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VERIFICATION OF NEW MODEL FOR CALCULATION OF CRITICAL STRAIN FOR THE INITIALIZATION OF DYNAMIC RECRYSTALLIZATION USING LABORATORY ROLLING

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This paper presents a new model for calculation of critical strain for initialization of dynamic recrystallization. The new model reflects the history of forming in the deformation zone during rolling. In this region of restricted deformation, the strain rate curve for the surface of the strip exhibits two peaks. These are the two reasons why the onset of dynamic recrystallization DRX near the surface of the rolled part occurs later than in theory during strip rolling. The present model had been used in a program for simulation of forming processes with the aid of FEM and a comparison between the physical experiment and a mathematical model had been drawn.

Key words: steel, hot rolling, finite element method (FEM), dynamic recrystallization

Vrednovanje novog modela proračuna kritične deformacije početka dinamičke rekristalizacije rabljenjem laboratorijskog valjanja. Članak daje novi model za vrjednovanje kritične deformacije početka dinamičke rekristalizacije. Novi model odražava razvoj oblikovanja pri valjanju, gdje utjecajem otežane deformacije, krivulja deformacijske brzine na površinskom sloju ima dva ekstrema. To su dva razloga gdje je početak dinamičke rekristalizacije blizu površine valjanog komada zakočen, protivno teoriji valjanja trake. Dati model je bio primijenjen u programu pri simulaciji procesa oblikovanja metodom konačnih elemenata (MKE), a provedena je i usporedba izmedju fizikalnog eksperimenta i matematičkog modela.

Ključne riječi: čelik, toplo valjanje, metoda konačnih elemenata (MKE), dinamička rekristalizacija

INTRODUCTION

Development of computer technology offers ever more elaborated and some novel mathematical modeling methods for description of materials response to rolling. Research in this field has been undertaken by a number of experts who proposed numerous particular models [1-7]. Using these models can provide detailed information on changes in thermomechanical variables during rolling and enable the prediction of microstructure formation and mechanical properties. One of the fundamental purposes of hot rolling is to obtain a final product with small and uniform ferrite grain size and resulting favourable properties. The ferrite grain size depends primarily on the austenite grain size at the end of the rolling process, on the amount of strain, the temperature schedule and other parameters [8].

It is possible to obtain required microstructure parameters with controlled forming combining suitable temperatures, reductions and delays between passes in relation to strain rate.

At present, a number of semi-empirical models were describing the kinetics of restoration processes in material [8-14]. However, these models still use simplified and do not fully utilize results obtained with mathematical modelling. The following section contains an introduction to a new model describing dynamic recrystallization in steel constructed directly for the use in FEM-based programs.

CRITICAL STRAIN FOR THE INITIALIZATION OF DRX

The critical strain for the onset of DRX (ε_c) is an important parameter employed in the mathematical modeling of microstructural evolution and of rolling load. Knowledge of the critical strain for the initiation of DRX is requirement for prediction of the operating softening mechanisms in hot forming processes. For the present purpose, it is useful to express the ε_c as a function of the initial grain size, temperature and strain rate [12]:

$$\varepsilon_c = 4{,}4 \cdot 10^{-4} \cdot d_0^{0,5} \cdot \left[\dot{\varepsilon} \cdot \exp\left(\frac{341000}{R \cdot T} \right) \right]^{0,089} \qquad (1)$$

where d_0 - initial grain size /μm, $\dot{\varepsilon}$ - strain rate /1/s, T - temperature /K, R - universal gas konstant /J/(mol·K), Q - activation energy /J/mol.

Values and distribution of thermomechanical parameters change during the forming process (strain, strain rate, temperature) Thanks to finite-element method modelling, it is possible to determine the time dependence

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and distribution of thermomechanical parameters in the part being formed. They are rather typical curves, particularly in strip rolling. The surface temperature of the strip decreases as a result of transfer of heat to rolls during rolling. It is now well known from FEM analysis that rolling deformation involves a high strain rate raise on entering the roll gap. FEM rolling simulations also predict a fast decay of strain rate within the deformation region after peaking due to the frictional cone [15].

It is this very special strain rate function for rolling, which led Bianchi and Karjalainen [16] to perform axisymmetric compression tests with abruptly changing true strain rates. Conditions which are explore by the experiments shown in Figures 1-3.

