DAMAGE AND MAGNETIC PARAMETERS OF STEEL AFTER PLASTIC DEFORMATION UNDER HYDROSTATIC PRESSURE

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Abstract: The effect of plastic tensile deformation on changes in density and on magnetic properties was investigated for samples of low-carbon steel under hydrostatic pressure of 0.1 to 500 MPa in a test chamber. It was shown that the parameters of minor magnetic hysteresis loops could be used to indicate the degree of plastic deformation and the deformation-related structural damage of metal.

Introduction: It is known [1] that during cold plastic deformation the discontinuity of metal occurs. Micropores and microcracks are observed as early as at early stages of plastic deformation, which is connected with the interaction between dislocation stress fields and barriers in the metal structure (grain boundaries, phase boundaries, inclusions, particles, dislocation clusters etc.) as well as with the decohesion of the matrix and inclusions due to a difference in their elastic properties. The formation of discontinuities is accompanied by partial relaxation of the elastic energy [2]. Along with the emergence and development of microdefects, defect "healing" occurs in plastically deformed metal under omnilateral compression. For instance, complete healing of discontinuities under omnilateral compression was observed for copper [3]. Besides, it was noted that defect healing under omnilateral compression is most efficient in plastic deformation of metal. The processes of discontinuity emergence and closing are accompanied by a local change in the elastic energy of material; therefore, there is also a change in the magneto-elastic energy of the ferromagnetic material in the regions adjacent to the defects, and this must affect the magnetic structure-sensitive characteristics [4 – 7]. The purpose of this work is to investigate the effect of changes in structural parameters and micro-defect accumulation in deformation under various stress states as applied to the development of magnetic methods for the determination of plastic strain degree and for the evaluation of the structural damage of metal.

Results: Commercially molten low-carbon (0,2 % C) steel was studied. Tensile test samples 5 mm in the test portion diameter were made of hot-rolled rods, which were ground and subjected to annealing for 1 hour in vacuummized ampoules at 700^{o}C. In order to change the stress state, at which deformation was performed, and to reduce the probability of micro-defect formation, tensile deformation was carried out on a test unit [8] under hydrostatic pressure of liquid in a working chamber, P = 0.1; 200 and 500 MPa. The pressure of the liquid was kept constant in the run of each test. Castor oil was used as the liquid in the working chamber. The samples were strained at various values of accumulated strain degree Λ not exceeding the strain degree at the instant of neck formation. The sample diameters, d_0 before testing and d_1 after it, were measured by an instrumental microscope at an accuracy of up to 5x10^{-3} mm. Shear strain degree was calculated by the formula $\Lambda = 2\sqrt{3}\, ln(d_0/d_1)$ [9]. For further investigations, a middle part was then cut out of the deformed samples to prepare samples 9.55±1 mm long and 4.7÷5.0 mm in diameter.

The change in the metal density was used to characterize the amount of discontinuity accumulation. The sample density measurements were taken by means of differential hydrostatic weighing [10] in tetra-bromoethane with a density of 2960 kg/m^3 at 20^{o}C. The temperature of the liquid was checked by means of a mercury thermometer. The density measurements at various temperatures were then corrected to the temperature of 20^{o}C by computing. The weighing result was an average over 5÷7 measurements.

The magnetic characteristics (coercive force and residual induction) were determined by means of ballistic technique on minor hysteresis loops during magnetization in moderate (B_{max}=0.45T) and weak (B_{max}=0.05T) magnetic fields.

Plastic deformation and fracture are the processes that hinder elastic energy accumulation under mechanical loading. Without thermal influence, deformation in BCC-metals is mainly effected by a dislocation mechanism, with each shift of dislocation being an elementary act of the local relaxation of elastic stresses. When load exceeds the yield point, the slip of existing dislocations and emergence of new ones occur in metals, dislocation clusters are formed at the barriers, and the accumulated energy grows thus necessitating greater stresses to continue the deformation (the process of strain hardening). The relaxation of elastic stresses only due to plastic deformation proves to be ineffective, and thus local micro-fractures appear and grow in the metal at the same time. In cold deformation, as a rule, these micro-fractures occur by the dislocation mechanism or they are caused by the decohesion of incoherent boundaries. Among numerous dislocation mechanisms of fracture, in BCC-metals the mechanisms related to the formation of elastic microcracks seem to be most probable, when the leading dislocations merge in flat dislocation clusters at the barriers (the Zener and Stroh-Yokobory mechanisms) and when slip bands are intersected (the Cottrell mechanism) [11]. In plastic metals such microcracks grow dull immediately and transform into micropores (Fig. 1, *a*). The initial size of such micropores ranges between 0.5 and 2.0 microns. The formation of micro-defects results in the development of fragmentation, the activation of collective dislocation defects, the development of the rotation mode of plastic deformation, and all this contributes to both metal hardening and local stress relaxation.

