ISSN 1027-5495. Functional Materials, 27, No.4 (2020), p. 723-729.
doi:https://doi.org/10.15407/fm27.04.723

The effect of sign variable bending on structural damage to low-carbon steel

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Received May 4, 2020

The formation and change in the structure of microdamages during successive deformations by tension and compression in the sheets of low-carbon single-phase steel DC04 (0.06 % C, up to 0.35 % Mn, up to 0.40 % Si, ~ 0.025 % S and P) during alternating sign variable bending (SVB) were studied. The deformation of the annealed bands at the initial stage (0.25 cycles) leads to the formation of a structure with microdamages in the form of pores in the stretched region, to decreasing in the frequency (ν) of natural vibrations of rectangular samples and normal elastic modulus (E). Straightening of the steel strips (deformation of the 0.5 cycle SVB) leads to the "degradation" of damages formed at the previous stage of the SVB in the stretched region of the strips, which is repeated with each straightening of the samples. The damage coefficient (D) increases with bending and returns to a value close to the previous one after straightening the strips. Changes in D with a change in the "tension — compression" strain occur intensively in the initial stages of SVB (0.25 1 cycles). With an increase in the SVB deformation to 10 or more cycles, the level of "degradation" of damage during straightening of the samples decreases, and the damage coefficient decreases slightly. Damages accumulate in the form of pores that do not undergo changes when the type of deformation changes.

Keywords: deformation, alternating bending, damage, structure, Young's modulus, degradation.

Вплив знакозмінного вигину на структурні пошкодження низьковуглецевої сталі. *А.А.Брюханов, Н.А.Волчок, С.І.Іовчев, Д.А.Дячок, Г.Герштейн, З.А.Брюханова*

Вивчено утворення і зміну структури мікропошкоджень при послідовних деформаціях розтягуванням і стисненням у листах низьковуглецевої однофазної сталі DC04 (0.06 % C, до 0.35 % Mn, до 0.40 % Si, ~ 0.025 % S і P), які моделювали знакозмінним вигином (ЗВ). Деформація відпалених смуг на початковому етапі (0.25 циклу) призводить до формування структури з мікропошкоджень у вигляді пір у розтягнутій області, до зменшення частоти (ν) власних коливань прямокутних зразків і модуля нормальної пружності (E). Випрямлення смуг (деформація ЗВ 0.5 циклу) сталі призводить до "деградації" пошкодження, що утворилися на попередньому етапі ЗВ у розтягнутій області смуг і повторюється при кожному випрямленні зразків. Коефіцієнт пошкодженості (D) збільшується при вигинах і повертається до значення, близького до попереднього, після випрямлення смуг. Зміни D при зміні деформації "розтягання — стискання" протікає інтенсивно на початкових стадіях знакозмінного вигину (0.25–1 циклу). При збільшенні деформації ЗВ до 10 і більше циклів величина "деградації" пошкодження при випрямленні зразків зменшується, коефіцієнт пошкодженості повільно збільшується. Відбувається накопичення пошкоджень у вигляді пір, які не зазнають змін при змінах виду деформації. Анізотропія D повторює анізотропію E.

Исследовано образование и изменение структуры микроповреждений при последовательных деформациях растяжением и сжатием в листах низкоуглеродистой однофазной стали DC04 (0.06 % C, до 0.35 % Mn, до 0.40 % Si, ~ 0.025 % S и P), которые моделировали знакопеременным изгибом (ЗИ). Деформация отожженных полос на начальном этапе (0.25 цикла) приводит к формированию структуры с микроповрежденностями в виде пор в растянутой области, к уменьшению частоты (ν) собственных колебаний прямоугольных образцов и модуля нормальной упругости (E). Выпрямление полос (деформация ЗИ 0.5 цикла) стали приводит к "деградации" поврежденностей, образовавшихся на предыдущем этапе ЗИ в растянутой области полос и повторяется при каждом выпрямлении образцов. Коэффициент поврежденности (D) увеличивается при изгибах и возвращается к значению, близкому к предыдущему, после выпрямления полос. Изменения D при смене деформации "растяжение — сжатие" протекает интенсивно на начальных стадиях знакопеременного изгиба (0.25–1 цикла). При увеличении деформации ЗИ до 10 и более циклов величина "деградации" поврежденностей при выпрямлениях образцов уменьшается, коэффициент поврежденности медленно увеличивается. Происходит накопление поврежденностей в виде пор, не претерпевающих изменений при изменениях вида деформации. Анизотропия D повторяет анизотропию E.

