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Simulation of recrystallization and mechanical properties under hot rolling and high temperature thermomechanical treatment

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ABSTRACT

Experimental design and the finite element method were used for the simulation of dynamic and static recrystallization and mechanical properties of steels under hot rolling and high-temperature thermomechanical treatment conditions. It is proposed that a recrystallization diagram of a special type could be used for the quantitative estimation of dynamic and static recrystallization development. The latter depends on the main high temperature thermomechanical treatment parameters: deformation temperature, strain and elapsed time followed by the end of deformation up to the start of accelerated cooling. It was found that mechanical properties changes correspond to recrystallization changes. Mathematical models and nomographs of recrystallization fraction and yield strength dependences from above mentioned parameters were obtained. The study results demonstrate the possibilities to use such type of recrystallization diagrams and the finite element method modeling simulation to predict structure and mechanical properties for different cross-sections of rolled billets and parts.

KEYWORDS

hot rolling • simulation • mechanical properties • high temperature thermomechanical treatment• recrystallization • finite element method

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Introduction

Hot rolling and high temperature thermomechanical treatment (HTMT) are the most popular metal production techniques [1–9]. Because of the link between structure and properties, it is essential to produce desirable microstructures during rolling, particularly in the case of the different steel grades. For this reason, there have been numerous studies in which rolling simulations have been carried out in order to characterize and optimize the types of structures that are likely to be produced in the plant [2,4,7,10–16].

The structure (and substructure) developed during and after hot rolling but before accelerate cooling define the technological (deformation plasticity), mechanical and other properties. In HTMT, deformation is realized in the hot and hot-warm temperature range. It is known that in this case the rearrangement of the dislocation structure of the high-temperature phase (for steels this is austenite) is a consequence of the competing and successively preparing each other processes of mechanical hardening, dynamic recovery (or cell formation), and dynamic recrystallization. In the hot rolling

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process, the thermoplastic action makes the structure evolve. With growth in the strain degree, all the levels (including atomic, micro- and meso-) are involved progressively. In the initial stages of the deformation, the prevailing process is the first one. With growth in the strain degree and strain rate, the dislocation density increases. In accordance with the modern theory of high plastic deformation, collective forms of motion arise in a dislocation ensemble and cause substantial restructuring, i.e., breakage of the body of grains first into somewhat off-oriented cells and then into fragments [17,18]. The structural transformations occurring at the meso-level are primarily responsible for formation of the final structure and hence for the properties of metals and alloys subjected to TMT [17]. In the process of hot rolling, the thermoplastic action makes the structure evolves. With growth in the degree of the deformation, all the levels mentioned above are involved progressively. The structural transformations occurring at the meso-level are primarily responsible for formation of the final structure and hence for the properties of metals and alloys subjected to TMT. Figure 1 presents the fine structure of the specimens treated under different rolling schedules, demonstrating the above-mentioned evolution.

