2$ for steels TR1 and TR2 are 4.3 MPa and 6.2 MPa respectively. It is not clear why temper rolling results in an increase in the ultimate tensile strength.

**UNIFORM ELONGATION AND TOTAL ELONGATION**

The uniform elongation $e_u$ and total elongation $e_t$ of steels TR1 and TR2 under different equivalent strains are plotted in Fig. 3. Both the uniform elongation and the total elongation decreased linearly with an increase in the equivalent plastic strain. The uniform elongation and total elongation of steel TR1 which had not been temper rolled were 21.3% and 33.5% respectively. Similar results for steel TR2 to those of steel TR1 were obtained. The relationships between the uniform elongation and the equivalent strain, and the total elongation and the equivalent strain of these two steels were obtained as follows:

- **Steel TR1**
  \[
  e_u(\%) = -0.9e_{eq} + 21.2 \\
  e_t(\%) = -0.9e_{eq} + 34.4
  \]

- **Steel TR2**
  \[
  e_u(\%) = -1.2e_{eq} + 23.3 \\
  e_t(\%) = -0.9e_{eq} + 34.2
  \]

where $e_u$ is the uniform elongation, $e_t$ is the total elongation, $e_{eq}$ is the equivalent plastic strain.

The second terms on the right hand side of equations (12) and (13) are 21.3 and 34.4%, which are very close to the uniform elongation 21.4% and the total elongation 33.7% of steel TR1 without temper rolling. Similarly, the second terms on the right hand side of equations (12) and (13) are 23.3 and 34.2%, which are also very close to the average uniform elongation 24.8% and the total elongation 34.3% of steel TR2 without temper rolling. Although the coefficients of the first term on the right hand side of equations (12) and (13) are 0.9 and 1.2 respectively, they are close to 1. Therefore, these results indicate that the uniform elongation and the total elongation of steels TR1 and TR2 under different equivalent plastic strains are those without temper rolling subtracted from their equivalent plastic strains. Thus the following relationships were obtained:

- **Steel TR1**
  \[
  e_u^0(\%) = e_u(\%) - e_{eq}(\%) \\
  e_t^0(\%) = e_t(\%) - e_{eq}(\%)
  \]

- **Steel TR2**
  \[
  e_u^0(\%) = e_u(\%) - e_{eq}(\%) \\
  e_t^0(\%) = e_t(\%) - e_{eq}(\%)
  \]

where $e_u^0$ is the uniform elongation without temper rolling and $e_t^0$ is the total elongation without temper rolling.

4 Effect of temper rolling on yield point elongation of steels TR1 and TR2

**YIELD POINT ELONGATION**

The yield point elongation $\epsilon_{YPE}$ of steels TR1 and TR2 without temper rolling is 2.5 and 4.5%, respectively. The values of yield point elongation for the steels TR1 and TR2 under different equivalent plastic strains are plotted in Fig. 4. Both decreased linearly with an increase in the equivalent plastic strain. The relationships between the yield point elongation and equivalent plastic strain were obtained as follows:

- **Steel TR1**
  \[
  \epsilon_{YPE}(\%) = -1.8e_{eq}(\%) + 23
  \]

- **Steel TR2**
  \[
  \epsilon_{YPE}(\%) = -2e_{eq}(\%) + 45
  \]

where $\epsilon_{YPE}$ is the yield point elongation expressed as a percentage.

The second terms on the right hand side of Equations (16) and (17) are equal or very close to the yield point elongations of steels TR1 and TR2 respectively. Therefore, these two equations can be expressed as follows:

- **Steel TR1**
  \[
  \epsilon_{YPE}(\%) = \epsilon_{YPE}^0(\%) + K_2e_{eq}(\%) \\
  \epsilon_{YPE}^0(\%) = -1.8e_{eq}(\%) + 23
  \]

- **Steel TR2**
  \[
  \epsilon_{YPE}(\%) = \epsilon_{YPE}^0(\%) + K_2e_{eq}(\%) \\
  \epsilon_{YPE}^0(\%) = -2e_{eq}(\%) + 45
  \]

where $\epsilon_{YPE}^0$ is the yield point elongation without temper rolling and $K_2$ is a constant.

The equivalent plastic strain which just makes a sample start to show continuous yield behaviour is called the ‘critical equivalent plastic strain’ and denoted as $e_{eq}^c$ here. This can be calculated from Equation (18). Because the constants $K_i$ for steels TR1 and TR2 are 1.8 and 2.0 respectively, their critical equivalent plastic strains are about half of their $\epsilon_{YPE}^0$ values, i.e. 1.3 and 2.3% respectively.

**WORK HARDENING EXPONENT**

The work hardening exponents $(n_1, n_2, n_3)$ of steel TR1 under different equivalent plastic strains are plotted in Fig. 5. The values of $n_1$, $n_2$, and $n_3$, were calculated from three plastic strain ranges i.e. from 5 to 10%, from 10 to 15% and from 10 to 20%, respectively. The work hardening exponents $(n_1, n_2, n_3)$ of steel TR1 without temper rolling are 0.254, 0.204, and 0.195 respectively. The work hardening exponents $n_1$, $n_2$, and $n_3$ decreased with increasing reduction. The $n_1$ value decreased much more rapidly than the either $n_2$ or $n_3$.

The work hardening exponents $(n_1, n_2, n_3)$ of steel TR2 under different equivalent plastic strains are plotted in Fig. 6. The average work hardening exponents $(n_1, n_2, n_3)$ of steel TR2 without temper rolling are 0.151, 0.240, and 0.231 respectively. The work hardening exponents $n_1$ and $n_3$
The specified strain intervals used in this work for work hardening exponents \(n_1, n_2,\) and \(n_3\) are 5 to 10\%, 10 to 15\%, and 10 to 20\% respectively. A comparison between experimental and calculated exponents, \(n_1, n_2,\) and \(n_3,\) are shown in Fig. 5. Very good agreement between the experimental results and the calculations was obtained.

Conclusions

1. The lower yield point of steels TR1 and TR2 (based on Fe–0.135C–0.66Mn and Fe–0.19C–0.18Mn respectively) decreases with an increase in reduction by temper rolling.
2. The ultimate tensile strength of steels TR1 and TR2 and yield strength of steel TR1 increases with an increase in reduction by temper rolling.
3. The lower yield point and ultimate tensile strength of steels TR1 and TR2 under different temper rolling conditions can be described by the equation \(\sigma = \sigma_0 + K\varepsilon_{eq},\) where \(\sigma\) is the strength after temper rolling, \(\sigma_0\) is the strength without temper rolling, \(\varepsilon_{eq}\) is the equivalent strain by temper rolling, and \(K\) is a constant.
4. The uniform elongation and total elongation of steels TR1 and TR2 under different reductions are those without temper rolling subtracted from their equivalent plastic strains.
5. The work hardening exponents of samples with different temper rolling reductions can be predicted using the tensile curves of samples which have not been tempered rolled. Very good agreement between the experimental results and the calculated data was obtained.
6. The critical equivalent plastic strains of steels TR1 and TR2 are about half of their uniform elongation in each case.

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References