

# Anisotropic Damage of Low-Alloy Steel Plates Under Uniaxial Tension After Alternating Bending

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## To cite this article:

Nataliia Shkatulyak, Elena Savchuk, Valentin Usov. Anisotropic Damage of Low-Alloy Steel Plates Under Uniaxial Tension After Alternating Bending. *American Journal of Mechanical and Industrial Engineering*. Vol. 1, No. 2, 2016, pp. 10-14.

doi: 10.11648/j.ajmie.20160102.11

Received: August 8, 2016; Accepted: August 19, 2016; Published: September 7, 2016

**Abstract:** Effect of low-cycle alternating bending and the crystallographic texture on the damage anisotropy of mild steel sheets DC01 (St 1.0330) at subsequent uniaxial tensile tests was examined. Analysis of anisotropy sheet material damage was performed using a symmetric tensor of damage  $D$  of the second order. In the case of uniaxial stress is not equal to zero only the sole component of this tensor. This component  $D$  was defined by the formula  $D = 1 - \sqrt{E/E_0}$ , where  $E_0$  is the elastic modulus of intact material;  $E$  is the current modulus determined at uniaxial tensile tests. Anisotropy of mechanical properties and damage take place in steel sheets at uniaxial tensile tests after deformation by alternating bending. The averaged damage of steel sheets at uniaxial tensile tests has minimal value after 3 cycles of alternating bending. The averaged damage of steel at uniaxial tensile tests increases with the intensity increase of "brittle" components of type  $\{001\} \parallel ND$  in the texture after alternating bending. Damage of steel at uniaxial tensile tests decreases with the intensity growth of "viscous" components such as  $\{110\}$ ,  $\{112\}$ ,  $\{111\}$  parallel to the rolling plane in the texture after alternating bending.

**Keywords:** Alternating Bending, Texture, Young's Modulus, Anisotropy, Damage, Low-Alloyed Steel

## 1. Introduction

Technological processing of coiled and sheet metal typically causes the formation of internal stresses in the material. This often leads to the known failure of products [1]. Therefore before using of the rolled metal the straightening by means of the roll straightening machine is often used. The material is subjected to alternating bending (AB) during the straightening. Such treatment reduces internal stresses in the metal and gives it the necessary planar characteristics that positively affects on the quality of the finished product. [1]. Changing of metal structure and mechanical properties occurs during the straightening, despite relatively small plastic deformations of stretching and compression [2]. In particular, there arise and accumulate uncontrollable micro cracks, micro pores, which have been detected already under stretching on 3-10% [3]. However, the effect of alternating bending on the anisotropy of damage accumulation in the sheet metal during the uniaxial tension has not been investigated. The emergence and accumulation

of micro defects indirectly reflected in changing of material properties, in particular, in changing of the Young's modulus. This can be used to measure the accumulation of damage in the metal structure [4].

The aim of this work is to establish the influence of low-cycle alternating bending and crystallographic texture on the anisotropy of damage sheets of mild steel DC01 (St 1.0330) at subsequent uniaxial tensile tests.

## 2. Material and Methods

Strips of steel DC01 (St 1.0312) ( $\geq 0.06$  C%;  $> 0.6\%$  Mn; 0.025% S; 0.025% P, Fe balance, wt. %) of thickness 1 mm in conditions "as received" after recrystallization annealing were used as initial material for research. Steel strips measuring  $100 \times 100$  mm were subjected to the AB by means roller diameter of 50 mm in the rolling direction (RD). The movement speed of the metal during bending was about 150 mm/s that corresponds to a strain rate  $\sim 10^{-2} \text{ s}^{-1}$ . Specimens for mechanical test in the RD, diagonal direction (DD) - at an

angle of 45° to the RD - and transverse direction (TD) and also samples for study of texture were cut from initial strips and strips after bending on 0.5; 1; 3 and 5 cycles. The mechanical tests samples cut in the RD, DD and TD were carried out at room temperature on a tensile testing machine Zwick Z250 / SN5A with power sensor at 20 kN. The total sample length was of 90 mm, the width of the working part was 12.5 mm. In each of above-mentioned directions were tested three samples. The value averaged by three samples was taken as meaning of mechanical properties in each direction.

