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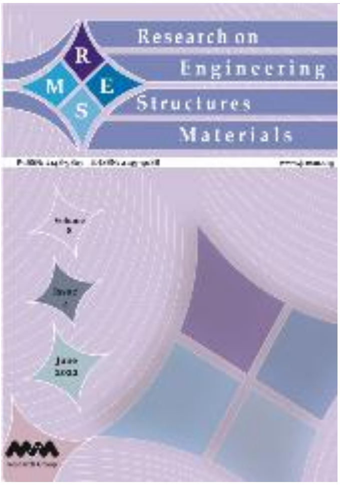

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Technical Note

Determination of the optimal temperature regime of plastic deformation of micro alloyed automobile wheel steels

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Abstract

It has been established that hot plastic deformation microalloyed steel 10HFTBch type accelerates the excretion of pearlite and causes structure refinement during subsequent cooling due to an increase of start of new phases' centers. This leads to the formation of a fine-grained dispersed two-phase structure consisting of ferrite with a high dislocation density and pearlite. It has been determined that at the optimum deformation temperature the prevailing mechanism of structure refinement is the fragmentation of austenitic and ferrite grains of a common initial orientation into misoriented subgrains (fragments) with low-angle dislocation boundaries of deformation origin. A thorough thermokinetic analysis of the course of this process made it possible to determine the optimal temperature regime for plastic deformation for this type of steel, which is 850-900 °C. Plastic deformation increases the range of of pearlite's transformation existence rates by 2.5 times, it was found that after 30% deformation at 950 °C, pearlite transformation begins at a cooling rate of 5 °C/s, and without deformation – at 2 °C/s.

1. Introduction

One of the main catalysts for the rapid development of the industrial economy sector is mechanical engineering [1]. And in this regard the automobile industry plays an important role [2]. Not only the performance of the transport as a whole, but also its efficiency depends on the reliability of the undercarriage components of trucks. One of the most critical units of trucks are wheel disks. Increasing their cargo, and hence energy efficiency [3], allows significant savings by reducing the number of trips for transporting various types of cargo [2]. And in this case, the development of new materials with special technological properties, such as specific strength [4] and impact strength [5], comes in a prominent position.

One of the ways to increase the carrying capacity of vehicles is the manufacture of rims from steels with improved characteristics. In this regard, a good alternative to conventional low-carbon steel, from which, as a rule, wheel rims of trucks are made, are micro alloyed steels, which include low-pearlite steel 10HFTBch, with the following ratio of components, %: C 0.08-0.12; Si 0.10-0.50; Mn 0.15-0.50; Cr 0.05-0,15; V 0.10-0.15; Ti 0.10-0.15; Nb 0.07-0.15; S ≤0.035; P ≤0.035; Ba 0.0005-0.0015; REM 0.001-0.010; Fe – other [6].

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Studies have shown that a simultaneous increase in the strength and resistance to brittle fracture of low-alloy and ordinary low-carbon steels is possible by microalloying [7]: the introduction of micro additives (up to 0.15%) of elements, mainly IV and V groups of the periodic system [8]. The most common microalloying elements are niobium [9], titanium [10] and vanadium [11]. These elements have a high affinity with nitrogen and carbon and readily form nitrides and carbides (or carbonitrides) [12]. When heated, carbonitrides dissolve in a solid solution, and when cooled, they release as a separate dispersed phase [13]. These processes are one of the main mechanisms of steel's hardening.

Thus, in the development of 10HFTBch type steel, in addition to traditional microalloying elements, introduction of such elements as barium and rare earth metals from the group of cerium, lanthanum, praseodymium, neodymium made it possible to obtain steel with improved mechanical characteristics and increased impact strength (tensile strength 500 MPa, yield strength 440 MPa, impact strength KCU=0,80 MJ/m2) [6], while achieving equal strength of the welded joint with the base metal, as well as an increase in the impact strength of the weld and the heat-affected zone [5].

