ISSN 2307–3489 (Print), ISSN 2307–6666 (Online)

Наука та прогрес транспорту, 2024, № 2 (106)

МАТЕРІАЛОЗНАВСТВО

UDC 669.141.24:621.785.4

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Influence of the Isothermal Transformation Temperature on the Structure and Properties of Low-Carbon Steel

Purpose. The study is aimed at evaluating the effect of the isothermal transformation temperature on the structure and properties of low-carbon steel. **Methodology.** The material for the study was a 3 mm diameter wire made of mild steel with the following chemical composition: 0.21% C, 0.47% Mn, 1.2% Si, 0.1% Cr, 0.03% S, 0.012% P. The 0.3 m long wire samples were subjected to austenitizing at 920 °C for 8...9 min, after which they were held isothermally for 11 min at temperatures of 650...200 °C, followed by cooling in air. The strength, plastic properties, and strain hardening coefficient were determined from the analysis of tensile curves**. Findings.** It was found that a decrease in the temperature of isothermal transformation, starting from 450...400 °C, increases the amount of Widmannstätten ferrite due to the disappearance of polyhedral ferrite grains. At the same time, the number of areas with locally located dispersed cementite particles similar to pearlite colonies increases, and bainite crystals appear. Against the background of a sharp decrease in the strain hardening coefficient in the range of 450...400 °C, the ability of the bainite phase to undergo plastic deformation should be considered one of the reasons for the delay in density reduction. **Originality.** The effect of steel hardening with a decrease in the pearlite transformation temperature is based on the grinding of ferrite grains, an increase in the amount of Widmannstätten ferrite, and the dispersion of pearlite colonies. The strengthening effect of steel with a bainite structure is based on an increase in the degree of supersaturation of the solid solution with carbon atoms and dispersion hardening by particles of the carbide phase. **Practical value.** The optimal structural state of steel intended for the manufacture of such critical elements as a support beam, railroad car bogie, etc. is a mixture of phase components with different dispersion and morphology, and their quantitative ratio is determined by the operating conditions of a particular product.

Keywords: low-carbon steel; austenite; ferrite; temperature; isothermal transformation; dislocation; recrystallization; yield strength

Introduction

For the manufacture of certain supporting elements of railway cars, such as a center beam, carriage bogie, etc. they use shaped rolled products from low-carbon steels [1]. It is believed that use of rolled products with increased strength properties is a key to increasing reliability at operation of the railway cars for various purposes.

doi: https://doi.org/10.15802/stp2024/307344

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Compared to the structure of low-carbon steel after hot plastic deformation, use of thermal strengthening in flow of a rolling mill is accompanied by qualitative changes at structural state and the corresponding set of properties.

Proportional to cross-section of the rolled product, the difficulty achieving a critical cooling rate causes to formation gradient of structures, starting from the surface of intensive heat removal [3]. Considering process formation of a thermally strengthened surface layer in rolled steel, several mutually dependent factors are discovered that determine mechanism of austenite transformation during steel cooling [13].

One of them is ability of ferrite to inherit chemical elements that are dissolved in austenite. This phenomenon can have a certain influence on the mechanism of austenite transformation [14]. For low-carbon steel, a fairly narrow temperature range transition from the shear mechanism of austenite transformation to intermediate one is sensitive to minor changes in cooling conditions [4]. Thus, low stability of low-carbon steel austenite during cooling [3, 5] and change in the activity of carbon atoms at inter phase during transformation process [14] can affect the transformation rate.

At same time, diffusion of carbon atoms in phase components of the steel should also change [13]. Based on this, a continuous decrease at cooling rate, as volumes of metal move away from surface of the rolled product, in its effect on the structure and properties, can be represented as an increase in the temperature at end of forced cooling. In this case, continuous change at dispersion and morphology phase components of the steel will correspond to gradient of temperature by forced cooling of the rolled product [7, 11].

Purpose

The purpose of the work was to assess influence temperature isothermal transformation on the structure and properties of low-carbon steel.

