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INFLUENCE OF HOT PLASTIC DEFORMATION ON PROPERTIES OF THE CARBON STEEL

Purpose. Determination of the influence of hot plastic deformation degree on the set of carbon steel properties.

Methodology. Steel with 0.6 % carbon was used for the study. The steel structure corresponded to the state after compression at 1,240 °C. Mechanical properties were determined by the tensile curve, friction stress of the ferrite crystal lattice and resistance of interphase boundary pearlite to propagation of deformation were estimated.

Findings. Depending on the structural state of austenite, dispersion of pearlite colonies is accompanied by different rates of change in the properties of carbon steel. For pearlite formed from austenite after annealing, the strain hardening coefficient and maximum ductility are inversely proportional. For pearlite formed from austenite with preserved substructure after hot deformation, the strain hardening coefficient and maximum ductility are related through the proportional relationship.

Originality. Preservation of the substructure of hot-deformed austenite affects propagation deformation in pearlite of the steel. Against the background of decreasing friction stress of the ferrite crystal lattice, there is an increase in resistance of ferrite-cementite boundary of the pearlite to the spread of deformation.

Practical value. For carbon steels with a pearlite structures, the accelerated increase in ductility from maintaining the proportion of hot work hardening of the austenite will improve technology for manufacturing rolled products of large sections. When producing thermally strengthened rolled products, achieving a simultaneous increase in strength and plastic properties is ensured by increasing ability of metal to strain hardening.

Keywords: *carbon steel, austenite, pearlite, dislocation, strain hardening*

Introduction. Under certain parameters of hot pressing of the carbon steel, formation of austenite structure is determined by ratio of the development of two competing processes: strain hardening and softening [1, 2]. At high temperatures of plastic deformation, dominance of softening processes in austenite over strain hardening can minimize effects of plastic deformation on steel structure formation after cooling. Based on this, a set of properties of the carbon steel after completion of hot deformation of the rolled product will hardly differ from the structure state formed as a result of cooling metal after annealing [3, 4].

On the other hand, inhibition of softening processes in hot deformed austenite can be considered as one of the means of changing complex of steel properties due to the influence on austenite decay during cooling. On the basis of this, increase in properties of the carbon steel should be expected from preservation of a portion of hot strain hardening austenite during formation of the pearlite colony [5]. Taking into account the fact that formation of the structure of the carbon steel in all elements of a railway wheel after completion of the last operation of forming, regardless of cooling conditions of the wheel, takes place according to the diffusion mechanism, the state of austenite acquires an exceptionally high value. It should be assumed that preservation of a portion of the hot-deformed austenite substructure will allow, due to effect on the pearlite transformation, hoping for an increasing properties of carbon steel of the railway wheel.

State of problem. Alternation of hot plastic deformation of a railway wheel blank with a technological pause between pressings determines development of structural transformations in austenite of the carbon steel. The beginning of the development of recrystallization at austenite by mechanism of the movement grain boundaries with a large angles of disorientation [6, 7] implies the need to accumulate a certain density of the dislocations. At the same time, there is a qualitatively different mechanism of structure transformation of the austenite, which is based on recombination of the dislocation structure [8].

In this case, final structure of austenite will be determined by the nature of movement of both individual dislocations and their clusters [4, 6]. Development of structural transformations according to the specified mechanisms leads to a qualitatively different structural state, which, in turn, will acquire a corresponding imprint on complex of the properties. Indeed, if formation of a structure in hot deformed austenite by the mechanism of movement boundaries of grains with a large angles of disorientation leads to an almost complete cleaning of internal volume of the grain from unbound dislocations, then recombination of dislocations, on the contrary, implies appearance of additional boundaries in the middle of the grain itself [8].

At the same time, in terms of their own build, indicated boundaries are largely reminiscent of subboundaries with a lower self-energy. Under conditions of hot pressing of a railway wheel billet, when the growth rate of the dislocation density is relatively small, recombination of dislocations should not lead to their noticeable annihilation.

