Deformation behaviour of low carbon steels under hot rolling service conditions is predicted utilising a combination of isothermal single step deformation test, anisothermal interrupted test and hot rolling simulation performed on torsion plastometer. The stress $\sigma_{0.05}$ at strain level $\varepsilon = 0.05$ and the restoring factor $f_r$ are proposed to be used for the description of the strengthening / restoring process during repeated deformation.

**Key words:** steels; hot rolling; dynamic phenomena; recrystallisation and recovery

**INTRODUCTION**

Phenomenological approach to the description of deformation resistance behaviour of steel and its microstructure development under the service hot rolling condition is still the most common useful and powerful. Utilising different experimental equipment such as torsion plastometer [1-5], compression plastometer [6-9], or advanced laboratory mills [10, 11] as well as different deformation techniques such as single step deformation and repeated deformations [12], compression [6, 7] test or stress relaxation method [8, 9], forward (monotonic) or reversed deformation [13], is possible to predict microstructural changes and flow stress curve of material on the service hot rolling mill with fairly good accuracy.

The main problem of above mentioned approaches and based on them models is that they operate only with narrow range of chemical composition of investigated steel or consider particular processes in material during hot rolling such as static and dynamic recovery, dynamic, static or metadynamic recrystallisation (SR, DR, DRX, SRX and MDRX respectively), i.e. softening/hardening behaviour of material under service hot rolling conditions. Also plastometer experiment output data need to be corrected because of “nature” restrictions such as, for example, inhomogeneous distribution of strain within the sample or rising of the temperature due to the deformation work [14].

Other big problem of hot deformation process modelling is connected with fact, that often laboratory facilities cannot provide applying of service rolling strain rate. With the aim to predict steel behaviour under service hot rolling conditions, two approximations of the laboratory test results should be applied: (i) interpass time correction; (ii) extrapolation of stress level [15, 16]. Rate of the material softening in between of passes is higher on the rolling mill than during the laboratory test due to higher stress level. Hence, the laboratory interpass times must be increased according to the relation [17]:

$$t_{lab} = t_{mill} \left( \frac{\varepsilon_{mill}}{\varepsilon_{lab}} \right)^{n}$$

where $t_{lab}$ and $t_{mill}$ subscripts correspond to the laboratory and industrial mill conditions respectively, $n$ - strain rate exponent, of which values for the low carbon steels are in the range of 0.6 - 1.1 [18-22].
Mean flow stress \( MFS \) value under the service condition can be predicted by classic equation [22]:

\[
MFS_{\text{mill}} = MFS_{\text{lab}} \left( \frac{\dot{\varepsilon}_{\text{mill}}}{\dot{\varepsilon}_{\text{lab}}} \right)^p
\]

(2)

where \( p \) is the strain rate exponent in the range of 0.11 - 0.15 [21, 22] or has slightly higher value of 0.29 [23]. More correct \( MFS \) on the service rolling mill can be predicted utilising modified equation [24]:

\[
MFS_{\text{mill}} = MFS_{\text{lab}} \left( \frac{\dot{\varepsilon}_{\text{mill}}}{\dot{\varepsilon}_{\text{lab}}} \right)^{p/T}
\]

(3)

where \( p' = p' \left( T, \dot{\varepsilon}_{\text{mill}} / \dot{\varepsilon}_{\text{lab}} \right) \).

Other important issue of hot rolling simulation is so-called no-recrystallisation temperature \( T_{nr} \). This temperature is claimed as a temperature below which material becomes strained during unisothermic interrupted test, i.e. softening processes are not completed during pause between the passes. To find this temperature, usually the \( MFS \) achieved in each stress is plotted against the inverse absolute temperature. Point where obtained in such way curve changes its slope, is \( 1/T_{nr} \). Further in this paper we will propose alternative method of \( T_{nr} \) establishing.

Although \( T_{nr} \) is only qualitative description of commencing of the material strengthening, we need to consider new approach for the quantitative description of the mentioned process.

EXPERIMENT

The 5 types of low carbon steel were used as an experimental material (see Table 1.). Bars with dimensions 20x20x220 mm were cut up from slabs after prerolling and homogenised at 1200 °C in vacuum. Samples with gauge length 50 mm and diameter 6 mm were machined from the annealed bars. The plastometer program was carried out on the torsion plastometer SETARAM and consisted of three types of test.