1. Introduction

The phenomenological models of fracture of solids currently being developed use data on the accumulation of damage during plastic deformation [1]. Damage $D(\mathbf{n})$ (damage coefficient) of the material is characterized by the ratio of the area of an element $dS^*(\mathbf{n})$ ($\mathbf{n}$ is normal to the plane) of the cross section of the body damaged by micropores, microcracks, piles of dislocations, to the total area $dS(\mathbf{n})$ without taking into account any microdamage:

$$D(\boldsymbol{n}) = \frac{dS^*(\boldsymbol{n})}{dS(\boldsymbol{n})}. \quad (1)$$

The production of parts from coiled steel by stamping methods requires preliminary straightening on rollers with successive multiple alternating bending (SVB), which means a violation of the straightness of the main axis of the sheet [2].

With the AB of flat objects, metal layers spaced apart from the median plane at a distance dy alternately experience compression and tensile deformations [3]. In this case, defects in the form of micro damages appear in the bulk of the metal subjected to tension, and their appearance changes when the type of deformation changes.

The aim of this work was to study the formation and changes in the structure of microdamage during successive tension and compression deformations in connection a change in the moduli of normal elasticity in single-phase low-carbon steel sheets.

2. Experimental

Determination of differential damage at different points of samples according to Eq. (1) by direct measurements of $dS(\mathbf{n})$ and $dS^*(\mathbf{n})$ requires cutting out the samples and special surface treatment for electron microscopy [4]. Integral damage distributed over the entire volume of a solid affects the characteristics of the interaction between its parts. This affects a number of properties of bodies, for example, the electrical conductivity of the body in the direction (n), the speed of propagation of sound waves, density, hardness, elasticity, etc. [5]. Therefore, $D(\mathbf{n})$ can be estimated by the change in these values relative to some standard which is considered undamaged. For viscoelastic materials, the most acceptable property for such purposes is the normal modulus (Young's modulus $E(\mathbf{n})$).

Young's modulus is determined from the stress-strain diagrams in the elastic region (static or isothermal modulus) and substantially depends on the density of defects in a plane perpendicular to the direction of tension. According to [5], the damage coefficient is determined by the ratio *of* the defective Young's modulus ($E_0 - \tilde{E}$) to its value in a defect-free state

$$D = \frac{E_0 - \tilde{E}}{E_0}, \quad (2)$$

where E_0 is Young's modulus in the intact state, i.e. in the linear part of the tensile curve; $\tilde{E}$ is Young's modulus of the sample in a damaged state.

This approach is destructive, involves cutting and sample preparation according to a special standard, for example [6].

In [7], the nucleation and development of damage in sheets of two-phase steel DP600 during tensile deformation was studied based on measurements of Young's modulus by the dynamic method. A satisfactory cor-

