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PREDICTION OF DEFORMATION RESISTANCE OF LOW CARBON STEELS DURING HOT ROLLING

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Deformation behaviour of low carbon steels under hot rolling service conditions is predicted utilising a combination of isothermic single step deformation test, anisothermic 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*

Izračunavanje otpora deformacije nisko ugljičnih čelika tijekom toplog valjanja. Deformacija nisko ugljičnih čelika tijekom toplog valjanja izračunava se kombinacijom jednokoračnog izotermnog testa na deformaciju, prekinutog testa i simulacije toplog valjanja izvedene na torzionom plastometru. za opis procesa jačanja/obnavljanja tijekom ponavljanja deformacije predlaže se uporaba naprezanja $\sigma_{0.05}$ na nivou deformacije $\varepsilon = 0.05$ i faktora obnavljanja f_r.

Ključne riječi: *čelici, toplo valjanje, fenomeni dinamike, rekristalizacija i oporavak*

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 strain rate and subsequently higher stress level. Hence, the laboratory interpass times must be increased according to the relation [17]:

$$t_{lab} = t_{mill} \left(\frac{\dot{\varepsilon}_{mill}}{\dot{\varepsilon}_{lab}} \right)^n \tag{1}$$

where $_{lab}$ and $_{mill}$ 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].

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Mean flow stress (*MFS*) value under the service condition can be predicted by classic equation [22]:

$$MFS_{mill} = MFS_{lab}\left(\frac{\dot{\varepsilon}_{mill}}{\dot{\varepsilon}_{lab}}\right)^{p} \tag{2}$$

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]:

$$MFS_{mill} = MFS_{lab}\left(\frac{\dot{\varepsilon}_{mill}}{\dot{\varepsilon}_{lab}}\right)^{p'T} \tag{3}$$

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

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, …, 750, 700 °C}, samples were deformed up to ε = 1, at two strain rates, $\dot{\varepsilon}$ = 0.045 s^{-1} and $\dot{\varepsilon}$ = 0.45 s^{-1}. Additionally, ST were performed at at T={1150, 1050, …, 750} with strain rates of $\dot{\varepsilon}$ = 0.023 s^{-1}, $\dot{\varepsilon}$ = 0.14 s^{-1}, and $\dot{\varepsilon}$ = 1.1 s^{-1} for steel C.
2. ***Anisothermic interrupted tests (AIT)***
AIT consisted of 12 equal deformation of ε = 0.24 at strain rate of $\dot{\varepsilon}$ = 0.45 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 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.

Table 1. **The chemical composition of steels, wt. %**
Tablica 1. **Kemijski sastav čelika, težina %**

Steel	C	Mn	Si	Mo	Ti
A	0.070	0.25	0.02	-	-
B	0.080	0.27	0.15	-	-
C	0.018	1.07	0.43	-	-
D	0.080	1.20	0.17	0.08	0.002
E	0.080	1.72	0.06	0.011	0.029
	Nb	V	P	S	Al
A	-	-	0.009	0.016	0.021
B	-	-	0.018	0.014	0.053
C	-	-	0.011	0.014	0.040
D	0.029	0.003	0.011	0.006	0.042
E	0.054	0.077	0.013	0.005	0.047

Table 2. **Typical service hot rolling schedule**
Tablica 2. **Tipični program toplog valjanja**

Number of mill	1	2	3	4	5	6
True strain	0.23	0.32	0.43	0.36	0.39	0.46
Time to next pass, s	12.2	25.7	21.0	15.2	17.3	43.8
Strain rate	0.96	0.88	1.77	4.42	6.77	6.26
Number of mill	7	8	9	10	11	12
True strain	0.31	0.43	0.38	0.26	0.23	0.15
Time to next pass, s	3.0	2.10	1.50	1.20	0.90	-
Strain rate	8.2	17.5	29.0	37.3	49.3	53.8

RESULTS AND DISCUSSION

Simple deformation test

We propose to claim the maximum stress value at the ST as peak stress σ_p and at both AIT and simulation as "maximum" stress σ_{max} 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_p values for steel D are shown. Due to the start of $\gamma \rightarrow \alpha$ phase transformation and lower deformation resistance of ferrite, the stress decreases below $A_{r_3} \approx 850$ °C.