Methodology

The material for study was a wire with a diameter of 3 mm, made of low-carbon steel, with a concentration of chemical elements: 0.21% *C*, 0.47% *Mn*, 1,2% *Si*, 0.1% *Cr*, 0.03% *S*, 0.012% *P*. Different structural states of steel were obtained after certain processing.

Wire samples 0.3 m long were subjected to austenitization at a temperature of 920 °C for 8…9 minutes. This was followed by isothermal holding for 11 minutes at temperatures of 650…200 °C and cooling on air. Heating of the samples to the austenitization temperature, isothermal holding of the metal was carried out in molten mixtures of various salts.

The preparation of objects and study of the microstructure were carried out using light and electron microscopy techniques [2]. Strength, plastic properties and strain hardening coefficient (*n*) were determined from the analysis of tensile curves [10, 12].

Findings

The process forming structure of the thermally strengthened steel after completion of hot deformation can be represented at form of an isothermal transformation of austenite at temperature of the end accelerated cooling.

At temperature range until the minimum stability of austenite is achieved, the diffusion transformation mechanism will determine morphology and dispersity structural components of the steel under study. Thus, at transformation temperature range starting from 650 °C, the formed structure consists of sections similar to Widmanstatten ferrite (Fig. 1, *a*), polyhedral ferrite grains and pearlite colonies of certain dispersion.

It should be expected that at temperatures isothermal transformation of the austenite by the diffusion mechanism, formation of the structure is determined by a quantitative relationship of the structural components and their dispersity, without qualitative changes in the phase composition of the steel. Indeed, with a decrease at isothermal transformation temperature to 600 °C, against the background dispersion of structural components, a progressive decrease at number of polyhedral ferrite grains is observed (Fig. 1, *b*). At the same time, proportion of the Widmanstätten ferrite and pearlite colonies of increased dispersion increases (Fig. 1, *c*).

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a

b

c

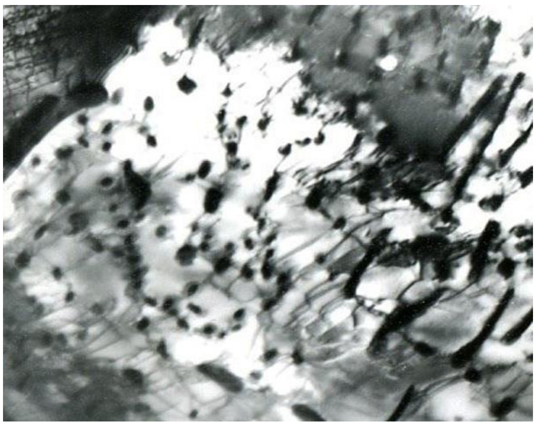


Fig. 1. Structure of the low-carbon steel after isothermal transformation at temperatures of 650 °C (*a*) and 600 °C (*b*, *c*). Magnification:
a – 1000; *b* – 6000; *c* – 10000

The absence of qualitative changes in the structure of steel when the transformation temperature is reduced to 600 °C is explained by the insufficient stability of the austenite during cooling [3, 12], which is similar to the effect of reducing the carbon concentration in steel. A further decrease at temperature isothermal transformation of the austenite to range of 500…400 °C, against the background of continued dispersion of the structural components, the first qualitative changes in the phase components of the steel are already observed (Fig. 2, *a*).

With a decrease at average grain size of the polyhedral ferrite and its volume fraction, there is a simultaneous increase at amount of Widmanstätten ferrite with a beginning of a change in its morphology (Fig. 2, *b*). This situation is more clearly illustrated structure of the steel after isothermal transformation of the austenite at 400 °C (Fig. 2, *c*).

Thus, number individual plates of the Widmanstätten ferrite that are formed at a temperature of 500 °C (Fig. 2, *a*) become significantly smaller at 400 °C. In proportion to decrease at transformation temperature, dispersion of compactly located cementite particles also increases (Fig. 2, *d*).

Moreover, Widmanstätten ferrite begins to form at form of two varieties: branched formations and in the form of a package of plates (Fig. 2, *c*). These changes at structure should be considered as an approach to the temperatures of a possible change at mechanism of the austenite transformation [3, 11]. Thus, when the isothermal transformation temperature decreases below 400 °C, qualitative changes at structural state of the steel should be expected.

