DEFORMATION BEHAVIOR AND MICROSTRUCTURE DEVELOPMENT OF 13CR25 FERRITIC STAINLESS STEEL IN HOT STRIP ROLLING

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DEFORMAČNÍ CHOVÁNÍ A VÝVOJ MIKROSTRUKTURY PŘI VÁLCOVÁNÍ PÁSU Z FERITICKÉ KOROZIVZDORNÉ OCELI 13CR25 ZA TEPLA

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Abstrakt

Byly zkoumány strukturotvorné procesy a deformační chování za tepla feritické korozivzdorné oceli obsahující 25 % Cr. Na základě výsledků laboratorního válcování plochých vzorků (tzn. měření válcovacích sil) byl vyvinut model popisující závislost středního přirozeného deformačního odporu na teplotě, deformaci a deformační rychlosti. Model se jeví jako dostatečně jednoduchý a přesný z hlediska jeho možné implementace do on-line řídicích systémů provozních válcovacích tratí. Experimenty ukázaly, že zkoumaná ocel v litém i protvářeném stavu je značně náchylná k hrubnutí zrna. Tento jev lze jen stěží eliminovat z důvodu podstatného zbrzdění rekrystalizačních procesů. Vzhledem k vysokému obsahu chrómu je obtížné iniciovat úplný průběh rekrystalizace deformované struktury a tím zjemnit hrubá zrna vznikající během ohřevu před válcováním této feritické oceli. Tato skutečnost se projevovala během válcování pásu za tepla v provozních podmínkách (na dvoustolicové Steckelově válcovně a.s. Mittal Steel Ostrava) jakož i při laboratorních simulacích válcování konvenčního, resp. prováděného v jednom žáru. Mikrostruktura vývalků byla ve všech případech velmi heterogenní. V diskutovaných podmínkách lze prakticky vyloučit dynamickou rekrystalizaci; statické rekrystalizaci silně konkuruje méně efektivní polygonizace. Navíc je u feritických ocelí mimořádně složité rozpoznat strukturální důsledky rekrystalizace a zotavení.

Abstract

Structure-forming processes and hot deformation behavior of a ferritic stainless steel containing 25 % Cr were investigated. The model of mean equivalent stress values depending on temperature, strain and strain rate was developed using the results of the laboratory hot flat rolling tests (i.e. measured rolling forces). This model seems to be simple and accurate enough for its implementation in the on-line steering systems of operational rolling mills. Experiments showed that the examined steel in as-cast and as-rolled state had a considerable susceptibility to grain coarsening. That phenomenon is very difficult to eliminate because of substantial inhibition of the recrystallization processes. Due to high chromium content it is very hard to initiate complete recrystallization of deformed structure and thus refine the coarse grains forming during the heating before hot rolling in this ferritic steel. That fact exhibited during the hot strip rolling in the operational two-stand Steckel type rolling mill in Mittal Steel Ostrava a. s. as well as in laboratory simulation of conventional and/or one-heat rolling. Microstructures of industrial strips as well as laboratory rolled samples were very heterogeneous. Dynamic recrystallization can be almost excluded in discussed conditions and static recrystallization severely competes with a less efficient polygonization. Moreover, it is extremely complicated to recognize the structural consequences of recrystallization and recovery in the ferritic steel grades.

Key words: High-alloy ferritic steel, hot strip rolling, simulation, recrystallization, recovery, grain size, mean equivalent stress

1. Introduction

Mittal Steel Ostrava a. s. is the biggest steel producer and also sole hot rolled strips producer in the Czech Republic. In the late 90ies the management of company decided to realize wide modernization program within the frame of which the production of hot rolled strips was also innovated. For this purpose the reversible Steckel mill was selected, above all with respect to the optimization of investment and operational costs. The aim was to produce more than one million tons of hot rolled strips annually. The one-stand Steckel rolling mills are insufficient for this quantity and therefore a two-stand Steckel rolling mill P1500 was chosen for operation in Mittal Steel Ostrava a. s. This type of rolling mill has not yet been constructed anywhere in the world but for the above-mentioned reason seemed to be optimal.