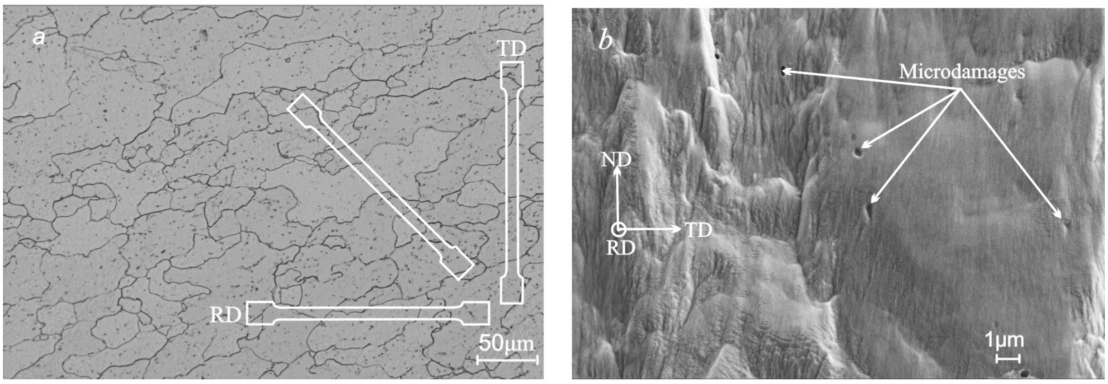

Fig. 1. Microstructure of steel sheets DC04. RD — rolling direction, TD — transverse direction, ND — normal direction.

relation of the level of damage was observed between the results obtained by measurements of Young's modulus and the data of direct measurements by electron microscopy.

Young's modulus is determined with high accuracy by measuring the frequency of natural vibrations of cylindrical or rectangular samples [8]. The method is based on solving the equation of transverse vibrations of a rod of constant cross section, obtained in the form [9]:

$$\frac{\partial^2 y}{\partial t^2} + b^2\chi^2\frac{\partial^4 y}{\partial x^4} = 0, \quad (3)$$

where $b^2 = E/\rho$ is the velocity of longitudinal vibrations in the rod, χ is the radius of inertia relative to the line passing through the axis and perpendicular to the plane of bending.

Solution of Eq. (3) is mainly determined by the border conditions. For a rod with free ends, the solution has the form [9]:

$$E = 1.108548 \cdot \rho \cdot \frac{l^4}{d^2} \cdot \nu^2, \quad (4)$$

where ν is the natural frequency of the plate; ρ is the density of the substance; l is the rod length; d is the thickness of the rod in the plane of bending.

It is essential that the natural frequency of the rod does not depend on its thickness in the direction perpendicular to the bending plane. For plates, only the length and thickness affect the accuracy of determining E.

For curved rods, the boundary conditions remain the same as for straight bars [9]. The ratio of the thickness of the samples to the radius of curvature of their bending is small; therefore, the corresponding corrections for an increase in length can be neglected [9] and for plates bent by rolling on rollers (in the absence of sharp bends) formula (4) can be quite acceptable.

When various discontinuities appear in the metal bulk, not only E changes, but also its density due to an increase in the sample volume. Therefore, to assess the level of damage to a polycrystalline sample, it is logical to use the parameter E/ρ in (1). Then (1) will take the form:

$$D = 1 - \frac{\tilde{E}}{E_0} \cdot \frac{\rho_0}{\tilde{\rho}} = 1 - \frac{\tilde{E}}{E_0} \cdot \frac{V_0}{\tilde{V}},$$

where V_0 is the volume of the sample in an undamaged state; $\tilde{V}$ is its volume in a damaged state.

Using the methods at our disposal, we did not find changes in V during bending deformations due to their smallness. Therefore, to estimate D, we used (2).

3. Results and discussion

The research material was steel sheets DC04 (0.06 % C, up to 0.35 % Mn, up to 0.40 % Si, ~ 0.025 % S and P) with a single-phase ferrite structure, 2 mm thick under delivery conditions from "Salzgitter Flachstahl" (Fig. 1a). Point contrasts within and along the boundaries of ferrite (Fe) grains are probably due to the presence of pearlite inclusions ($Fe + Fe_3C$). Their volumetric amount in steel with 0.06 % carbon is 5 %. This amount of pearlite (88 % ferrite + 12 % Fe_3C) does not significantly affect the properties of steel. Within the framework of these studies, steel can be considered single-phase.

Scanning electron microscopy with magnification (×5000) reveals the presence of damages in the form of pores distributed over the grains and their boundaries (Fig.

