МАТЕРІАЛОЗНАВСТВО

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PHENOMENON OF THE SOFTENING COLD-DEFORMED LOW-CARBON STEEL DURING ALTERNATING BENDING

For cold-rolled low-carbon steel, detected softening during alternating bending is accompanied by an increase in ductility and ability to strain hardening. The softening process is accompanied by a change at morphology of ferrite grains. Elongated grains after cold rolling acquire a shape close to a polyhedron after alternating bending. Compared to the strength properties, for which a maximum decrease corresponds to four bending cycles, the ductility and strain hardening ability of the metal continue to increase even after eight cycles. The non-monotonic nature of change in dislocation density depending on the number of bending cycles indicates complex substructural changes in cold-rolled metal, which has a dislocation cellular structure varying degrees of the perfection.
Keywords: *steel; dislocation density; ferrite; strength; strain hardening; elongation.*

Для холоднокатаної низьковуглецевої сталі виявлено пом'якшення при знакозмінному згині, яке супроводжується зростанням пластичності та здатності до деформаційного зміцнення. Процес пом'якшення супроводжується зміною морфології зерен фериту. Витягнуті зерна після холодної прокатки набувають форми, наближеної до поліедру після реверсивного вигину. Порівняно з властивостями міцності, для яких максимальне зниження відповідає чотирьом циклам вигину, пластичність і здатність металу до деформаційного зміцнення продовжують зростати навіть після восьми циклів. Немонотонний характер зміни густини дислокацій від числа циклів вигину свідчить про складні субструктурні зміни холоднокатаного металу, що має дислокаційною комірчастою структурою різного ступеня досконалості.
Ключові слова: *сталь; щільність дислокацій; ферит; міцність; деформаційне зміцнення; відносне видовження.*

Problem's formulation

The use of plastic deformation as a tool for controlling set properties of cold-worked low-carbon steel is an urgent problem. Based on this, purpose of the work was to assess degree of softening cold-rolled low-carbon steel during alternating bending.

Analysis of recent research and publications

The intensive development of mechanical engineering is accompanied by increasing requirements for products made of the metal materials. Considering production volumes, rolled carbon steels are the most popular type of metallurgical products. Against the background of most characteristics, the ratio of strength and plastic properties deserves special attention [1—3]. For most metal materials, the increase in strength properties is limited by the level of ductility. In general, development of phase transformations leads to the formation of the required structural state and associated set of the properties metal [4—6]. Considering that most types of rolled products have a complex cross-sectional shape and are the long products, it is not possible to achieve simultaneous development of phase transformations both at cross section and along the length. As a result, in proportion of the degree heterogeneity of temperature distribution, plastic deformation along the cross-section and length, and the non-simultaneous development of phase transformation processes, decrease at straightness of rolled products is observed. The use of alternating bending to level a long product should influence a set of properties, especially resistance to small plastic deformations [7—9]. In this case, one should expect an increase in effect of influence in proportion to the degree deviation of the metal structure from the equilibrium state. Based on this, process of leveling a product may be of some interest as a technology for changing properties of the cold-deformed metal [3, 6, 10].

Formulation of the study purpose

The purpose of the work was to assess degree of softening cold-rolled low-carbon steel under alternating bending.

Presenting main material

The material for study was hot-rolled sheet metal *2 mm* thick, made of low-carbon steel with a carbon content of *0.07 %*. The remaining chemical elements were within the *08ps* steel grade composition. At the cold rolling mill, the strip was reduced in thickness by *20*, *40* and *60 %*.

The cold-rolled strip was subjected to alternating bending in a special installation [10], with the number of bending cycles (m) being calculated. One cycle of alternating bending corresponded to one movement along metal strip of a special stand with two rollers for bending.

The mechanical properties of the samples were determined by tensile tests at room temperature and a strain rate of $10^{-3}\ s^{-1}$. The microstructure of steel was examined under a light microscope. The dislocation density (ρ_{110}) was estimated from broadening (β) of X-ray interference (*110*) [11]:

$$\rho_{110}=m\cdot\beta^2\cdot ctg^2\Theta/b^2, \qquad (1)$$

where Θ is interference angle of the (*110*) line, b is the Burgers vector.

Compared to the hot-rolled state, an increase at degree of cold deformation by rolling is accompanied by the quite expected hardening of the metal (Fig. 1).

