

МАТЕРІАЛОЗНАВСТВО

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INFLUENCE OF DYNAMIC STRAIN AGING ON THE PROPERTIES OF COLD-DRAWN CARBON STEEL

For cold-drawn carbon steels, the regularities governing the influence of alternating deformation and temperature on the development of dynamic strain aging (DSA) processes have been established. It was found that a change in the deformation sign (compression-tension) leads to a shift in the onset of the first flow stress serrations toward higher strain levels. Based on the analysis of a stress unrevised motion of dislocation and coefficient of strain hardening, it is shown that the suppression of DSA during reverse loading is caused by a disruption in the kinetic relationship between the dislocation waiting time (for interaction with solute atoms) and the duration of their free motion. It has been established that applying alternating bending within the temperature range of 250–275 °C achieves a plasticization effect in high-carbon wire without compromising its strength properties. The results are explained by dislocation recombination processes and changes in the conditions of their pinning by impurity atom atmospheres. The necessity of forced cooling of the metal after deformation is justified to prevent the development of static strain aging (SSA) in coils, thereby preserving the positive effect of increased ductility.

Keywords: carbon steel; dynamic strain aging (DSA); dislocation, temperature; strain hardening; plasticization.

Для холоднотягнутих вуглецевих сталей встановлено закономірності впливу знакозмінної деформації та температури на розвиток процесів динамічного деформаційного старіння (ДДС). Виявлено, що зміна знаку деформації (стиснення–розтягання) призводить до зміщення моменту появи перших зривів деформуючого напруження у бік більших ступенів деформації. На основі аналізу напруження необерненого руху дислокацій та коефіцієнта деформаційного зміцнення показано, що пригнічення ДДС при реверсивному навантаженні зумовлене порушенням кінетичного співвідношення між часом очікування дислокацій та часом їх вільного пробігу. Встановлено, що застосування знакозмінного згину в температурному діапазоні 250–275 °C дозволяє досягти ефекту пластифікації високо вуглецевого дроту без зниження його характеристик міцності. Отримані результати пояснюються процесами рекомбінації дислокацій та зміною умов їх блокування атмосферами домішкових атомів. Обґрунтовано необхідність примусового охолодження металу після деформації для запобігання розвитку статичного деформаційного старіння в бунтах, що дозволяє зберегти отриманий позитивний ефект підвищення пластичності.

Ключові слова: вуглецева сталь; динамічне деформаційне старіння (ДДС); дислокація; температура; деформаційне зміцнення; пластифікація.

Problem's Formulation

Modern technological advances are unthinkable without ever-increasing demands on metals and alloys, especially those used to manufacture structures subject to complex thermal and mechanical loading. A significant number of components used in mechanical engineering are manufactured using plastic deformation, which is a one of the-forming operation. Under various combinations of heating temperature, degree, and type of deformation, the resulting structural changes in the metal determine its behavior not only during manufacturing of the structures but also during operation its.

One of the characteristics metallic materials during deformation is their ability to increase their resistance to deformation propagation. This phenomenon is called strain hardening. As a result of development strain hardening processes, changes in many properties of metals and alloys are observed. In general, the nature of ratio between acting stress and magnitude of deformation comes down to the development of corresponding processes of structural changes occurring in the metal when it is loading. At a certain temperature-to-strain rate ratio, non-monotonic stress changes with different in the external signs of their manifestation can be observed at loading diagrams. Depending on the temperature and strain rate, non-monotonic stresses serrations, may appear and then disappear. They may then reappear with different amplitude and cycling frequency. While non-monotonic stress-strain curves for carbon steel at low temperatures are associated with development of plastically unstable flow [1], the observed serrations during deformation in the temperature range of 100–300 °C are caused by other processes. In the literature, the observed phenomenon is called dynamic strain aging (DSA) [Babich V. K. et al., 1972]. In addition to dynamic deformation aging, in approximately the same temperature range but under very complex loading schemes, the development of other processes of structural transformations allows changing the strength characteristics at a very wide range of values [2]. This discontinuous plastic deformation (the Portevin-Le Chatelier effect), which occurs in many alloys [3], is caused by the interaction of dissolved atoms with dislocations, leading to instability at propagation of plastic deformation. This limits the use of such materials at production of components subject to plastic deformation. This necessitates a thorough analysis of the mechanisms behind these phenomena and the systematization of existing data regarding methods for controlling metal properties under such conditions.