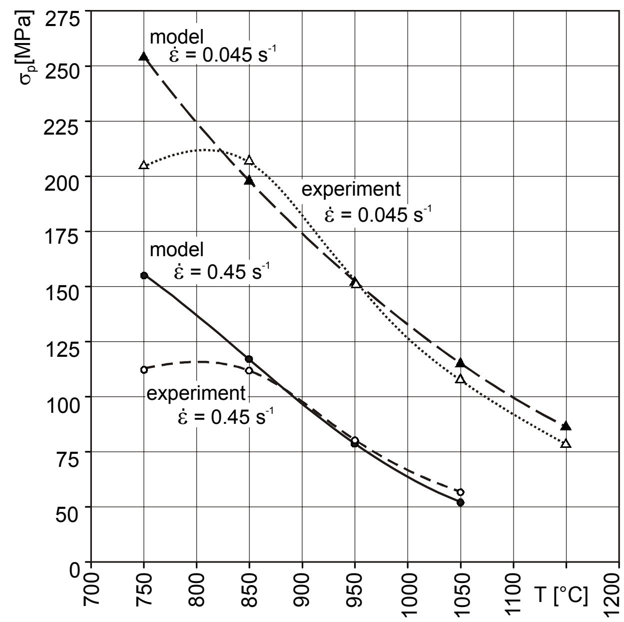

Figure 1. **Temperature dependence of peak stress value σ_p. Steel C, simple test**
Slika 1. **Ovisnost temperature o vrijednosti maksimalnog naprezanja σ_p; Čelik C, jednostavni test**

For accurate prediction of MFS during simulation utilising eq. (3), it is necessary to find out functional dependence of the strain rate sensitivity coefficient $p'=p'(T, \dot{\varepsilon}_{mill} / \dot{\varepsilon}_{lab})$. 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.

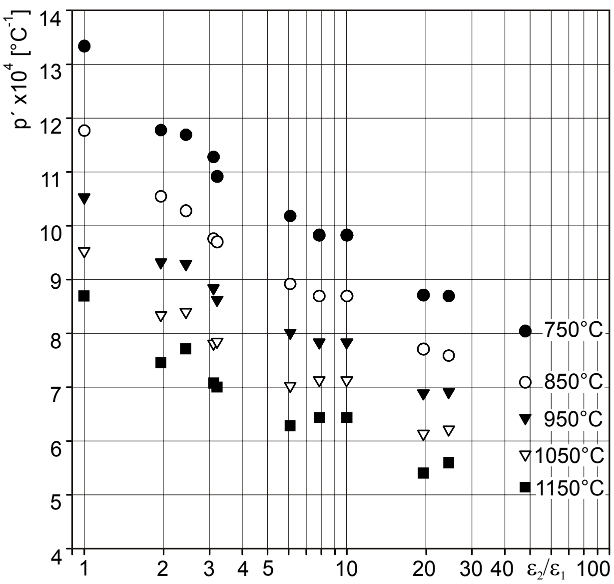

Figure 2. **Dependence of strain rate exponent *p'*, derived from eq. (3), on temperature and strain rate ratio. Steel B**
Slika 2. **Ovisnost eksponenta brzine naprezanja *p'*, izvedenog iz jednadžbe (3), o temperaturi i odnosu brzine naprezanja; Čelik B**

Anisothermic interrupted tests

In Figure 3., the $\sigma_{0.05}$ value at strain $\varphi = 0.05$ 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.

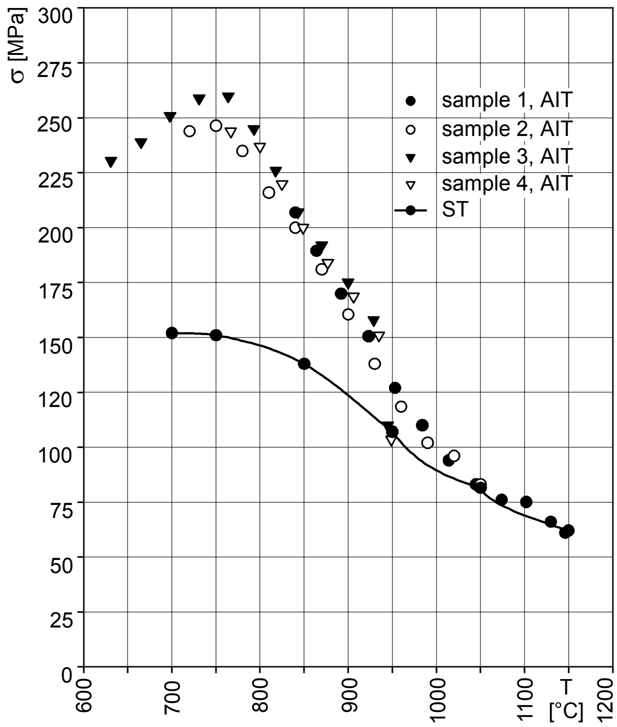

Figure 3. **Comparison of $\sigma_{0.05}$ from anisothermic interrupted test and simple test. Steel E, strain rate $\dot{\varepsilon} = 0.045$ s^{-1}**
Slika 3. **Usporeďivanje $\sigma_{0.05}$ iz anizometričkog prekinutog testa i jednostavnog testa; Čelik E, brzina deformacije $\dot{\varepsilon} = 0.045$ s^{-1}**