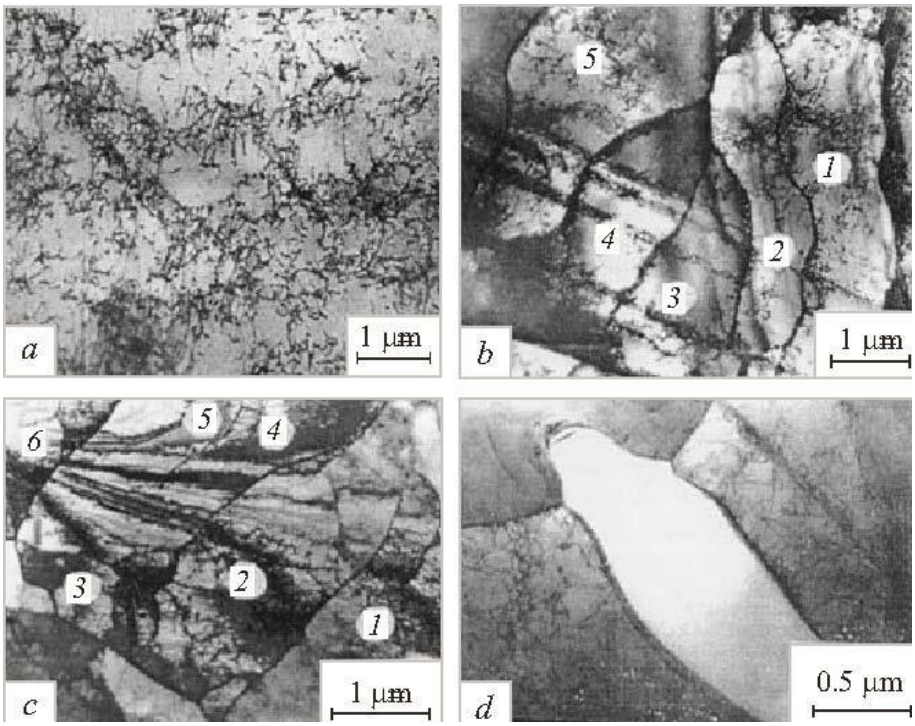


Fig. 1. Weakly misoriented cellular (a), fragmented (b,c), and recrystallized (d) structures in austenitic AISI321steel after fractional deformation (c) and after single-stage deformation (a,b,d): (a) number of passes n = 1, ε = 10 %; (b) n = 1, ε = 10 %; (c) n = 5, ε = 10 %; (d) n = 1, ε = 30 %; 1–6 fragments on which crystallographic orientation (θ) has been determined [17]

From the standpoint of the modern physics of plastic deformation of crystals, the appearance of collective forms of motion means the appearance of rotary modes of plasticity in the crystals. At a specific loading rate, the deformed material becomes incapable of dissipating the mechanical energy supplied to it due to only plastic displacements. Therefore, it breaks into a set of randomly oriented microregions (cells, fragments), each of which turns in a plastic manner in the deformation process and thus

absorbs additional portions of energy. With growth in the loading rate (growth in the strain degree and strain rate of the deformation) the rotary modes and their structural feature (fragmentation), should intensify continuously. This goes on until the rate of supply of mechanical energy to the preform exceeds the next threshold value at which the fragmented structure becomes unsteady and dynamic recrystallization, which is the most powerful structural mechanism of energy dissipation, comes into play. It is the change in the thermomechanical temperature-strain parameters which is responsible for the kinetics of the processes of structure evolution, for the attainment of this or that state (often a heterogeneous structure consisting of regions of this or that structural mode in various proportions and distributed with different degrees of uniformity over the volume of the stock, and, correspondingly, for the attainment of a specific combination of properties.

The softening mechanisms – recovery and especially recrystallization (dynamic and static) – are responsible for the mechanical behavior of steels during conventional hot deformation, realized in the industrial rolling mills under HTMT and controlled rolling [7,19–23]. Figure 2 represents the scheme of grain structure formation during and after hot rolling. HTMT of steel, involving hot deformation of austenite and its subsequent accelerated cooling, is aimed at increasing the complex of mechanical properties. This occurs as a result of the formation of a developed fragmented substructure, but often it is impossible to completely prevent the development of recrystallization processes at the industrial conditions [4,19,22,24,25]. Meanwhile, it is known that the development of recrystallization leads to a decrease in strength and an increase in plastic properties.

The main aim of computer modelling and simulation is to contribute to making better products cheaper and/or faster. The hot metal forming processes, including high temperature thermomechanical treatment (HTMT), are aimed at shape formation and also at improving the mechanical properties. The last ones result in the formation of the products of hot deformed austenite transformation to martensite, bainite or pearlite due to hereditary influences on their morphological and substructural characteristics [1,15,26,27].

As for industrial conditions of hot deformation, it is difficult to prevent the start of recrystallization processes because of different reasons (temperature and strain rate changing, layout of rolling mill and accelerated cooling equipment, materials peculiarities and etc.).The mechanical and some functional properties of metals and alloys result in hot deformation and HTMT are determined by the special feature of the structure formed of two competitive processes: strengthening (work hardening) and softening (dynamic and meta-dynamic recrystallization) [1,19,20]. The kinetics of these processes depends on the temperature-strain parameters and are determined by the combined influence of the last ones, i.e., HTMT is a multiple-factor process.

To achieve precise prediction control of product quality, the details of microstructural evolution occurring during hot deformation and cooling should be illustrated in the model. The past decades have involved a number of investigators in many countries developing mathematical models to predict the final structure and mechanical properties of hot deformed steels [10,13,16,20,28]. The physical models developed by different groups differ in detail in the form of relationships used in each physical sub-model, but essentially, they operate in the same way to compute the evolution of microstructure [10,15,16,25]. This greatly complicated the search for the optimal conditions. A number of studies have shown that the experimental design

method (EDM) makes it possible to study the influence of several technological parameters on certain properties to be optimized, including influence of HTMT parameters on the grain structure and mechanical properties [11,15]. For this reason, EDM has been used for the examination of the combined influence of the mentioned above parameters on the structure and mechanical properties. The main problem in the development of HTMT is the construction of the regression model, which could be used to control the process, moreover, to create mathematical model, which may be foundation for computer modelling. To achieve precise prediction control of product quality, the details of microstructural evolution occurring during to deformation and accelerate cooling and the relationship between the treatment parameters, structure and mechanical properties is still somewhat complicated. It is important to obtain a quantitative estimation of the development of recrystallization (dynamic and static) for various values of the main treatment parameters. In view of the fact that hot deformation (including HTMT) schedules are, in many respects, dependent on the characteristics of a given rolling mill (permissible loading of the mill stand, distance from the rolling mill to the quenching installation, etc.), it seems necessary to use diagrams enabling a quantitative evaluation of the development of recrystallization to be made in relation to major process parameters.