Under increasing strain rate conditions, two situations may occur. If the strain rate changes in the work hardening region of the first schedule (Figure 1), the critical strain value for the initialization of DRX does not shift at the following stage. However, if DRX occurs during the first stage (Figure 2), the decrease in accumulated strain causes the shift of the critical strain value for the initialization of DRX by an amount, which might be called corrective strain $\varepsilon_{cor.}$

Due to the reduction of the instantaneous strain with decreasing strain rate $\dot{\varepsilon}_1$, a change of this started in the hardening region easily falls in the DRX region of the second constant strain rate $\dot{\varepsilon}_2$. If the second constant strain rate is very low, softening is extremely fast followed by a new work hardening cycle (Figure 3), due to this ε_c was increased by the ε_{cor} value. The corrected critical strain for the initialization of DRX would be therefore determined as follows:

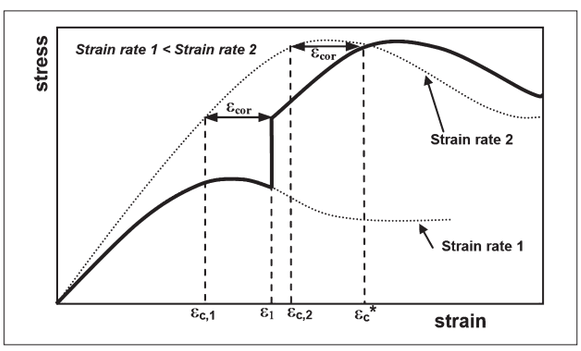

Figure 1. Strain-stress curve with an abrupt increasing of strain rate after initiation of DRX.

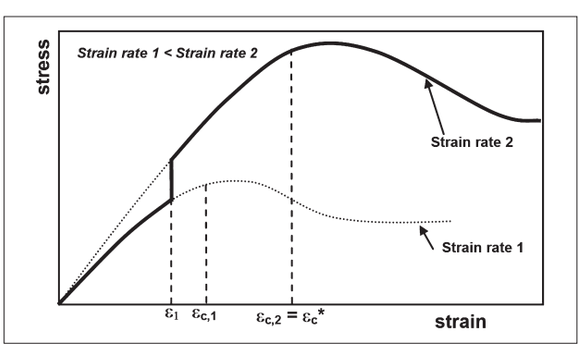

Figure 2. Strain-stress curve with an abrupt increasing of strain rate before initiation of DRX.

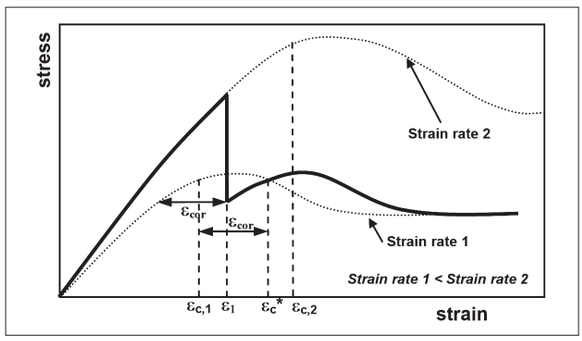

Figure 3. Strain-stress curve with an abrupt decreasing of strain rate before initiation of DRX.

$$\varepsilon_c^{*} = \varepsilon_c + \varepsilon_{cor} \tag{2}$$

where ε_{cor} may attain the following values:
under conditions shown in Figure 1:

$$\varepsilon_{cor} = \varepsilon_1 - \varepsilon_{c,1} \tag{3}$$

under conditions shown in Figure 2:

$$\varepsilon_{cor} = 0 \tag{4}$$

under conditions shown in Figure 3:

$$\varepsilon_{cor} = \varepsilon_1 \cdot \left(1 - \frac{\varepsilon_{c,2}}{\varepsilon_{c,1}}\right) \tag{5}$$

where: ε_1 - strain (-) with strain rate $\dot{\varepsilon}_1$, $\varepsilon_{c,1}$ and $\varepsilon_{c,2}$ - critical strain for the initialization of DRX with strain rate $\dot{\varepsilon}_1$ and $\dot{\varepsilon}_2$ respectively.

EXPERIMENTAL METHODICS

The use of equations (2) to (5) for determination of the critical strain for initialization of DRX will be demonstrated for rolling of low carbon steel with carbon content below 0,1 wt. % and no alloying elements. The current laboratory equipment, TANDEM rolling mill [17], was used to introduce the required accumulated strain in the material. Thanks to the arrangement of two rolling mills in sequence, joined with a short roller bed, it was possible to run an experiment consisting in two consecutive passes. The microstructure of rolled specimens was stabilized immediately upon their exit from the rolling gap and, for the purpose of comparison, upon two-second delay. A set of samples with dimensions of $5{,}5 \times 35 \times 100$ mm was cut by milling.

Direct heating to the rolling temperature was selected with soaking time of 5 - 8 minutes. The experiment was conducted at temperatures of 850, 800 and 750 °C. Microstructure of specimens upon pre-heating was examined upon stabilization (quenching in water).

