MODELLING THE MICROSTRUCTURAL EVOLUTION DURING HOT ROLLING

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***Abstract*-- A metallurgical model that describes the microstructural evolution of C-Mn steels in the hot strip mill, and that predicts the yield strength and the ultimate tensile strength based on the steel chemistry and the processing conditions is presented. The model comprises the microstructural evolution during hot deformation in the austenitic range (taking into account the effects recrystallization and grain growth), and the austenite decomposition during cooling (formation of ferrite, perlite and/or bainite). A comparison between calculated and measured yield strength and ultimate tensile strength values for several steels and processing conditions is also included.**

***Keywords*-- hot rolling, recrystallization, grain growth, phase transformation.**

I. INTRODUCTION

Improving the hot strip mill process is mandatory for the steel industry owing to the increasingly severe specifications being imposed by end users. Within this objective the development of a metallurgical model that links the operating variables in the mill with microstructure and mechanical properties of the final products becomes of great importance. This model could provide useful information for process control and optimization, reducing the need of costly on-line experimentation.

The aim of this work is to present a metallurgical model that could describe the microstructural evolution of C-Mn steels during hot rolling, and could predict the final mechanical properties based on the steel chemistry and the processing conditions.

During hot deformation the average dislocation density of the material increases several orders of magnitude. Two metallurgical processes become active to reduce the dislocation excess: recovery and recrystallization. In austenite, the later is the most important restoration process. Depending on temperature, strain and strain rate the recrystallization could begin during deformation (dynamic recrystallization) or in the interpass time (static recrystallization). In order to describe the microstructural evolution it is needed a description of the recrystallization progress and the resulting austenite grain size after each reduction step in the rolling mill. In addition further modifications of the grain size could take place if the recrystallization after deformation is complete and is followed by grain growth.

After hot deformation the austenite transforms to ferrite, perlite and/or bainite. The transformation kinetic and final phase distribution depend strongly on the austenite microstructure (grain size and accumulated strain), and on the cooling and coiling conditions. Due to the important metallurgical differences between the several phases that may appear, it is needed an accurate description of the final microstructure in order to evaluate the mechanical properties of the material.

II. EXPERIMENTAL PROCEDURE

Stress relaxation tests (Liu and Jonas, 1988) performed with a Gleeble 3500 thermo-mechanical simulator have been used to measure the kinetic of recovery and recrystallization for different processing conditions (deformation temperature, strain and strain rate). In order to study the recrystallized grain size and the kinetic of grain growth, samples were deformed in compression and quenched after different holding times. The boundaries of the prior austenite grains were revealed using standard metallographic methods.

Dilatometric tests were also performed in the Gleeble machine to study the kinetic of austenite decomposition into ferrite, perlite and/or bainite.

Several low carbon–manganese steels were analyzed, the chemistries were within the following ranges [C] = 0.09-0.17 wt%, [Mn] = 0.8-1.2 wt% and [Si] = 0.1-0.3 wt%.

III. HOT ROLLING MODEL

In the present model the average grain size and the accumulated strain have been used to characterize the microstructure of the steel in the austenitic range. For the calculation of the microstructural evolution during hot deformation we have considered the effects of recrystallization and grain growth.

If the accumulated strain in a single reduction is lower than the critical value (ε_c) for the initiation of dynamic recrystallization, static recrystallization proceed after deformation (interpass time). The kinetic of static recrystallization was modelled using an Avrami type equation as proposed by Sellars (1980):

$$X = 1 - \exp\left[-0.693\,(t/t_{0.5})^n\right] \qquad (1)$$

where X is the volume fraction of the material recrystallized, $t_{0.5}$ is the time to 50% recrystallization and n is an empirical parameter. Several expressions have been

proposed to describe the $t_{0.5}$ dependence with austenite grain size (d_0), strain (ε), strain rate ($d\varepsilon/dt$) and holding temperature (T) (see Devadas *et al.*, 1991). In the present model the functional form proposed by Hodgson and Gibbs (1992) was adopted:

$$t_{0.5} = A_t\, \varepsilon^{-p}\, d_0^{\,q}\, \left(\frac{d\varepsilon}{dt}\right)^{r} \exp\left(\frac{Q_{rex}}{RT}\right) \qquad (2)$$

The parameters of this equation (A_t, p, q, r, Q_{rex}) were fitted using experimental data from stress-relaxation tests. Some of the results obtained with this technique are presented in Fig. 1, where the recrystallization start and finish times for a C-Mn steel are plotted as a function of temperature.

