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Thermo-mechanical treatment of the C-Mn steel with Nb, Ti, V and B microadditions

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ABSTRACT

Purpose: The paper presents the investigation results of the thermo-mechanical treatment parameters influence on the structure and mechanical properties of the low-carbon steel with Nb, Ti, V and B microadditions, destined for the weldable heavy plates production with the yield point above 960 MPa.

Design/methodology/approach: Metallography, hot torsion test, tensile test, Charpy test have been used.

Findings: It was found out that failing to attain the total static austenite recrystallization between the consecutive deformation stages results in a development of the segregation bands, causing the significant deterioration of the crack resistance of steel at the lowered temperature.

Research limitations/implications: TEM investigations on structure of the steel after thermo-mechanical treatment were predicted.

Practical implications: The investigation results obtained make it possible to work out the industrial scale technology for the weldable heavy plates with high strength and crack resistance at the lowered temperature, using the energy-saving thermo-mechanical method integrated with a ladle metallurgy of the molten steel and continuous slab casting.

Originality/value: Adjusting the interval times between the deformation cycles in the multi-pass rolling process to the total recrystallization time of the plastically deformed austenite, by employing the retention shield, and the isothermal holding of the product at the temperature of the end of hot working for time $t_{0.5}$ before quenching, offers the possibility of obtaining the homogenous austenite structure, and therefore, manufacturing the rolled products displaying high mechanical properties.

Keywords: Thermo-mechanical treatment; Heat treatment; Mechanical properties; Crack resistance

MATERIALS MANUFACTURING AND PROCESSING

1. Introduction

The thermo-mechanical treatment, integrating the hot working of steel with the direct quenching of the products at the end of rolling temperature or after their preceding holding at this temperature for a certain time, is an energy-saving steel-making technology. In comparison with the classic heat treatment, boiling down to quenching and tempering, the steel products made from the toughening steels using the thermo-mechanical methods, require tempering only [1-4].

Rolling with the controlled recrystallization features the typical thermo-mechanical treatment of plates and long profile sections, consisting in the multi-pass rolling of the charge within the correct temperature range, whereas, in intervals between the consecutive passes, total recrystallization of austenite should take place, and after completing the rolling, before quenching, one should provide conditions to forming the 50% fraction of the recrystallized austenite. This technology is especially useful for production of the heavy plates with high strength and brittle resistance at the lowered temperatures from the low-carbon weldable steels, containing Mn, Cr, Ni, and Mo – improving their hardenability, and the microadditions like Nb, Ti, and V – making it possible to control the development of the austenite microstructure during the hot working and after its completing, before quenching. Microadditions made to the steel, with a strong affinity to N and C develop, during the hot working, the dispersive precipitations of nitrides, carbonitrides, and carbides with the NaCl lattices, slowing recovery and static recrystallization of the austenite in intervals between the successive rolling passes, however, limiting grain growth of this phase. This makes developing of the fine-grained austenite structure possible, and therefore, development of the fine-grained transformation products of this phase, having a significant input into its strengthening and into the increase of its crack resistance [5-14].

The desired effect is attained only when the correct hot working temperature range is chosen for precipitation kinetics in the austenite of the interstitial phases of micro-additions introduced into the steel, described by the following equation: $\log [M][X] = B - A/T$ (1)

where: [M] and [X] – are the relevant mass fractions of the metallic microaddition and metalloid dissolved in solid solution at temperature T. Values of constants A and B for various interstitial phases are published in [3,6,15].

The goal of the work is investigation of the effect of hot working of steel on the structure heterogeneity and mechanical properties of austenite and determining conditions of the thermo-mechanical treatment (rolling with the controlled recrystallization) of the Cr-Mo steel, destined for manufacturing of the heat treated heavy plates, with the yield point exceeding 960 MPa and with the guaranteed cracking resistance at the lowered temperature.

2. Experimental procedure

The investigations were made using the imported heat treatable steel, delivered as 40 mm thick plate. The steel containing 0.17% C, 1.37% Mn, 0.26% Si, 0.012% P, 0.001% S, 0.24% Cr, 0.48% Mo, 0.05% Ni, 0.019% V, 0.004% Ti, 0.025% Nb, 0.06% Al, 0.002% B, and 0.004% N, is destined for manufacturing the weldable heavy plates with the yield point exceeding 960 MPa and the fracture appearance transition temperature T_{45J} equal to –40°C.

