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MODELLING AND PROCESS OPTIMISATION FOR HEAVY PLATE ROLLING OF STRUCTURAL STEEL

TADEUSZ SIWECKI

Corrosion & Metal Research Institute, KIMAB
Drottning Kristinas väg 48, 114 28 Stockholm, Sweden

Abstract

The aim of the paper is to present the recent developments (in Sweden) regarding microstructure and mechanical property enhancement through thermo-mechanical controlled processing (TMCP) of structural steel plate and the use of predictive models. Simulation of the TMCP treatment in laboratory scale as well as the computer models for calculation of microstructure development and precipitate evolution during hot rolling are invaluable for design of rolling schedules.

A brief survey is made of the models developed at the Corrosion & Metals Research Institute and used by the Swedish Steel Industry. The models can be used for predictions of recrystallization and grain growth of austenite after deformation, precipitation or dissolution of microalloying carbo-nitrides in austenite and phase transformation behaviour during accelerated cooling.

The effect of TMCP- parameters, low reheating and high finish rolling temperature, as well as rolling schedules, cooling rate will be discussed with regard to the transformation characteristics as well as the microstructure and strength of structure steels.

Key words: HSLA steel, modelling, microstructure, grain size, recrystallization, transformation, precipitation, microalloying, mechanical properties, hot rolling, accelerated cooling

1. INTRODUCTION

The key to success with TMCP-processing is to define rolling schedules combining a maximum degree of microstructural refinement with acceptably low rolling loads, good shape and surface control and high productivity. In this context, the simulation of the TMCP treatment in laboratory scale as well as the computer models for calculation of microstructure development and precipitate evolution during hot rolling are invaluable for design of rolling schedules.

For good control of final microstructure, it is invaluable to have a computer model for prediction of microstructure evolution during TMCP, to enable optimal design of rolling and cooling schedules. By modelling of microstructure evolution, the steel composition and the properties of the final product can be optimised without expensive testing. This can reduce the production cost of the high strength steels, making it more competitive in more applications. It is intended that the developed models will give steel producers essential advantages in thermomechanical processing and will be applicable to structural/microalloyed steels to achieve a useful optimisation of process parameters and steel chemistry. It is an ambitious effort to raise the quality and applicability of knowledge concerning individual metallurgical processes and transform thus into a sophisticated tool for modelling and prediction.

Several models based on the empirical and/or semi-empirical equations describing recrystallization and recovery and have been developed around the world and applied successfully for specific steels

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(Sellers et al.1979, Siwecki et al.1992-1997). However, they have a limited improvement potential and they typically suffer from difficulties in applicability to different steels even when these are quite similar in chemical composition. In order to gain flexibility, the models should be based on a physical description of microstructure evolution, including deformation, recovery, recrystallization, precipitation and phase transformation (Siwecki et al. 2000, Howe et al. 2002, and Wang et al. 2003). Such so-called physical models should be intrinsically capable of handling multi-component systems. Computer programs based on the semi-empirical model have been developed at KIMAB (Siwecki et al) and others (Sellers et al.), and applied practically to different kinds of steels, with series of fitting parameters gained from laboratory results. A preliminary program frame of the newer physically based model, was also established recently (Wang et al. 2003).

The aim of the paper is to present the recent developments (in Sweden) regarding microstructure and mechanical property enhancement through thermo-mechanical controlled processing (TMCP) of structural steel plate and the use of predictive models. The recent progress that has been made at KIMAB in computing physical processes to develop physically based models.

The effect of TMCP- parameters, low reheating and high finish rolling temperature, as well as rolling schedules, cooling rate will be discussed with regard to the transformation characteristics as well as the strength, hardness and microstructure of structure steels.

2. THE MODELS

The KIMAB`s model focuses on the microstructure evolution during and after hot deformation, which includes austenite grain structure, precipitation state, transformation behaviours, final microstructure and properties. The model is based on physical metallurgy phenomena concerning the thermo-mechanical processing and their mathematical descriptions. This fundamental character of the model aims to improve the applicability of the model to a wide range of deformation schedules and chemical compositions. Three major aspects are taken into consideration in current development of sub-models:

- Modelling of austenite microstructure evolution, this includes;
    - flow stress and dislocation density evolution, which are affected by deformation, recovery / recrystallization and precipitation,
    - static recrystallization after deformation, which is controlled by dislocation density and precipitation,
    - integration of the precipitation sub-model with the model for calculation of the microstructure evolution in austenite.
- Modelling of phase transformation with special reference to low temperature products (acicular ferrite, bainite etc). This sub-model will be integrated with the precipitation sub-model for calculation of the precipitate evolution after transformation.
- Relationship between product microstructures and mechanical properties (yield strength and toughness).