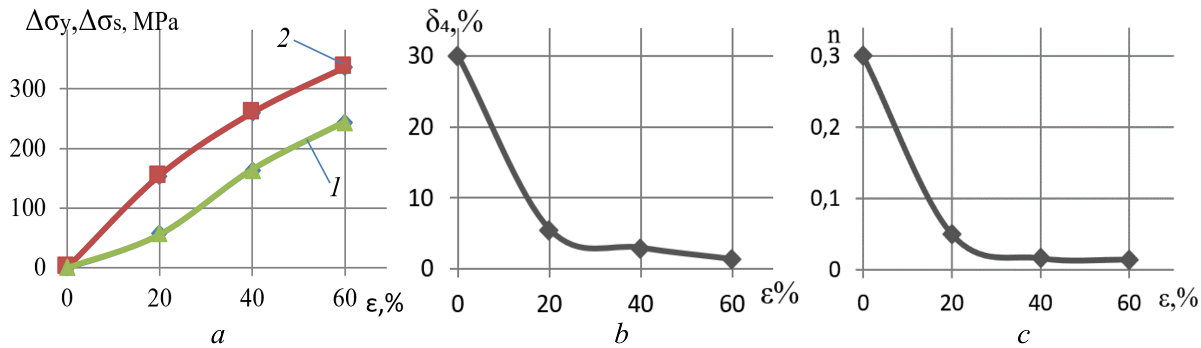

Fig. 1. The influence degree of deformation on the increase in yield stress (*1*) and strength (*2*) (a), decrease in relative elongation (b) and n (c) of steel after hot rolling

Strength characteristics increase, and plasticity and strain hardening coefficient decrease (Fig. 1, b, c). The difference at rate increase in yield stress ($\Delta\sigma_y$) and strength ($\Delta\sigma_S$) after different degrees of plastic deformation is due to qualitative changes at structure of cold-rolled steel. One of the reasons should be considered a change at nature of accumulation and distribution defects of the crystal structure depending on degree of deformation [6—12]. Indeed, a difference at rate of increase in σ_y and $\Delta\sigma_S$ from magnitude of deformation during rolling is primarily due to the influence of strain hardening processes on the internal structure of the metal.

From comparative analysis it follows that if the value of σ_y corresponds to the state of metal when the first signs of plastic deformation appear, then at σ_S the structure has already undergone significant qualitative changes. Changes in the structure begin from appearance first acts propagation of plastic deformation, through formation and improvement of the dislocation cellular structure and end with formation of the first submicrocracks. Simultaneously with increase in strength characteristics, a sharp decrease at ductility of the metal is observed (Fig. 1, b). Already after deformation of 20 %, there is a sharp decrease at relative elongation, approximately 5 times (from 30% after hot rolling to 5.4 %). This nature of the change in δ_4 is due to substructural changes internal structure of the cold-deformed metal.

After all, at 20…25 % plastic deformation, the beginning formation of a dislocation cellular structure is observed [3, 12, 13]. Compared to deformations up to 10…15 %, when the increase in quantity dislocations is accompanied by a relatively uniform distribution, the certain probability development of dislocation annihilation during deformation itself is quite high. In this case, even minor recombination of dislocations at low degrees of deformation will ensure preservation of a certain level of plasticity. During decay of a uniform distribution of dislocations [14], cells with a rather imperfect structure are first formed [7]. A characteristic feature of such a structure is the formation large cells, with dislocation concentrations inside them and at subboundaries practically no different from each other [10].

In this case, mutual blocking of dislocations that are located in different crystallographic slip systems will lead to rapid exhaustion resource of their accumulation by metal until maximum permissible value. This is confirmed by a sharp decrease at ductility and ability of the metal to strain hardening (estimated by the value $n = (\sigma_S - \sigma_y)/\sigma_y$ [7]), Fig. 1 b, c. To subjected a cold-deformed metal to only two cycles of alternating bending, significant softening is observed (Fig. 2, a), the plasticity and ability of the metal to strain hardening increase several times (Fig. 2, b, c).