The rolling mill P1500 has also the vertical stand – see Fig. 1. The slabs reheated in walking-beam furnace are rolled in a reverse way by five or seven double-passes. Furnace coilers are located at the entry and exit side of stands and are able to hold temperature up to 1050 °C. The roughing passes are performed without use of furnace coilers, whereas finishing passes with using them, which makes possible to roll even such steel grades which are characterized by high deformation resistance [1].

The mill P1500 was put into operation in June 1999. After obtaining of experiences and knowledge about rolling and properties of deep-drawing, structural, high-carbon [2] and HSLA steels [3], technology for rolling of ferritic stainless steel has been designed.

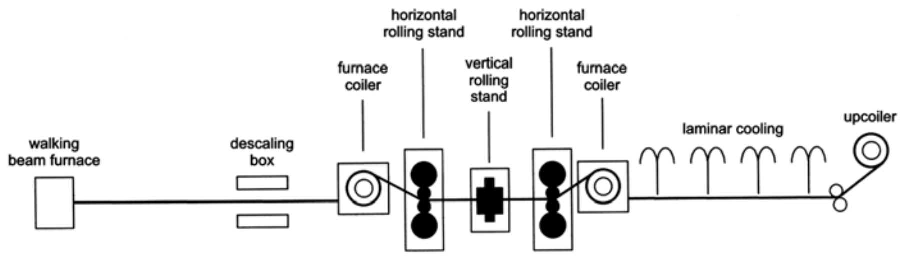
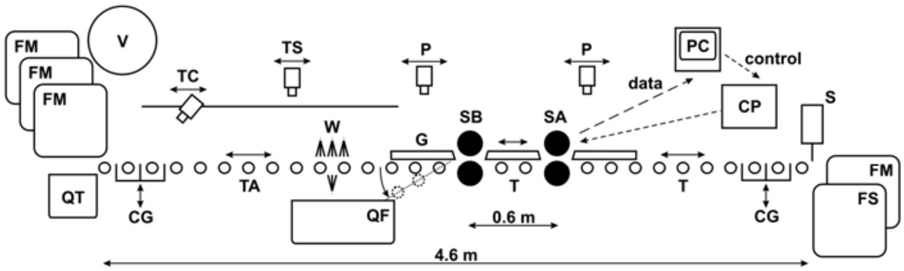


Fig.1 Layout of the two-stand reversible Steckel rolling mill P1500 [7]

For modelling of rolling process in the mill P1500 laboratory rolling mill Tandem in the Institute of Modelling and Control of Forming Processes at VŠB-TUO is very often and very effectively used. This mill has been already described many times in detail [4-6] so it is sufficient to emphasize in the presented work that it has two reversible stands and is equipped by one stable and four mobile electric furnaces – thus it can exactly simulate rolling process in the mill P1500 (compare Figs. 1 and 2).

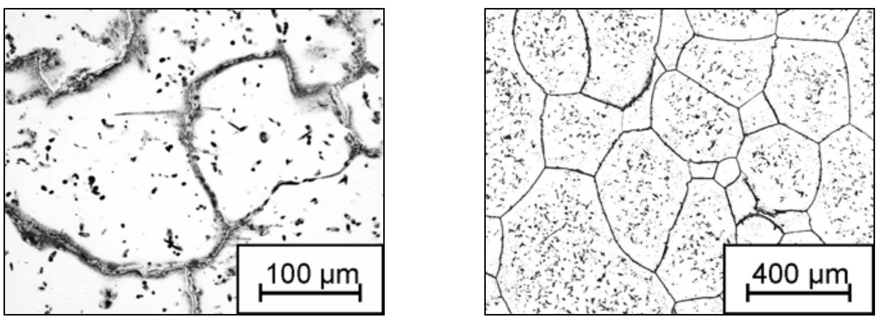


CG	extensible cooling grates (2 units)	S	electric shearing machine
CP	control panel	SA	reversible roll stand A
FM	mobile electric heating furnace (4 units)	SB	reversible roll stand B
FS	stable electric heating furnace	T	roller table with constant speed (2 sections)
G	adjustable side guards (3 units)	TA	roller table with adjustable speed
P	portable pyrometer (2 units)	TC	2-color ratio thermometer
PC	industrial computer	TS	infrared temperature sensor (on bracket)
QF	water quenching facility	V	vacuum induction furnace (melting, casting)
QT	quenching tank	W	slot nozzles for controlled water spraying