On the other hand, during sequential movement of dislocations from internal volumes towards the sub-boundaries, not only the partial cleaning of the austenite sub-grains from unbonded dislocations, but also increase in the angle of disorientation between the neighboring sub-grains. Development formation of the structure according to a specified mechanism is accompanied by an increase in softening effect of the hot deformed carbon steel [1, 9]. After completion of the hot plastic deformation, upon subsequent cooling, the features of the austenite structure should acquire a certain imprint on formation of a pearlite colony of the carbon steel. In addition to the formation of subboundaries in the middle of the grains, with differences in their own structure, from ordinary grain boundaries to subgrains, there is an assumption about peculiarities of their dislocation structure [8, 10].

Given that the size of the micro volumes and the disorientation angles between them depends on the density of dislocations introduced into the metal during hot pressing [1, 11], formation of internal interfaces in the austenite grain should be accompanied by the occurrence of additional twisting moments [8]. Such a mechanism involves the mutual rearrangement of crystal lattices between adjacent fragments at angles that will be proportional to the accumulated density of dislocations. The specified distortions of the crystal lattice of the austenite should be sufficient to violate conditions for the formation of a pearlite colony, at cooling after full annealing [9, 12]. As a result, the size fragment at austenite grain should influence the growth of the pearlite colony.

The existence of such a mechanism of the structure transformations is confirmed by the results [9], according to which hot plastic deformation of austenite will contribute to an increased number of the pearlite colonies. The expected sensitivity of pearlite colony formation processes to the structural state of austenite is confirmed by the influence on structural transformations during hardening of the steel [7, 10].

Based on this, determination of the development mechanism of the austenite structure formation processes during hot pressing acquires a certain importance for obtaining optimal structural state of steel before its final cooling [7, 13].

Purpose. Determination of influence of the degree of hot plastic deformation on the set of carbon steel properties.

Methodology. Carbon steel of a railway wheel with 0.6 % carbon and the amount of chemical elements within the standard composition of steel 60 was used for the research.

A different degree of hot plastic deformation of austenite was like manner conditions of sequential pressing of the railway wheel blank in the line of the wheel rolling mill. The size of the austenite grain and the thickness of the ferrite pro-layer of the pearlite colony were determined by methods of quantitative metallographic.

The mechanical properties of the steel (σ_y – yield stress; σ_s – strength stress; δ – relative elongation; ψ – relative narrowing) and coefficient of strain hardening (n) were determined by stretching the samples, under conditions of "Instron" type testing machine, at room temperature and strain rate of 10^{-3} s^{-1}. On the deformation curve (Fig. 1), point A corresponds to the yield stress, point E – to the stress strength, and point B corresponds to stress irreversible movement of dislocations.

The section AC corresponds to the area of discontinuous flow, and CE – to the area of uniform strain hardening [14]. Deformation (ε_n) corresponds to the moment of violation on the curve of directly proportional ratio $\lg\sigma - \lg\varepsilon$ (point D, Fig. 1). At stresses higher than point D, a breakdown of the uniform distribution of dislocations into structures with a certain periodicity occurs. According to absence on the deformation curves of carbon steel of the railway wheels after hot plastic deformation, the section of discontinuous flow, n was determined by the ratio

$$\sigma = K \cdot \varepsilon^n, \tag{1}$$

where K is the proportionality factor. After logarithmic transformation by (1), according to geometric calculations (Fig. 1), the value of n on the section CD was determined

$$n = \operatorname{tg}\alpha = \Delta\lg\sigma/\Delta\lg\varepsilon. \tag{2}$$

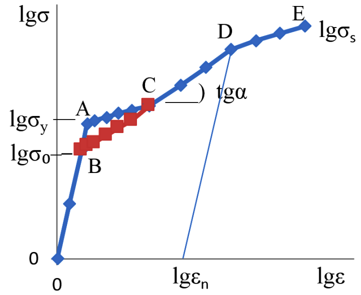

Fig. 1. General view of the deformation curve at logarithmic coordinates ($\lg\sigma - \lg\varepsilon$)

The nature of the change in the strain hardening coefficient makes it possible to determine evolution of structural transformations during plastic deformation of a metallic material and corresponding set of the properties [14, 15].

Based on the analysis of influence of the pearlite colony dispersion on strength characteristics, frictional stress of the ferrite crystal lattice and resistance of the inter phase boundary in pearlite to the propagation of the plastic deformation were determined.