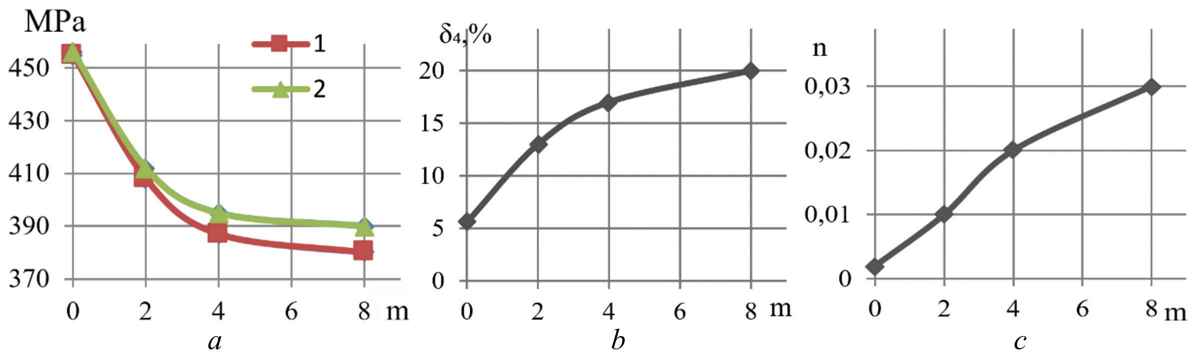

Fig. 2. The influence number of bending cycles on the yield stress (*1*) and strength (*2*) — (a), relative elongation (b) and the value of *n* (c) of 20 % cold-rolled steel

Considering that relative elongation values are 5.4 % after 20 % deformation, an increase to 13 % after two bending cycles (Fig. 2, b) should be considered significant. A similar increase was found for ability of the metal to undergo strain hardening (Fig. 2, c). Compared to a deformation of 20 %, alternating bending of steel after 40 and 60 %, in addition to reducing the temp of change properties is not accompanied by qualitative changes at dependencies (Fig. 3). The decrease in strength properties and increase in ductility and the ability of the metal to strain hardening also continue.

Moreover, as follows from at nature dependence of the strength properties, four cycles are already sufficient to achieve 90 % of the total softening effect (Fig. 2 a and 3 a). However, achievement maximum values of δ_4, as shown in Fig. 2b and 3b and n (Fig. 2 c and 3 c), should be expected after more than 8 number of cycles. In general, the nature dependence strength and plastic properties after alternating bending indicates a fairly stable effect softening of the cold-rolled steel.

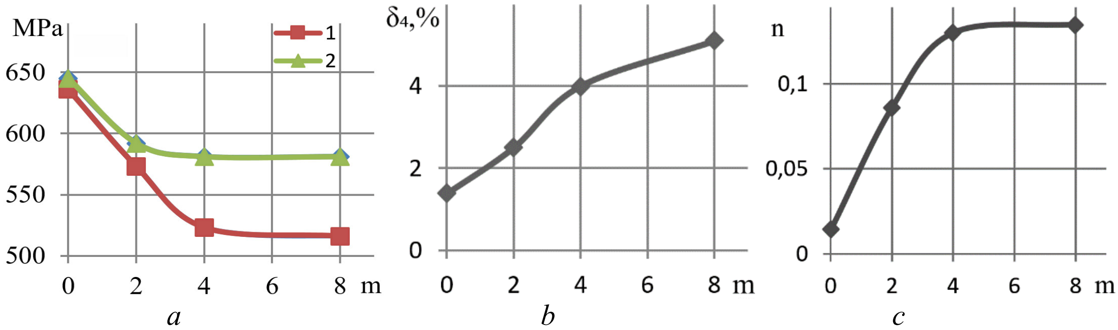

Fig. 3. The influence number of bending cycles on the yield stress (1) and strength (2) — (a), relative elongation (b) and the value of *n* (c) of cold-rolled 60 % steel

The results microstructure study should be considered as confirmation observed effect of the softening (Fig. 4).

After cold deformation, for example, 40 %, equiaxial ferrite grains structure after hot rolling (Fig. 4 a), turns into elongated, with a predominant orientation at direction of the main plastic deformation during rolling (Fig. 4 b). The subsequent 8 cycles of alternate bending lead to qualitative changes. The elongated grains of cold-rolled steel after alternating bending become more equiaxed (Fig. 4 c), and their average size approaches grain size of the hot-rolled state.