Fig.2 Layout of the laboratory two-stand hot rolling mill Tandem

2. Investigated material

The aim of the realized research works was to study deformation behavior as well as the possibilities of grain refining in hot strip rolling of the ferritic stainless steel 13Cr25. Its chemical composition was as follows: 0.07 C – 0.33 Mn – 0.78 Si – 0.028 P – 0.009 S – 25.5 Cr – 0.43 Ni – 0.15 Mo – 0.07 Al (all in wt. %). The input material was delivered in form of a hot-rolled slab with heterogeneous structure, large individual ferritic grains and carbide precipitates (see Fig. 3). Some material was remelted and cast in a vacuum inductive furnace. Shape of such casting with thickness 20 mm and its microstructure is represented by Fig. 4. It is surprising that microstructure of such casting exhibits in fact much finer grains than the rolled slab – see Fig. 3a for comparison with Fig. 3b.



a) rolled slab b) laboratory casting

Fig. 3 Microstructure of the input material (surface regions)

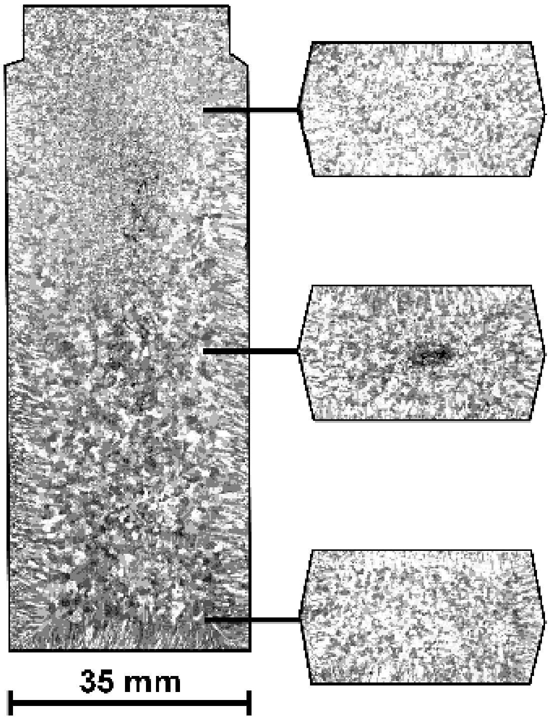
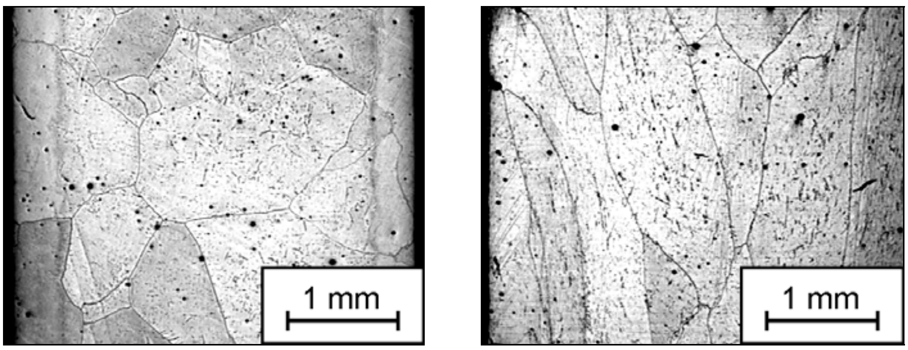


Fig. 4 Macrostructure of the laboratory casting in longitudinal and transverse sections [8]