In Figure 4., the σ_{max} values from AIT are compared with σ_p values from ST for the steel B. It is obvious, that at any corresponding temperature sp value is higher than σ_{max}. Hence, it can be concluded that sp value from ST is upper limit for the σ_{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.

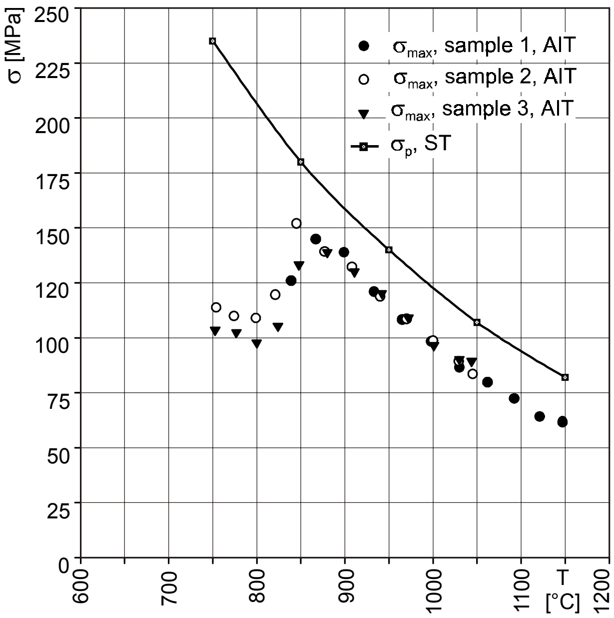

Figure 4. **Comparison of σ_{max} from anisothermic interrupted test and σ_p from simple test. Steel B, strain rate $\varepsilon' = 0.45\ s^{-1}$**

Slika 4. **Usporedba σ_{max} iz anizotermičkog prekinutog testa i σ_p iz jednostavnog testa; Čelik B, brzina deformacije $\varepsilon' = 0.45\ s^{-1}$**

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

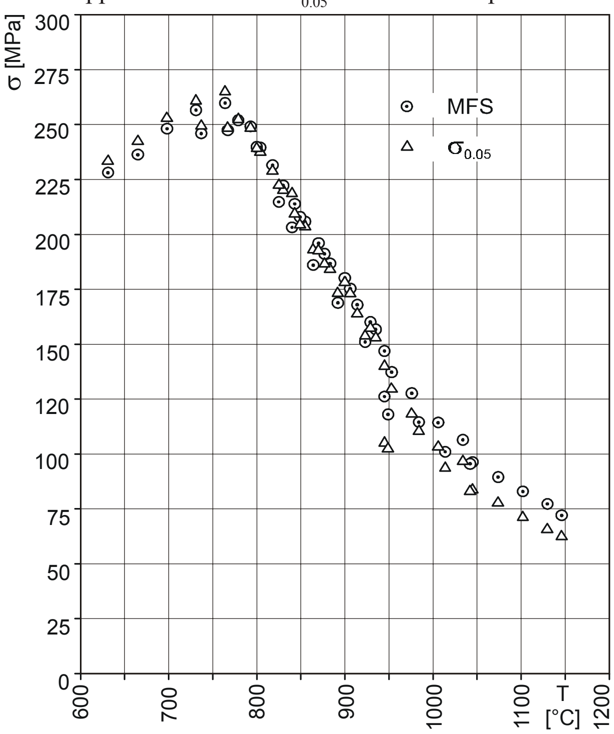

Figure 5. **Comparison of $\sigma_{0.05}$ and *MFS* values from anisothermic interrupted test. Steel E**

Slika 5. **Uspoređivanje $\sigma_{0.05}$ i vrijednosti *MFS* iz anizometričkog prekinutog testa; Čelik E**

result of strain-induced phase transformation, which "dynamically" starts at some stress threshold value. At the same temperature, partial deformation resistance of α-phase is lower than one of γ-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:

$$f_r^i = \frac{\sigma_{0.05}(AIT_i) - \sigma_{0.05}(ST)}{\sigma_{max}^i - \sigma_{0.05}(ST)} \tag{4}$$

where $\sigma_{0.05}$ (ST) and $\sigma_{0.05}$ (AITi) 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, σ_{max}^i - 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 axample, in Figure 6., the f_r temperature dependence for the steel E under AIT conditions is shown.