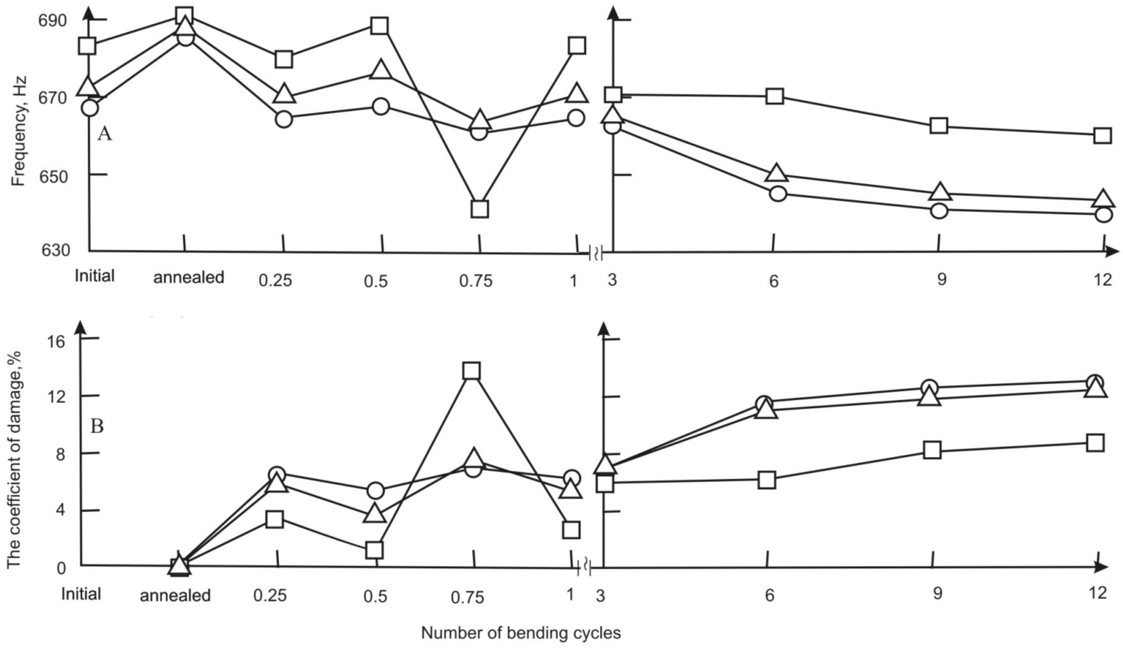

Fig. 2. Changes in the natural transverse vibrations of flat samples (A) and in the damage coefficient (B) for DC04 steel after deformation by a different number of alternating bending cycles in the directions: ○ — RD, □ — RD + 45°, Δ — TD.

1b). The company declares a guaranteed yield point ($\sigma_{0.2}$) < 210 MPa, ultimate tensile strength (σ_u) in the range of 270–350 MPa, density — 7870 kg/m^3 [10].

Cards 120×120 mm^2 in size were cut from the sheets and were annealed at a temperature of 275°C in a neutral gas atmosphere for 24 h to obtain the maximum possible intact structure [7, 11]. Rectangular samples (strips) 12×80 mm^2 in size were cut from the cards in the rolling direction (RD, RD + 45°) of the sheet and the transverse direction (TD), respectively (see Fig. 1a). Samples were processed in a bag, achieving the same size. In this case, equation (2) taking into account (4) takes the form:

$$D = 1 - \frac{\tilde{\nu}^2}{\nu^2}, \quad (5)$$

where $\tilde{\nu}$, ν are the vibration frequencies of samples with damaged and undamaged (annealed) structures, respectively.

The samples were subjected to deformation by alternating bending (SVB) with 0.25, 0.5, 0.75, 1, 3, 6, 9, and 12 cycles on the rollers with a diameter of 50 mm. An installation for bending by rolling ensured uniform deformation along the entire length of the sample.

One deformation cycle included bending to one and the opposite sides and returning the sample to a straightened state. The plates were straightened by hand using clamps and a correction tool. Thus, 0.25 deformation cycle implies deformation of opposite sides of the samples by compression and tension. Surface layers to a depth of 0.2 mm were deformed by ~ 3–4 %.