Considering absence heating of the cold-rolled steel, it is of some interest to explain phenomenon of changes at morphology of the ferrite grains as a result of alternate bending. Estimating the dislocation density (ρ_{110}) using relation (1) indicates its proportional increase depending on the degree of cold deformation (Fig. 5 a). As follows from the analysis of above relationships (Fig. 5 b), decrease at total dislocation density as a result of alternated bending should be considered as one of the reasons for decrease at strength properties of cold-rolled steel (Fig. 2 a, 3 a).

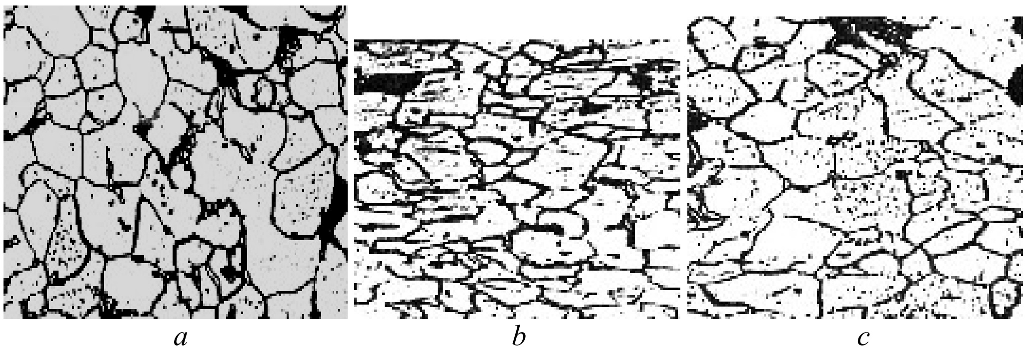

Fig. 4. Microstructure of the steel after hot rolling (a), cold reduction 40 % (b) and eight bending cycles (c). Magnification 800

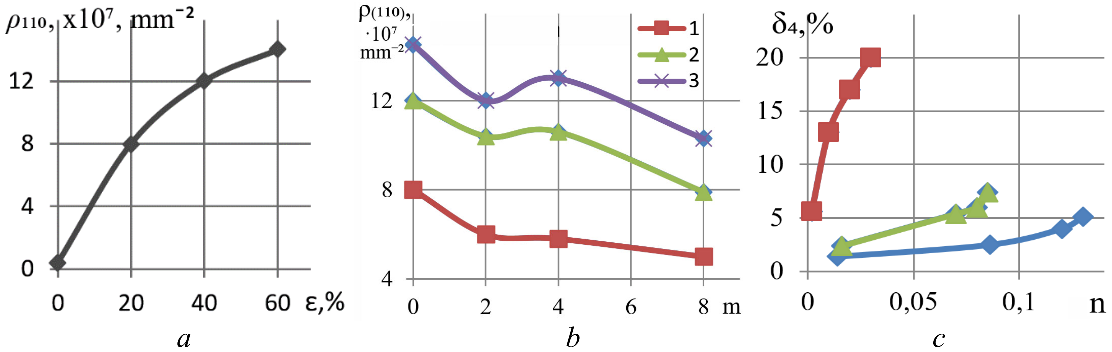

Fig. 5. Influence of the degree deformation (a), deformation of rolling (1—20; 2—40; 3—60 %) and *m* on (ρ_{110}) (b) and the mutual of change n and δ_4 (c)

However, this is not enough to explain effect softening of metal with a qualitatively different structural state. Compared to unidirectional deformation, especially at region of small plastic deformations, when the distribution of dislocations corresponds to an almost uniform distribution, the softening of metal when the sign of loading changes is explained by the annihilation of dislocations from the initial deformation [6, 7]. In this case, the maximum softening for different steels appears at a certain degree of preliminary deformation, which is 3…8 %. Exceeding the indicated values is accompanied by a gradual decrease in the effect and, after deformation, 6…10 % it almost disappear.

The observed phenomenon of soften after alternate bending of cold deformed steel by 20…60 % (Fig. 2, 3), is quite difficult to explain only by the development annihilation of the dislocations. The main difficulty is the replacement of uniform distribution of dislocations by the dislocation cell structure. Indeed, in proportion to the degree of plastic deformation, ranging from deformations of 20…25 %, the uniform distribution of dislocations turns into periodic structures, of varying degrees of the perfection [10, 12].