3. Research of recrystallization by single-pass rolling and its discussion

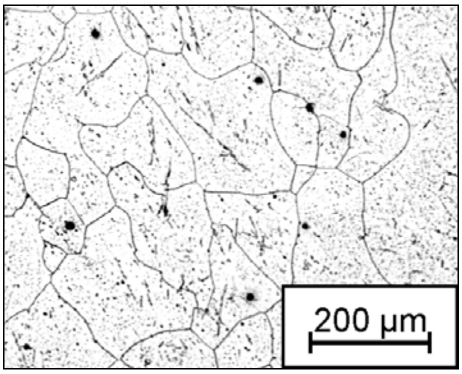
Softening processes were studied by hot rolling of the flat samples with varying thickness (4.0 to 6.5 mm) in the two-high rolling stand K350 [5,6]. The initial state was hot-rolled. The rolls' diameter was 140 mm and their velocity 100 r.p.m. A single pass of such sample ensured equivalent strain 0.15, 0.19, 0.35 and 0.51, respectively, in the individual steps of every rolled sample. Rolling temperatures 800 – 1100 °C were applied which in combination of quite large strain levels presumed fast progress of recrystallization at least in some samples, but the experiments confirmed a heavily inhibiting role of the high chromium content [9]. It was almost impossible to initiate dynamic recrystallization in this high-alloy steel – see the microstructures in Fig. 5 obtained after deformation and immediate water-quenching.



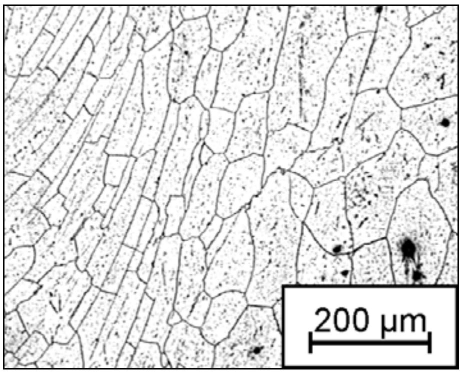
a) strain 0.15 b) strain 0.51

Fig.5 Quenched microstructure after rolling at 1000 °C

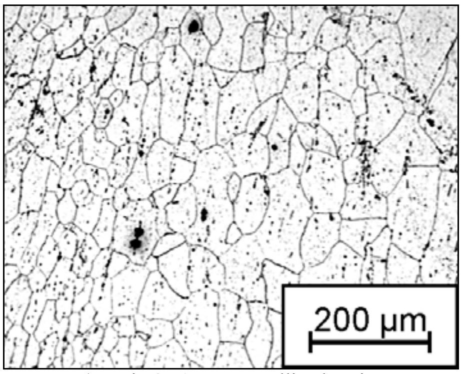
Static recrystallization was acting during high-temperature annealing – see Fig. 6. All micrographs represent the longitudinal sections of the samples across their heights. Near-surface layers of rolled samples are presented, where the heavier deformation and thus heterogeneous (non-isotropic) structure can occur. The grain refinement takes place after large previous deformation and relatively long-term annealing.



a) strain 0.19



b) strain 0.35 – elongated grains



c) strain 0.51 – recrystallized grains

Fig.6 Microstructure after rolling at 1000 °C and annealing 1000 °C / 2 min / air-cooling

Similar results were presented in [10] – inhomogeneities of strain and recrystallization were observed over the thickness of rolled specimens of stainless steels. A layer of finely recrystallized grains was probably connected with maximum equivalent strain just below the surface.

4. Simulation of the multiple-pass hot strip rolling

Machined or cast samples of thickness 20 mm were hot rolled in both two-high stands of the laboratory mill Tandem – conventional or one-heat rolling was thus simulated. After heating at 1150 °C, the 8-pass rolling regime was applied (altogether 4 double-drafts with minimal inter-pass time). The rolls' diameter was about 159 mm and their velocity 180 to 220 r.p.m. Real rolling conditions in Mittal Steel Ostrava a.s. were simulated, including the function of furnace coiler (furnace with temperature 1000 °C after the 6th pass) or slow cooling of the coil (furnace with temperature 530 °C). The finishing temperature was about 930 °C, individual height-reductions 18 to 21 %, and final strip thickness 3.7 to 3.8 mm – see Fig. 7 for an example of the rolling time schedule.