Results and their discussion. Compared with the structure of the pearlite colony of the carbon steel after annealing (Fig. 2, *a*), hot plastic deformation acquires a certain influence on its morphology (Fig. 2, *b*). One of the explanations above changes in the structure of the pearlite colony is based on the possibility of preserving a portion of hot plastic deformation of the austenite and its effect on the pearlite transformation during cooling of the carbon steel [9, 16].

Indeed, based on the analysis of the above structures, it can be determined that the pearlite colony at steel after hot pressing has a less regular structure compared to the pearlite formed in the metal after annealing. Considering qualitatively different nature of participation of the lamellar and globular cementite at development of cold plastic deformation process-

a

b

Fig. 2. The structure of the pearlite colony of the carbon steel after annealing (a) and after hot deformation at a temperature of 1,240 °C (b). Magnification: a – 800; b – 1,200 × 2.5

es, their quantitative ratio in the volume of metal can have a significant impact on the overall complex of steel properties. Formally, it should be recognized that micro volumes of metal with the plate form of cementite, due to its participation in plastic deformation, will lead to the achievement of the increased level of the strength and plasticity characteristics.

For micro volumes of steel with a globular shape of cementite, they lead to another ratio between the mechanical properties [17, 18]. Based on this, when analyzing the mechanism of the development of strain hardening processes in steel with such a structure, one should expect difficulties in determining the main element of the structure and its size.

Taking into account the additive character of the contribution of components of the structure to overall level of the strength properties, the given uncertainty can be resolved by taking into account the percentage of pearlite with a regular structure and plots with a compact arrangement of the globular cementite particles. More often, the coefficient is used that clarifies the value of the thickness layer of the ferrite at pearlite colony with a regular structure, for the presence of a certain proportion of the globular cementite in the structure of the carbon steel. Under conditions of hot deformation, the average value of the thickness of the ferrite layer of the pearlite colony (λ) from the degree of plastic deformation (ε) is obeyed to an inversely proportional relationship (Fig. 3, *a*).

Analysis of changes in strength properties, plastic characteristics, and strain hardening coefficient depending on the degree of hot plastic deformation (Fig. 4) indicates possibility of existence of a certain correlation of relationship with λ.

In fact, the influence of the value of *ε* on the properties of steel should be considered as confirmation, at least qualitative, that pearlite structure corresponds to the structural state of the hot deformed austenite.

On the other hand, a relatively low rate of the deformation under conditions of crimping a railway wheel blank at state line and high rate development processes of diffusion determine increased mobility of the austenite grain boundaries during development of the recrystallization processes.

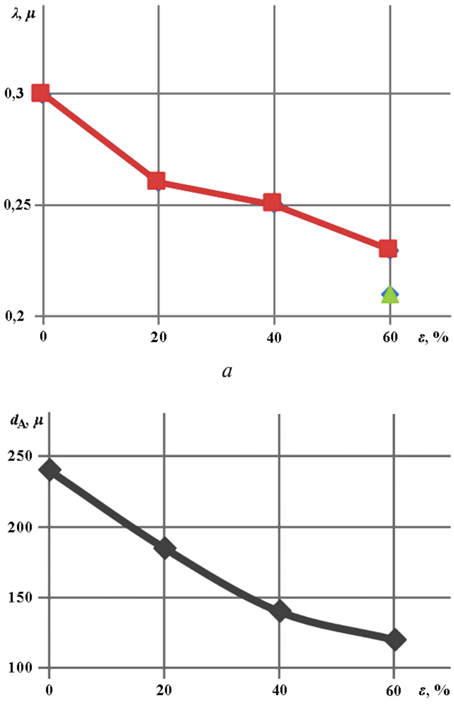

Fig. 3. The effect of ε at a temperature of 1,240 °C on λ of the steel with 0.6 % C after hot plastic deformation (■), 0.57 % C after hot plastic deformation 60 % and cooling at a rate of 2 °C/s [9] *(▲) – (a) and austenite grain size (♦) (b)*

Thus, according to [9, 19], the temperature of a plastic deformation of 1,240 °C should be sufficient for almost complete completion of the recrystallization processes of "insitu" in austenite.