Microstructure modeling at KIMAB has been transformed from MicDel to PhysMic.

MicDel is a semi-empirical model based on the recrystallization (*x & drex)* kinetics and grain growth for multi-step rolling of practical steels. The model application was very successful for the steels; however, it is not flexible for different steel composition. So, it was necessary to develop the physical based model, see figure 1, which will be much better flexible for steels and alloys with various composition without knowledge of recrystallization data.

Descriptions of the intended formulations for each sub-model are presented below where the deformation, recovery, and recrystallization as well as precipitation are taken into consideration, and they are mathematically described in the model according to the appropriate physical metallurgy principles;

(i) Dissolution of Second Phases It is very important to be able to predict the precipitate evolution in association with thermal or thermo-mechanical controlled processing. Models of the ThermoCalc type (Wang et al.2003) are well suited to describe the dissolution or growth of precipitates once the density of these has been established. In commercial HSLA steels processing should be controlled in such a way as to ensure that the microalloyed elements which are added to steel must be brought as fully as possible into solution in the austenite so that their precipitation potential can be utilised during or after thermo-mechanical treatment.

(ii) Flow stress and dislocation density The microstructure change during hot working can be regarded as a competition between work hardening and dynamic recovery. So dislocation density is calculated as a result of competition between generation and dynamic recovery/recrystallization. The flow stresses can be well predicted according to this dislocation evolution description. The rate of evolution of dislocation structure depends on strain rate, temperature and current dislocation density (Siwecki and Engberg, 1997). These parameters will be incorporated to describe the flow stress at high temperature during hot rolling.

(iii) Recrystallization and grain growth The recrystallization of deformed material is considered as a nucleation-growth process and is driven by the stored energy provided by dislocations. Nucleation of recrystallization is described as a discontinuous subgrain growth process [Wang et al.]. The growth of recrystallized grains is driven by the stored energy of deformation. Grain boundary energy and second phase particles have retarding effects on the growth. The recrystallized structure is not stable yet, and further grain coarsening of recrystallized grains will follow, which is driven by a reduction in the sum energy of grain boundaries.

(iv) Precipitation of carbonitrides The addition of microalloying elements, such as Nb or/and Ti leads to precipitates of Nb(C,N) or (Ti,Nb)(C,N). The precipitates in austenite affect the recrystallization and grain growth strongly (Sellers and Palmiere, 2005). Precipitation of carbonitrides is described as a typical nucleation and growth process.