Moreover, already starting from the deformation of about 10 %, the observed appearance of first signs formation of structural elements with a predominant crystallographic orientation is accompanied by significant changes at complex of properties. The effect of softening from alternate bending at steel studied should be considered as corresponding to a developed cellular structure of the dislocation, which has an acute texture after cold rolling. Therefore, conduct of additional studies changes of the substructure of cold deformed metal after alternate bend will allow, to a certain extent, to approach the explanation of the soften mechanism. In addition, the execution of the ratio $\delta_4 \sim f(n)$ (Fig. 5 c) deserves a certain attention. If the previously indicated ratio was observed mainly for low - carbon steels with a relatively equilibrium structural state [10, 12] and polyhedral form of ferrite grains, then for cold deformed steel, its implementation is unexpected.

Indeed, as follows from Fig. 5 c, regardless of the structural state, starting from the hot-rolled structure, cold-rolled textured metal and after alternate bending, the strain hardening coefficient and the ductility of low-carbon steel are directly proportional.

Conclusions

1. Soften during alternating bending of cold-rolled low-carbon steel is accompanied by an increase in ductility and ability to strain hardening.

2. The number of alternating bending cycles has a different effect on the change at strength and plastic properties of cold-rolled steel. Almost the maximum reduction in strength properties is achieved after 4 cycles, and the increase in relative elongation and strain hardening coefficient continues even after 8 cycles.

3. Alternating bending of cold-rolled low-carbon steel is accompanied by a change at morphology of the ferrite structure. Ferrite grains elongated in the rolling direction, after 8 cycles of alternating bending, become close in shape to a polyhedron.

4. The non-monotonic nature of the change in dislocation density depending on the number of bending cycles indicates complex substructural changes in cold-rolled metal.

5. For low-carbon steel, regardless of the degree of cold reduction and the number of bending cycles, the strain hardening coefficient and ductility are directly proportional.

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ЯВИЩЕ ПОМ’ЯКШЕННЯ ХОЛОДНОДЕФОРМОВАНОЇ НИЗЬКОВУГЛЕЦЕВОЇ СТАЛІ ПРИ ЗНАКОЗМІННОМУ ЗГИНІ

Реферат

Використання пластичної деформації в якості інструменту керування комплексом властивостей холоднодеформованої низьковуглецевої сталі є актуальною проблемою. На підставі цього, метою роботи стала оцінка ступеня пом’якшення холоднокатаної низьковуглецевої сталі при знакозмінному згині. Для досягнення мети необхідно вирішити наступні завдання:

– дослідити вплив ступеня холодної деформації прокаткою на поєднання міцністних, пластичних властивостей, здатності сталі до деформаційного зміцнення;

– оцінити ефект впливу знакозмінного вигину на структуру та властивості холоднодеформованої сталі;

– оцінити зміни густини дефектів кристалічної будови холоднодеформованого металу після використання знакозмінного вигину.

У результаті виконання роботи було виявлено, що: пом’якшення при знакозмінному вигині холоднокатаної низьковуглецевої сталі супроводжується зростанням пластичності та здатності до деформаційного зміцнення. Число циклів реверсивного вигину по-різному впливає на зміну міцністних та пластичних властивостей холоднокатаної сталі. Практично максимальне зниження міцністних властивостей досягається вже після 4 циклів, а збільшення відносного подовження та коефіцієнта деформаційного зміцнення триває навіть після 8 циклів. Реверсивний вигин холоднокатаної низьковуглецевої сталі супроводжується зміною морфології структури фериту. Витягнуті в напрямку прокатки зерна фериту після 8 циклів реверсивного вигину за формою стають близькими до поліедра. Немонотонний характер зміни щільності дислокацій від числа циклів вигину свідчить про складні субструктурні зміни холоднокатаного металу. Для низьковуглецевої сталі, незалежно від ступеня холодного обтиснення та числа

циклів реверсивного вигину, коефіцієнт деформаційного зміцнення та пластичність пов'язані прямо пропорційним співвідношенням.

Отримані результати можуть становити певний практичний інтерес — можливість, без зміни форми холоднодеформованого прокату та використання нагріву, підвищувати його пластичні характеристики.

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