Analysis of recent research and publications

A review of contemporary scientific literature indicates significant attention to elucidating the microscopic nature of deformation processes. Of particular interest are the results indicating that the mobility of chemical element atoms during DSA processes should not effect on stress of friction of the crystal lattice and the interaction of impurity atoms with dislocations should be sensitive to the strain rate [4]. The most common explanations for the occurrence of stress serrations at elevated temperatures are based of the interaction moving dislocation with clouds of impurity atoms that are formed either during process of dislocation motion [5] or over a certain period of the time [6].

In addition to DSA processes, technologies of plastic deformation at elevated temperatures, which are accompanied by a change at phase composition of the metallic material, have become widespread. To achieve a high-strength state in manganese steel, altering the plastic deformation temperature was used to alter the phase transformation mechanism [7]. At temperatures below 100 °C, a martensitic transformation was induced. An increase temperature to 225 °C was accompanied by a bainite transformation, and up to 350 °C, twinning was observed. Above 350 °C, dislocation slip primarily occurred. Similar results were obtained in [8], where deformation temperature determines mechanism and strain hardening of steel. As deformation temperature increases, twinning is suppressed, and the role of dislocation slip increases, which is explained by a change in stacking fault energy.

The certain practical interest represents by increase endurance of carbon steel with a ferrite-pearlite structure at elevated fatigue temperatures [9]. The increase in fatigue strength is due to the development of DSA, which eliminates serrations and intermittent flow while maintaining barriers to dislocation movement. The DSA effect increased the proportion of screw dislocations, which reduced the overall energy of the system. This led to a reduction at number of slip marks on the surface, preventing the initiation of fatigue cracks.

The study influence development of DSA processes on behavior of medium-carbon steel in low-strain fatigue deserves some attention [10]. At a temperature of 200 °C, alternating processes hardening and softening of the metal are observed until to moment of crack formation. An attempt has been made to differentiate structural transformations at different stages of loading. If the first stage of strengthening is due to plastic deformation and an increase number of dislocations, then subsequent isotropic strengthening can be associated with DSA processes.

Dynamic strain aging develops in carbon steels regardless of the cementite morphology [11, 12]. For both plate cementite (pearlite) and globular cementite, the initial microstructure, through its activation energy, determines conditions for the onset and termination of the DSA phenomenon. Microstructural studies show that cementite destruction is responsible for the onset of dynamic strain aging, depending on the applied strain rate and deformation temperature. Thus, the phenomenon of dynamic strain aging in carbon steels is quite widespread, especially at elevated plastic deformation temperatures. The development of this phenomenon can have qualitatively different effects on a range of properties, leading to both hardening and softening, plasticizing or brittle of the metal.

Formulation of the study purpose

To evaluate the possibility of increasing the ductility of cold-drawn carbon steel by utilizing dynamic strain aging processes.

Presenting main material

The study influence of DSA processes on the development of plastic deformation in carbon steel at temperatures of 200—300 °C consisted of two parts. The first part devoted to investigate influence of carbon content and alternating deformation temperature (compression-tension) on the nature of plastic flow. The studies were conducted under laboratory conditions on specimens on ordinary quality steels with carbon content of 0.1—0.5 % C, after annealing. Cylindrical specimens (diameter 8 mm) were used, with dimensions that ensured geometric stability of the specimen's working portion under compression. The second part of the study was devoted to assessing the plasticization possibilities of industrial production cold-drawn high-carbon steel.