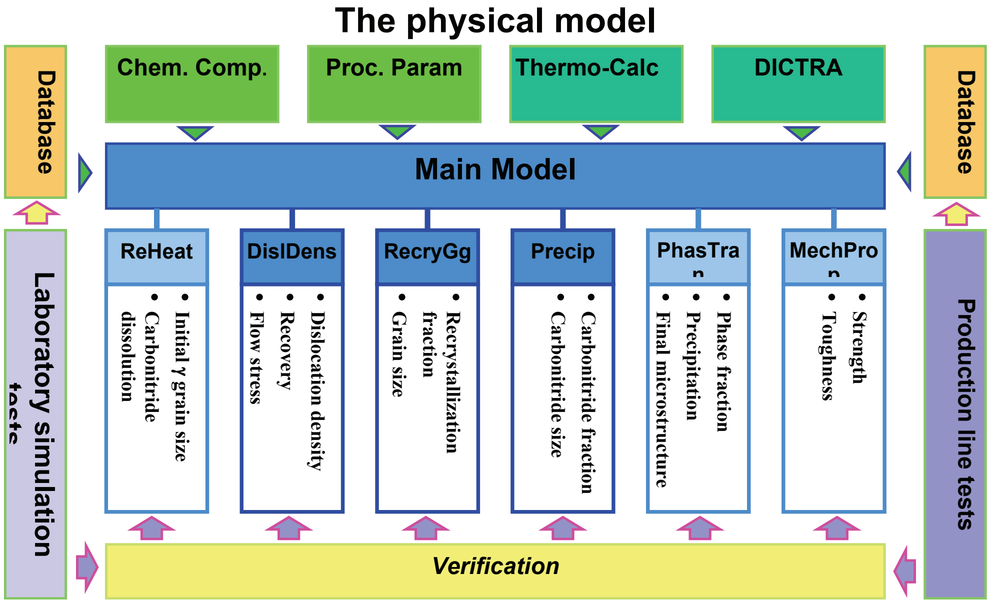

***Fig. 1**. Scheme of the Physical Model.*

For deformed material, it can be assumed that nucleation on dislocations is the dominating nucleation mechanism with growth of the particle considered as diffusion controlled growth process. The driving force for precipitation will be determined using ThermoCalc together with a special database for HSLA steels. The particle size and fraction will than be calculated by diffusion controlled growth of carbonitrides (Wang et al. 2003).

(v) Phase transformation The end properties of the steels are determined by the structures that result after transformation of the steel on cooling (Howe et al. 2002). In the usual models for microstructure evolution the ferrite, grain size is calculated based on the austenite grain size and cooling rate using empirical expressions which must be found for each class of steel by experiment (Siwecki et al.). This is satisfactory for many purposes but more fundamentally based models are necessary if different types of transformation products are to be described as well as the temperature range of the transformation.

A model has been developed on the base of established mechanisms for the formation of ferrite, pearlite, bainite and martensite. Thermodynamic driving forces can be determined from ThermoCalc assuming para-equilibrium conditions.

The model should have the capability of predicting phase proportions and ferrite grain size and even thermal properties that can be utilised in process control. The model should also be capable of giving more refined predictions of acicular structures such as packet and lath size.

(vi) Mechanical properties The final mechanical properties such as yield strength and toughness are dependent on the microstructure parameters and structure elements such as: fraction of different phases, ferrite grain size and size distribution, precipitates size and volume fraction, dislocation density, lath size, packet size and residual austenite.

During full scale TMCP processing of rolled sections some heterogeneity of microstructure can be observed which is strongly dependent on the distribution of temperature, strain and strain rate. The microstructure evolution models, therefore, are suitable for combining with FEM plasticity models for predicting heterogeneity of microstructure through the cross section / thickness of a hot rolled profile or heavy plate.

3. OPTIMISATION THE TMCP PROCESS PARAMETERS FOR PROPERTY IMPROVEMENT

The mechanical properties and the final microstructure of microalloyed steels are dependent on the following process parameters; reheating temperature, rolling schedules (reduction, rolling temperature and pause time), cooling parameters (accelerated cooling rates (ACC) and finish accelerated cooling temperature) and steel chemistry.

3,1. Microstructure evolution during Recrystallization Controlled Rolling (RCR) simulation at MEFOS and full scale processing at SSAB Oxelösund

The computer models of austenite microstructure development have been extended to different steel compositions and permit comparison to be made of the effect of various material parameters (Siwecki and Wang, 2003). Figure 2 show examples of predicted microstructure evolution during realistic recrystallization hot rolling of 0.01Ti-V-N steels having different levels of carbon and manganese when subjected to the same rolling schedule at MEFOS. The data in the figure refers to rolling of 40 mm plate in 10-11 passes, and for 70mm thick plate in 7-8 passes, starting from 1120°C or 1150°C.

Heavy reductions that have been applied during rolling simulation with schemes N3, N4 and even N5 have shown strong influence on the microstructure development. The final austenite grain size for these variants was in the range of 21-24μm.