Effect of deformation temperature was investigated within the temperature range of 1100 to 900°C by twisting the specimens in the SETERAM-7N torsional plastometer with the rate of 3 s^{-1}. The plastically deformed austenite recrystallization kinetics was also determined in the same temperature range with $\varepsilon = 0.2$ at the deformation rate 3 s^{-1}, i.e., in conditions close to rolling of heavy plates.

Investigation results of the austenite strain strengthening kinetics decay were employed for determining the total austenite recrystallization time t_R and the time $t_{0.5}$ necessary for developing the 50% fraction of the recrystallized phase γ as a function of temperature. These investigations made it also possible to work out conditions of the thermo-mechanical treatment – rolling with the controlled recrystallization – of the flat bar with the 200 x 40 mm transverse section to the 15 mm thick plate in five passes within the temperature range of 1000 to 900°C with decrements of 50°C. Pass reductions of 20% were applied in the first three passes, and 15% in the last two ones.

The thermo-mechanical treatment of plates was carried out according to two variants. In the first one, the strip was air cooled between the passes to the temperature of the successive pass and held for the $t_{0.5}$ time in stable conditions after completing the rolling, before quenching in water. In the second variant, however, the retention shield was used, making it possible to adjust intervals between successive passes to time close to t_R and to hold the plate isothermally at the temperature of end of rolling for time $t_{0.5}$ before its quenching.

The test specimens of plates were tempered within the temperature range of 550 to 650°C. To evaluate the effect of the conditions of plastic deformation on structure and mechanical properties of steel, the conventional heat treatment of the steel was carried out, i.e., quenching of specimens at the austenitizing temperature of 900°C, proper for this steel, and tempering in the conditions identical with those applied to the rolled and quenched test plates.

3. Results of investigations

Continuous torsion tests of the specimens carried out made it possible to determine the effect of temperature within the range of 1100 to 900 °C on the σ-ε curves shapes and on deformations ε_m - corresponding to the maximum yield stress value (Fig.1), and therefore, evaluation of the deformation necessary to originate the dynamical austenite recrystallization $\varepsilon_{cd} \approx 0.8\ \varepsilon_m$.

The torsion tests of the specimens made to obtain the required deformation revealed, that depending on temperature and time of holding the specimens between two deformation stages, partial or total decay of strain hardening occurs. It is a result of recovery and static recrystallization processes of the plastically deformed austenite.

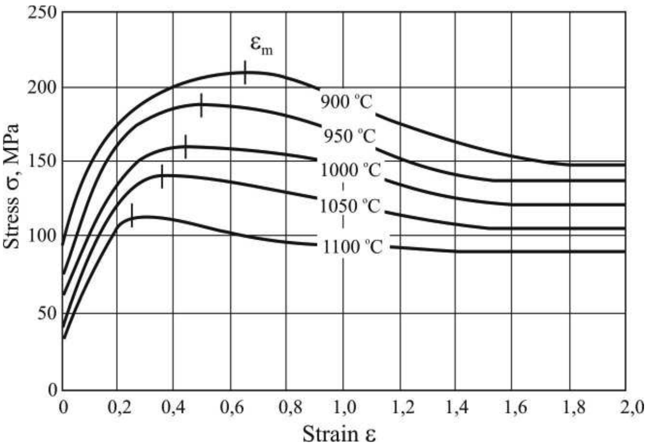

Fig. 1. Effect of temperature on the σ-ε curves in the twist test with the deformation rate of 3 s^{-1}

The strain hardening decay kinetics curves obtained for the austenite (Fig.2) demonstrate that the time of the total austenite recrystallization t_R at temperature of 1100 °C is about 50 sec and increases to about 300 sec at a temperature of 900 °C. However, the $t_{0.5}$ time required for developing of 50% fraction of the