Crystallographic texture was investigated by X-ray method [5] with the inverse pole figures (IPF). Samples were chemically polished to a depth of 0.1 mm for removing distorted surface layer before the recording of diffractograms. Reference sample (without texture) was produced from recrystallized fine powder of investigated steel. For the study of texture in RD were produced composite samples in the form strips of 3 mm wide pasted to each other that were cut perpendicular to the RD. Recording of diffractograms was performed on a DRON-3M in the filtered radiation  $K\alpha$ -Mo on both surfaces of the samples after the above-mentioned number of cycles of AB. Further were constructed IPF of

normal direction (IPF ND) and rolling direction (IPF RD).

Metallographic structures have been photographed by the microscope Axioplan 2 of the KARL ZEISS firm on end surfaces of samples cut in the RD and TD.

Analysis of anisotropy damage of steel sheets was performed by means a symmetric tensor of damage of the second order [6-8]. In the case of uniaxial stress is not equal to zero only the sole component of the tensor. This component  $D$  is defined by the formula [6-8]:

$$D = 1 - \sqrt{E/E_0}, \quad (1)$$

Where  $E_0$  is the elastic modulus of intact material;  $E$  is the current modulus determined at uniaxial tensile tests.

### 3. Results and Discussion

Results of mechanical tests and the damage after different number of AB cycles are shown on Fig. 1. Appropriate IPF's and the microstructure are shown on Fig. 2 and 3, respectively. Anisotropy of mechanical properties and damage  $D$  are observed (Fig. 1).