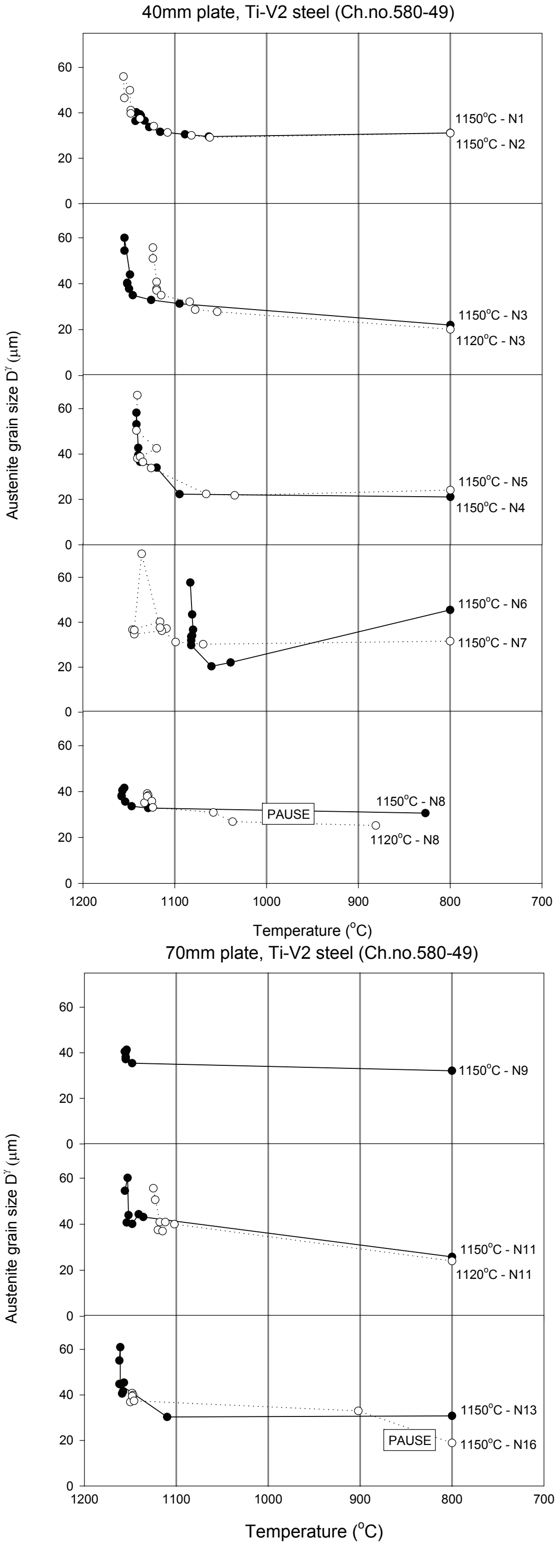

***Fig. 2.** MICDEL predicted austenite structure evolution during hot rolling of 40mm and 70mm thick plats of Ti-V2 steel with various rolling schedules, N1-N8*
(Rolling schedules for 40mm and 70mm thick; (More details in work by Siwecki & Wang, 2003).
N1 - Equal large reductions in each step, N2 - The first step divided into two small reductions,
N3 - Minimising in the two first steps and maximum reduction in the last one,
N4 - Minimising reduction in the two first steps and maximum reduction in the two last steps,
N5 - Minimising reduction in the first step and maximum reduction in the next to last, and 2% smooth reduction at the last one,
N6 - Minimising reduction in the first step and maximum reduction in the next to last, and 4% smooth reduction at the last one,
N7 - Small reduction in the middle of schedules,
N8 - Equal large reduction in each step. Pause time before the last step, finish rolling temperature ~ 900°C),
N9 - Equal large reduction in each step,
N11 - Two small reductions in the beginning of rolling. Large reduction in the last step,
N13 - Large reduction in the last but one, and smooth reduction at the last one,
N16 - Equal large reduction in each step. Pause time before the last step, finish rolling temperature ~ 900°).

As is clear from figure 2 the austenite grain size is strong dependent on the deformation sequences applied during rolling. Lower reheating temperature (1120°) has some influence on the microstructure evolution during beginning of the rolling, but not at the end of rolling, see results for schedules N3 reheated at 1120° and 1150°C.

A pause time applied before the last step at about 900°C (see results for schemes N8 and N9) are very important for recrystallization process and by this refinement of structure, as shown in these figures. The final austenite grain size of steel Ti-V2 was in the range of ~20μm at transformation start temperature (<800°C). The results presented in figure 2 show that the most effective refinement of microstructure has been obtained for rolling schemes N11 for the both steels reheated at 1120°C and 1150°C. The austenite grain size of these steels before transformation was in the range 19–26 μm.

On the base of the results of microstructure evolution and the final mechanical properties obtained on the specimens after hot rolling simulation at MEFOS, the rolling schedules with variation of the reduction, number of passes and finish rolling temperature has been applied for the full scale rolling at SSAB Oxelösund.