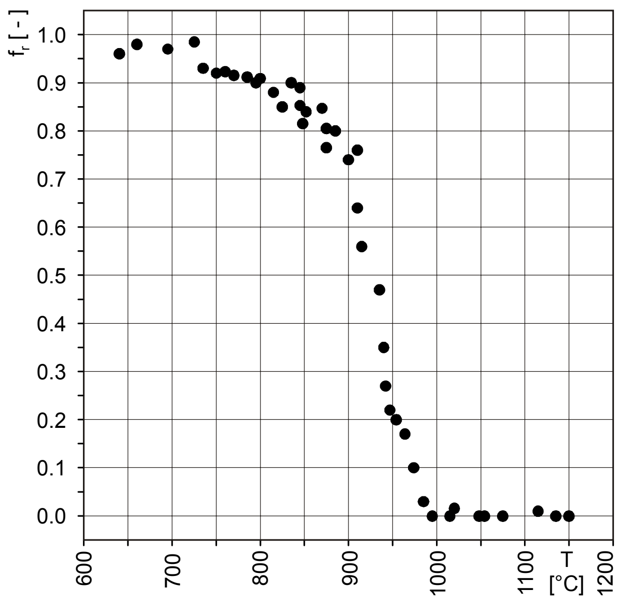

Figure 6. **Temperature dependence of restoring factor f_r. Steel E, anisothermic interrupted test**

Slika 6. **Ovisnost temperature faktora obnavljanja f_r; Čelik E, anizometrički prekinuti test**

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.

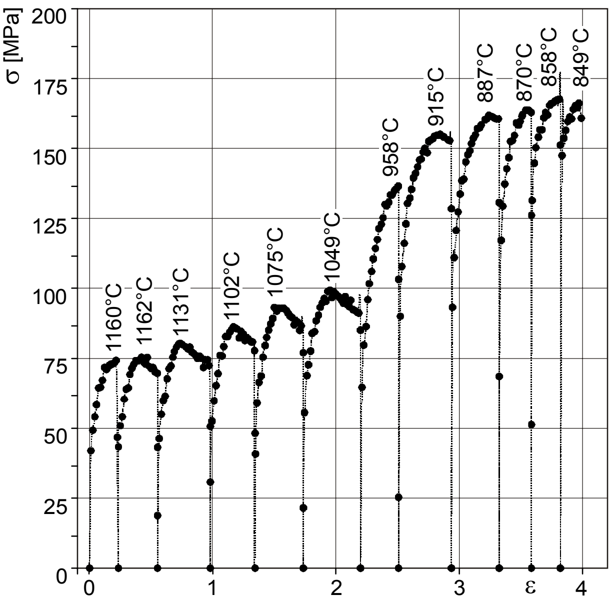

Figure 7. **Flow stress curve during simulation experiment. Steel C**
Slika 7. **Krivulja toka naprezanja tijekom simulacije eksperimenta; čelik C**

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.

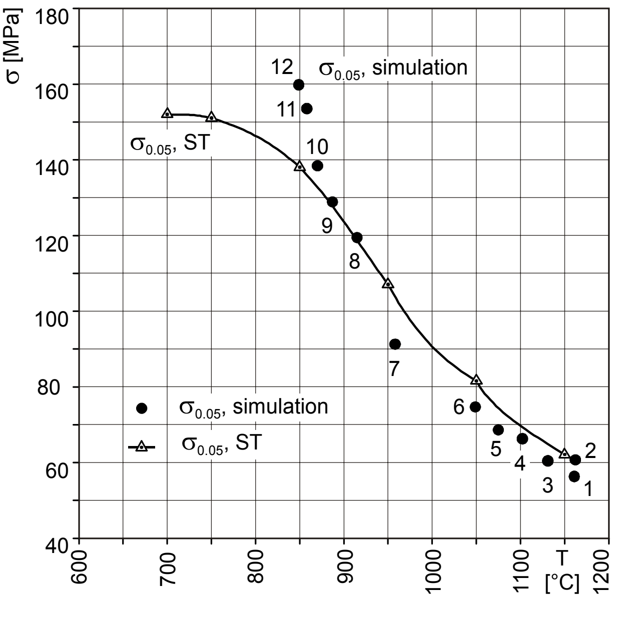

Figure 8. **Comparison of $\sigma_{0.05}$ from simulation and simple test. Steel C**
Slika 8. **Usporedba $\sigma_{0.05}$ iz simulacije i jednostavnog testa; čelik C**