Simulation of hot deformation and HTMT for the definite cross-section of profile by FEM on the base of the data obtained by experiment design method allowed to predict structure and mechanical properties and to develop computer modelling for the different cross-section of rolling profile. Mechanical properties as a result of HTMT are determined by special features of structures that are formed by two processes: strengthening and softening. The kinetics of these processes depend on the temperature-strain parameters of HTMT and are determined by the combined influence of parameters. This shows that HTMT is a multifactorial process.

Typically used methods for studying the influence of temperature-strain parameters of HMTP deformation temperature (T_d, ºC), strain (ε, %), strain rate ($\dot{\varepsilon}$, s^{-1}), and the time elapsed from the end of deformation to the start of quenching (τ, s) on the structure and mechanical properties imply a linear approach, when one parameter is varied while others are constant, which does not allow obtaining a model of the dependence of the studied optimization parameters (in our case, mechanical properties) on the parameters of the HTMT process. For this reason, the method of experimental design was used for the examination of the combined influence of the HTMT parameters on the structure and mechanical properties. To achieve precise prediction for controlling the product quality, the details of microstructural evolution during hot rolling and cooling should be illustrated in the model. The data required for these models was primarily obtained through hot torsion, which allows large strains and very short interpass times (~30 ms).

Some equations applied to a widen stain range and describing kinetics of static recrystallization are reported by Kwon [29]. The dynamic recrystallization was studied because its occurrence influences the austenite microstructure directly. It is known that dynamic recrystallization operates not only during rough rolling at high temperature but also during successive tandem rolling at the finishing stand.

It is obvious that it is necessary to take into account both dynamic and static recrystallization phenomena. The available types of recrystallization diagram [23] cannot

be used for this purpose, as they were proposed for the estimation of grain size during heating for cold-deformed metal. Due to the fact that HTMT schedules are strongly dependent on the characteristics of a given rolling mill (permissible loading of the stand, distance from rolling mill to quenching installation, etc.), it seems necessary to develop diagrams enabling a quantitative evaluation of the development of recrystallization to be made in relation to major process parameters.

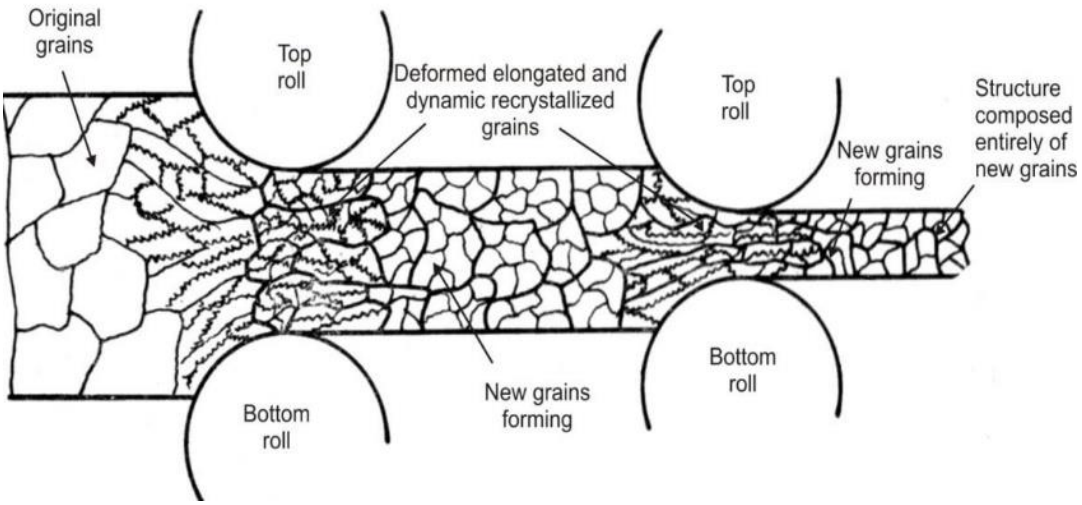


Fig. 2. Grain structure formation of steel during and after multipass hot rolling

Materials and Methods

This work studied the influence of the mentioned parameters of HTMT under non-isothermal conditions during air cooling on the evolution of grain structure and mechanical properties of typical austenitic AISI 321 stainless steel 0.07 % C, 18.2 % Cr, 10,1 % Ni and 0.7 % Ti.