The results of microstructure evolution (fraction of recrystallized austenite, recrystallized grain size, grain size before transformation and even predicted ferrite grain size) during RCR and CR of 40 and 70mm thick plates are shown in figures 3-6. The finish rolling temperature for rolling of 40mm plate was in the range of 840°-970°C, whereas for rolling of 70mm thick plate the finish rolling temperature was in the interval 900° to 1000° or 1050°C, depending of steel composition. The effect of deformation sequences and finish rolling temperature on the austenite grain size changes during RCR as well as CR rolling of 40mm thick plate for Ti-V2 (0.15C-0.01Ti-0.046V) steels is shown in figure 3.

The optimum finish rolling conditions involve large reductions at relatively high temperatures. In industrial practice, however, the final pass cannot normally be so large since there are conflicting requirements of flatness and dimensional tolerance. There is, accordingly, a danger that the final sizing pass may bring about an unfavourable coarsening of the austenite structure.

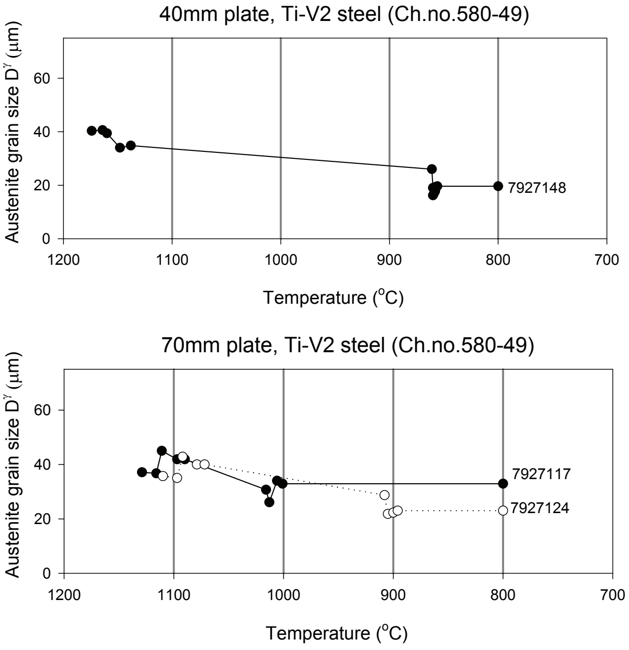

Fig. 3. *MicDel predicted austenite structure evolution during full scale hot rolling of 40mm and 70mm thick plates of Ti-V2 steel with various reduction and finish rolling temperature, processed at SSAB Oxelösund.*

3.2. Comparison of model predictions with rolling trials

The simulations of hot processing and cooling in laboratory scale and full-scale production have be carried out to verify the model. Pilot rolling at MEFOS, thermo-mechanical processing at SSAB Oxelosund and modelling have been employed to establish what can be achieved by simulation of TMCP treatment followed by cooling in comparison to the model prediction. Microstructures evaluated on hot rolled products have been compared with model predictions for the final structure.

Figure 4 presents the comparison of ferrite grain sizes calculated and observed in 40 and 70mm thick plates of Ti-V2 steel for various rolling schedules applied, whereas figure 5 shows the comparison of ferrite grain sizes calculated and observed for both plates of Ti-V2 steel full scale rolled. Quite good agreement between calculated and observed grain sizes has been obtained for both plate thickness of Ti-V2 steel as shown in figures 4 and 5.

So, the conclusion from these results presented above is that the MicDel software can be used for prediction of microstructure evolution in connection with full scale hot rolling and followed accelerated cooling as a good method for microstructure analyses. This method gives possibility to predict structure for different variants of thermo-mechanical processing and by this optimise the rolling schedules without carry out any treatment.