As early as at the early stages of elastic-plastic deformation, the loosely held boundaries between the metal matrix and the structure inhomogeneities in the form of non-metal particles, inclusions, intermetallides, carbides, etc. are prone to decohesion. The formation of these micro-defects leads to the relaxation of microstresses in a certain volume of the matrix, which depends on the size of the structure inhomogeneities and can range from a few microns to tens of microns, with the resulting micro-fractures being of the same size. As the deformation proceeds, the micro-defects grow, merge by the mechanism of internal neck formation, and microcracks (pores) appear (Fig. 1, *b*). The microcracks (pores) form a front of prefracture where a breaking crack occurs. Pores formed by decohesion on hard-to-deform inclusions gradually become elongated in the direction of maximum tensile strains (Fig. 1, *c*).

Fig. 2, *a* shows that, as strain degree Λ grows, the material suffers plastic loosening due to the formation and development of discontinuities. This loosening is characterized by a monotonic decrease in the relative density of the sample material $\Delta\gamma/\gamma_0 = (\gamma_i-\gamma_0)/\gamma_0$, where γ_0 = 7872.4 kg/m^3 is initial sample material density and γ_i is sample material density after deformation. It is obvious that the greater is the value of omnilateral compression.

Discussion: *P* in the test chamber, the smaller is the value of $\Delta\gamma/\gamma_0$, and this is associated with a decrease in the intensity of micro-discontinuity formation. The increasing hydrostatic pressure hinders the development of micro-defects during deformation and facilitates the closing of some previously formed defects. As the strain degree rises, the coercive force and residual induction both measured at various magnetic fields grow (Fig. 2, *a*), and this is indicative of hampered magnetization and reversal magnetization due to higher values of the critical fields of interaction between the domain boundaries and the defects in the metal structure [5, 12 to 20].

Fig.1

Discussion: A number of factors influence reversal magnetization. A notable change in the magnetic characteristics occurs as early as at small values of strain degree. According to the model representations of the effect of dislocations on reversal magnetization [13, 15 to 19], the coercive force is associated with the dislocation density as $H_c \sim \sqrt{N}$. Therefore the coercive force increases as the dislocation density grows at the initial stage of deformation. The further increase in the values of magnetic characteristics results from the evolution of the dislocation and domain magnetic structures, which is associated with the formation of dislocation walls as they are the effective areas for domain boundary fixing. Near the inclusions and in the regions of high microstress gradients [4, 21 to 23] there appears a disperse structure of 90^o magnetic domains, which is typified by critical fields approximately 1.5 times as great as those for magnetic structures with 180^o domains [24]. As this occurs, these regions may be quite large in volumes, as is the case in [21, 22] demonstrating that the domain structure distortion zone near an inclusion may be 300 times as great as the inclusion itself.

Under the effect of loads applied in plastic deformation there also appears a magnetic texture accompanied by induced magneto-elastic anisotropy leading to the appearance of a predominant direction of reversal magnetization (magnetic uniaxiality) [4, 25]. At positive values of magnetostriction, this will somehow facilitate the magnetization and reversal magnetization processes when the direction of the magnetic field coincides with the direction of loading. Under sufficiently heavy loads, plastic flow may appear in some regions near micro-defects, and this may result in microstress relaxation in these regions. These processes will be accompanied by the relaxation of elastic energy E_y in the neighboring local volumes, and they will cause lower magneto-elastic energy E_{me} in these volumes. This, in turn, will entail the rearrangement of the domain structure and a smaller number of 90^o domains having stronger critical fields of interaction between the 90^o-domain boundaries and the defects [24]. According to the "inclusion theory" [7,9,13], the micropore-type defects appearing in metal volumes must be accompanied by the generation of magnetic fields of scattering and by higher magnetostatic energy in these volumes. This will hinder the mobility of domain walls and increase the coercive force. The effect of pores on the mobility of domain walls depends greatly on their size and on the positional relationship between a defect and a domain wall. In case of an extensive defect located parallel to a displacing wall, the coercive force can increase tens of times [26 to 28]. However, in our case the contribution of this mechanism seems to be small compared to the reduction in the volume of 90^o domain boundaries as a result of stress relaxation in the zones adjacent to the micropores.

Fig.2

As was previously shown, reversal magnetization is influenced by a number of factors, which often differ in their effect on the magnetic properties thus making it difficult to assess the influence of each above-mentioned mechanism on magnetic characteristics. Fig. 2, *a* testifies that additional deformation under omnilateral compression exerts rather weak influence on reversal magnetization occurring in weak magnetic fields

(B_{max}=0.05T). This indicates that it is stress relaxation near the pores that influences reversal magnetization the most (see Fig. 2, *b* for the coercive force $h_{c_{0.05}}$ and residual induction $b_{d_{0.05}}$). Measurements taken in stronger magnetic fields lead to a conclusion that the influence of additional deformation by omnilateral compression manifests itself to a greater extent for the coercive force (see Fig. 2, *a*, the curves for $H_{c_{0.4}}$ and $H_{c_{1.5}}$). The reason for a relatively weak influence of omnilateral compression is that the additional deformation imposed on plastically deformed material does not cause any essential effect on the structural changes in the basic matrix of the material under study.