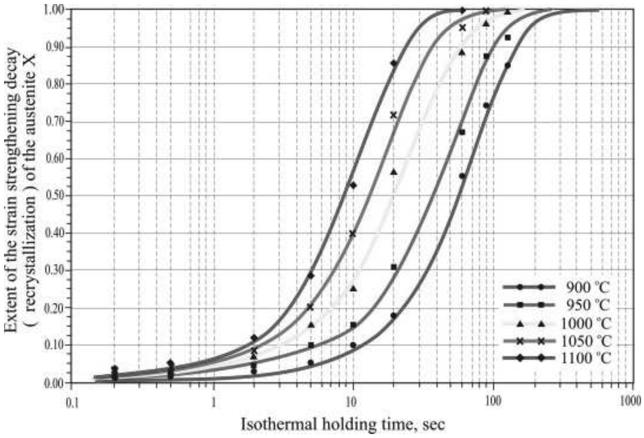

Fig. 2. Effect of the test temperature on the strain hardening (recrystallization) kinetics decay curves of the plastically deformed austenite in the torsion test at the rate of 3 s^{-1} ($\varepsilon = 0.2$)

recrystallized austenite at a temperature of 1100 °C is 9 sec, and increases to 60 sec at a temperature of 900 °C.

The metallographic examinations of the specimens deformed in cycles revealed that if the interval between the consecutive deformations is smaller than the time of the total austenite recrystallization t_R, then because of the superposition of the consecutive deformation cycles shearing bands develop in the austenite. The similar segregation bands were revealed in the primary austenite (Fig.3) and in martensite (Fig.4) of the test sections of plates made using the first variant of the thermo-mechanical treatment. Segregation bands do not develop if the interval between the successive deformation cycles makes total recrystallization of the plastically deformed austenite possible. Adjusting the interval times between the consecutive deformation cycles to time t_R, by employing the retention shield, and the isothermal holding of the rolled strip for time $t_{0.5}$ at the temperature of the end of hot working before quenching, has added to improvement of the chemical composition homogeneity. Steel structure developed in these conditions contains about 20% of the fine-grained, statically recrystallized austenite, and the remaining portion of the phase in the significantly larger grains of the statically recovered austenite, with no traces of segregation bands (Fig.5).

The differentiated steel structure, both in the quenched state for both thermo-mechanical working variants and in the tempered state has small effect on the mechanical properties, however, a significant one on the Charpy V-notched specimens' breaking energy at a temperature of – 40 °C and anisotropy of the plastic properties of the plate test segments, expressed by the ratio of the transverse to longitudinal KV_{-40^oC} specimens. Tensile test results indicate that the test plate segments made in both thermo-mechanical working variants, tempered in the temperature range 550 to 650 °C's demonstrate the comparable mechanical properties, that is: yield stress $R_{p0.2}$ from 1000 to 1089 MPa, Ultimate Tensile Strength R_m from 1030 to 1120 MPa, elongation A from 17 to 19%, and reduction of area at fracture Z from 60 to 69%.