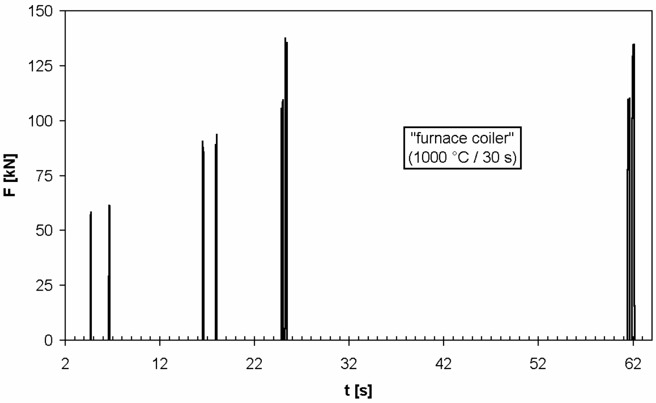
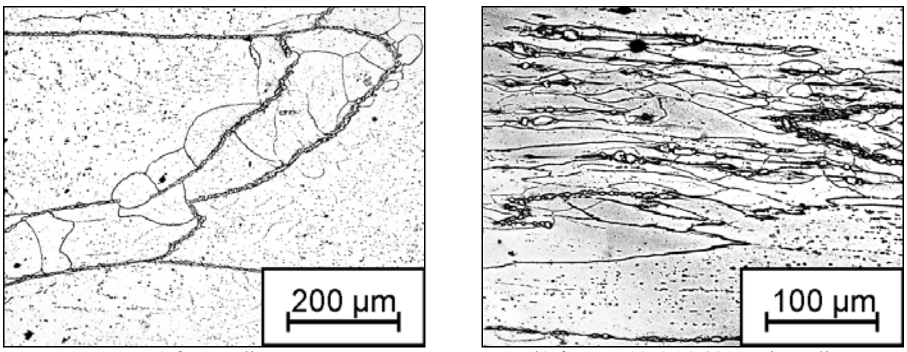


Fig.7 Time dependence of the measured total rolling force values

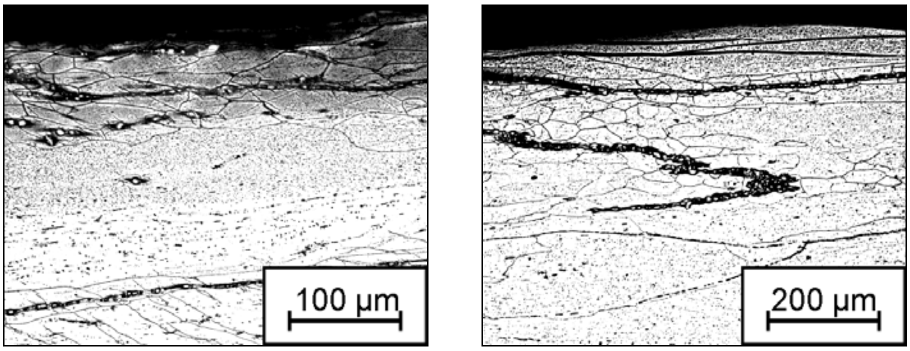
Mechanical properties of the laboratory rolled products were evaluated by tensile testing at the room temperature. Time interval spent in the "furnace coiler" as well as the cooling conditions of final strip did not have any remarkable effect. The influence of initial state of the steel was the most important – strips made from laboratory castings exhibited mostly better ductility (elongation over 20 %) and lower yield stress (YS) to ultimate strength (US) ratio 0.77. For comparison, elongation was about 17 % and YS/US = 0.80 after similar rolling schedule of the sample obtained from the rolled slab. The yield stress values ranged from 390 to 450 MPa according to the applied rolling and cooling regime.