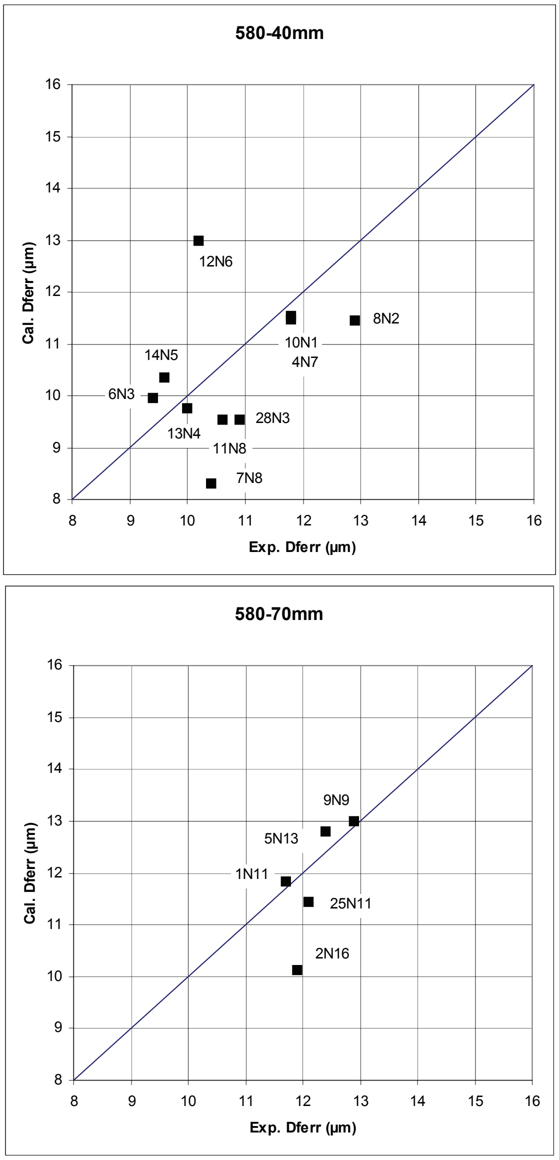

Fig. 4. Ferrite grain size calculated using MICDEL and observed in the hot rolled samples to 40mm and 70mm of Ti-V2 steel processed at MEFOS.

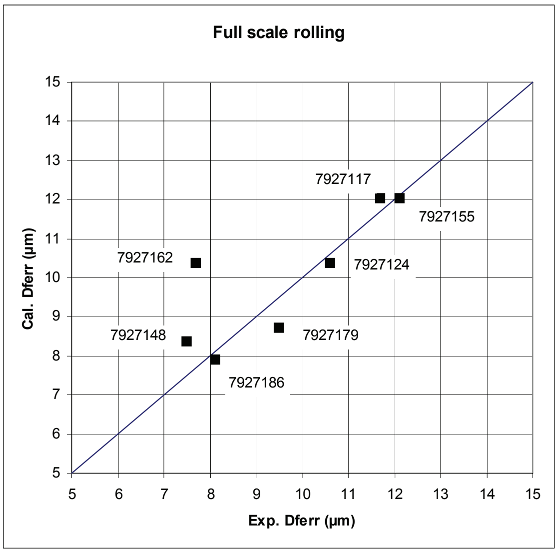

Fig. 5. Comparison between the calculated and observed results for full scale rolling at SSAB Oxelösund of 40 and 70mm thick plates of Ti-V2 steel.

3.3. Effect of rolling schedules and steel composition on the yield stress of RCR steels

The upper yield stress, R_{eH}, or tensile strength, R_m, is commonly analysed in relation to the various available TMCP process parameters. Generally, it is believed that the chemical composition and morphology of the austenite together with the cooling rate during the transformation stage are the prime parameters determining the final microstructure as well as precipitation strengthening. The yield stress of the RCR processed plate is strongly affected by the scale and morphology of the microstructure and the precipitation strengthening. The yield strength of the present steels has been described by a modified Hall-Petch relationship, where the effect of grain size is combined with the lattice, solid solution, dislocation and precipitation strengthening. All the remaining terms are dependent both on composition and processing history.