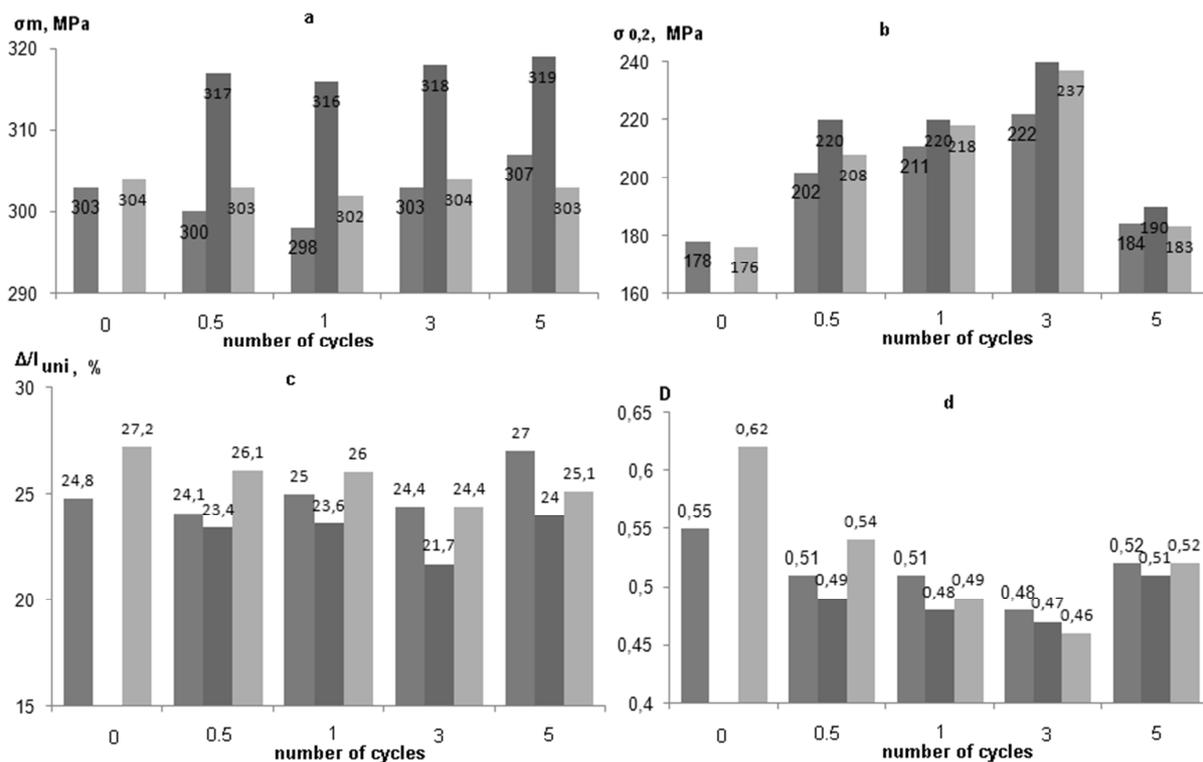


Figure 1. Dependence of tensile strength, proof strength, uniform elongation, and damage  $D$  from the number of AB cycles.

In the initial annealed samples the minimum of the ultimate strength and proof strength  $\sigma_{0.2}$  is observed in the TD, the maximum is in RD. Elongation showed the opposite result.

Tensile strength and yield strength have a maximum value in the DD (RD+45°) after the AB. The minimum value of the above properties is observed in the RD, while these properties have intermediate value in the TD. Elongation

shows the opposite result.

The average value of tensile strength  $\sigma_m$  increases from 304 MPa in the initial state to 310 MPa after 5 cycles of the AB. A similar trend is observed for  $\sigma_{0.2}$ . Mean value of the  $\sigma_{0.2}$  increased from 177 MPa in the initial state to 234 MPa after 3 cycles of the AB. After 5 cycles of the AB average value of  $\sigma_{0.2}$  decreased to 186 MPa.

Average values of relative uniform elongation  $\Delta l/l_{uni}$  and

damage  $D_{av}$  value averaged by direction in sheet are decreased with increasing number of AB cycles to 3. So  $\Delta l/l_{uni}$  decreased from 26% in the initial state to 23.5%, while  $D_{av}$  decreased from 0.68 in the initial state to 0.63 after 3 cycles of AB. After 5 cycles of the AB was observed an increase  $\Delta l/l_{uni}$  up to 25.4%. The average value of  $D_{av}$  at the same time increased to 0.64%.

Anisotropy coefficient of properties  $k$  in the sheets plane was calculated by the formula.

$$k = [(F_{max} - F_{min}) / F_{min}] \cdot 100\% . \quad (2)$$

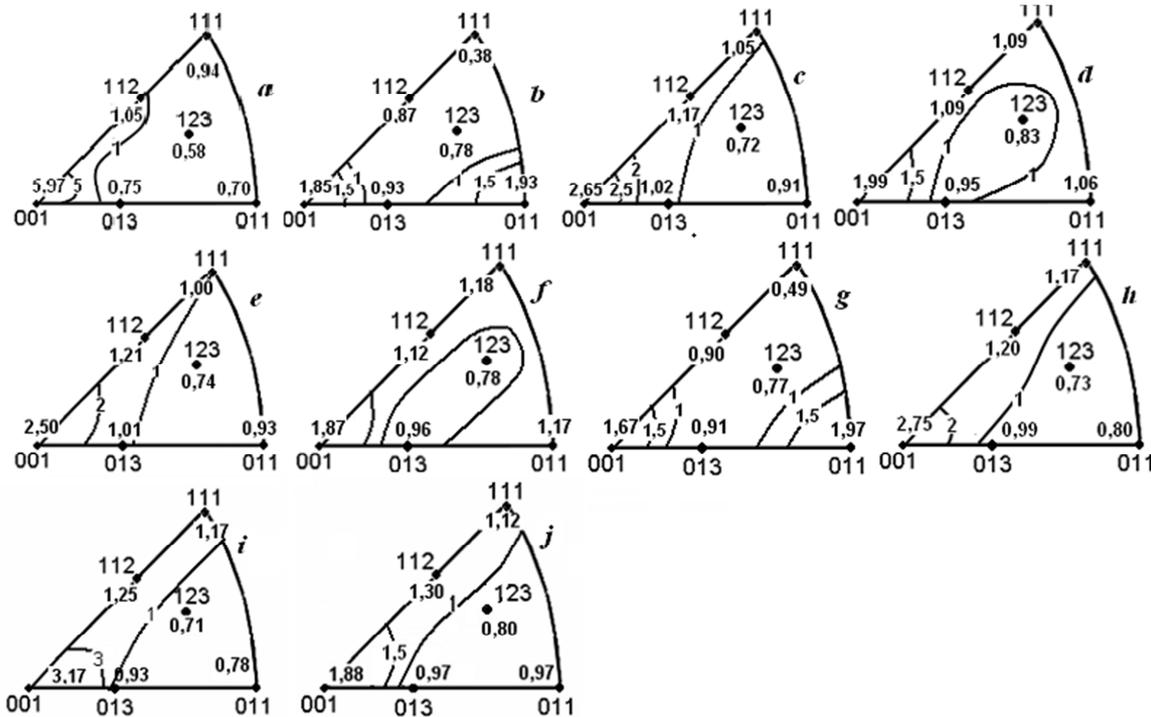
Here  $F$  is the corresponding property.