The formed structure after isothermal transformation at temperatures of 300 and 200 °C confirms these expectations. Considering that even a slight decrease at isothermal transformation temperature, starting from 350 °C, leads to a rapid decrease at number of the polyhedral ferrite grains [3, 12], at 300 °C it is quite difficult to detect them (Fig. 3, *a*).

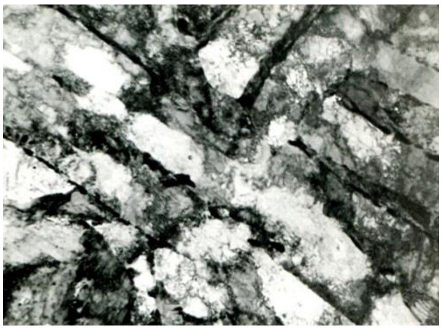
At the same time, areas resembling highly dispersed pearlite colonies are found (Fig. 3, *b*), and the appearance volumes of metal with a bainite structure (Fig. 3, *c*) should be considered as evidence of its qualitative changes.

After reducing isothermal transformation temperature to 200 °C, no signs of austenite transformation by a shear mechanism were found in the steel structure (Fig. 4).

doi: https://doi.org/10.15802/stp2024/307344

a

b



c

d

Fig. 2. The structure of low-carbon steel after isothermal transformation at temperatures of 500 °C (*a*, *b*) and 400 °C (*c*, *d*). Magnification: *a*, *c* – 1000; *b* – 6000; *d* – 14000

a

b

c

Fig. 3. Structure of the low-carbon steel after isothermal transformation at temperature of 300 °C. Magnification: *a* – 1000; *b*, *c* – 18000

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a

b

c

Fig. 4. Structure of low-carbon steel after isothermal transformation at a temperature of 200 °C. Magnification:
a – 1000; *b*, *c* – 18000

The structure consists of bainite crystals (Fig. 4, *a, b*) and fine cementite particles with a local arrangement, similar to the eutectoid colony (Fig. 4, *c*). One of the reasons for the absence of martensite may be a low stability of the austenite in low-carbon steel due to the high temperature of the onset martensite transformation (M_S). M_S can be estimated using A. Popov's relation:

$$M_S=520-320\,(\%\,C)-50\,(\%\,Mn)-30\,(\%\,Cr)-$$

$$-20\,(\%\,\mathrm{Ni}+\%\,\mathrm{Mo})-5\,(\%\,Si+\%\,Cu),\quad(1)$$

where $\%\,C$ – is designation concentration of the carbon and other chemical elements, showed a value of 423 °C, which coincides with a known experimental data (420…400 °C) [3, 11].

Based on this, preventing intermediate decomposition of austenite during cooling and isothermal holding at 200 °C is a rather difficult task. As a result of partial decomposition of austenite, in proportion to degree of its super cooling, starting from temperatures order of 400 °C, a gradual increase at volume fraction of the bainite phase in the steel structure occurs. In general, it can be assumed that at process of isothermal cooling low-carbon steel to temperatures order M_S, qualitatively similar structures are formed, differing only in the ratio of structural components and their dispersion.

When the temperature decreases below M_S, a gradual replacement products of austenite transformation by the diffusion mechanism with an intermediate one occurs [8]. The observed transformation of the steel structure depending on the temperature isothermal transformation of austenite corresponds to a very definite nature change in mechanical properties (Fig. 5).

In view of the fact that range changes in the relative narrowing is 73…75%, uniform elongation (δ_P) was used as a characteristic plasticity of the steel.

From analysis of the presented dependences it follows that an increase at transformation temperature is accompanied by a quite expected decrease in strength characteristics and increase ductility. At the same time, ability of the metal to strain hardening changes according to a more complex dependence (Fig. 5, *c*).

In general, the observed violations monotonic nature of changes in properties indicate to need for conditionally dividing curves into separate sections: *I* (650…500 °C), *II* (450…350 °C), *III* (300…200 °C), with qualitatively others character behavior.