Unlike low-carbon steels, which are used for the production of wheel rims for trucks, for example, low-carbon steel 15 (tensile strength 470 MPa, yield strength 370 MPa, impact strength KCU=0.73 MJ/m^2), the proposed steel has 15-20% increased strength properties. This makes it possible not only to proportionally increase the carrying capacity of the wheels, but also to extend their survivability by about 2-2.5 times, which was confirmed by mechanical tests according to a specially developed technique in [14]. At the same time, some technological issues arise when this steel is put into mass production.

The most rational method for processing low-alloy steel is controlled rolling [15]. Distinctive features of this type of processing are: a reduced temperature of workpiece heating [16] for final rolling, a strictly regulated deformation regime, and a low temperature at the end of rolling. All this provides a sharp refinement of the austenite grain, and, consequently, the ferrite formed from it, moderate precipitation hardening, dislocation and sub grain strengthening. Microalloying with niobium and vanadium enhances the effect of controlled rolling, ultimately providing a fine austenite grain, and after a phase transformation, a fine ferrite grain, which is accompanied by a corresponding improvement in mechanical and cold-resistant properties.

With traditional rolling [17] microalloying additives increase the strength of the steel mainly due to dispersion hardening [18], and with controlled rolling or normalization (austenization with air cooling) – mainly by grain's grinding [19]. And the influence of the morphology of integral-phase layers [20] on the properties of a polycrystalline composite is covered in researches, but the process of plastic deformation [21] of micro alloyed steels with increased impact strength has not yet been fully studied and is of practical interest from the point of view of establishing the optimal temperature regime for its implementation [22].

The main raw material for the production of car wheel rims is sheet steel produced using plastic deformation methods. The proposed micro alloyed 10HFTBch steel is experimental and has not been put into mass production. This is related to the high cost of performing full-scale experiments to work out the technological modes of the proposed steel's plastic deformation to obtain a steel sheet. Therefore, simulation modeling of these processes comes to the fore. Modeling the process to establish the optimal temperatures for performing plastic deformation of a sample of the proposed micro alloyed steel will not only significantly reduce financial investments in the development of the technological process of sheet rolling, but will also speed up the process of introducing the development into production with the subsequent possibility of promptly influencing the expansion of the products' range produced from the proposed steel.

2. Materials and Methods

To study chemical reactions and phase transformations in the researched steels, occurring with the release or absorption of heat, the method of thermogravimetric analysis was applied using a Q-1500 derivatograph. To implement the modeling process, a Gleeble 3800 metallurgical process simulator, a DIL 805A/D dilatometer, and a «Setaram» plastometer were used.

The phase composition of the structural components and nonmetallic inclusions was studied by the energy-dispersive PCMA method on a JEOL JSN-6360LA raster electron microscope equipped with a JED-2300 X-ray microanalysis system.

According to the given task, experimental melting of micro alloyed steel was performed in an induction furnace with a crucible capacity of 150 kg. Melting parameters: power from the thyristor converter – 320 kW, pouring temperature of the test sample –1660 °C, the temperature was controlled by immersible W-Mo thermocouple with an accuracy of ± 10°C. Modifiers in the form of cylindrical briquettes were introduced into the melt mass after melting the charge with mechanical mixing. The duration of the melt after modifications was from 1 to 3 minutes, depending on the amount of modifier introduced. During the melting, technological samples for determination of chemical composition were selected by spectral method. Cylindrical samples with a diameter of 10 mm and length of 12 mm were received after smelting and casting, with the following mechanical characteristics of the received samples: tensile strength – 520 MPa, yield strength – 450 MPa.

3. Experimental Studies

The study of the obtained sample of steel of the 10HFTBch type by the PCMA method was carried out using a focused high-energy electron beam, which emerges from the electron gun of the microscope, is accelerated by high voltage, and is shown in Fig. 1. When hitting a sample, some of the electrons scatter, depending on the atomic number of the element and its environment in the crystal structure, and some excite the atoms of the object's substance, causing the emission of characteristic emitting. The advantage of this method is that by analyzing the energy spectrum of the emitted X-ray radiation arising from the interaction of an electron beam and atoms of a sample of the resulting steel, using an electron microscope detector, it additionally becomes possible to study its composition as well [23].