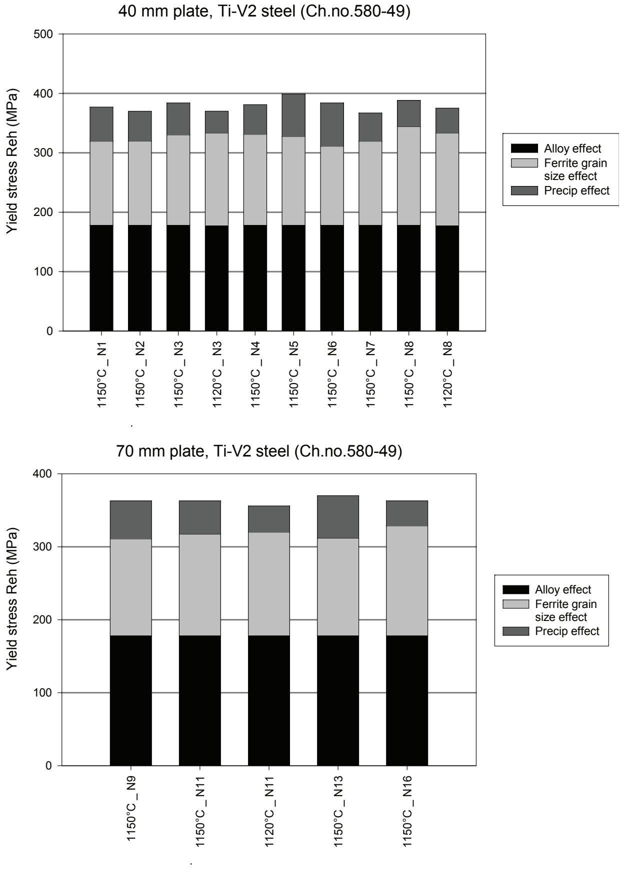

Fig. 6. Effect of rolling schedules applied at MEFOS during RCR simulation of 40mm and 70mm thick plates on the yield stress of Ti-V2 steel. Dependence of Reh on microstructure, precipitation strengthening and steel chemistry according to theory is also included.

The mechanical properties of structural steels are dependent on the steel chemistry, ferrite grain, volume fraction and size of phases as well as size and precipitation strengthening (size and distribution of precipitates). Examples of the obtained variations in the yield stress, Reh, in association with hot rolling of 40 and 70 mm plates of Ti-V2 steel with various schedules are shown in figure 6. It is evident that the hot rolling schedules (height reduction and deformation temperature) and cooling rate/thickness of plate have an influence on the final properties of the rolled plates in relation to grain size (predicted or observed) and precipitates.

4. SUMMARY

- Physically bases models for predictions of recrystallization and grain growth of austenite after deformation, precipitation or dissolution of microalloying carbo-nitrides in austenite and phase transformation behaviour during accelerated cooling has been described.
- TMCP simulation in the laboratory scale as well as a computer routine for prediction of microstructure evolution during TMCP processing are available for design rolling schedules of plate of microalloyed HSLA steel.
- The MicDel model has been utilised to predict the optimum rolling schedules on a given rolling mill for obtaining maximum microstructure refinement for rolled heavy plates.
- The effect of TMCP-parameters, low reheating and high finish rolling temperature, as well as rolling schedules, cooling rate are discussed with regard to the transformation characteristics as well as the strength and microstructure of structure steels.
- Good agreement has been obtained between predicted and determined ferrite grain sizes for Ti-V2 steels after TMCP simulation of heavy plates in laboratory-scale at MEFOS and full-scale rolling of heavy plates at SSAB Oxelösund AB.

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MODELOWANIE I OPTYMALIZACJA PROCESU WALCOWANIA BLACH GRUBYCH ZE STALI KONSTRUKCYJNYCH

Streszczenie

Celem artykułu jest przedstawienie ostatnich osiągnięć (w Szwecji) w zakresie poprawy mikrostruktury i własności stali poprzez termomechaniczne walcowanie (TMCP thermo-mechanical controlled processing). Przedstawienie zastosowań komputerowego modelowania w tym zakresie jest drugim celem artykułu. Symulacja TMCP w skali laboratoryjnej oraz komputerowe modelowanie w celu przewidywania rozwoju mikrostruktury i procesów wydzieleniowych podczas walcowania na gorąco są ważnym wspomaganiem projektowania technologii walcowania. W pracy przedstawiono krótki przegląd modeli opracowanych w Corrosion & Metals Research Institute i stosowanych przez przemysł metalurgiczny w Szwecji. Modele są stosowane do przewidywania rekrystalizacji i rozrostu ziarna austenitu po odkształceniu, procesów wydzieleniowych i rozpuszczalności węgliko-azotków w austenicie oraz przemian fazowych podczas przyspieszonego chłodzenia. Otrzymane parametry TMCP – niższe temperatury wygrzewania i wysokie temperatury końca walcowania, plany przepustów, i prędkości chłodzenia są omówione w artykule ze względu na ich wpływ na charakter przemiany fazowej oraz na mikrostrukturę i wytrzymałość wyrobów ze stali konstrukcyjnych.

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