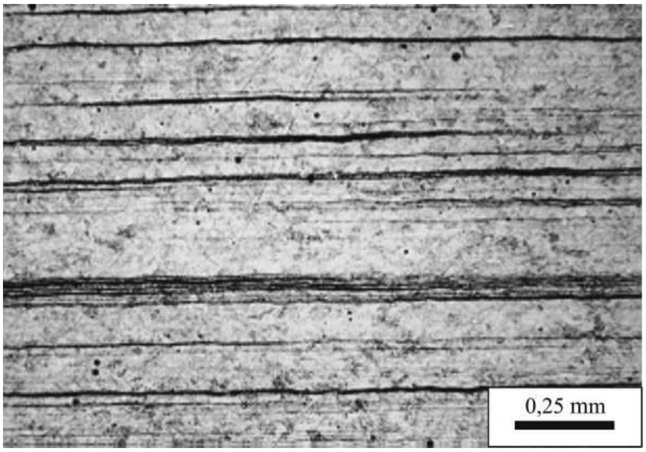

Fig. 3. Austenite structure with distinct segregation bands

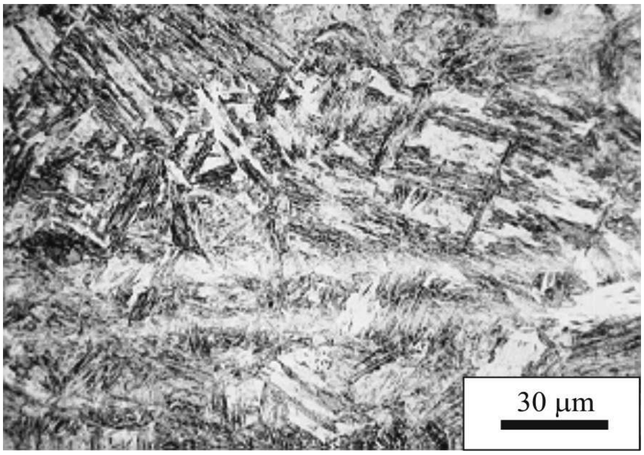

Fig. 4. Low-carbon lathe martensite with distinct segregation bands

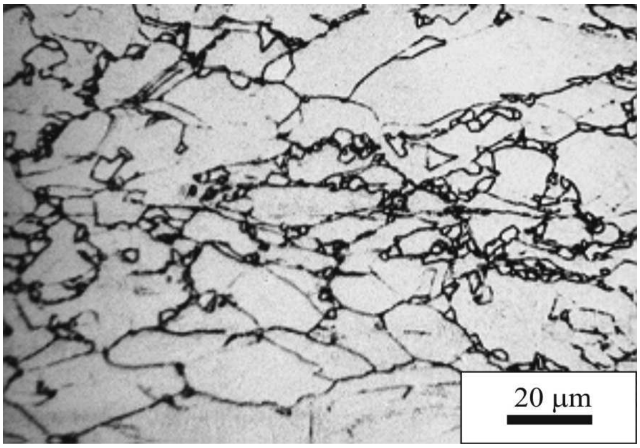

Fig.5. Fine grains of the statically recrystallized austenite distributed at the grain boundaries of the statically recovered austenite; deformation temperature 900 °C, $t_{0.5}$ = 60 sec

Top $R_{p0.2}$ and R_m values refer to the test plate segment made using the first thermo-mechanical working variant, whereas, the bottom ones refer to the second variant. Moreover, the transverse specimens have, in general, slightly better strength properties, and lower plastic ones. However, the conventionally quenched steel, after austenitizing the specimens at the temperature of 900 °C demonstrates the properties comparable with those given above for the thermo-mechanically worked specimens, only after tempering at a temperature of 550 °C. Increasing the tempering temperature to 650 °C results in decreasing the yield stress $R_{p0.2}$ to 990 MPa with UTS (R_m) of about 1040 MPa, A about 19% and Z from 67 to 70%. The significant differences refer to crack resistance of the test segments of the plate made using both variants of the thermo-mechanical working, and after the conventional quenching and tempering of the steel. It turns out, from V-notched Charpy test results at the temperature of -40 °C that KV energy, for both transverse specimens and for the longitudinal ones, increase along with the increase of the tempering temperature. However, the energy values of breaking the specimens taken from the segment of the plate manufactured in the conditions of total recrystallization of the plastically deformed austenite at intervals between the successive rolling passes and isothermal holding for time $t_{0.5}$ at the temperature of finish-rolling prior to quenching, is nearly two times larger than the energy of breaking the specimens taken from the test segments of the plate made in the first thermo-mechanical working variant.

4. Conclusions

The investigations carried out revealed that the process of plastic deformation of steel in the temperature range from 1100 to 900 °C in conditions close to heavy plate rolling is controlled by the dynamic recovery flow, where the strain hardening decay of the austenite between the successive deformation cycles occurs through static recovery and static recrystallization. The nonuniform plastic metal flow is a reason for origination of the deformation bands (shearing) in the plastically deformed austenite, spreading in the direction of the load, disappearing during the static recrystallization of the austenite.

The time of the total recrystallization t_R of the plastically deformed austenite of $\varepsilon = 0.2$ with a rate of 3 s^{-1} at the temperature of 1100 °C is 50 sec, and increases to about 300 sec at the temperature of 900 °C. However, time $t_{0.5}$ - necessary to develop 50% fraction of the recrystallized austenite after plastic deformation of steel at the temperature of 1100 °C, determined basing on the strain hardening decay kinetics - is 9 sec and increases to 60 sec at the temperature of 900 °C.

If the intervals between the plastic deformation cycles are shorter than the time of the statical recrystallization of the austenite then overlapping of the nonuniform flow of plastic metal in the successive deformation cycles leads to development of the shearing bands in the austenite.

The deformation (shear) bands do not develop if the time between the consecutive deformation cycles makes total recrystallization of the plastically deformed austenite possible. Adjusting the interval times between the deformation cycles in the multi-pass rolling process to the total recrystallization time of the plastically deformed austenite, by employing the retention shield, and the isothermal holding of the product at the temperature of the end of hot working for time $t_{0.5}$ before quenching, offers the possibility of obtaining the homogenous austenite structure, and therefore, manufacturing the rolled products displaying high mechanical properties.

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