However, the extreme nature of dependence of properties of strength and relative narrowing on the amount of hot deformation (Fig. 4) indicate existence of at least one more factor, in addition to the size of the austenite grain, affecting the specified characteristics. Such a factor can be the partial preservation of substructure elements formed during hot deformation of the austenite. In this case, one should expect a certain influence of the degree of hot deformation on the process of pearlite colony formation during cooling of the carbon steel.

Thus, with an increase in the degree of hot plastic deformation, grinding of the austenite grain (Fig. 3, *b*) should contribute to a decrease in the probability of the austenite grain splitting into separate fragments with boundaries that have reduced mobility [8, 20]. The analysis of changes of properties of strength, plastic characteristics, and strain hardening coeffi-

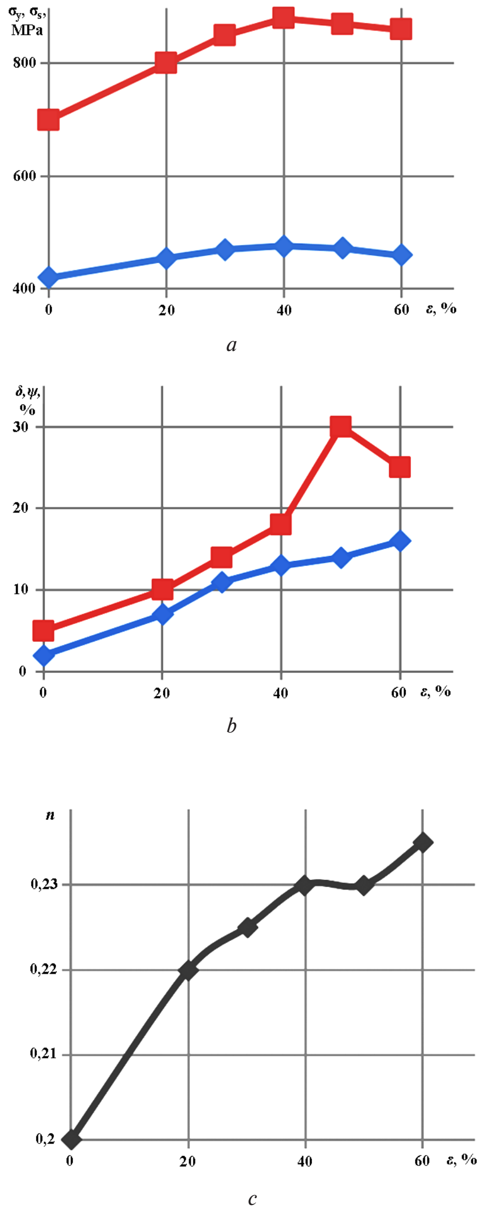

Fig. 4. Influence ε at a temperature of 1,240 °C on the properties of strength (a), plasticity (b) and coefficient of the strain hardening (c) carbon steel with 0.6 % C (♦ – yield stress and relative elongation; ■ – strength stress and relative narrowing)

cient depending on the degree of hot plastic deformation (Figs. 4, *a–c*) indicates existence of a certain correlation relationship with both λ and d_A. In fact, the influence of the value of ε on properties of the steel should be considered as a confirmation, at least qualitatively, inheritance structure state of the hot deformed austenite by the pearlite structure.

On the other hand, with an increasing degree of hot deformation, increasing intensity of the development of the strain hardening processes should contribute to a decrease in stability of austenite at the beginning of the pearlite transformation. As a result, all things being equal, one should expect an effect similar to the acceleration development of the pearlite transformation. This effect should be similar by nature to the decrease in austenite transformation temperature under isothermal conditions. The resulting dependence dispersion colony of the pearlite on the degree of hot plastic deformation (Fig. 3, *a*) can be considered as a qualitative confirmation development of the specified processes of structural changes in the carbon steel. On the other hand, assessment of the nature of the dependence strength and plastic properties on dispersion of the pearlite colony of hot-deformed steel will allow confirming or refuting the expected presence of substructure elements. For this purpose, an analysis of the execution of the Hall-Petch type relationship for carbon steel with a pearlite structure was carried out

$$\sigma_y,\ \sigma_s = \sigma_i + k_y \cdot \lambda^{-0.5}, \qquad (3)$$

where σ_y and σs are yield and strength stresses, respectively; λ is the thickness of ferrite gap of the pearlite colony; σi is the stress; depending on the studied characteristic, it has different name.