The work piece for the study was a cold-drawn wire with a diameter of 3 mm, made of steel with the chemical composition of 0.78 % C; 0.62 % Mn; 0.25 % Si; 0.04 % S; 0.03 % P; 0.05 % Cr; 0.1 % Cu; balance Fe. Considering that initial structure for obtaining a significant range of cold-drawn wire is dispersed pearlite, the work piece was heated to a temperature above A_{c3} before drawing, held to complete the phase transformations, cooled under isothermal conditions at a temperature of 550 °C until the austenite transformation process was completely completed. On a drawing mill of industrial cold-formed wire production, the blank was deformed by 78 %. Wire lengths (3 mm in diameter) with a working length of 1 m served as samples for the cold-formed wire drawing process study. The samples were placed in a furnace with a pre-set temperature of 225—300 °C. The wire was held in the furnace for 3 minutes, followed for at one pass through a single-plane, four-roller bending device (roller diameter 35 mm) at a speed of 1 m/s (1 s^{-1}). To minimize effects of static deformation aging, the wire was forced cooled by a stream of air after the roller bending device.

Mechanical properties of the wire were determined under tension using an Instron testing machine. The rate of tensile strain was 10^{-3} s^{-1} , and temperature range was 225—300 °C. A special climate chamber was used for testing at elevated temperatures. After converting the technical tensile diagram into a true one, the proportionality limit (σ_{pl}), a stress unrevised motion of dislocation (σ_0), yield stress (σ_y), strength stress (σ_s), relative elongation measured on the basis of 30 wire diameters (δ_{30}), coefficient of strain hardening (m), amplitude stress of serrations (σ_d) and strain at which the first stress serrations appear (ε_c) were determined.

At considering kinetic conditions of the process blocking a moving dislocation by an atmosphere of impurity atoms, relationship between the macroscopic strain rate (ε'), density of mobile dislocations (ρ_m) and time formation of a cloud impurity atoms, called the waiting time (τ_0), is described by the dependence [6]:

$$\varepsilon' = \rho_m(l \cdot b) / \tau_0, \quad (1)$$

where l is the mean free path of the dislocation, and b is the Burgers vector.

From the analysis of relation (1), it follows that, if b remains constant, any change at waiting time should be reflected at change value of ρ_m . A study nature of changes properties of carbon steels under tension depending on degree preliminary of deformation at 250 °C shows that an increase in carbon content changes conditions for the development of dynamic deformation aging processes and the Bauschinger effect [1]. In examining the phenomenology of serrated flow, it's important to note the existence of two types of serrations (Fig. 1, *a*).