The change in the physico-mechanical properties of the sample during thermoplastic processing is a consequence of a significant restructuring of the micro- and mesostructure of the material. It is impossible to describe such processes without studying and creating appropriate models that explicitly take into account the physical causes of the evolution of the material microstructure under large deformations. Considerable attention in physical theories is given to the modification of hardening laws in connection with new experimental data obtained using high-resolution equipment and with obtaining experimental hardening curves for large plastic deformations by the plastometry method.

The dilatometric method was chosen for constructing thermokinetic diagrams. To implement the process, a DIL 805A/D dilatometer with a plastometer attachment was used. DIL 805A/D is a special dilatometer designed to determine expansion parameters under deformation conditions. Its distinguishing feature is the ability to operate at very high heating and cooling rates. This equipment has a built-in processor system that controls the operation of the generator, hydraulic system, measurement recording, gas supply, vacuum installation and security system. The dilatometer DIL 805A/D has the following main specifications:

• maximum compression force	20 кН;
• strain rate	0.001-20,0 с$^{-1}$;
• maximum tensile force	100 кН;
• maximum temperature	1500 °C;
• heating rate	up to 4000 °C/s;
• heating method	inductive

Hot steel tests were carried out on a modern Gleeble 3800 plastometer and a dilatometer. Working parameters of the plastometer:

– temperature of the test – 20-1700 °C;
– punch speed – up to 2000 mm/s;
– degree of logarithmic deformation – ε_{com} =0.01-1.2; ε_{str} =0.01-0.15.

Model DIL 805A/D can work as a cooling and deforming dilatometer. When working with a cooling dilatometer, a cylindrical sample is inductively heated to a given temperature, and then sequentially cooled according to various (linear or exponential) schemes. Phase transformations that occur during cooling or in the isothermal regime are determined by the change in length. The beginning and end of the transformation determine the area of existence of ferrite, carbides, graphites, pearlites, bainite, martensite, and other phases.

In the study on a plastometer, samples with a diameter of d=10 mm and a height of h=12 mm were placed in a chamber, inside which air was pumped out and a vacuum was created to exclude metal oxidation. At certain intervals during loading, the yield stress and logarithmic strain were recorded. Table 1 presents the sampling parameters and limiting temperatures for thermomechanical testing of samples. The maximum heating of the central part of the studied samples, measured using thermocouples, at the moment of hot deformation was 952°C.

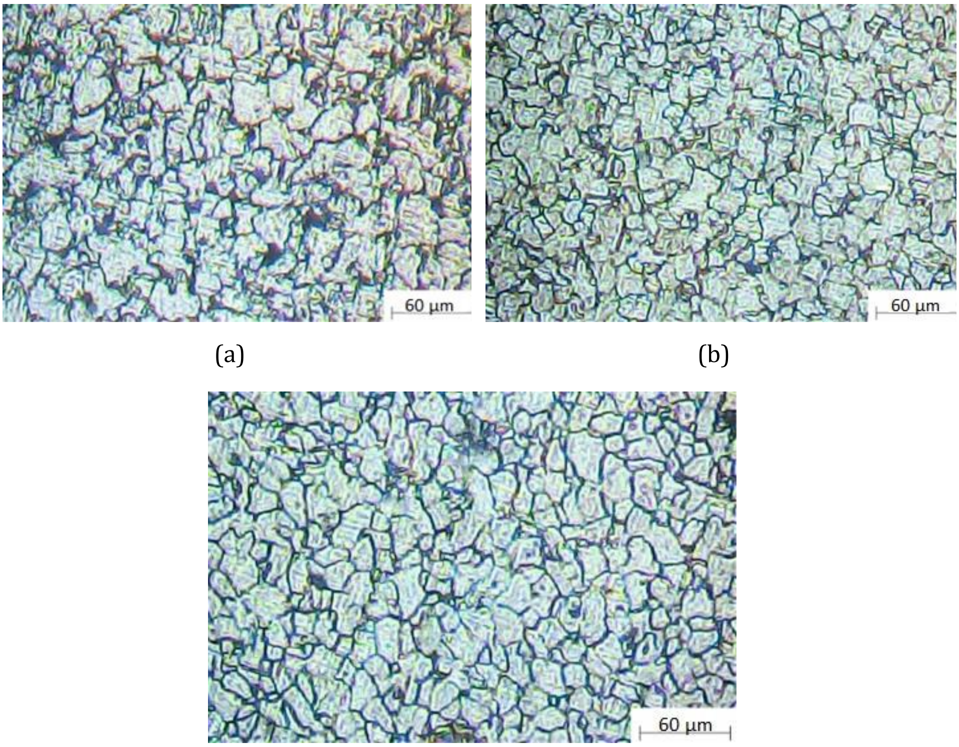
Table 1. Sampling parameters and limiting temperatures for testing samples