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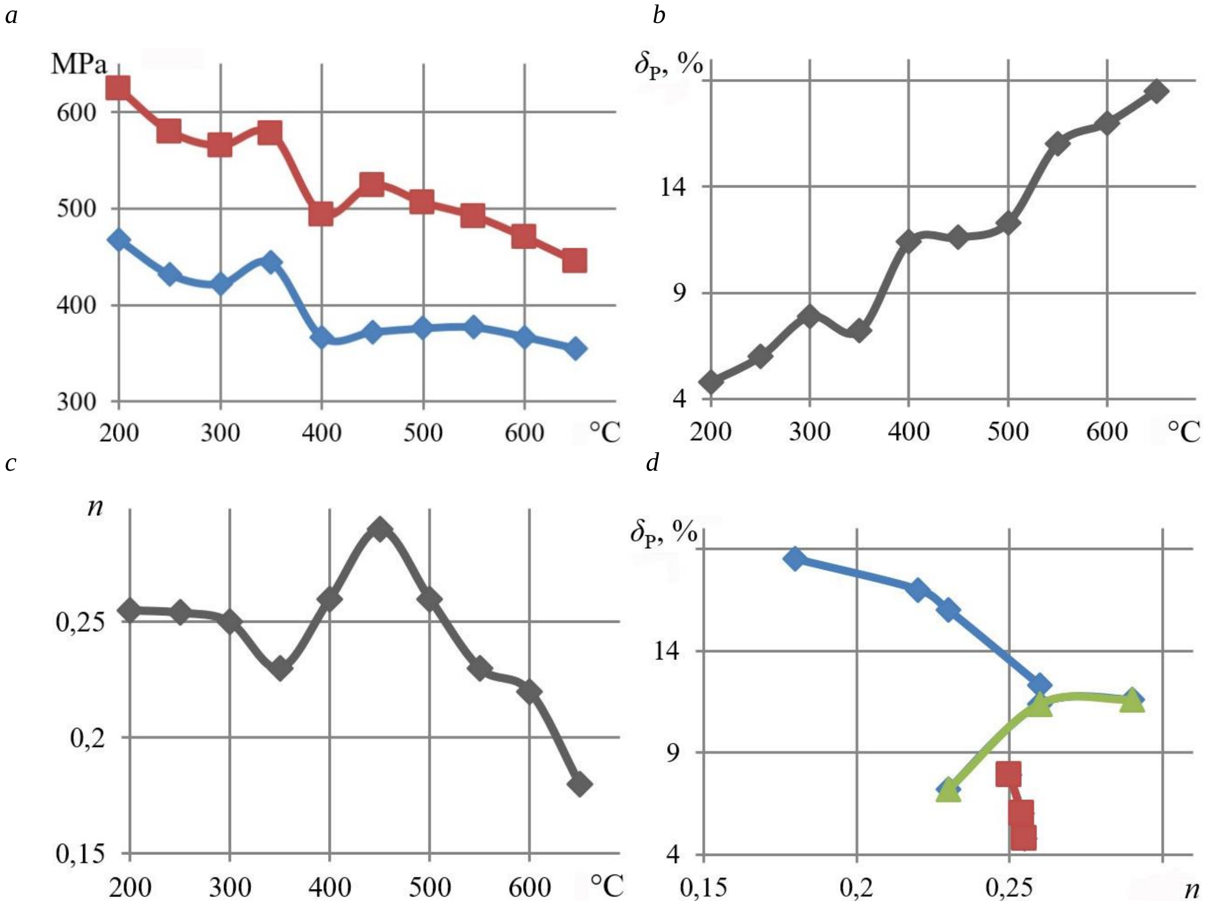

d)

Fig. 5. Influence temperature isothermal transformation of the austenite on yield strength (♦), strength (■) – (*a*), uniform elongation – (*b*), strain hardening coefficient (*c*) and the mutual change in *n* - δ_P (for sections of temperature: *I* – ♦; *II* – ▲; *III* – ■) (*d*)

For section *I* (Fig. 5), starting from 650 °C, a gradual decrease at isothermal transformation temperature to 500…450 °C is accompanied by a monotonic decrease in δ_P, an increase in strength characteristics (yield stress – σ_y and strength stress – σ_S) and ability of the metal to strain hardening (*n*).