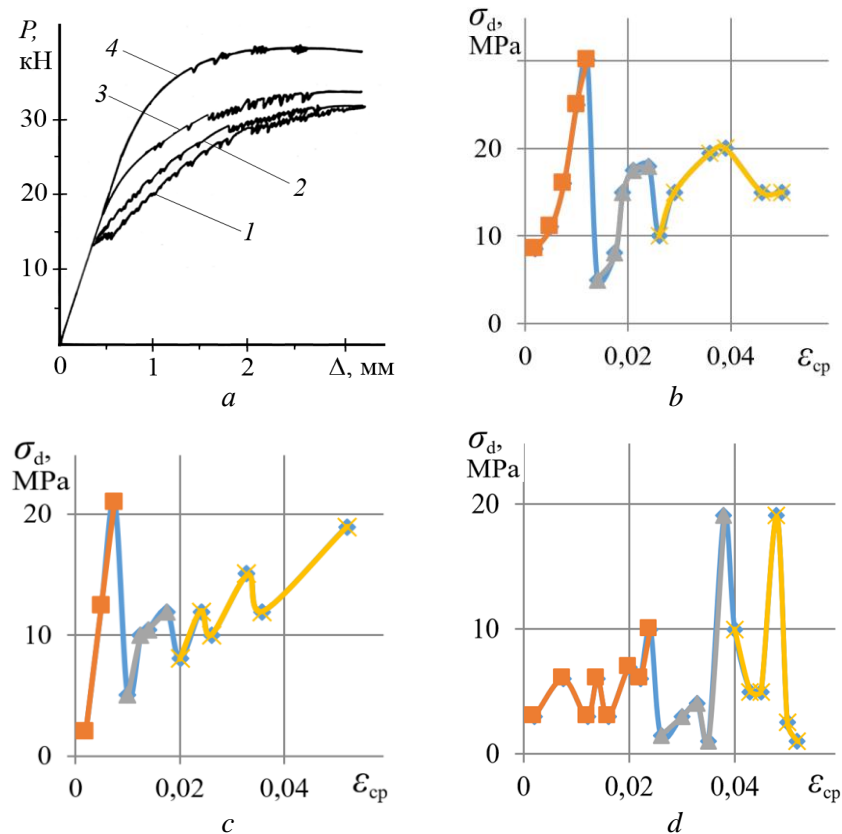


Fig. 1. The stress-strain curves at 250 °C, depending on preliminary compression (1 — 0; 2 — 2; 3 — 5; 4 — 10 %) of steel with 0.1 % C, after normalization — (*a*), effect ε_{cp} and carbon content (*b* — 0.1; *c* — 0.3; *d* — 0.5 % C) on σ_d during tension

The first type involves isolated serrations of stress alternating with sections of a smooth stress-strain diagram. The second type of serration occurs when, in a specific section of the diagram, an increase at degree of deformation is accompanied by a linear increase magnitude at stress of the serrations (σ_d). After reaching a certain strain value, a sharp decrease in σ_d occurs (Fig. 1, *b*, *c*), followed by a further increase in serration. Typically, after the yield plateaus (if present) or nominal yield point, type I deforming stress serration occurs. After approximately 4—6 % strain, type II serrations appear (Fig. 1, *d*).

An analysis of the position of the boundary between sections with different types of deforming force serration showed that this phenomenon, at deformation, coincides with the moment of a sharp decrease in the strain hardening coefficient [1]. Considering that the appearance of a second section at region of uniform strain hardening is due to the formation of a dislocation cell structure, the change type of serration is probably associated with this phenomenon. Compared to unidirectional deformation, pre-compression (ε_{cp} shifts the moment occurrence of the first peak (a serration) deforming stress (ε_c) toward greater deformations. In the vast majority of cases, the magnitudes of pre-compressive deformation (ε_{cp}) and ε_c are quite close in absolute values (Fig. 2, *a*). However, a detailed analysis shows that lower carbon content in the steel, the greater difference between values of ε_{cp} and ε_c .

Thus, for steel with 0.5 % C, we can say that they are practically identical. To explain the nature of the influence of preliminary deformation on the development of DSA processes, will use a stress unrevised motion of dislocation (σ_0), determined on the analysis of stress-strain curve [1]:

$$\sigma_0 = \sigma_i + k_y / \sqrt{2d} + \alpha \cdot \mu \sqrt{\rho_m}, \quad (2)$$

where σ_i is the friction stress of ferrite crystal lattice, k_y is the angular coefficient, d is the size structural element of steel (for low-carbon steel this is a size of the ferrite grain, for the eutectoid composition it is a thickness of the ferrite gap of pearlite), α is the proportionality coefficient, μ is the shear modulus.

As analysis of deformation curve showed, an increase preliminary compressive strain with an increase volume fraction of cementite is first observed as a decrease in σ_0 , and then an increase (Fig. 2, b). Moreover, higher carbon content in the steel, the greater decrease in σ_0 . The strain hardening exponent changes inversely proportion to σ_0 (Fig. 2, c). Considering that at a temperature of 250 °C during alternating bending, the stress friction of crystal lattice (the first term of relation (2)) and dispersion of the pearlite dispersion (the second term) remain practically unchanged, their influence on σ_0 can be neglected. Then, the effect of alternating bending on σ_0 will be determined by the third term of dependence (2). Based on this, relation (2) takes the form:

$$\sigma_0 \sim f(\sqrt{\rho_m}), \quad (3)$$

From relation (3) it follows that when the sign of deformation changes, decrease in σ_0 is primarily due to a decrease in the density of mobile dislocations. If used (1), then with a decrease in ρ_m , τ_0 should decrease and τ_1 will become greater than τ_0 , which will violate conditions for the development of DSA. To restore condition $\tau_0 = \tau_1$, it is necessary to decrease τ_1 . This can be achieved either by decreasing l in (1) or by decreasing ε' . Considering that ε' remains constant, a decrease in τ_1 is possible only if velocity moving of dislocation (v) will be increased ($\tau_1 = l/v$). Then, as ρ_m decreases, to maintain condition of continuous deformation propagation, the v must be increase, and τ_1 will decrease. Then the effect of DSA processes will increase to a greater extent (Fig. 1, a).

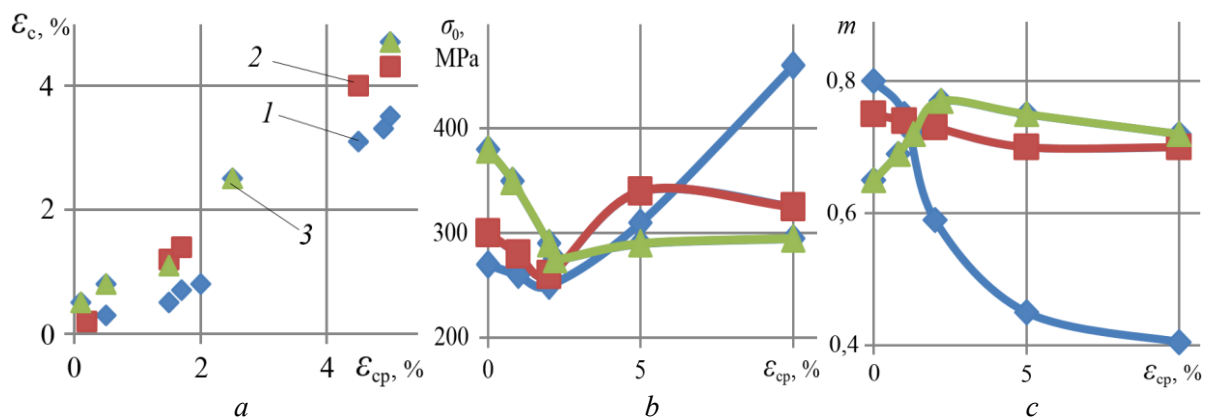


Fig. 2. Effect compression deformation (ε_{cp}) and carbon content in steel (1 — 0.1; 2 — 0.3; 3 — 0.5 % C) on strain appearance serrations of stress under tension (ε_c) — (a), change in σ_0 (b) and m (c)

Compared to DSA, a qualitatively different mechanism of dislocation recombination is observed when sign of plastic deformation changes. Thus, for steel with a carbon content of 0.1 %, the dislocation density after small degrees of plastic deformation at the ferrite grain boundaries is higher than within the grain [1]. At that time concentration of impurity atoms is also higher on the grain boundaries.

At the heating temperatures studied, after preliminary compressive deformation, after changes of sign deformation and deforming stress begins to increase, dislocations located within the ferrite grains, annihilating with dislocations introduced during tension, will lead to a change in σ_0 [1]. However, this effect is significantly lower than from the blocking of dislocations near boundary. The overall effect of these processes is shown in Fig. 2, b. With a decrease at volume fraction of structurally

free ferrite, the role of pearlite colony at development of the DSA effect increases. This is due to the fact that in ferrite of pearlite colony, shorter distances for the delivery of carbon atoms from carbide to the dislocations [Babich V. K. et al., 1972] contribute to an increase effect of strain hardening, including effect on the kinetics of DSA development.

The more significant change in σ_0 with increasing pearlite volume fraction is due not only to a decrease in dislocation density due to annihilation processes but also to the possible unblocking of dislocations. In this case, a decrease in σ_0 is accompanied by an increase in m . At higher degrees preliminary of plastic deformation (ε_{cp}), the onset formation a cell structure of dislocation reduces dislocation mobility, which reduces the change in these characteristics. Thus, with constant temperature-speed parameters of deformation, in steels with medium and high carbon content, by only change in the sign of deformation makes it possible to change conditions for the manifestation of dynamic strain aging and, as a consequence, influence processes propagation of plastic deformation of the metal.