The total (accumulated) strain is shown in Table 1. The effort to maintain constant total strain ε_S was complicated by the wide range of tempera tures used, which strongly affected the material's resistance to deformation during forming. This resulted in differences in the roll skip during rolling despite different roll gap settings.

Changes in microstructure

Microstructures of specimens upon heating and forming at different temperatures are shown in Figures

Table 1. **Summary of technological parameters of rolling**

#	Tempera-ture/ °C	Rolling force/kN		Total strain ε_S / -	Delay/ s
		mill A	mill B		
B85P	850	91,1	136,7	0,690	0,5
B85S	850	87,5	130,2	0,675	2,0
B80P	800	87,0	135,5	0,679	0,5
B80S	800	98,7	143,0	0,654	2,0
B75P	750	116,0	167,4	0,637	0,5
B75S	750	128,0	176,3	0,609	2,0

4-6. The figures show regions below the surface and in the centre of specimens.

Microstructures obtained upon heating (Figures 4-6 A) present a clear evidence that rolling took place in the two-phase region containing α and γ phases. The dark areas contain bainite and martensite, into which the overcooled austenite transformed, while white regions contain ferrite. The proportions of hardened microstructure are different below the surface and in the centre of specimens (being lower near the surface; possibly due to decarburization caused by heating). At 750 °C, the central region of specimens contained about 7 % austenite, while there was virtually no austenite near the surface. At 800 °C, the amount of austenite increased to 14 % in the centre and 10 % near the surface of specimens. At 850 °C, the proportion of γ was 18 % in the centre and 12 % near the surface of specimens. Average α grain size prior to rolling ranged from 20 μm at 750 °C to 30 μm at 850 °C.

The proportion of austenite had an effect on the appearance of the grain after rolling. The micrographs clearly show that rolling of material with lower proportion of austenite lead to more pronounced elongation of grains in the rolling direction.

The following zones can be identified in the micrographs showing microstructure upon rolling (Figure 4-6 B): equiaxed (polyhedral) α grains with size of around 20 μm (lightest areas) which evidence the occurrence of DRX followed by metadynamic recrystallization (MDRX). The second group consists of grains which are heavily elongated in the rolling direction; with grain area equal to the initial α grains area (most often grey in the micrograph). Finally, there are islands of hardened microstructure (dark regions). At higher temperatures, these exhibit signs of initiated static recrystallization (SRX) of austenite (minute grains of no more than 3 μm).

The last mentioned finest grains, which are present only in previous austenitic locations, are not a proof of occurrence of DRX. The reason is that due to different resistance to deformation in ferrite and austenite, these regions were subjected to about 60 % lower strain than the ferrite grains. Moreover, the kinetics of SRX of austenite show higher rates than that of ferrite. This is due to lower stacking fault energy in austenite, which inhibits potential recovery.

Hence, the attention turned to regions where microstructure formed by MDRX was found. At 750 °C, such

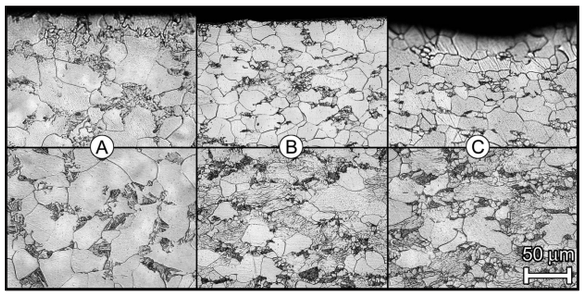

Figure 4. Microstructure at temperature 850 °C (A – after heating, stabilized within about B – 0,5 s, C – 2 s after rolling)

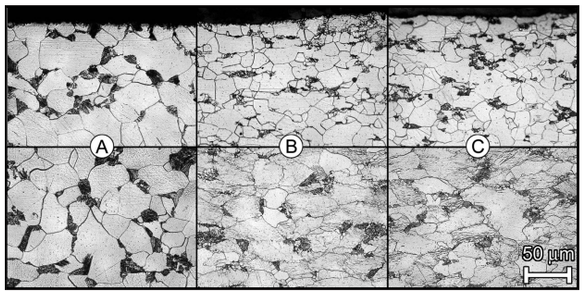

Figure 5. Microstructure at temperature 800 °C (A – after heating, stabilized within about B – 0,5 s, C – 2 s after rolling)