The given nature change in mechanical properties is explained by the evolution of the structure and phase composition of steel. Indeed, as follows from analysis of the microstructure (Fig. 1), when isothermal transformation temperature decreases from 650…600 °C (Fig. 1) to 500 °C (Fig. 2, *a*, *b*), there are practically no qualitative changes structure. The phase composition remains largely constant and only quantitative ratio and dispersion of the structural components changes.

In general, increase in strength properties is due to increase in the amount of Widmanstätten ferrite, a decrease grain size of polyhedral ferrite (d_P) and thickness ferrite gap of the pearlite colony (λ) [3, 12]. If we take into account that according to stoichiometry for the steel under study, the amount of pearlite component does not exceed 30%, for temperatures of 650…600 °C, d_P should be taken as the main structural element, although presence of Widmanstätten ferrite may distort its effect.

On other hand, when assessing the role of d_P, it should be taken into account that only at absence substructural components and super saturation of the ferrite with carbon atoms, the main structural element of low-carbon steel is a ferrite grain size.

In this case, strain hardening coefficient and plasticity of steel are directly proportional to each other [9]. For a pearlite colony, a qualitatively dif-

doi: https://doi.org/10.15802/stp2024/307344

ferent relationship is observed: decrease in λ promotes an increase ductility of eutectoid steel with a decrease in n [12]. Thus, when the austenite transformation temperature changes from 650 to 500 °C, ferrite grain refinement, an increase in the amount of Widmanstätten ferrite and its super saturation with carbon atoms are the main factors reducing δ_P. Dispersing pearlite colonies, on the contrary, should increase δ_P.

However, the amount of perlite is not enough to have an effective effect and the end result is a decrease in δ_P. In this case, the strain hardening coefficient and d_P are inversely proportional to each other (Fig. 5, *d*). A decrease at temperature of the isothermal transformation austenite in section (*II*) is accompanied, similarly to (*I*), by an increase in strength and a decrease in plastic characteristics. The exception is n.

The observed nature of the n dependence indicates the appearance of changes in the steel structure that can influence development of strain hardening processes (Fig. 5, *c*). Indeed, as follows from analysis of the microstructure (Fig. 2, *c*), decrease at isothermal transformation temperature starting from 450…400 °C increases amount of Widmanstätten ferrite due to the disappearance of polyhedral ferrite grains. At the same time, the number of areas with locally located dispersed cementite particles, similar to pearlite colonies, increases.

Moreover, as follows from results of study [7, 11], for steel of a similar composition after isothermal transformation of austenite at 450…400 °C, volumes are found in the structure that are similar in appearance to bainite crystals. Based on this, it can be assumed that appearance of the bainite phase is one of reasons for qualitative changes in the dependencies of steel properties. Against the background of a sharp decrease at strain hardening coefficient in the range of 450…400 °C, the ability of the bainite phase to undergo plastic deformation [3, 13] should be considered as one of the reasons for delay in reducing δ_P.

On other hand, at a temperature of 350 °C, the almost complete disappearance of Widmanstätten ferrite and increase at amount of bainite phase, dispersion particles of cementite (Fig. 3, *c*) and decrease at number of pearlite colonies (Fig. 3, *b*), together lead to a sharp decrease at ductility of steel. As an additional source of reduction in steel ductility, differences in the ability to strain hardening of bainite and pearlite should be considered, which is confirmed by the $n - \delta_P$ ratio (Fig. 5, *d*, designation ▲).

In section *III*, a decrease in temperature from 300 to 200 °C is accompanied by the formation bainite structure (Fig. 3, 4). In this case, the strain hardening coefficient remains practically unchanged (Fig. 5, *d*), which is confirmed by the equidistant arrangement of the curves σ_y and σ_S versus transformation temperature (Fig. 5, *a*).

The sharp decrease in steel ductility is due to the combined effect super saturation of the solid solution with carbon atoms during formation of bainite crystals [13, 14] (Fig. 3, *c* and 4, *b*) and dispersion strengthening from carbide phase particles (Fig. 4, *c*) [2, 6].