Samples	1	2	3	4	5
Temperature, °C	770	800	850	900	950
Strain rate, s^{-1}	100				
Degree of deformation, ln ε	0.01-1.2				

To predict the formation of the structure during thermomechanical treatment of low-alloy steel 10HFTBch, the features of phase transformations during continuous cooling after plastic deformation in the austenitic region below the recrystallization temperature were studied. To do this, the sample in the as-delivered state was heated to a temperature of 950 °C and plastically deformed by 30%. Next, the sample was cooled to 20°C and, in order to analyze the effect of plastic deformation on the formation of the structure, it was reheated to 950°C.

4. Results and Discussion

It has been established that the plasticity of the base metal and welded joints of two-phase steels of the 10HFTBch type used for wheel rims of vehicles is greatly affected by the hardening effect [24] caused by the appearance of quenching structures [25]. The initial structure of the studied steel can also change depending on the ratio of austenite-forming (C, N, Mn) [26] and ferrite-forming (Cr, Ti, V, Nb, Si) [27] elements [28], which is shown in Fig. 1.



(a) (b)

(c)

Fig. 1. The microstructure of undeformed steels of various compositions after hot deformation and heat treatment at 900 °C: a – lower, b – medium, c – upper value of the content of alloying elements

The main reason for the reduced plasticity of open cast low-carbon steels is the presence of a two-phase ferrite-martensite structure. At the same time, dispersed particles of chromium, vanadium, and titanium carbonitrides, while inhibiting the growth of ferrite and austenite grains during heat treatment, can significantly increase strength by means of dispersion strengthening.

The results of research and analysis of the structure of an undeformed 10HFTBch steel sample at various cooling rates are summarized and presented in the form of a thermokinetic diagram and are shown in Fig. 2. Under the cooling curves there are figures characterizing the average cooling rate (V, °C/s) in the temperature range from 950 to 350 °C. Analysis of the transformation shows that the $\gamma \rightarrow \alpha$ transformation begins with the release of free ferrite for all the cooling rates studied. Pearlite transformation occurs at a cooling rate of 3 °C/s at temperatures ranging from 600 to 700 °C. Cooling at a rate of 3°C/s leads to the formation of a ferrite-pearlite structure consisting of 75% ferrite grains with an average size of 20 μm. Increasing the cooling rate to 20 °C/s leads to the formation of a ferrite structure, the proportion of which decreases to 50%, the size of the ferrite grain is 8 μm. A further increase in the cooling rate to 50 °C/s leads to a refinement of the structure (the size of the ferrite grain is 5 μm) and a decrease in the proportion of ferrite to 40%.

The results of studying the structure of a deformed sample of 10HFTBch steel at various cooling rates are presented in the form of a thermokinetic diagram and are shown in Fig. 3. An analysis of the transformation shows that the plastic deformation of steel at a temperature of 950 °C has practically no effect on the temperatures at which the phase transformation of austenite into ferrite begins during continuous cooling. Only after cooling at a rate in the range from 1 to 10 °C/s hot plastic deformation affects the increase in the ferrite transformation temperature by an average of 18 °C. Preliminary plastic deformation, in the austenitic region below the recrystallization temperature, has a stronger effect on pearlite transformation at low cooling rates in the range from 0,5 to 10 °C/s.