Experimental design method

The properties of the steel after HTMT are determined by the special features of the structure formed in the final stage of treatment. This structure is formed in the conditions of the occurrence of two processes: hardening and softening. The kinetics are determined by the combined effect of the temperature-strain-time parameters, i.e. HTMT is a multifactoral process. The conventional methods of examination of the effect of the HTMT parameters, the main of which are deformation temperature (T_d, ºC), strain degree (ε, %), strain rate ($\dot{\varepsilon}$, s^{-1}), and divisibility (n) of deformation, the time elapsed from the end of deformation to the start of quenching (τ, s) and, for a number of steel groups, also aging (tempering) temperature (T_t, ºC), are based on the variation of one factor with the remaining process parameters being constant. This greatly complicates the search for the optimum conditions of the process. For this reason, there are many different modeling techniques that have been proposed to optimize the final structure and properties [10,14,29]. The method of experiment design has been used on an increasing scale for the examination of the combined effect of the HTMT parameters on the structure and properties [11].

The main problem in the development of TMT technology is the construction of a model which could be used to control the process. In the first stage, this includes the construction of polynomial models for various steels, alloys and, possibly, also of their groups. The second stage may consist of optimization in respect of the main optimization parameter both, by means of the Box-Wilson method (if limitations in respect of the accompanying optimization parameters (if this is necessary) [11]. The optimization parameters (target functions) were represented by recrystallization degree (R, %) and yield strength (YS, MPa). There may be other optimization parameters according to the customer request. The level of the factors variations and their combinations were selected based on of the actual possibilities of the process realization. Experiment of type 3^3 was realized. Three experiments were conducted at each point, giving three to six determinations. All the 22 × 22 mm^2 section billets were heated to 1100 ºC and held at this temperature for 50 min rolling in an electric furnace prior to rolling. Rolling was carried out in a two-high mill with a 210 mm roll diameter at a speed of 0.3 m/s. Some of the specimens were rolled at 1100 °C, and the remainder were rolled after air cooling to 1000 and 850 °C. The rolling reduction ratios used were 10, 20, and 30 %, and the times between the end of rolling and the start of quenching were 1, 100, and 1000 s. The large interval between holding times was dictated by the relatively low susceptibility of the studied steel (with low stacking-fault energy) to static recrystallization [30]. Planimetric methods of metallographic analysis were used to evaluate the grain structure of the steel after HTMT [31]. The recrystallization degree (the fraction of recrystallized grains) was determined based on the area ratio. Three parallel tests were made for each point in the experiment. Curves plotting the distribution of the fraction (%) of recrystallized grains were derived for each specimen and were used to estimate the average size of the proportion. Data from measurements of 20–30 sections were used to plot the distribution curves.

The experimental data were processed by a computer [31]. In addition to the calculation of regression coefficients, an algorithm made it possible to verify the adequacy of the model based on the Fisher criterion at 5 % significant level. The significance of the regression coefficients was verified by means of Student's criterion at 5 % significance level [31].

Finite element method

Finite element method (FEM) on the base of the data obtained by physical simulation and EPM allowed to predict the structure and mechanical properties and to develop computer modelling for the different cross-sections of rolling profiles. The stress-strain state of the complex section was estimated in the DEFORM environment using FEM. Such thermophysical properties of steel as thermal conductivity, heat capacity, density, coefficient of linear expansion, and metal deformation conditions were used for simulation. Their values were chosen according to the AISI 321 steel included in the DEFORM database of materials. The properties of the steel are distributed in the temperature range from 100 to 1200 °C. The coefficients of heat exchange with rolls and the environment were also used in the simulation. The properties of the rolls were also set from the material database.

The properties of the rolls were also set from the material database, the technique of studying a dynamically recrystallized grain with computer simulation we can analyze the structure that forms in a part during deformation, and to optimize the process of production of the part in order to ensure its required properties.

Results

Figure 3 shows a recrystallization diagram which can be used to determine the fraction of recrystallization *R* in relation to rolling temperature (*t* roll), strain (rolling reduction ε, %), and time between the end of rolling and start of the accelerated cooling (τ, s). Mechanical properties of steel at different stages in softening during rolling in HTMT conditions are presented in Table 1.