Micropore formation under plastic deformation and micropore development retardation resulting from omnilateral compression, due to microstress relaxation and the decrease in the volumes of 90^o domain boundaries, influence the behavior of magnetic characteristics measured both in the weak and moderate magnetic fields (see Fig. 2, *b*, the curves h_c, H_c and b_r). Under operating conditions articles may suffer both plastic deformation and microdefect formation resulting in failure, therefore, for this failure to be prevented, it is desirable to detect the development of micropores at early stages. It can be concluded from the analysis of Fig. 2, *a* and *b* that the use of magnetic characteristics measured in various magnetic fields enables one to assess the amount of plastic strain and the change in the density of the material caused by the development of discontinuities under deformation in weak magnetic fields characterized by the irreversible displacement of domain boundaries when the latter separate from defects with the critical fields below the value of the coercive force H_c.

If we considered formally the relationships between the decreasing metal density $\Delta\gamma/\gamma_0$ during deformation and the change in the magnetic characteristics during reversal magnetization, we could come to a conclusion that the appearance of volume microdefects in the metal being deformed augments h_c and b_d (Fig. 2, *b*). The accepted scheme of the experiment enabled the samples with similar degree of strain Λ but different values of density change to be obtained by changing the pressure in the working chamber.

By regression analysis, the contribution to the change of magnetic characteristics was divided into that made by higher degree of strain and that made by loosening due to the accumulation of microdefects. As a result, the following analytic dependencies have been obtained:

$$h_{c0,05} = 0.33 + 1.60\cdot\Lambda^{0.33} + 3.42\cdot\Lambda\cdot\Delta\gamma/\gamma_0;\ b_{d0,05} = 0.074 + 0.40\cdot\Lambda^{0.32} + 0.80\cdot\Lambda\cdot\Delta\gamma/\gamma_0;$$

$$h_{c0,4} = 1.16 + 4.38\cdot\Lambda^{0.37} + 25.11\cdot\Lambda\cdot\Delta\gamma/\gamma_0;\ b_{d0,4} = 0.30 + 1.47\cdot\Lambda^{0.43} + 9.71\cdot\Lambda\cdot\Delta\gamma/\gamma_0. \quad (1)$$

Fig.3 shows these dependencies as 3D images enabling one to estimate the possibility of using magnetic characteristics for the determination of the plastic strain degree and the volume of micropores caused by this strain. The reason for a decrease in h_c and b_d during the formation of deformational microdefects seems to be the fact that their role as factors facilitating elastic energy relaxation is more significant as compared to the mechanism of change in the magnetic energy on the micropores. It follows from Fig.3 that the magnetic characteristics measured in the moderate magnetic fields are the most sensitive to microstress relaxation during micropore formation. The variation of the values of $\Delta h_{c_{0.4}}$, $\Delta b_{d_{0.4}}$ in Fig. 3, *c* and *d* are approximately twice as great as the values of $\Delta h_{c_{0.05}}$, $\Delta b_{d_{0.05}}$ in Fig. 3, *a* and *b*. Magnetic characteristics are also sensitive to plastic strain degree and, therefore, when interpreting the data presented in Fig. 3, one can assess both plastic strain degree and the processes of microdefect development.

A parameter of material damage ω is used in mechanics to indicate the level of development of deformational microdefects. In order to evaluate the damage of samples subjected to deformation, we use the phenomenological theory [9], according to which $\omega = 0$ before deformation, whereas $\omega = 1$ when a fracture crack emerges. The initial data to be used for calculating damage in the tensile tests of 3sp steel samples can be found in [29].

Fig.3

As the changes in density and damage are proportional, the graphic functions "$H_c(B_d) \sim \Delta\gamma/\gamma_0 \sim \Lambda$" and "$H_c(B_d) \sim \omega \sim \Lambda$" (Fig. 4) are qualitatively similar. The regression equations (1) can be complemented by the following equations:

$$h_{c0.05} = 0.33 + 1.60\cdot\Lambda^{0.32} - 2.95\cdot\Lambda\cdot\omega;\ b_{d0.05} = 0.074 + 0.040\cdot\Lambda^{0.32} - 0.68\cdot\Lambda\cdot\omega;$$

$$h_{c0.4} = 1.16 + 4.58\cdot\Lambda^{0.384} - 24.78\cdot\Lambda\cdot\omega;\ b_{d0.4} = 0.30 + 1.55\cdot\Lambda^{0.517} - 9.44\cdot\Lambda\cdot\omega. \quad (2)$$

Unlike the physical characteristic $\Delta\gamma/\gamma_o$, measured de facto in structural elements, the quantity ω is analytical, and it can be used to predict durability proceeding from a current state.

Conclusions: The result of the study performed demonstrates that it is possible to monitor high degrees of uniaxial deformation and the deformation-related damage of metal by means of magnetic characteristics measured on minor loops of magnetic hysteresis. Knowing material density, the initial values of magnetic characteristics and operating conditions, one can, e.g. by the coercive force or residual induction measured on a minor loop at maximum induction 0.4 T, estimate the development of microdefects related to the changes in the density of the material of an item in use or determine current metal damage *ω*. In turn, knowing the parameters *Λ* and *ω*, one can calculate the remaining service life of an item using corresponding mechanical models

Fig.4

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