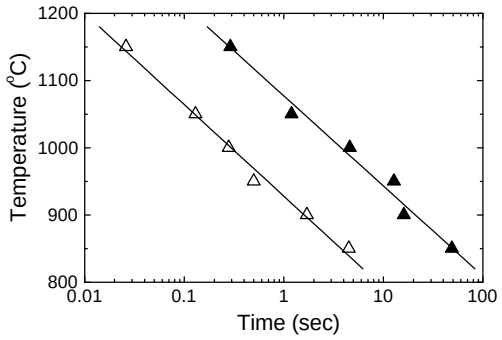

Figure 1: Recrystallization start and finish times as a function of temperature. Measurements performed with the stress-relaxation technique. Deformation conditions: ε=0.3, dε/dt = 10/sec.

There are many empirical expressions that attempt to describe the austenite grain size after static recrystallization (see Devadas *et al.*, 1991). In our case the predictions obtained with IRSID equations (Perdrix, 1987) presented the best agreement with experimental data.

The critical strain value to produce dynamic recrystallization was determined using the following expression (Sellars, 1980):

$$\varepsilon_C = A\, d_0^{\,1/2}\, Z^m \qquad (3)$$

where Z is the Zener-Hollomon parameter that depends on temperature and strain rate. We assume that when dynamic recrystallization takes place, it is followed by metadynamic recrystallization. In the present model the equations proposed by Hodgson and Gibbs (1992) to describe the kinetic of metadynamic recrystallization and to evaluate the size of the recrystallized grains were used.

The grain growth kinetic was modelled using a well known isothermal law (Sellars, 1980):

$$d^m = d_{rec}^{\,m} + k\, t \exp\left(Q_g / RT\right) \qquad (4)$$

where d_{rec} is the fully recrystallized grain size, t is the time after complete recrystallization, and m, k and Q_g are empirical parameters that were adjusted as was described in Section II.

IV. PHASE TRANSFORMATION

To describe the austenite decomposition into proeutectoid ferrite, perlite and bainite an empirical model based on the Miettinen work was used (Miettinen, 1996). The start temperature for each transformation was calculated with empirical expressions that take into account the chemical composition of the steel (C, Mn, Si), the cooling rate, and the austenite grain size. The effect of the accumulated strain during hot rolling was considered using an effective austenite grain size (Suehiro *et al.*, 1987).

The progress of the proeutectoid ferrite, perlite and bainite reactions was described using Avrami type equations:

$$X^{\phi} / X_{eq} = 1 - \exp\left[-k\, t^n\right] \qquad (5)$$

where X^{ϕ} is the volume fraction occupied by ϕ phase at time t (ϕ: ferrite, perlite or bainite), and X_{eq} is the thermodynamic equilibrium fraction for proeutectoid ferrite or the maximum available volume fraction in the case of perlite and bainite. The following dependence of k with the temperature was adopted:

$$k = P_1 \exp\left[-\left(\frac{T - P_2}{P_3}\right)^{P_4}\right] \qquad (6)$$

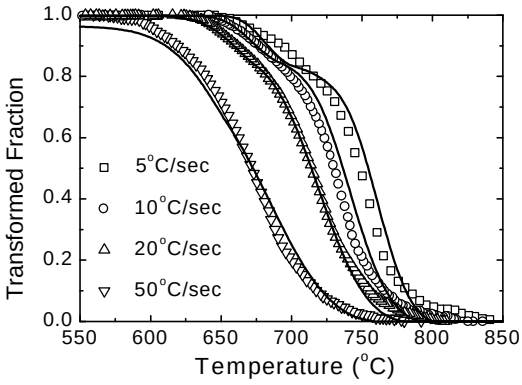

Figure 2: Transformed fraction of austenite as a function of temperature for different cooling rates. Symbols: experimental results obtained from dilatometric tests , lines: model predictions. Steel chemistry: C = 0.15 wt%, Mn = 0.8 wt%, Si = 0.2 wt%

The empirical parameters (n, P_i) that appear in Eqns. 5 and 6 were fitted for each reaction using data obtained from dilatometric tests. Experimental results and the comparison with the model predictions are shown in Fig.2.