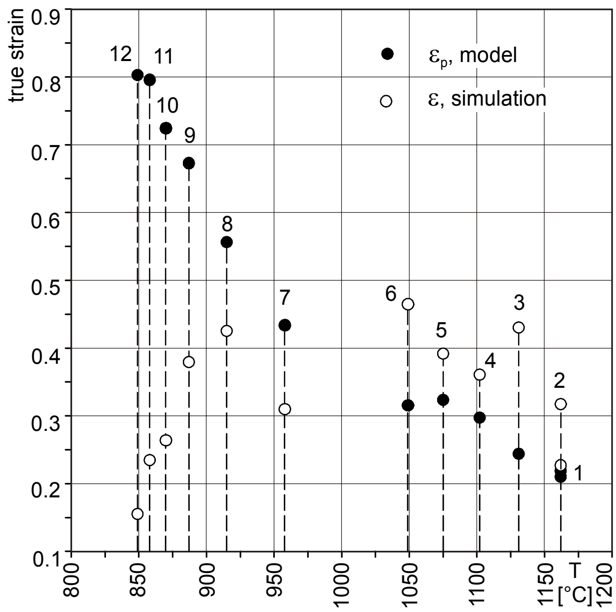

Figure 9. **Comparison of strain ε according to service hot rolling schedule and peak strain ε_p, calculated utilising model [2, 3]. Steel C**
Slika 9. **Usporedba ε prema programu toplog valjanja i maksimalnoj deformaciji ε_p, izračunatoj pomoću modela [2, 3]; čelik C**

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 ε_p under the service condition and the strain values from simulation is shown. It is clear than even in the case of real strain rates application, MDRX occurs after all deformations during roughing (1st - 6th 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 (7th - 12th 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 *p* and *p´* for eq. (2) and eq. (3) respectively. *p* has linear dependence on *T*, *p´* could be described with good accuracy (R=0.98) by the polynom of the 4th order for both independent variables *T* and $\dot{\varepsilon}_{mill} / \dot{\varepsilon}_{lab}$. Afterwards, MFS values under the service hot rolling conditions were calculated (see Figure 10.).

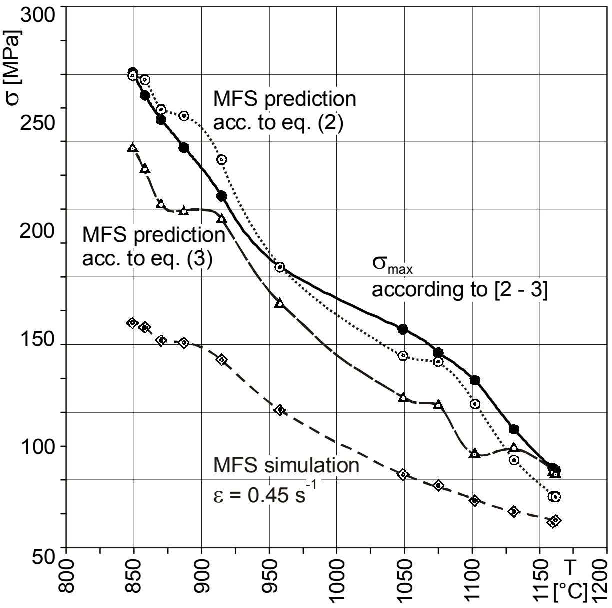

Figure 10. **Prediction of *MFS* under service hot tolling conditions utilising result of simulation test. Steel C**

Slika 10. **Izračunavanje *MFS* u uvjetima toplog valjanja pomoću rezultata testa simulacije; čelik C**

From comparison of MFS values predicted by both methods and maximum stress values according to the Medina-Hernandez's model [2, 3], it can be concluded that prediction of deformation resistance under the industry conditions is more accurate when "modified" eq. (3) is applied.

SUMMARY

1. Peak stress value from single step deformation test is an upper limit for the maximum stress during repeated deformation even in the case of strain accumulation below T_{nr}.
2. $\sigma_{0.05}$ stress value at strain $\varphi = 0.05$ is proposed to use as characteristic value for establishing of the no-recrystallisation temperature T_{nr} during repeated deformation.
3. The restoring factor f_r 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:

$$MFS_{mill} = \left(MFS_{lab} \frac{\dot{\varepsilon}_{mill}}{\dot{\varepsilon}_{lab}} \right)^{p'T}$$

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

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