Coefficients of anisotropy  $k$  of properties in the plane of the sheets have grown with the increasing cycle's number of AB to 3. After 3 cycles of the AB  $k = 5.0, 6.8, 12.4,$  and  $13.6\%$ , respectively, for  $\sigma_m, \sigma_{0.2}, \Delta l/l_{uni},$  and  $D$ . Minimum of  $k$  values were observed after 5 cycles AB. Namely  $k = 3.9, 3.8, 4.5,$  and  $3.2\%$ , respectively, for  $\sigma_m, \sigma_{0.2}, \Delta l/l_{uni},$  and  $D$ .

Pretty strong quadratic correlation is observed between the damage  $D_{av}$  value averaged by direction in sheets and numbers  $n$  of AB cycles

$$D_{av} = 0.013n^2 - 0.079n + 0.567 . \quad (3)$$

Correlation coefficient  $R^2$  was 0.83.



**Figure 2.** IPF's of sheets steel in the initial state (a, b correspond to the ND and RD, respectively) and after deformation 0.5; 1; 3 and 5 cycles of AB (c - j corresponds to the ND); c, e, g, i, correspond to the sides of the sheet subjected to tensile deformation on the previous step; d, f, h, j correspond to the side of the sheet subjected to compression, respectively.

Figure 2 shows that in initial steel sheets are formed the texture, which is a combination of the rolling texture and recrystallization. This texture can be described as the  $\{001\} <110> + \{112\} <110> + \{001\} <100>$ . The first two of these components are typical deformation textures of body-centered cubic (bcc) metals and alloys [9]. The latter orientation is the typical recrystallization texture of face-centered cubic (fcc) metals, but not for steel with a bcc lattice. However, under certain conditions, when the treatment temperature exceeds of the temperature of polymorphic transformation, in the steel can be formed a strong cubic texture of  $\{001\} <100>$  [10].