The final ferrite grain size was calculated using a semi-empirical expression proposed by Suehiro *et al.* (1987), with parameters adjusted by comparison with experimental results. The interlamellar spacing of perlite was estimated as $\lambda = 5\ \lambda_{eq}$, where λ_{eq} corresponds to the equilibrium interlamellar spacing (static interphase between austenite and perlite, see Christian, 1975).

V. MECHANICAL PROPERTIES

The metallurgical model has been used to predict the mechanical properties of hot rolled C-Mn steels. Due to the steel chemistries covered in this study and the applied cooling rates, the final microstructures were mixtures of proeutectoid ferrite and perlite. The yield strength (YS) and ultimate tensile strength (UTS) were calculated using the set of equations developed by Gladman *et al.* (1972). These equations take into account the effects of the steel chemistry, the volume fraction of ferrite and perlite, the ferrite grain size, and the interlamellar perlitic spacing.

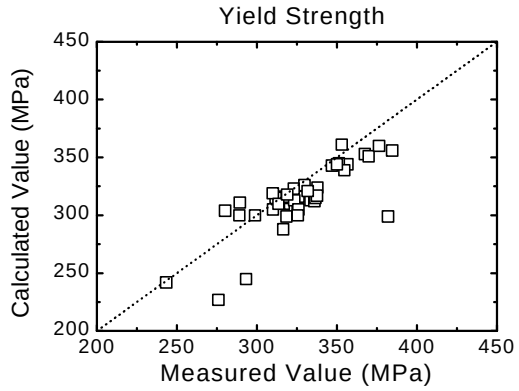

Figure 3: Comparison between experimental and theoretical values of yield strength for several steels.

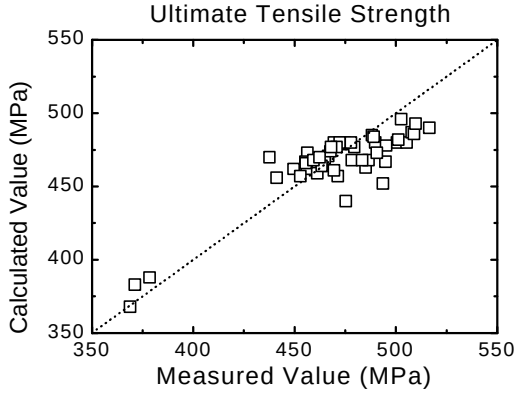

Figure 4: Comparison between experimental and theoretical values of ultimate tensile strength for several steels.

The model input data (strains, strain rates, deformation temperatures and interpass times) were calculated from the hot rolling mill set up (reduction schedule, strip velocities, average temperatures, work roll diameters and rotational speeds). The coiling temperature and the cooling bed operation parameters were used to estimate the cooling rate during transformation. In Figs. 3 and 4 a comparison between the calculated and measures values of YS and UTS is shown for several C-Mn steels. It can be seen in these graphs that there is a good agreement between measured and theoretical results.

There are some discrepancies between theoretical and experimental values of YS and UTS that can be ascribed to carbon and manganese contents out of the experimentally adjusted chemical range reported in Section II. The model parameters were adjusted for carbon and manganese compositions higher that 0.09 wt% and 0.8 wt%, respectively. The materials that exhibit higher deviations in the YS values have C concentration between 0.04 wt% and 0.05 wt% and Mn concentrations between 0.4 wt% and 0.6 wt%. In these cases some differences in the kinetics of recrystallization and grain growth that were not taken into account in the model may appear and, in addition, there could be changes in the rate of the austenite decomposition that affect the final ferrite grain size.

VI. SUMMARY

A metallurgical model that comprises the prediction of the microstructural evolution during hot rolling (austenitic range) and the subsequent phase transformation was developed for C-Mn steels. This model allows the prediction of some of the final product mechanical properties (YS and UTS). The calculated values of YS and UTS present a good agreement with experimental results. We have observed some discrepances that we have ascribed to steels chemistries outside the range covered when the empirical parameters of the model were adjusted.

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