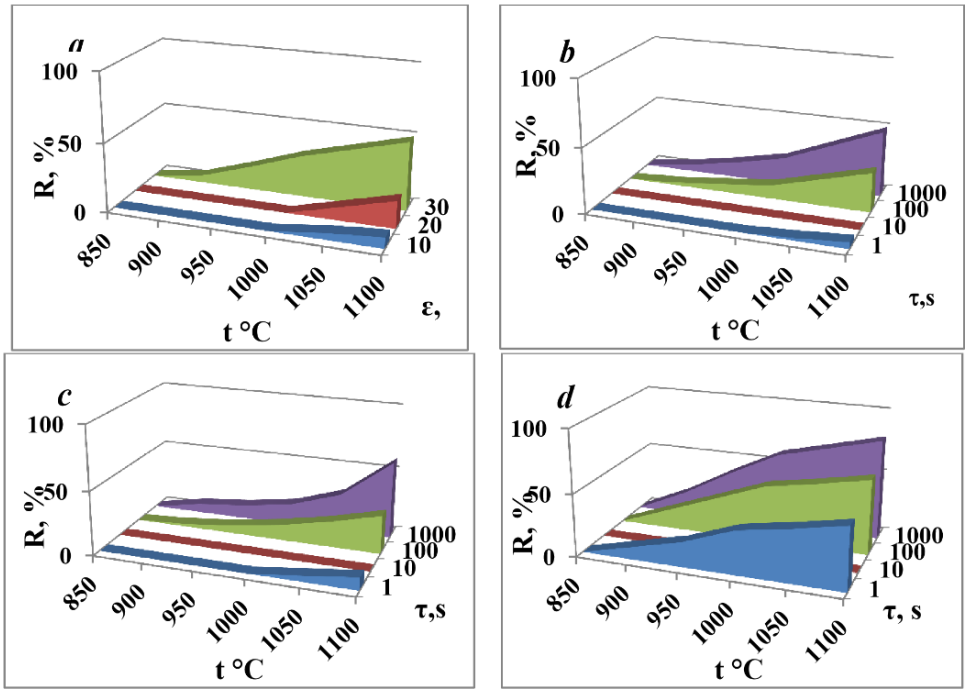


Fig. 3. Recrystallization diagrams for AISI321 steel under hot deformation conditions: (a) τ = 1 s; (b) ε = 10 %; (c) ε = 20 %; (d) ε = 30 %

It can be seen from Fig. 3 that dynamic recrystallization (τ = 1 s) occurs only at the deformation temperatures above 1000 °C with a strain (reduction) greater than 20 %. During the deformation temperature of 850 °C, no recrystallized grains were observed in any of the specimens studied.

As a result of the data treatment regression equations describing the dependence of the yield strength (*YS*) and *R* on the hot rolling parameters were obtained for the experimental material and the given region of the factorial space. The recrystallization's degree and yield strength – T_d, ε, τ relationship was obtained by accounting for the experimental design method:

$$R = 24.1 + 14.2X + 23{,}9.0Y + 13.1Z + 15.3XY + 8.3YZ - 5.1Y^2 - 3{,}9XYZ - 3.6XY^2Z + 2.6Z^2, \quad (1)$$

$$YS = 317 - 21{,}8X - 45Y + 22Z + 6XY - 14YZ - 7YZ^2 + 4Y^2Z, \quad (2)$$

where *X*, *Y*, *Z* are varying factors, correspondingly $X = 2/3\log\tau$; $Y = 0.01T_d - 10$; $Y^2 = 291 - 0.6T_d + 0.0002T_d^2$; $Z = 0.01\varepsilon - 2$; $Z^2 = 10 - 1.3\varepsilon + 0.002\varepsilon^2$.

Table 1. Mechanical properties of AISI 321 stainless steel at different stages in softening during rolling in HTMT conditions.

Treatment parameters				Mechanical properties			
ε, %	T_d,^{0}C	τ, s	*R*, %	Yield strength, MPa	Tensile strength, MPa	Elongation, %	Reduction in area, %
10	1100	1	1	266	528	64.5	79.1
		100	36	245	547	64.1	79.2
	1000	1	0	329	560	63.0	75,3
		100	7	299	536	64.2	77.3
	850	1	0	362	565	59.3	78,6
		100	0	335	564	54.1	78.1
		1000	0	314	561	60.5	79.1
20	1100	1	14	309	581	51.2	75.7
		100	45	279	561	60.9	76.0
		1000	81	271	555	66.7	76.7
	1000	1	0	351	602	50.2	76.3
		100	21	341	577	60.2	77.7
		1000	31	319	561	58.9	79.1
	850	1	0	392	590	50.0	77.6
		100	0	358	601	50.1	73.5
30	1100	1	49	286	596	57.2	77.1
		100	70	256	541	63.1	79.4
		1000	92	259	574	58.9	76.1
	1000	1	37	363	614	50.4	77.0
		100	57	305	555	581.0	76.7
	850	1	0	478	646	45.1	74.7
		100	0	432	594	44.9	76.2
		1000	0	411	588	44.4	763