1. Simple (single step) deformation test (ST)

Before the deformation, the samples were austenised for 10 min at 1200 °C. ST were carried out at \( T = \{1200; 1150; 1050; \ldots, 750, 700 \}^\circ C \}, \) samples were deformed up to \( \varepsilon = 1 \), at two strain rates, \( \dot{\varepsilon} = 0.045 \text{ s}^{-1} \) and \( \dot{\varepsilon} = 0.45 \text{ s}^{-1} \). Additionally, ST were performed at at \( T = \{1150, 1050, \ldots, 750 \}^\circ C \} \) with strain rates of \( \dot{\varepsilon} = 0.023 \text{ s}^{-1} \), \( \dot{\varepsilon} = 0.14 \text{ s}^{-1} \), and \( \dot{\varepsilon} = 1.1 \text{ s}^{-1} \) for steel C.

2. Anisothermic interrupted tests (AIT)

AIT consisted of 12 equal deformation of \( \varepsilon = 0.24 \) at strain rate of \( \dot{\varepsilon} = 0.45 \text{ s}^{-1} \), with different commencing temperature within temperature range 1150 - 630 °C. First deformation was realised after 1200 °C/10 min sample holding, pauses between deformations were 10 s, average samples cooling rate was 3 °C/s.

3. Simulation

Simulation was performed according to the time-deformation schedule of typical service hot rolling (see Table 2.), but at constant strain rate \( \dot{\varepsilon} = 0.45 \text{ s}^{-1} \). Few different temperature schedules were applied within temperature range of 1200 - 770 °C. Afterwards \( MFS \) value at each pass was approximated on the service strain rate.

RESULTS AND DISCUSSION

Simple deformation test

We propose to claim the maximum stress value at the ST as peak stress \( \sigma_{\text{p}} \) and at both AIT and simulation as “maximum” stress \( \sigma_{\text{m}} \), with the aim to distinguish maximum stress value in the case of non-strengthened and strengthened/restored material. For all five investigated steels, the ST results have very good agreement with values predicted by semi-empiric model presented in [2, 3].
For example, in Figure 1., both experimental and model σ values for steel D are shown. Due to the start of γ → α phase transformation and lower deformation resistance of ferrite, the stress decreases below $A_γ = 850 \, ^\circ C$.

In the Figure 2., such dependence for steel C is shown. Further we will compare MFS prediction by the approximation of the simulation results on the service hot rolling strain rate utilising both “classic” (eq. (2)) and “new” (eq. (3)) methods.

**Anisothermal interrupted tests**

In Figure 3., the $\sigma_{0.05}$ value at strain $\phi = 0.05$ for both ST and AIT are compared (E steel). In the temperature range of 1150 - 980 °C, both $\sigma_{0.05}$ values are practically the same. Below 980 °C, the difference between ST and AIT $\sigma_{0.05}$ values increases significantly. It means, that below this temperature, the recovery process in-between deformations are not complete and strain accumulation is observed. Hence, the $\sigma_{0.05}$ value could be used as a critical value for no-recrystallisation temperature $T_{nr}$ establishing.

In Figure 4., the $\sigma_{max}$ values from AIT are compared with $\sigma_p$ values from ST for the steel B. It is obvious, that at any corresponding temperature $sp$ value is higher than $\sigma_{max}$. Hence, it can be concluded that $sp$ value from ST is upper limit for the $\sigma_{max}$ during repeated deformation even in the case of strain accumulation below $T_{nr}$. This fact can be used for the simple way estimation of the maximum values of the steel deformation resistance under the service hot rolling conditions.
In Figure 5., the $\sigma_{0.05}$ and MFS values during AIT are compared (steel E). An unusual phenomenon is observed below app. 775 °C: $MFS < \sigma_{0.05}$. This can be explained as a result of strain-induced phase transformation, which “dynamically” starts at some stress threshold value. At the same temperature, partial deformation resistance of $\alpha$-phase is lower than one of $\gamma$-phase. Therefore, the total deformation resistance of material decreases after the start of $\gamma \rightarrow \alpha$ transformation, what reflects in the lowering of MFS value.