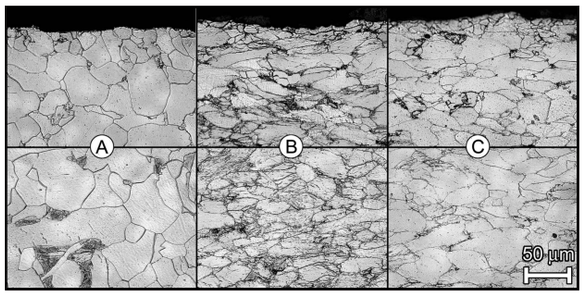

Figure 6. Microstructure at temperature 750 °C (A – after heating, stabilized within about B -0,5 s, C – 2 s after rolling)

microstructure did not actually exist in specimens, with the exception of subsurface regions (Figure 6 B, above) where such equi-axed grains are scattered. However, they do not cover more than 4 % of the total area. At 800 °C, microstructure upon full metadynamic recrystallization can be seen in the subsurface region (Figure 5 B, above). In the centre of specimen (Figure 5 B, below), the recrystallized grains cover less than 5 % of the total area. At 850 °C, the surface of the specimen consists of fully recrystallized microstructure, as expected. Moreover, nuclei of SRX of austenite can be observed in greater quantities. The centre of specimen exhibits a mixture of recrystallized and non-recrystallized grains. The proportion of recrystallized microstructure was identified by measurement as 21 % (Figure 4 B, below).

Grains formed by MDRX have the size of 16 μm and 18 ìm at 800 °C and 850 °C, respectively. Micrographs of structure stabilized at 2 seconds upon rolling show the grain growth upon the completed MDRX. In theory, the grain diameter should grow by about 30 % within the

2 seconds. However, in our case, the growth is not pronounced. In the regions, which underwent full MDRX, i.e. the surface, the growth was about 12 %. However, the grain growth in the regions which did not undergo full recrystallization, is considerable. The centre of specimen heated to 850 °C exhibits in 2 seconds the growth of recrystallized grain of more than 60 % (Figure 4 C, below).

Finite element simulation

Strip hot rolling simulation was performed by FormFEM 2D. The parameters of the mathematical simulation reflected the conditions of laboratory rolling very accurately. Our previous model for calculation of critical strain for DRX initialization was incorporated in the program. The algorithm for the calculation was published in [18]. It was found that, as a result of work of deformation, the temperature increased by 35 °C and 45 °C at initial temperatures of 850 °C and 750 °C, respectively. The strain rate curve for the surface of the specimen showed 3 peaks. The maximum value (about 650 1/s) was reached in the first peak. From this point onwards, the strain rate did not exceed 60 1/s. The value of strain was greater at the surface: about 1,2. Lowest value was observed, as expected, in the centre of the specimen: about 0,9. The fraction of dynamically recrystallized microstructure was calculated with the following formula [19]:

$$X_D = 1 - \exp\left(-0{,}682 \cdot \left(\frac{\varepsilon - \varepsilon_c}{\varepsilon_c}\right)^{1{,}295}\right) \qquad (6)$$

For the purpose of comparison, X_D was also determined by a conventional method. This involved the critical strain computed from the average strain rate found as:

$$\dot{\varepsilon}_s = \frac{1}{\varepsilon_i} \int_0^{\varepsilon_i} \dot{\varepsilon} d\varepsilon \qquad (7)$$

CONCLUSION

Results of both models and proportions of recrystallized microstructure measured by metallographic techniques are compared in the chart in Figure 7. It is evident that in the newly proposed model the critical strain shifted towards higher values. The resulting distribution of recrystallized structure X_D in areas near the centre of the specimen is in good agreement with measured values. However, neither model captured the measured tendency towards steep increase of recrystallized structure proportion along the line towards the surface. In this region, 100 % softening was observed upon the actual rolling. This could be due to the processing consisting in two immediately following passes, which brought several unknowns into the calculation. Another explanation might involve different chemical compositions of the surface and the remainder of the specimen (lower amount of austenite in particular). A following study will thus comprise verification of the model for a ferritic or ultra-low carbon steel. In these steels it should be possible to reach the critical strain with a single pass in one-phase region.

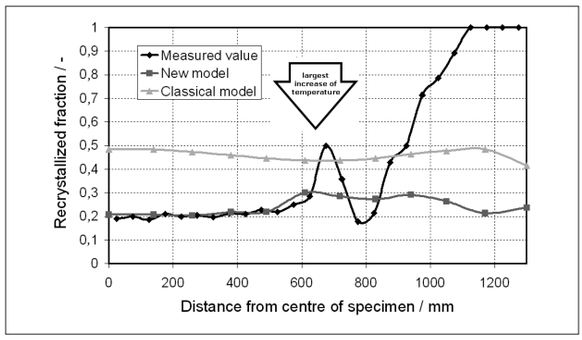

Figure 7. Distribution of recrystallized fraction at rolling temperature 850 °C.

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