From Eqs. (1) and (2), we notice that the regression equations which describe the effect of HTMT parameters on the *R* and *YS* are quadratic. Besides, the regression equations also contain several significant terms which take into account the paired interactions. The statistical models (1) and (2) give the possibility to fit such relationship between parameters T_d, ε and τ in the solution of the problem of quality control which will provide the required level of *R* and, respectively, mechanical properties, in particular $YS = f(R)$. In order to use the performed laboratory experiment results, which were carried out with the 22 × 22 mm^2 prior to deformation section billets for the plates or profiles of other cross-section shape with various thickness of the same steel type it is required to complement the (1) and (2) statistic models which describe the thermal operations conditions of required steel plates thickness. As is evident from Eq. (1), in the examined range of the factorial space, corresponding to the real industrial conditions, the most significant factor is deformation temperature and cooling time until quenching paired interaction. From a physical point of view, this interaction is determined by the quenched temperature. It is necessary to follow the conditions of physical similarity of laboratory and industrial processes for applying the results of laboratory investigations of the dependences of recrystallization fraction, yield strength and other characteristics from deformation temperature, reduction, quenched temperature applying to the kind of hot deformation and HTMT. Physical simulation has been provided by the corresponding

thermophysical and deformation characteristics of processes. Thermophysical process modelling has been achieved by solving of the unsteady heat transfer differential equation with boundary conditions of the third mode with given heat change surface condition of the sample or workpiece (metal sheet or other profile). When the heat transfer task is solved and the temperature in every point of the cross-section of the profile at every required moment of time is known, we transfer the results of laboratory studies to the industrial workpiece. For transferring of the results of laboratory investigations to the real object, it is necessary to simulate process of deformation. It has been achieved by solving of the plastic flow task for a definite cross-section of the profile or forge piece. The form changing process from initial to final profile is followed during solvation. In every spot (in each node of the finite element) at every moment the components of deformation, stresses and movements is being counted. Thus, the degree and rate of deformation are known in each point of cross-section. If it`s known, we can refer to the results of corresponding the laboratory experiments. To be use the recrystallization diagrams, which were constructed on the basis of experimental data (Fig. 3) in order that to predict properties of rolled plates of the AISI 321 type steel with various thickness it is necessary to go over from the combination of $T_d - \varepsilon - \tau$ – factors to the combination of $T_d - \varepsilon - T_q$ – factors (where T_q is the quenching temperature), simultaneously to retain invariable heat exchange conditions. Mathematical models of $YS = f_1(T_d, \varepsilon, T_q)$ dependences can be obtained by accounting for cooling curves of 22 × 22 mm^2 rolled in the 210 mill with the air cooling after deformation. Under three factors (3^3), experimental design data treatment instead of the time factor it will take part in the other one, conforming to the start of rapid cooling billet temperature which in actually is the quenching temperature. As a result, the models according to the $T_d - \varepsilon - T_q$ – factor system will stand up as follows:

$$YS = 322 + 18X - 59Y + 24Z - 22YZ, \quad (3)$$

$$R = 25 - 11.4X + 24.2Y + 14.2Z - 11.9XY + 9.5YZ - 4.4ZY^2 + 4.1XYZ, \quad (4)$$

where $X = T_q/300 - 2$; $Y = 0.001T_d - 10$; $Z = 0.1\varepsilon - 2$; $Y^2 = 298 - 0.6T_d + 0.0003T_d^2$.

For the calculation of the yield strength and recrystallization fraction in case of the required thickness (h) plate rolling with the designated reduction and temperature, it is necessary to simulate the cooling process for the concrete plate billet under deformation in the rolling stand and following air cooling. As this takes place the time when the billet between the rolls from start to the end of the rolling will be result from the linear rolling speed – $\upsilon = \omega \times r$ and the length of arc of the roll contact – $l = \sqrt{rx\Delta h}$ corresponding to rolling in the rolls with the radius r, angular roll rotation speed ω, where Δh is draught. Heat changes conditions are similar to the experimental ones with the 22 × 22 mm^2 cross-section billets. If we will follow to the deformed plate cooling conditions, it is possible to definite the time when the plate temperature will reach the quenching temperature. This quenching temperature in combination with the set preliminary rolling temperature (T_d) and reduction (ε) will give the required properties level which are calculated according to Eqs. (3) and (4). Thermo-physical processes modelling of rolling with the following cooling are realized by means of numerical solution of the unsteady heat transfer equation by the finite elements with the time various third mode boundary conditions. As an example of graphic illustration, the designed cooling and properties in

the centre of the rolled plates with the initial thickness h_o = 50 mm and rolling with reduction ε_i = 10, 20 and 30 % and T_d = 1100 ºC and 1000 ºC, (a) and (b) respectively to the plates with the finite thickness h_i = 35 mm are shown in Fig. 4. But it is necessary to take into account that cooling in water is realized in a designated time with the plate temperature corresponding to this time.