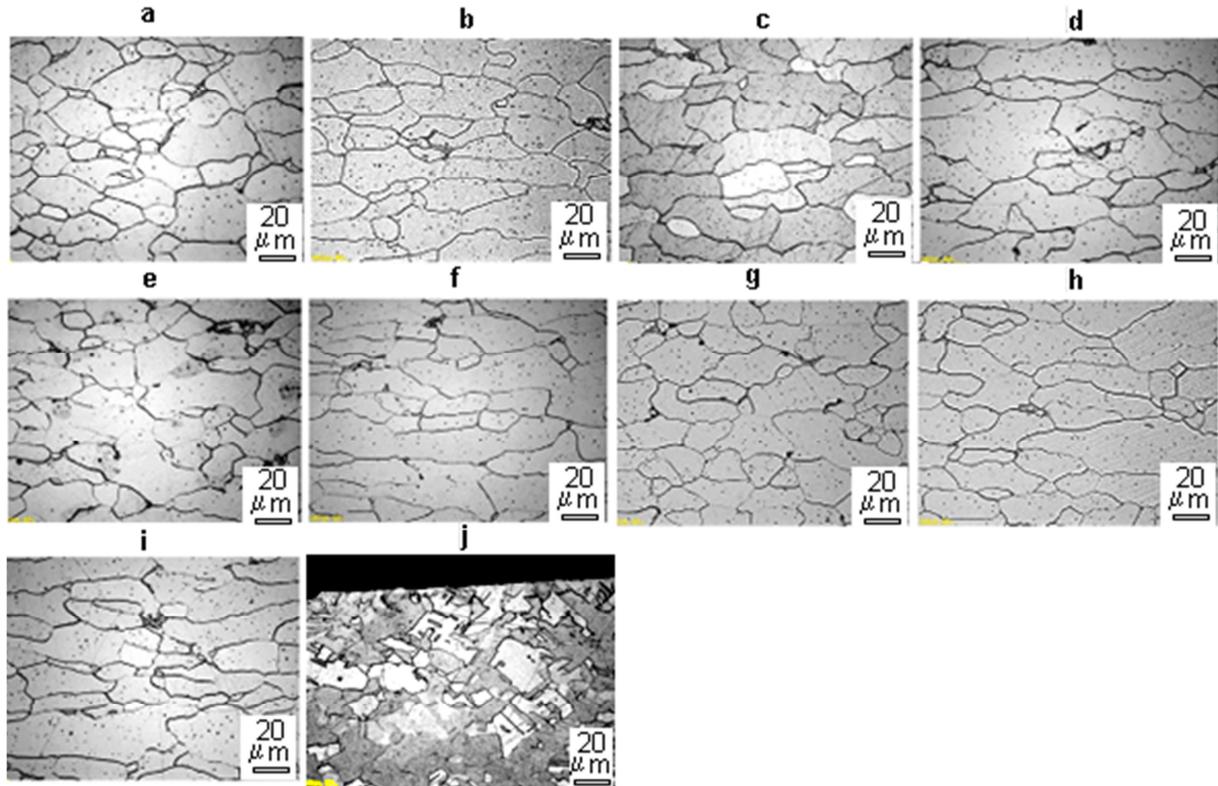
After deformation by 0.5 cycles of AB along with the above mentioned deformation texture begins formation of a component of the  $\{011\} <100>$  that are usually observed after strain by torsion [11]. Formation of shear texture component during the AB can explain the following model

deformation. Grains of metal layers on the convex side exposed to the action of tensile stresses when bending in one direction of the sample (0.25 cycles). In the same time, on the concave side arise compressive stresses. In the strip is initiated the shear deformation as a result of the action of stresses opposite sign. Direction of acted stresses is reversed when bending the strip in the opposite direction. Thus, in the metal strip occur alternating shear deformations, which lead to the formation of the shear texture components during the AB. Authors were observed previously [12] the formation of shear texture components in steel.

The maximum intensity of component shear texture along with increased of intensity of components deformation texture is observed after 1 cycle of AB. Increasing of cycles number of AB to the 3 promotes to further increase the intensity of the above components of deformation texture. The pole density of component shear texture is decreased at

this. Research nature texture during rolling differently oriented single crystals of silicon iron Fe - 3% Si showed that crystals of  $\{011\} \langle 100 \rangle$  are deformed not only by slip, but also by twinning on systems  $\{112\} \langle 111 \rangle$  and by turning around  $\{110\}$ . This leads to a change in texture on  $\{111\} \langle 112 \rangle$ . Grains of polycrystalline silicon iron with the initial

orientation  $\{011\} \langle 100 \rangle$  are changed the orientation in the sequence  $\{011\} \langle 100 \rangle \rightarrow \{111\} \langle 112 \rangle \rightarrow \{112\} \langle 110 \rangle \rightarrow \{001\} \langle 110 \rangle$  at the rolling [13]. A similar trend in texture transformations is observed and after 3 and 5 cycles of AB (Figure 2). The twinning also occurs after 3 cycles of AB as shown on the respective microstructure (Figure 3).



**Figure 3.** The microstructure of steel sheets in the cross sections perpendicular to the RD and TD in the initial state (a, b) and after deformation of 0.5; 1; 3 and 5 cycles of AB; c, e, g, i correspond to the RD; d, f, h, j correspond to the TD.

The twinning as is known occurs when arise the difficulty of the slip during the deformation. The twinning promotes ductility increase, and also, due to the reorientation, provides more favorable development of the basic mechanism of plastic deformation i.e. slip [14].