Micrographs in Figs. 8 and 9 demonstrate some examples of the structure development during hot rolling. With proceeding deformation, the grains elongate and some polyedrical products of recrystallization or polygonization occur. Inter-pass heating leads to a more pronounced nucleation of such formations (mostly in some clusters). Dividing of large ferritic grains develops faster in the surface regions with higher deformation level. Strips made from casting give a more homogeneous microstructure but the final grains are always elongated according to the rolling direction.



a) free cooling b) furnace 1000 °C / 30 s, air cooling

Fig.8 Microstructure of the rolled sample after the 6th pass (initial state – rolled slab; central regions of the laboratory strip)



a) initial state – rolled slab; free cooling after finishing rolling

b) cast initial state; cooling in furnace 530 °C / 5 min

Fig.9 Details of microstructure in the surface regions (including the "furnace coiler" simulation; after the 8th pass)

5. Mathematical description of mean equivalent stress

The simple model of mean equivalent stress (MES) σ_m [MPa] values depending on temperature T [°C], logarithmic height strain e_h and equivalent strain rate $\dot{e}$ [s^{-1}] was developed using the results of the laboratory hot flat rolling tests (the applied method was clarified in detail e.g. in [11-13]). Surprisingly it could not be possible to describe the influence of temperature ranging from 700 to 1150 °C by a single expression and thus two models had to be developed in fact:

for temperature 700 – 990 °C

$$\sigma_m = 2949\ e_h^{0.31} \exp(-0.76\, e_h)\, \dot{e}^{0.03} \exp(-0.0019\, T) \tag{1}$$

for temperature 1010 – 1150 °C

$$\sigma_m = 11817\ e_h^{0.14} \exp(-0.52\, e_h)\, \dot{e}^{0.04} \exp(-0.0036\, T) \tag{2}$$

Then values of „mathematical" MES according to Eqs. 1 and 2 were recalculated for the given experimental conditions, including their relative errors RE [%] in comparison with the „measured" values:

$$RE = \frac{\sigma_m - \sigma_{m-c}}{\sigma_m} \cdot 100\ , \tag{3}$$

where σ_m is MES obtained from experimental results; σ_{m-c} is MES recalculated according to Eqs. (1) and (2).

Using the values of relative errors reached in this way, their dependence on temperature, strain or strain rate could be designed and plotted in graphs in Fig. 10. From these graphs pertinent ranges of deformation conditions can be obtained: strain 0.1 – 0.7 and strain rate 15 – 150 s^{-1}. Deviations of relative errors give very good results of scattering. Calculated RE values do not exceed 8 % of the actual values of MES, which may be considered to be a very good result in the applied wide range of deformation conditions.