Thus, when constructing the ratio $\sigma_y \sim f(\lambda^{-0.5})$, where d is a size of the grain, σi is often called frictional stress crystal lattice of the metallic material, the yield strength of a single crystal, etc. The value k_y is the angular coefficient. For low carbon steels, for which the main structural element is a size of the ferrite grain, k_y value is a measure resistance boundaries of the ferrite grain to the propagation of plastic deformation. For a pearlite colony of the carbon steel, k_y is a measure of resistance interface between phases (ferrite – cementite) to the propagation of deformation.

There are different explanations for the absolute values of the angular coefficient according to relation (3), at dependence on the size of ferrite grain and for λ of the pearlite colony. According to data [1, 19], there is a coincidence k_y values for dependence of yield stress on the size of the ferrite grain and thickness of a ferrite gap of the pearlite colony, although there are ideas about their difference [9]. Plotting the ratios σ_y and σ_s from λ of hot-rolled carbon steel (Fig. 5) shows that dependence (3) is fulfilled for the studied interval λ (Fig. 3, *a*).

In order to determine the influence of sub-structural elements of the austenite on the formation of the pearlite colony at cooling of steel after hot deformation, data of similar steel were used, without hot compression [21]. Comparison analysis shows that steel after hot deformation has about three-time smaller interval λ than after transformation of the austenite at isothermal conditions.

According to the analysis of the ratios (Fig. 5), existence should be noted of certain differences in values of σi and k_y for carbon steels after isothermal transformation of the austenite and after hot plastic deformation. The obtained values of the parameters of the equation (3) should actually reflect the features of the structural state of the austenite and, as a result, confirm its influence on the formation of the pearlite colony. Thus, after isothermal transformation of austenite [21], the ratio σ_y from $\lambda^{-0.5}$ determined that k_y is 4.4 N/mm$^{3/2}$, and for σ_s it is slightly more than 6.7 N/mm$^{3/2}$. The given discrepancy at values of k_y has its own explanation. The values of k_y for ratio σs from $\lambda^{-0.5}$ are due to the development of strain hardening processes in the ferrite plates of the pearlite colony and participation of cementite plates at plastic deformation when the metal is loaded from the yield point to strength (Fig. 1). For

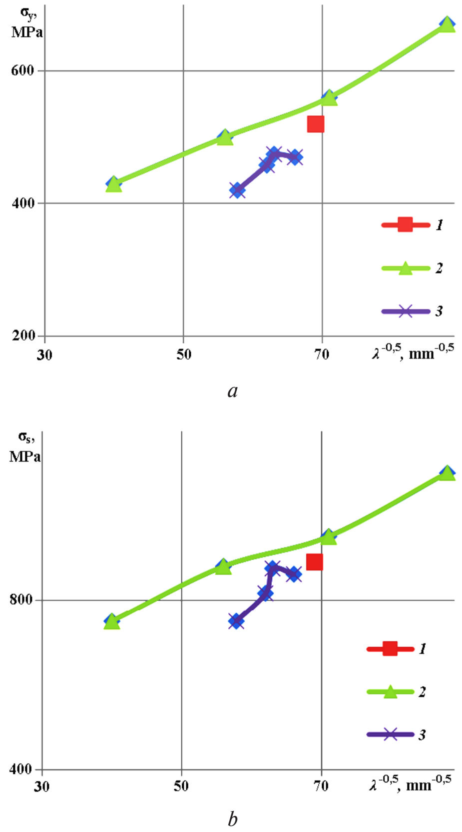

Fig. 5. The influence of λ on the yield stress (a) and strength stress (b) of the steels with 0.57 % C after hot plastic deformation of 60 % and cooling at a rate of 2 °C/s (1) [9]; *0.58 % C after isothermal decomposition of austenite at temperatures of 550–625 °C of the annealed steel (2)* [21] *and after hot plastic deformation of the steel with 0.6 % C (3)*

the hot-rolled steel, k_y value becomes higher. According to the ratio $\sigma_y \sim f(\lambda^{-0.5})$, k_y is equal approximately 8 N/mm$^{3/2}$, and for dependence of σ_s, it reaches the highest value: 14 N/mm$^{3/2}$.