Deformation by 5 cycles of the AB leads to the gain of deformation texture. The shear texture is completely disappears. Number of twins increased on corresponding micrograms after 5 cycles of AB (Figure 3i, j). The presence of twins on the corresponding micrographs indicates the activation of mechanism of plastic deformation by the twinning. Mechanisms of the twinning in bcc metals were considered, for example, in [13]. One of the consequences of the twinning is the reduction of work hardening rate due the shift by twinning [15]. Twinning abruptly reduces the force needed to deformation [15]. Thus, at the activation of the twinning should expect a decrease in strength properties and an increase of the plasticity, in line with our experimental data. Earlier it was noted during the deformation of hexagonal AZ31 alloy [16].

The planes of the cube are main planes of the brittle cleavage in bcc metals [14]. Therefore, we should expect a damage value increase with the growth of pole density  $P_{001} \parallel$

ND to the rolling plane. Let's call these orientations of crystals "brittle" steel texture components.

Texture with crystallographic planes  $\{111\}$  parallel to the sheets plane improves their plastic properties [14]. Consequently, the increase in the texture of sheets pole density  $P_{111} \parallel$  ND will promote to reduce the damage. Orientations  $\{110\}$  and  $\{112\}$  will render probably a similar influence [12]. Let's call such crystal orientation "viscous" components of the texture of steel.

Crystallographic planes of type  $\{001\}$ ,  $\{110\}$ ,  $\{112\}$ , and  $\{111\}$  basically are disposed parallel to the rolling plane (Figure 2).

Close correlations were established between averaged by direction in sheets  $D_{av}$  and averages on both sides of sheets values of pole densities  $P_{001}$ ,  $P_{110}$ ,  $P_{112}$ ,  $P_{111}$  on IRF's ND (Figure 2). For example, there is a strong linear correlation of the damage  $D_{av}$  with the pole density  $P_{001}$

$$D_{av} = 0.026P_{001} + 0.434. \quad (4)$$

Correlation coefficient  $R^2$  was 0.90. Thus, the damage increases with increasing intensity of the "brittle" components in the texture of steel.

The strong linear correlation was established between  $D_{av}$  and pole density  $P_{av} = (P_{110} + P_{112} + P_{111})_{av}$  averaged over all IPF ND. Correlation coefficient  $R^2 = 0.99$

$$D_{av} = -0.454P_{av} + 0.996. \quad (5)$$

Thus, the damage decreases with increasing intensity of "viscous" components in the texture of steel.

## 4. Conclusion

- (1). Texture of low-alloy steel sheet in the initial (annealed) state is a combination of orientations of the rolling and recrystallization  $\{001\} \langle 110 \rangle + \{112\} \langle 110 \rangle + \{001\} \langle 100 \rangle$ .
- (2). Deformation of steel sheets by 0.5, and 1 cycles of alternating bending promotes the development of the typical texture of deformation of bcc metals and alloys, as well as of the shear texture component  $\{011\} \langle 100 \rangle$ .
- (3). Increasing of cycles number of alternating bending to the 3 promotes to further increase the intensity of the above components of deformation texture. Average values of strength are increased, and plasticity and damage are decreased.
- (4). Deformation by 5 cycles of the alternating bending leads to the gain of deformation texture. The shear texture is completely disappears, and the number of twins observed in the microstructure of the steel increases.
- (5). Anisotropy of mechanical properties and damage take place in steel sheets at uniaxial tensile tests after deformation by alternating bending.
- (6). Damage has minimal value at uniaxial tensile tests after 3 cycles of the alternating bending.
- (7). The damage  $D_{av}$  of steel at uniaxial tensile tests after the alternating bending of steel increases with the intensity increase in texture of "brittle" components type of  $\{001\} \parallel \text{ND}$ .
- (8). The damage  $D_{av}$  of steel at uniaxial tensile tests after the alternating bending decreases with the intensity growth in texture of "viscous" components such as  $\{110\}$ ,  $\{112\}$ ,  $\{111\} \parallel \text{ND}$ .

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