The above position is confirmed by the results of the analysis of the influence of alternating bending on the properties of cold-drawn carbon wire. The process of drawing a steel blank is accompanied by an increase in deformation temperature proportional to the amount of reduction. This inevitably leads to DSA and SSA (static strain aging after coiling of coil), which significantly impact the metal's properties. With increasing degrees of cold plastic deformation, the development of strain hardening processes is accompanied by an increase in strength characteristics, while accumulation defects of crystalline, coupled with the difficulty of internal stress relaxation, increases brittleness of the metal [1]. In addition to tempering, level of these stresses and, consequently, ductility of the metal can be reduced by introducing defects of crystalline (primarily dislocations) different signs. This will allow, through dislocation recombination, to change the location and number of dislocations after cold drawing. This state of the metal can be achieved using alternating deformation, for example, through bending [13].

An analysis of the tensile stress curves shows that increasing heating temperature of cold-drawn metal in the first instance leads to a decrease in strength due to softening processes, and then increases (due to the influence of SSA), reaching maximum values at 250 °C (Fig. 3, *a*). Meanwhile, ductility, while virtually unchanged, begins to decrease after 250 °C (Fig. 3, *c*). An analysis change in relative elongation suggests that optimal alternating bending temperature for achieving high ductility may be around 250 °C. By subjecting cold-drawn wire to alternate bending at room temperature, decrease at strength properties of cold-drawn wire (Fig. 3, *a*, *b*, marked 4) and some increase in plasticity were observed (Fig. 3, *c*).

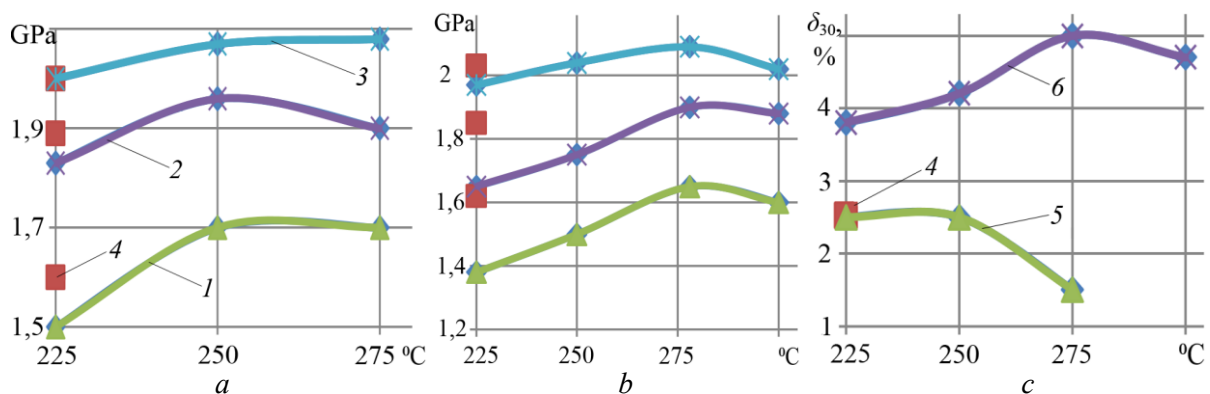


Fig. 3. Influence temperature of heating on σ_{pl} — (1), σ_y — (2), σ_s — (3) of cold drawn steel (without heating — (4) — (a), after alternating bending — (b), δ_{30s} , after SSA (5), after alternating bending (6) — (c)

Increasing the alternating bending temperature to 225 °C resulted in minor changes in properties compared to the cold drawn state. Strength properties decreased, while relative elongation increased slightly. Proportionally to the increase in alternating bending temperature, up to 275 °C, a simultaneous increase in ductility and strength was observed (Fig. 3, *b*, *c*).