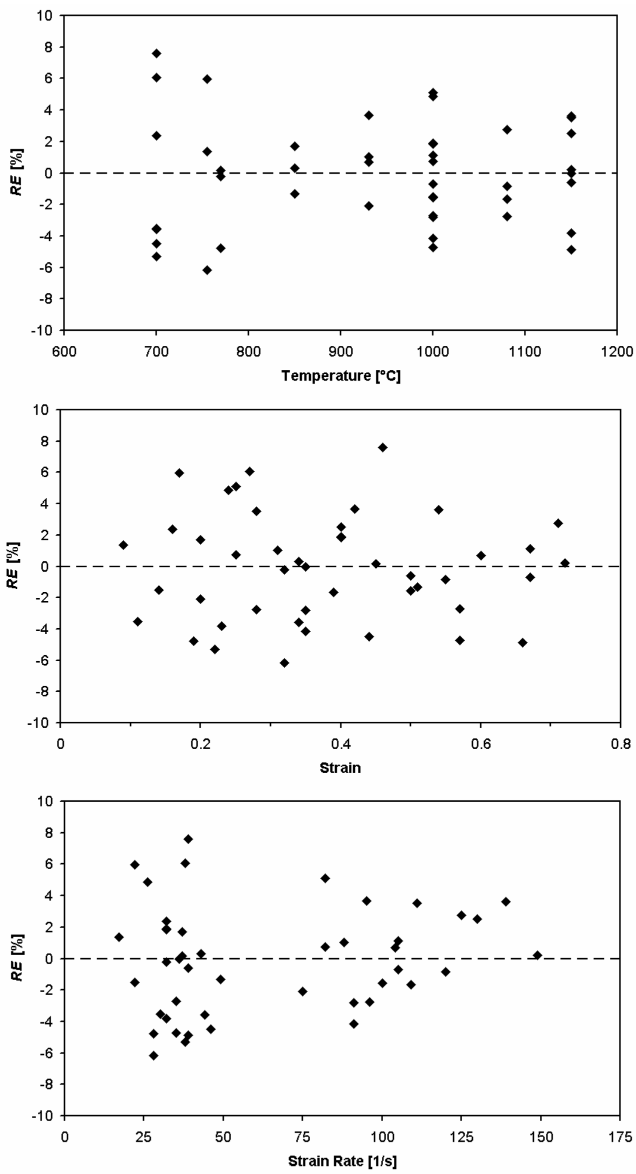
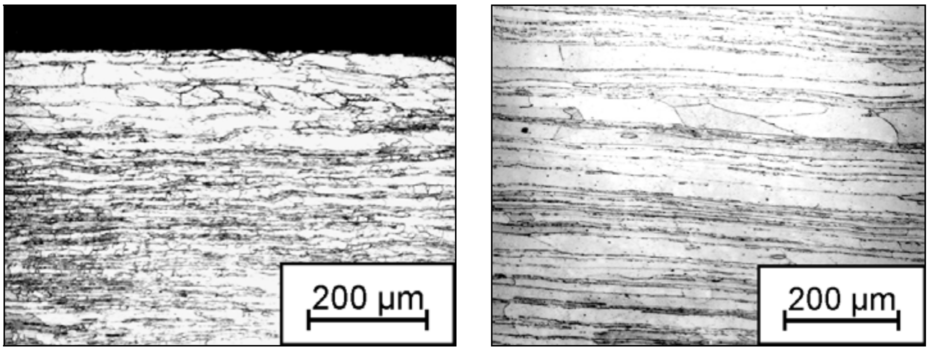


Fig.10 Relative errors *RE* of MES values calculated according to Eq. (3) in relation to temperature, logarithmic height strain and equivalent strain rate

6. Results of the industrial hot strip rolling

Developed models describing MES of the 13Cr25 steel grade facilitated the prediction of rolling forces in operational strip rolling. Slabs with cross-section dimensions 750 x 120 mm were rolled into strip 765 x 4 mm in the mill P1500. They were heated for approximately 300 minutes in temperature 1180 °C. After heating and descaling, rolling process with 10 passes followed. The relative height strain varied in particular pass between 18 % and 36 %. The rolling temperature dropped from 1070 °C to 870 °C. The coiling temperature was about 540 °C. The specimens for metallographic analyses were taken from the finished strip. Ferrite and carbides formed the microstructure in industrial hot rolled strips. The structure is markedly heterogeneous which is given by the different size and shape of ferritic grains. Slightly deformed ferritic grains dominate at surface. A thin layer (ca 0.3 – 0.4 mm) with very fine-grained recrystallized structure occurs under surface which is in accord with laboratory results (compare micrographs in Figs. 9 and 11). Strongly deformed and rough grains dominate in central parts of strip. All structural characteristics are more marked on the longitudinal than on transverse sections.



a) surface layer b) central part

Fig.11 Details of microstructure of the industrial strip (longitudinal sections)

7. Summary

- Models of MES enabling fast prediction of the rolling forces were developed.
- Due to high chromium content it is very difficult to initiate complete recrystallization of deformed structure (and thus refine the coarse grains forming during the heating before hot rolling) in this ferritic stainless steel under operational conditions and in laboratory rolling as well. Microstructures of industrial strips as well as laboratory rolled samples were very heterogeneous. The grains larger than several millimeters have been observed practically in all samples.
- Dynamic recrystallization can be almost excluded in such conditions and static recrystallization severely competes with a less efficient polygonization. Moreover, it is extremely complicated to recognize the structural consequences of recrystallization and recovery in the ferritic steel grades [14,15] – intended additional TEM analyses just might bring some relevant information in this case.

Acknowledgement

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