The samples were placed on resonator prisms, one of which was moved by means of a "screw-nut" pair. To achieve a stable sound, the positions of the nodes of the standing wave were found according to the condition of 22.43 % of the distance from the ends of the plate [9]. The natural vibrations of the plate were excited by the impact of a graphite rod on its central part. The frequency of the natural vibrations was measured by the resonance method with the Spectra PLUS computer program [12]. The level of damage was evaluated according to (5) relative to the annealed state. The measurement results are shown in Fig. 2.

The vibration frequency of the annealed steel samples is higher than that of those cut from sheets directly on delivery. The frequency and Young's modulus in RD + 45° are higher than in TD and RD.

A 0.25 cycle bend reduces the vibration frequency in all measuring directions. Straightening, i.e., opposite deformation, leads to an increase in the vibration frequency of the samples and, consequently, to an increase in Young's modulus. Since the samples had the same linear dimensions, the

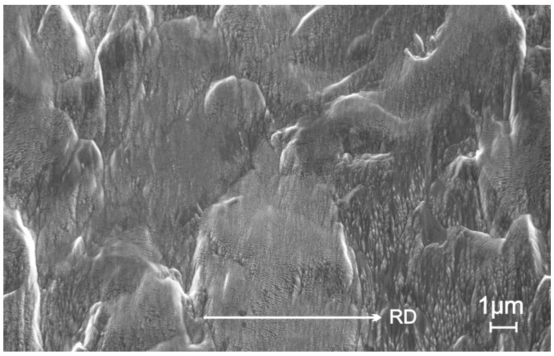

Fig. 3. Microstructure of DC04 steel sheets after pre-crystallization annealing.

change in ν^2 characterizes the changes in elastic moduli in the case of SVB. This, in turn, makes it possible to estimate the density of damages *D* in steel during SVB (Fig. 2b).

The most dramatic changes in the frequency during bending are observed at the initial stages of SVB (0.25–1 cycles). Accordingly, for these cycles, a greater decrease in Young's modulus and an increase in *D* are observed. With an increase in the number of SVB cycles, a decrease in the amplitudes of frequency vibrations and *D* coefficients was observed. The frequency curves show slight declines in all directions, and the damage curves show deceleration.

Microstructures were studied on a SUPRY 40VP electron microscope. To study the microstructure, samples 5×5 mm^2 in size were cut from the central part of the strips after annealing and after SVB deformation.

To reliably distinguish between damage in the form of pores and other discontinuities, as well as to exclude the effect of mechanical damage in the form of grinding and polishing on the morphology of the sample surfaces, they were subjected to ion polishing. For this, the surface was treated with an ion beam on a GATAN Met Etch 683 3 kV installation for 90 min at an angle of inclination of 30°. Cross-sectional images of the samples were obtained from areas without cracks close to surfaces (~ 0.1 mm). The area of the electron spot on the sample surface was about (75×110) μm. In the annealed strips, damage in the form of pores is clearly not visible (Fig. 3). Their condition is close to a quasi-undamaged state [13].

After 0.25 cycle bending of the steel strips, on the side subjected to tensile deformation, damage was observed in the form of pores, predominantly spherical, inside the grains and at their boundaries (Fig. 4a). No obvious damage of the surface subjected to compression was observed (Fig. 4b).

After further deformations "bending — straightening", on microstructures against the general background of an increase in the number of damages and their sizes, their periodic decrease is observed when passing from tension to compression deformation (Fig. 5).

Microdamages are almost always present in technical materials even before an external load is applied [1]. In the field of viscoelastic deformation, they become provocateurs of the appearance and development of larger damages. Pre-crystallization annealing reduces the level of damage in the material. We see this in Fig. 3, where microdamages are not clearly observed, although the images of the microstructure contain darkened areas, which can be interpreted as remnants of microdamages of steel in its as-delivered state. Natural vibration frequencies and moduli of normal elasticity of samples increase. This is expressed in a decrease in the integral damage coefficient. The *D* changes are opposite and agree with *E* changes.