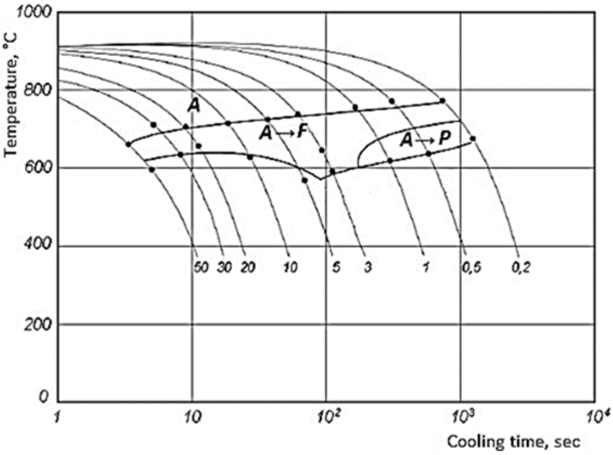


Fig. 2. Thermokinetic diagram of austenite decomposition of steel 10HFTBch during continuous cooling in a wide range of speeds: A – austenite, F – ferrite, P – perlite

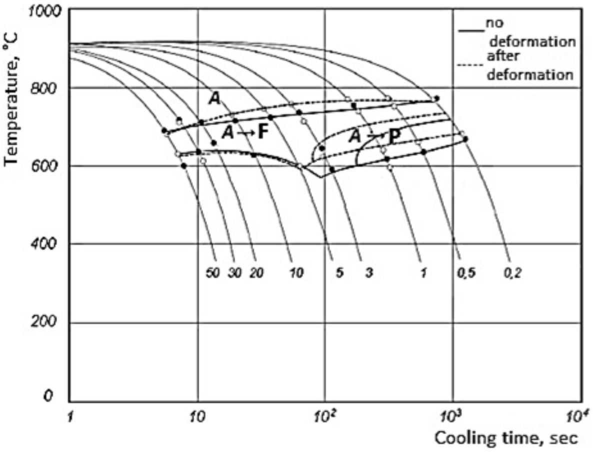


Fig. 3. Thermokinetic diagram of austenite decomposition of steel 10HFTBch during continuous cooling after plastic deformation: A – austenite, F – ferrite, P – perlite

The light dots in the diagram correspond to the onset of austenite transformation after deformation, the black dots – without deformation. The dotted curve in the diagram is the line of transformations after plastic deformation.

Thus, plastic deformation increases the speed range of existence of pearlite transformation. After deformation of 30% at 950°C, pearlite transformation begins at a cooling rate of 5°C/s, and without deformation, at 2°C/s. Also, hot plastic deformation leads to structure refinement.

5. Conclusions

The main reason for the reduced ductility of open-melted low-carbon steels is the presence of a two-phase ferrite-martensite structure. One of the most rational ways to refine the austenite grain, and, consequently, the ferrite formed from it, is to control the parameters of plastic deformation during strip rolling, namely a strictly regulated deformation mode and a low temperature at the end of the rolling. The results of the studies show that uneven deformation during hot rolling can significantly influence the process of structure formation at the time of forming. Moreover, the grain size non-homogeneity can either increase or decrease under the influence of temperature development in the zone of intense deformation.

It has been established that with an appropriate choice of modes of thermoplastic deformation of steel of the same composition, increased strength or plastic properties can be obtained, which makes it possible to control the production of a given set of properties, and in the future, from steel of a unified chemical composition, to obtain either sheet metal of different strength category, or sheet products with different viscous-plastic properties, depending on the operating conditions.

Hot plastic deformation, which intensifies diffusion transformations, accelerates the excretion of pearlite and causes structure refinement during subsequent cooling due to an increase in the centers of nucleation of a new phase. Such a phase-forming process leads to the formation of a fine-grained dispersed two-phase structure consisting of ferrite with a high dislocation density and pearlite. An analysis of the course of this process made it possible to choose the temperature range of hot deformation for micro alloyed steel 10HFTBch, which is from 850 to 900 °C.

Abbreviations and Nomenclature

KCU, impact strength, (MJ/m^2), ε_{com}, degree of logarithmic deformation (compression); ε_{str}, degree of logarithmic deformation (stretching); d, sample diameter (mm); h, sample height (mm); V, average cooling rate, (°C/s)

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