According results of the studies [2 ,5, 7], it is determined that steels with perlite structures after thermal strengthening, compared to martensite and beinite structures, have increased resistance against heating and cyclic loads.

On a basis of this, one of the directions determining optimal structural state of steel for manufacture of a particular product, should be mixture with a various ratio of phase components, taking into account the conditions of its operation.

Originality and practical value

The effect of steel strengthening with a decrease at pearlite transformation temperature is based on the refinement of the ferrite grains, an increase at amount of Widmanstätten ferrite, and dispersion of pearlite colonies. The strengthening effect at steel with bainite structure based on an increase degree of super saturation of the solid solution with carbon atoms and dispersion strengthening by carbide phase particles.

The directions determining optimal structural state of steel for manufacture backbone beam, wagon trolley, etc., should be mixture with various ratio of phase components, taking into account the conditions of its operation.

Conclusions

1. A change at mechanism of austenite transformation during isothermal cooling of the steel is accompanied by qualitative changes in structure and properties.

doi: https://doi.org/10.15802/stp2024/307344

2. The effect of steel strengthening with a decrease at pearlite transformation temperature is based on the refinement of the ferrite grains, an increase at amount of Widmanstätten ferrite, and dispersion of pearlite colonies.

3. The transition from the diffusion mechanism of austenite transformation to the intermediate one leads to the gradual replacement of Widmanstätten ferrite and pearlite colonies with bainite crystals. The strengthening effect in steel is based on an increase in the degree of super saturation of the solid solution with carbon atoms during the formation of bainite and dispersion strengthening by carbide phase particles.

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doi: https://doi.org/10.15802/stp2024/307344

ISSN 2307–3489 (Print), ISSN 2307–6666 (Online)

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Вплив температури ізотермічного перетворення на структуру і властивості низьковуглецевої сталі

Мета. Дослідження спрямовано на оцінку впливу температури ізотермічного перетворення на структуру та властивості низьковуглецевої сталі. **Методика.** Матеріалом для дослідження був дріт діаметром 3 мм, виготовлений із низьковуглецевої сталі з таким хімічним складом: 0,21 % C, 0,47 % Mn, 1,2 % Si, 0,1 % Cr, 0,03 % S, 0,012 % P. Зразки дроту довжиною 0,3 м піддавали аустенізації за температури 920 °С протягом 8…9 хв, після чого виконували ізотермічну витримку протягом 11 хв за температур 650…200 °С з подальшим охолодженням на повітрі. З аналізу кривих розтягу визначали міцність, пластичні властивості та коефіцієнт деформаційного зміцнення. **Результати**. Установлено, що зниження температури ізотермічного перетворення, починаючи з 450…400 °С, збільшує кількість фериту Відманштеттена за рахунок зникнення поліедричних феритових зерен. При цьому збільшується кількість ділянок із локально розташованими дисперсними частинками цементиту, схожими на колонії перліту, та з'являються кристали бейніту. На фоні різкого зниження коефіцієнта деформаційного зміцнення в діапазоні 450…400 °С однією з причин затримки зниження щільності слід вважати здатність бейнітної фази до пластичної деформації. **Наукова новизна.** Ефект зміцнення сталі зі зниженням температури перетворення перліту заснований на подрібненні зерен фериту, збільшенні кількості фериту Відманштеттена та дисперсії колоній перліту. Зміцнювальний ефект сталі зі структурою бейніту ґрунтується на підвищенні ступеня перенасичення твердого розчину атомами вуглецю та дисперсійного зміцнення частинками карбідної фази. **Практична значимість**. Оптимальний структурний стан сталі, призначеної для виготовлення таких відповідальних елементів, як опорна балка, візок вагона та ін., становить суміш фазових складових із різною дисперсністю та морфологією, а їх кількісне співвідношення визначають за умовами експлуатації конкретного виробу.

Ключові слова: низьковуглецева сталь; аустеніт; ферит; температура; ізотермічне перетворення; дислокація; рекристалізація; межа плинності

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Надійшла до редколегії: 29.02.2024
Прийнята до друку: 28.06.2024

doi: https://doi.org/10.15802/stp2024/307344