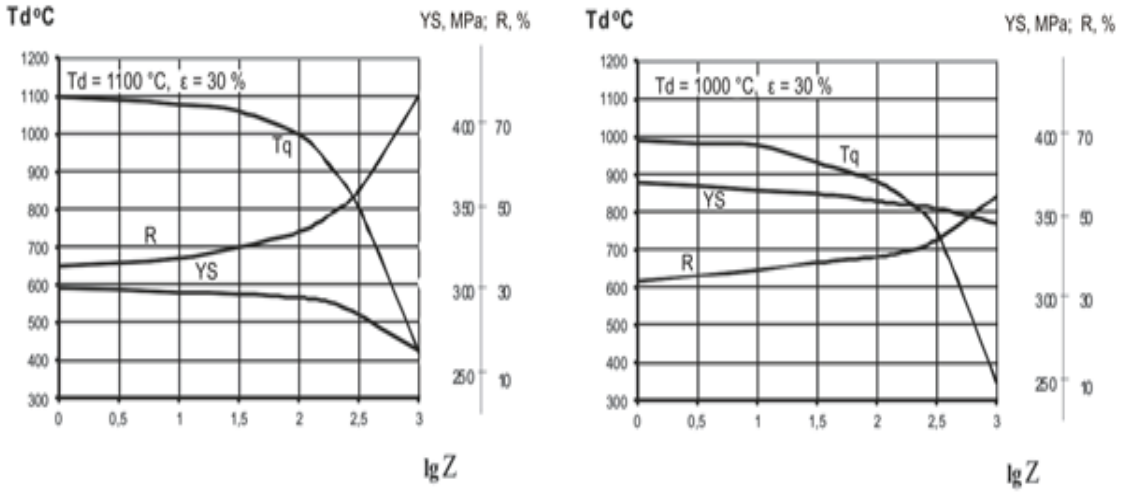


Fig. 4. Nomograms for defining of the recrystallization fraction, *R* and yield strength, *YS* in the billet with final thickness of 35 mm: T_d = 1100 ºC (a) and 1000 ºC (b), T_q is quenching temperature, *R* is fraction (degree) of recrystallization

Thus, mathematical simulation of thermo-mechanical processes of the real object allows to set up the temperature, time and deformation at each point of the profile cross-section. As a result, knowing this combination of parameters, we can find the properties of the workpiece from the same material, which are known at based on laboratory experiments with samples.