For quantitative description of material strengthening/restoring behaviour during repeated deformation, we propose to us the restoring factor $f_r$:

$$f_r = \frac{\sigma_{0.05}(AIT_i) - \sigma_{0.05}(ST)}{\sigma_{max} - \sigma_{0.05}(ST)}$$

(4)

where $\sigma_{0.05}(ST)$ and $\sigma_{0.05}(AIT_i)$ are the $\sigma_{0.05}$ values for the single step deformation (ST) and $i$ iteration from AIT respectively, both realised at the same temperature and with the same strain rate. $\sigma_{max}$ - maximum stress value from $i$ deformation of AIT. The restoring factor claimed in such manner describes development of the restoring processes between deformations. If $f_r = 0$, material is fully restored. Is $f_r \rightarrow 1$, the restoring of material during the interpass pause is minimal. As an example, in Figure 6., the $f_r$ temperature dependence for the steel E under AIT conditions is shown.

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**SIMULATION**

Typical hot rolling process of strips can be considered as two-stage process with quite distinct conditions of rolling. During a roughing typical interpass time is within range of 10-50 s and strain rate within range of 1 - 20 s\(^{-1}\). Interpass
time within range of 0.1 - 3 s and strain rate within range of 10-150 s\(^{-1}\) are applied during a finishing part of hot rolling. Because of this crucial difference, it is necessary to analyse roughing and finishing separately.

On the first stage, we realised simulation experiment without interpass time correction. Example of flow stress curve during such simulation is in Figure 7. (steel C, strain rate \(\dot{\varepsilon} = 0.45\) s\(^{-1}\), temperature schedule is indicated on the graph). First six deformations are the roughing part of hot rolling simulation, last six ones are the finishing part of it (see Table 2.). It is obvious, that, excepting pause after the 1st deformation, the MDRX occurs after each deformation during roughening. Although considerable increase of deformation resistance is observed from 7th deformation, strain accumulation occurs only after the 9th deformation (see Figure 8.). Hence stress increase at 7th, 8th and 9th deformations is only subsequence of temperature decrease, but not accumulation of strain.

Under the service conditions strain rate is higher than applied during simulation (see Table 2.). In Figure 9., comparison of model [25] values of a peak strain \(\varepsilon_p\), calculated utilising model [2, 3], with strain of service hot rolling schedule is shown. It is clear that even in the case of real strain rates application, MDRX occurs after all deformations during roughing (1\(^{st}\) - 6\(^{th}\) pass). Because of higher industry strain rates, kinetics of the softening processes in-between the deformations under the service conditions will be higher, than during simulation. As it was mentioned above, during roughening stage of simulation material is fully recrystallised between passes. Hence, during roughening it is not necessary to apply correction of interpass times.

During next step of simulation experiment we applied the same schedule but with interpass time correction according to the eq.(1) for finishing (7\(^{th}\) - 12\(^{th}\) deformations). Obtained in such way MFS values, we approximate on the real strain rate by applying either eq. (2) or eq. (3). Utilising
data of ST, were found functional dependencies of \( \rho \) and \( \rho' \) for eq. (2) and eq. (3) respectively. \( \rho \) has linear dependence on \( T \), \( \rho' \) could be described with good accuracy (\( R=0.98 \)) by the polynom of the 4th order for both independent variables \( T \) and \( \dot{\varepsilon}_{\text{mill}} / \dot{\varepsilon}_{\text{lab}} \). Afterwards, MFS values under the service hot rolling conditions were calculated (see Figure 10.).

3. The restoring factor \( f \) can be used for the quantitative description of the strengthened/restored state of the material in each deformation during sequence of them.

4. It is not necessary apply the interpass time correction during the simulation of the roughening stage of hot rolling of low carbon steels.

5. For the accurate prediction of the MFS by simulation and approximation on the service strain rates, the next equation have to be used:

\[
MFS_{\text{mill}} = \left( \frac{\dot{\varepsilon}_{\text{mill}}}{\dot{\varepsilon}_{\text{lab}}} \right)^{\rho' T}
\]

where \( \rho' = \rho' (T, \dot{\varepsilon}_{\text{mill}} / \dot{\varepsilon}_{\text{lab}}) \).

### REFERENCES

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