Bending up to 0.25 cycles initiates the formation of new damages in the region of elastic-viscous tension and the restoration of old ones left after factory processing. Electron-microscopic images show damages in the form of micropores, mostly spherical, in the stretching zone of the sample. Natural vibration frequencies and Young's moduli decrease in all measured directions (Fig. 2a). Damage factors increase in all three directions (Fig. 2b).

After straightening the samples, i.e. after deformation for 0.5 cycles, the natural vibration frequencies of the samples increase, and respectively, the coefficients D decrease. A change in the type of deformation at this stage of alternating bending leads to "degradation" of the microdamaged structure formed after bending 0.25 cycles in the tension region; this determines the frequency of natural vibrations of the samples and elastic moduli. The next bending (0.75 cycles of SVB) again leads to a decrease in the vibration frequencies of the samples and Young's moduli and to an increase in the damage coefficients. Thus, at this stage of SVB, the number of damages per unit of cross-sectional area not only increases, but also their morphology changes (Fig. 5b). If at the first stage of SVB the damages are mostly spherical, now they have a shape close to elliptical. This indi-

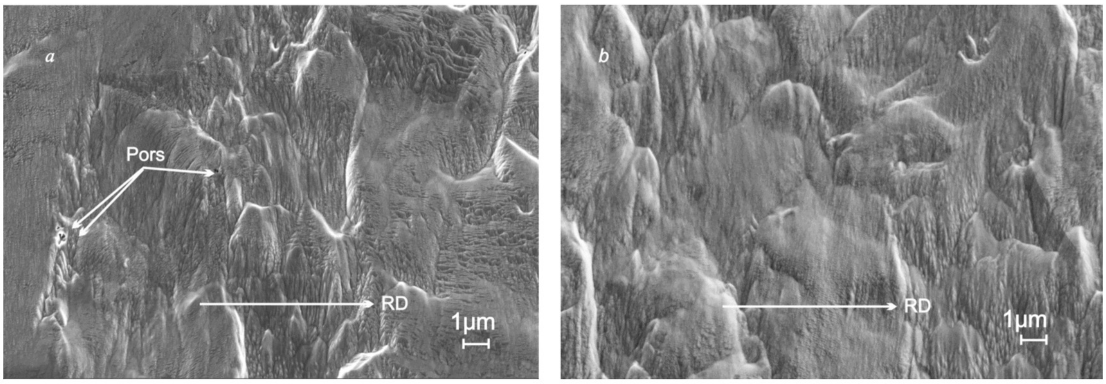

Fig. 4. Microstructure of steel sheets DC04: a) — in the field of tension, b) — in the field of compression.

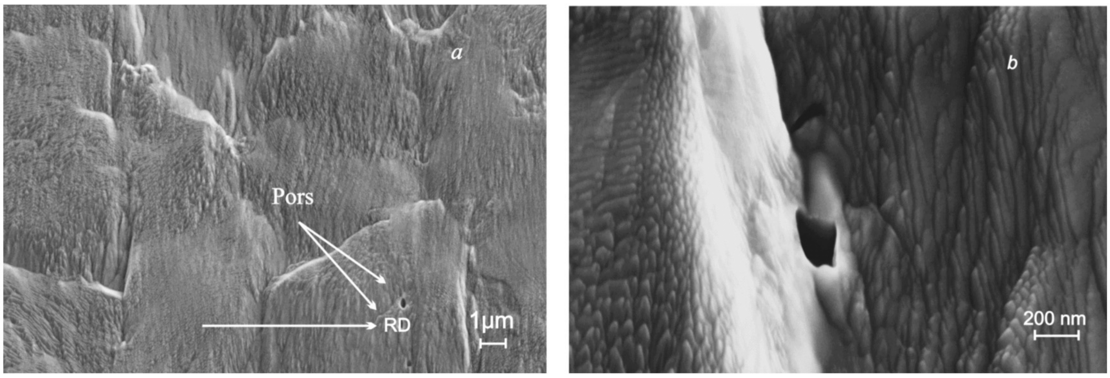

Fig. 5. Microstructure of DC04 steel sheets after deformation by 12 cycles of alternating bending: a) — × 5000, b) — × 20000.

cates the tendency to the formation of anisotropy in D. Scanning electron microscopy confirms this fact in the papers on the effect of tensile and compressive loads on the microstructure of low-carbon steels [14].