Thus, for steel after hot deformation, the value of k_y exceeds corresponding values for steel after isothermal transformation of the austenite (undeformed austenite), by approximately two times. For σ_i, in terms of absolute values, a sufficiently qualitative agreement was obtained with the friction stress of the ferrite crystal lattice of low-carbon steel after annealing [1]. This indicates that during formation of a pearlite colony, there is practically no super saturation of carbon atoms in the ferrite component. For carbon steel after isothermal transformation (without hot deformation), in proportion to the degree of super cooling of the austenite during formation of the pearlite colony, the degree of super saturation of the carbon atoms in ferrite will be increased. As a result, the value of σ_i should exceed the similar characteristic of hot deformed steel, reaching values at the level of 200–250 MPa (Fig. 5, *a*).

Based on this, increase in frictional stress of the ferrite crystal lattice after isothermal transformation of the austenite can be considered one of the factors in increasing strength properties of the carbon steel with pearlite structures.

Similar to strength properties, plasticity characteristics and strain hardening coefficient have certain dependencies on λ (Fig. 6). An increase in dispersion of the pearlite colony is accompanied by a simultaneous decrease in the thickness of the ferrite layer and cementite plates. Based on this, in inverse proportion to the thickness of the cementite plate (as part of the pearlite colony), its ability to withstand significant plastic deformations will increase. This phenomenon explains increase in maximum plasticity when drawing steel with a pearlite structure. At the same time, effect of reducing thickness of the ferrite

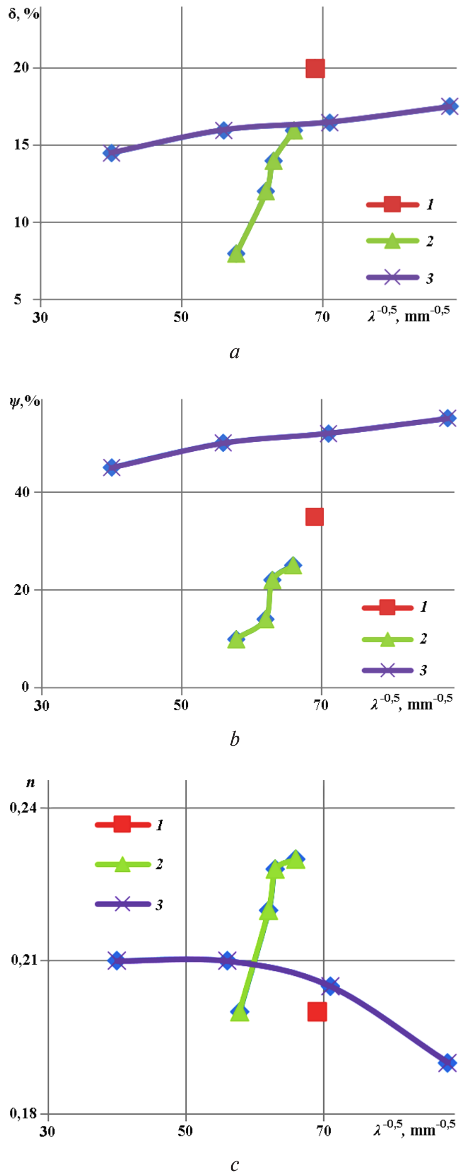

Fig. 6. The influence of λ on the relative elongation (a), contraction (b) and strain hardening coefficient (c) of steels with 0.57 % C after hot plastic deformation of 60 % and cooling at a rate of 2 °C/s (1) [9]; 0.58 % C after isothermal decomposition of austenite at temperatures of 550–625 °C of annealed steel (2) [21] and after hot plastic deformation of steel with 0.6 % C (3)

gap in pearlite remains similar to the effect of ferrite grain size of the low-carbon steel on the strain hardening coefficient [16, 19].