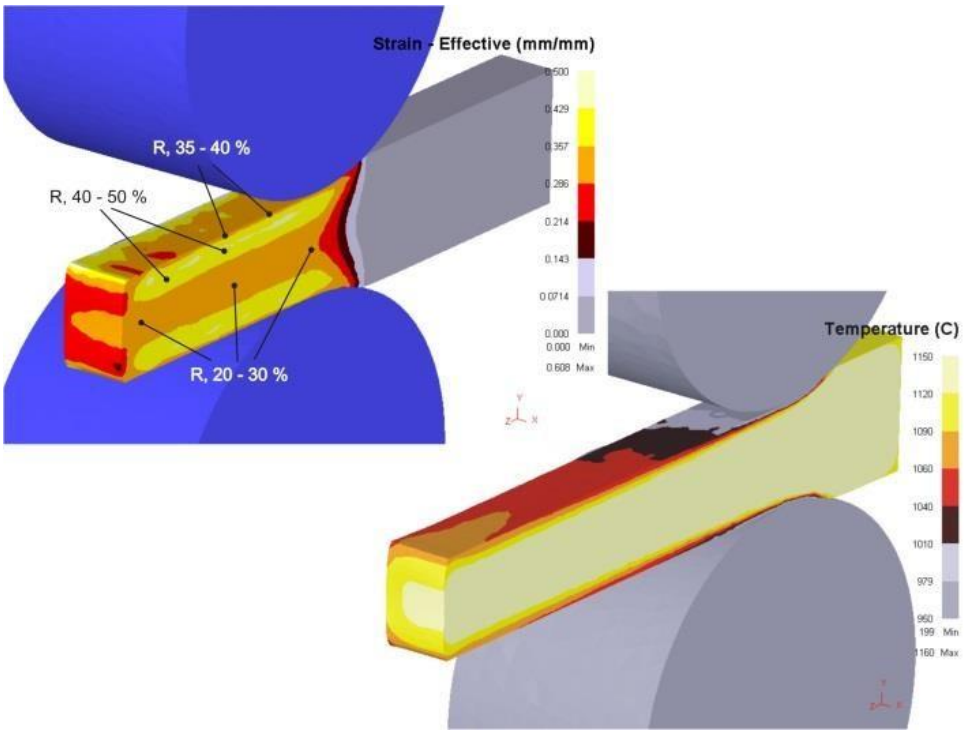


Fig. 5. Cross-sectional dynamic recrystallization distribution

It is necessary to follow the conditions of physical similarity of laboratory and industrial processes for applying the results of laboratory investigations of the dependences of a recrystallizations degree, yield strength and other characteristics from deformation temperature, strain degree, the quenched temperature, applying to the mode of thermomechanical treatment. Heat changes conditions are similar to the experimental ones with the 25 × 25 mm^2 cross-section billets. If we follow the deformed plate cooling conditions, it is possible to define the time when the plate temperature reaches the quenching temperature. This quenching temperature in combination with the set preliminary rolling temperature, T_d and ε will give the required properties level which are calculated according to Eqs. (3) and (4). Thermophysical processes modelling of rolling with the following cooling are realized by means of numerical solution of the unsteady heat transfer equation by the FEM with the time various third mode boundary conditions. An example of a FEM calculation shown in Fig. 5.

Discussion

Experimental data shows that the recrystallization of austenite follows a similar general pattern during HTMT of various steels. Different steel types have a temperature-deformation-time zone where no visible recrystallization occurs, a second zone where recrystallization starts to develop, and a third zone in which the structure is fully recrystallized. The boundaries of these zones in austenitic steels are, however, displaced considerably towards longer holding times. This is linked to the relatively low stacking-fault energy of such steel type [30]. As the temperature and strain increases, these zones shift towards shorter holding times. As temperature and strain increases, these zones shift towards shorter holding times. Dynamic recrystallization (τ ~ 1 s) occurs only at deformation temperatures t ~ 1000 °C with reduction ε ~ 20 %. As a result of HTMT at the deformation temperature of 850 °C, no recrystallized grains were observed in any of the specimens studied**.** Static recrystallization undergoes marked development during the post-deformation holding period of τ ~ 100 s. Temperature and strain degree have a strong influence (Table 1, Fig. 3). Tensile test results showed that the change in mechanical properties corresponds generally to the recrystallization kinetics (Table 1). A softening process was, however, observed during HTMT in this case. There is a continuous decrease in yield strength (without an incubation period) with increasing deformation temperature and post-deformation holding time. At 850 °C, with a reduction of 30 % in particular, the tensile properties were found to decrease with increasing post-deformation holding and no recrystallization was observed (Table 1), thereby indicating the onset of recovery phenomena in the pre-recrystallization stage of softening. This is also confirmed by the temperature dependence of the yield strength from which it is clear that, in HTMT with immediate quenching, there is a continuous decrease in the yield strength with increasing rolling temperature. The rate of softening increases with the shift towards higher rolling reductions, which corresponds to the shift towards the stage of developing recrystallization processes and shows that they have a greater influence on mechanical properties than recovery. The rate of softening increases with the shift towards higher rolling reductions, which corresponds to a shift towards the stage of developing recrystallization processes and shows that they have a greater influence on

mechanical properties than recovery. The statistical models (1) and (2) give the possibility to fit such a relationship between parameters T_d, ε and τ in the solution of the problem of quality control that will provide the required level of R and correspondingly mechanical properties, in particular $YS = f(R)$. In order to use the laboratory experiment results which were carried out with the 25 × 25 mm^2 prior to deformation section billets for the plates or profiles of other cross-section shape with various thickness of the same steels type, it is required to complement the (1) and (2) statistic models which describe the thermal operations conditions of the required steel plates thickness. As it is seen from Eq. (1), in the examined range of the factorial space (simulation of real industrial conditions), the most significant factors (the largest values of the regression coefficients) are deformation temperature and cooling time until quenching (paired interaction). From physical point of view, this interaction is determined by quenched temperature.

Conclusions

The proposed technique of modeling, including the application of a recrystallization diagram of a special type, can be used to determine the fraction (degree) of recrystallization R in relation to rolling (deformation)temperature, strain degree (rolling reduction), and time interval between the end of rolling and the start of the accelerated cooling. In addition to the experiment design method was proven to be a good tool for the definite relationship between HTMT parameters, recrystallization and mechanical properties. Simulation of HTMT for the definite cross-section of profile by FEM on the base of the data obtained by experiment design method allowed to predict the structure and mechanical properties for different cross-sections of rolling profile. Mathematical simulation of thermo-deformation processes of the real object allows to set up temperature, time and deformation at each point of the rolling profile cross-section. Thus, knowing this combination of parameters, we can find the properties of a workpiece from the same material that is known based on laboratory experiments with samples.

CRediT authorship contribution statement

Andrey I. Rudskoi: writing – review & supervision**; Georgii E. Kodzhaspirov**: writing – original draft, investigation; editing, data curation.

Conflict of interest

The authors declare that they have no conflict of interest.

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