Studies at higher temperatures revealed a simultaneous decrease in these properties, which is likely due to a violation of conditions (1). From the obtained results it follows that by subjecting cold-drawn high-carbon steels to alternating bending at temperatures of 250–275 °C, without reducing the strength properties; it is possible to achieve a certain increase in plasticity. However, the use DSA must provide ability to control process parameters. If the degree of alternating bending is controlled by the device, and the heating temperature is controlled by the drawing mill's process instructions, then ability to stop heating the metal remains an unresolved issue.

Depending on degree of reduction, temperature in the coil of the metal can reach 300–350 °C. If after alternate bending is not prevented development of SSA at wound into a coil, the plasticization effect on the metal will be almost completely suppressed. One of the solution to this problem may be used to forced cooling of the metal, both by the dies themselves and during of pause between reductions [Fetisov V.P. et al., 1975]. Then, the plasticization effect of cold-drawn wire made from high-carbon steels will gain some interest.

Conclusions

1. At temperatures of 225–300 °C, compared to unidirectional deformation, reversible deformation shifts the moment onset development of dynamic strain aging processes toward greater strains.
2. Based analyses changes in a stress unrevised motion of dislocation (σ_0) and coefficient of strain hardening m , it is shown that suppression of DSA processes upon reversal of deformation sign is caused by a disruption at relationship between the waiting time (for dislocations to interact with carbon atoms) and duration of free dislocation motion.

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ВПЛИВ ДИНАМІЧНОГО ДЕФОРМАЦІЙНОГО СТАРІННЯ НА ВЛАСТИВОСТІ ХОЛОДНОТЯГНУТОЇ ВУГЛЕЦЕВОЇ СТАЛІ

Реферат

У роботі оцінено можливість підвищення пластичності холоднотягнутої вуглецевої сталі шляхом використання процесів динамічного деформаційного старіння (ДДС) при знакозмінній деформації. Матеріалом для дослідження слугували вуглецеві сталі з вмістом 0,1—0,5 % C, а також промисловий високовуглецевий дріт діаметром 3 мм (0,78 % C, 0,62 % Mn, 0,25 % Si, 0,04 % S, 0,03 % P, 0,05 % Cr; 0,1 % Cu, залізо — основа). Для отримання вихідної структури дисперсного перліту заготовки піддавали ізотермічному перетворенню за температури 550 °C з наступним холодним волочінням зі ступенем деформації 78 %. Знакозмінний згин зразків проводили в температурному діапазоні 225—300 °C зі швидкістю деформації 1 с⁻¹. Механічні властивості та параметри деформаційного зміцнення визначали за аналізом істинних кривих розтягування. Встановлено, що знакозмінна деформація за температур 225—300 °C призводить до пригнічення процесів ДДС на початкових етапах навантаження, що виражається у зміщенні моменту появи серрацій (зубців) напруження у бік більших деформацій порівняно з односпрямованим розтяганням. Наукова новизна роботи полягає у фізичному обґрунтуванні цього явища: пригнічення ДДС при зміні знаку деформації зумовлене порушенням кінетичного співвідношення між часом очікування (необхідним для взаємодії дислокацій з атомами вуглецю) та тривалістю вільного руху дислокації. Виявлено, що оптимальним режимом для досягнення ефекту пластифікації високовуглецевого дроту є температурний інтервал 250—275 °C, який забезпечує реалізацію кінетичних умов процесу блокування рухомої дислокації атмосферою домішкових атомів, що стабілізує протікання процесів ДДС. Встановлено, що при нагріві понад 275 °C вказана умова порушується, що призводить до втрати контролю над розвитком ДДС і супроводжується одночасним зниженням як пластичності, так і міцності металу. Практична цінність роботи полягає в обґрунтуванні необхідності примусового охолодження металу безпосередньо після знакозмінної деформації, що запобігає розвитку статичного деформаційного старіння в бунтах та дозволяє зберегти набутий рівень пластичності.

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