A qualitatively different nature of dependence $n \sim f(\lambda)$ is observed for the steel with a pearlite structure after hot plastic deformation (Fig. 6, *c*), which indicates the need for a more detailed analysis of development of the strain hardening processes. From a comparative analysis of the ratios δ, $\psi \sim f(\lambda)$ (Figs. 6, *a*, *b*) and $n \sim f(\lambda)$ (Fig. 6, *c*), it was determined that for a pearlite colony formed from austenite after annealing (curve *3*), the fulfillment of the ratio $n \sim 1/(\delta, \psi)$ is quite clear (curve *3*, Fig. 6). On the other hand, it is of some practical interest to perform the ratio $n \sim f(\lambda)$ for steel after hot deformation (point 1 and curve *2*, Fig. 6, *c*).

Formally, it can be determined that in steel during hot deformation and subsequent cooling, the peculiarities of formation of the pearlite colony responsible for a qualitative change in the ratio of the strain hardening coefficient and plastic properties (point 1 and curve *2*, Fig. 6, *c*). As shown in Figs. 5 and 6 by the dependences and values of σi, k_y and *n*, it can be assumed that for steel after hot deformation there is an additional influencing factor in addition to dispersion of the pearlite. A detailed analysis of the ratios δ and ψ from *n* indicates a qualitative coincidence with a similar dependence on the grain size of ferrite of the low-carbon steel

$$n = 5/(10 + d^{-0.5}), \qquad (4)$$

where *d* is a grain size of the ferrite. According to relation (4); *n* increases in proportion to *d*.

On the other hand, it was experimentally found [1, 19] that an increase in *d* is accompanied by an increase in plasticity of the low-carbon steel. Based on this, existence of the proportional relationship $d \sim f(n, \delta)$ is fully justified. The mechanism of this phenomenon is based on the proportional dependence of the size cell of the dislocation on *d* and the ability of the cellular structure to change during plastic deformation, maintaining as much as possible a uniform distribution of the dislocations. For steel with a completely pearlite structure, the ratio of *n* from λ is qualitatively similar (4)

$$n = 15/(10 + \lambda^{-0.5}). \qquad (5)$$

Different values of the numerator in ratios (4 and 5) are associated with differences in the nature of the influence boundaries between ferrite grains and between the "ferrite-cementite" phases in the pearlite colony, on the propagation of plastic deformation and the formation of the dislocation periodic structures. However, according to experimental data [21], for carbon steel with a fully pearlite structure, the coefficient of the strain hardening and maximum plasticity have an inversely proportional relationship.

In general, the value of maximum plasticity of the metal, regardless of the structural state, is limited by moment of reaching maximum allowable concentration of the dislocations, above which destruction occurs [16, 19]. As a result, not only increase in the density of the dislocations during deformation determines plasticity margin of the metal, but also development of the dislocation recombination processes [8] (formation of the dislocation periodic structures, their improvement, etc.). Therefore, the nature of accumulation of the dislocations should have a certain importance in achieving high level plastic characteristics of the metal.

For steel with a completely pearlite structure, regardless of the structural state of austenite, increase in λ is accompanied by a decrease in plasticity (Figs. 6, *a*, *b*). At that time, the rate of decrease is significantly different. Compared to the properties of strength and plasticity, for which the nature of the effect of change depends to a small degree on the scheme of steel processing, the strain hardening coefficient illustrates qualitatively different ratios. The results of the analysis of dependence of *n* on λ (Fig. 6, *c*) and $n \sim f(\delta$ and $\psi)$ (Fig. 7) confirm the above statements.

The data obtained at formation of the pearlite colonies with a slight additional cooling of the hot-rolled steel deserve special attention (Fig. 7, designation 1).

The given difference in *n* (point 1) from the values for the structural state of austenite after annealing (curve *3*) and hot deformation (curve *2*) is due to a change in the stress state of the metal: from uniaxial when determining the relative elongation, to three axial – for narrowing.

Thus, pearlite colonies formed as a result of decomposition of the hot deformed austenite are similar only in external features to the pearlite at isothermal transformation steel after annealing. Peculiarities of development of strain hardening processes in pearlite, which is formed from austenite with different structural state, acquires a certain practical significance when developing and improving the technology to produce rolled products with pearlite structures.