One complete SVB cycle again leads to "degradation" of the damaged structure in the area of change in tensile-compression deformation; however, the "degradation" does not reach the level corresponding to the previous stage in the straightened state (0.5 cycle). That is, there is a process of accumulation of damage in the sample bulk.

It was shown in [15] that the texture of industrial steel sheets of DC04 is characterized by a set of orientations: {111}<123> and {111}<112>, as well as close to them {554}<225> and {10 8 7}<135>. The scattering region includes the orientations {335}<712 3> and {112}<681>. The orientation {100}<001> is clearly present. The scattering region also includes {100}<012>. These observations are consistent with generally accepted data on the texture of recrystallization of bcc metals [16]. Therefore, the test steel is subjected to processing during the production process by means of final or intermediate recrystallization annealing. The main orientations of the {111} <UVW>type and those close to them are isotropic, but increase the average modulus of elasticity in the plane of the sheet. They act in the opposite direction to the actions of the damage.

The main contribution to the anisotropy of the elastic properties of the initial sheets is made by sharply anisotropic orientations {112}<110>, {100}<011>. For these orientations, the value of E in TD is higher than in RD. However, in representing the anisotropy of the elastic properties of these orientations in the form of Fourier series, the amplitudes of their fourth harmonics (A_4) have opposite signs and $|A_4|_{\{100\}} > |A_4|_{\{112\}}$ (see Table 1 in [14]). The total effect of these orientations leads to a decrease in the value of E in RD + 45°.

At the initial stages, deformation occurs in systems of maximum atomic density. For steels with a bcc lattice, these are {011}, {112}, {123} <111>. Stress as a characteristic of a tensor of the second dimension for a cubic crystal is isotropic. Therefore, the damages also occur in the form of pores with high symmetry. With multiple "tensile-compression" deformations, the accumulation of residual stresses and the activation of other, more rigid crystallographic deformation systems are possible. This leads to a violation of the symmetry of the shape of the damages.

4. Conclusions

The changes in the dynamic elastic modulus (*E*) of steel, measured by the frequency (ν) of natural vibrations of flat samples, make it possible to assess the level of integral damage (*D*) of a polycrystal at each stage of deformation by compression and tension.

When straightening DC04 steel (0.06 % C, up to 0.35 % Mn, up to 0.40 % Si, ~ 0.025 % S, P) on rollers, the strips were deformed by alternating bending (SVB). At the initial stage (0.25 cycles), this leads to a decrease in the frequency of natural vibrations and the modulus of normal elasticity of rectangular samples which is caused by the formation of a structure with microdamages in the form of pores in the stretched region. The level of integral damage is estimated by the ratio of the decrease in the elastic modulus to the modulus of the defect-free standard.

At the stage of 0.5 cycle (straightening of the strips), the deformation with SVB also leads to an increase in ν and *E* for three directions (RD — rolling direction, TD — transverse direction, and RD + 45°); according to the results of scanning electron microscopy, this is caused by the "degradation" of damage during deformation by compression of metal regions previously damaged by tensile deformation. The damage coefficient increases with bending and returns to a value close to the previous one in a straightened state.

Changes of *D* during the alternating "tension — compression" deformation are more intensive in the initial stages of the sign variable bending (0.25–1 cycles).

With an increase in the SVB deformation to 10 or more cycles, the value of "degradation" of damage during straightening of the samples decreases, and the damage coefficient increases slightly. Damages are accumulated in the form of pores, which are preserved by changes in the type of deformation. The character of the anisotropy of *D* is similar to the anisotropy of *E* for steel sheets and remains the same for the SVB with a large number of cycles.

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