Conclusions.

1. According to the technology production rolled products of the large cross-sections from carbon steels, preservation of portion of hot slander of the austenite will contribute to simultaneous increase in properties of strength and plasticity.

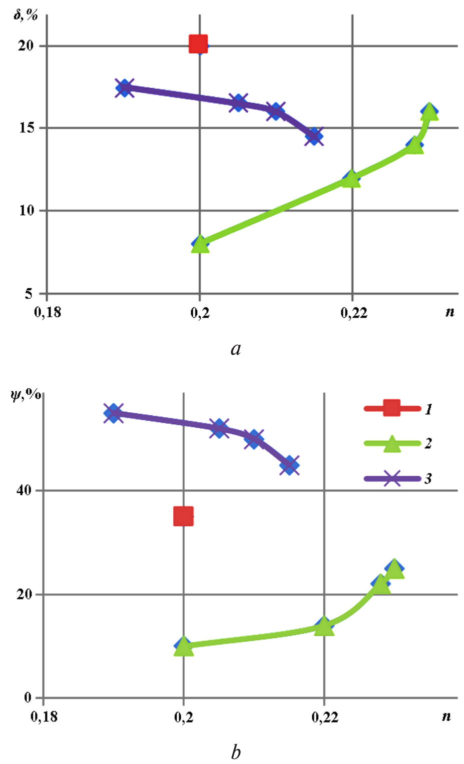

Fig. 7. The influence of the strain hardening coefficient on the relative elongation (*a*) *and relative narrowing* (*b*) *of steels with 0.57 % C after hot plastic deformation of 60 % and cooling at a rate of 2 °C/s* (*1*) [9]; *0.58 % C after isothermal decomposition of the austenite at temperatures of 550–625 °C of annealed steel* (*3*) [21] *and after hot plastic deformation of the steel with 0.6 % C* (*2*)

2. The coefficient of strain hardening of carbon steel with a pearlite structure, in addition to dispersion, is determined by the structural state of the austenite.

3. For the pearlite colonies formed from austenite after annealing, the strain hardening coefficient and maximum plasticity of the steel are inversely proportional.

4. For the pearlite colony, with a partial preservation substructure after hot deformation of the austenite, the coefficient of strain hardening and the maximum plasticity of the steel are directly proportional.

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Вплив гарячої пластичної деформації на властивості вуглецевої сталі

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Мета. Визначення впливу ступеня гарячої пластичної деформації на комплекс властивостей вуглецевої сталі.

Методика. Для дослідження використана сталь з 0,6 % вуглецю. Структура сталі відповідала стану після обтиснення за температури 1240 °С. Механічні властивості визначали за кривою розтягу, оцінювали напруження тертя кристалічної решітки фериту та опір міжфазної межі перліту розповсюдженню деформації.

Результати. Залежно від структурного стану аустеніту, диспергування перлітних колоній супроводжується різним темпом зміни властивостей вуглецевої сталі. Для перліту, що сформований з аустеніту після відпалу, коефіцієнт деформаційного зміцнення й максимальна пластичність пов'язані обернено пропорційною залежністю. Для перліту, що утворюється з аустеніту зі збереженою субструктурою після гарячого обтиснення, коефіцієнт деформаційного зміцнення й максимальна пластичність пов'язані пропорційним співвідношенням.

Наукова новизна. Збереження субструктури гарячедеформованого аустеніту впливає на розповсюдження деформації в перліті сталі. На фоні зниження напруження тертя кристалічної решітки фериту, відбувається збільшення опору межи ферит-цементит перліту, розповсюдженню деформації.

Практична значимість. Для вуглецевих сталей із перлітною структурою прискорене підвищення пластичності за рахунок збереження частки гарячого зміцнення аустеніту дозволить удосконалити технологію виготовлення прокату великого профілю. При виробництві термічно зміцненого прокату досягнення одночасного підвищення міцності та пластичних властивостей забезпечується підвищенням здатності металу до деформаційного зміцнення.

Ключові слова: *вуглецева сталь, аустеніт, перліт, дислокація, деформаційне зміцнення*

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