Diagnostics of Microstructural Conditions of Metastable Austenitic Steels Subjected to Deformation by Magnetic Analysis

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Abstract. A complex of magnetic characteristics of high-alloy Fe-Mn- and Fe-Mn-Cr-based structural steels subjected to elastic-plastic deformation at room temperature under the scheme of uniaxial tension and torsion is investigated. Peculiarities of changes in magnetic properties caused by an accumulated amount of deformation for metastable steels of different composition and deformational stability of austenite are detected.

Introduction

Long-term use of articles, constructions and engineering structures under complicated temperature and loading conditions frequently causes essential changes in the initial structure and degradation of the physico-mechanical properties of materials, and this can result in the premature failure of equipment and crashes. This is especially true in regard to a large group of steels and alloys with the structure of metastable austenite, when martensitic transformations occur under the action of applied stresses. In this connection, a scientific and technical challenge of today is to diagnose a current microstructural state and to give a prompt evaluation of applied stresses and the level of damage accumulated in products made of structural steels with metastable austenite using nondestructive techniques, in particular, magnetic methods. The application of magnetic methods is efficient for the examination of metastable austenitic steels owing to abrupt changes in their magnetic characteristics caused by the appearance of ferromagnetic martensite in the structure and the change of the ratio between the magnetic (α- and α'-martensite) and nonmagnetic (austenite and ε-martensite) phases in the course of deformation.

1. Research Procedure and Material

The investigation is concerned with Fe-Mn-Cr austenitic steels with different deformational stability of the γ-phase (steels of grades 03G21Kh13 and 30G21Kh13) and Fe-Mn metastable steel of grade 05G20S2 with a two-phase *(γ+ε)*-structure. After homogenization and hot rolling, samples of these steels were quenched from temperature of 950-1000 ºC with cooling in water. The contents of chemical elements in the steels and the phase composition of the quenched samples found by the X-ray analysis are presented in the table.

The test pieces were deformed to fracture at room temperature according to the scheme of uniaxial tension and torsion. Cylindrical specimens with a gauge diameter of 7 mm and a gauge length of 70 mm were used as test pieces. The velocity of the active grip was 1 mm/min in tension and 90º/min in torsion.

***Table**. The chemical and phase composition of quenched steels*

Steel grade	Element content, mass %				Phase composition, %	
	C	*Mn*	*Si*	*Cr*	γ	ε
05G20S2	*0.05*	*19.70*	*1.48*	-	*40*	*60*
*03G21Kh13**	*0.03*	*21.66*	*0.14*	*13.22*	*96*	*4 (δ_f)*
30G21Kh13	*0.28*	*20.74*	*0.14*	*4.25*	*100*	*0*

*The structure of the quenched 03G21Kh13 steel contained 4 % of δ-ferrite.

The amount of shear strain Λ was used as a universal measure of plasticity, and this, according to [1], enables the amounts of strain reached at different expedients of loading to be compared correctly. The values of Λ in torsion were determined on the basis of the hypothesis that there is no radius distortion in the specimen cross section in the course of deformation as $\Lambda=\mathrm{tg}\varphi$ (φ is the slope of the mark printed on the specimen surface with respect to the generatrix).

The accumulated amount of shear strain was determined by summing the amounts of strain obtained at all the previous stages of deformation. The values of Λ in tension to necking were determined by the formula

$$\Lambda=2\times\sqrt{3}\times\ln(d_0/d_1) \quad (1)$$

where d_0 is specimen diameter before deformation; d_1 is specimen diameter after deformation. The value of damage was determined with use of the formula proposed by V. Kolmogorov [2]

$$\varpi=\frac{\Lambda}{\Lambda_P} \quad (2)$$

where Λ_P is the amount of shear strain at the instant of fracture.

Proceeding from the principle of linear damage summation, accumulated damage was determined by the formula

$$\varpi_{sum}=\sum_{i=1}^{n}\frac{\Lambda_i}{\Lambda_P} \quad (3)$$

where Λ_i is the amount of shear strain on the i-th stage of deforming; n is the number of deformation stages.

The measurements of the magnetic characteristics of the specimens under stressing were made by a permeameter circuit. A magnetic field was applied along the specimen axis, the axis of the search induction coil being also parallel to the specimen axis. The strength of the internal magnetic field H was measured by a potentialmeter. The maximal magnitude of the internal field reached H_{max} = 60 kA/m. The magnetic hysteresis loop was recorded on the plane *J-H* (*J* is magnetization) by storing 2500 points. The error of the field, induction and magnetization measurements did not exceed ±3 %. Hysteresis loops and magnetic parameters obtained from the loops, namely, the coercive force H_c, residual induction B_r and magnetization at the maximal field intensity J_{max} were considered. At each stage of stressing, the specimen was deformed to a specified degree under tension or torsion conditions, the magnetic properties being measured thereafter. The specimen was demagnetized before and after each magnetic measurement.

2. Experimental Results and Discussion

In the initial state, the 30G21Kh13 steel with the structure of stable austenite, where deformation is not accompanied by the formation of the ferromagnetic α'-phase, is a diamagnetic with magnetic permeability of -6.5×10^{-3}. It conserves its diamagnetic properties under torsion over the whole interval of strains. However, this steel becomes paramagnetic (magnetic susceptibility grows to 4.3×10^{-3}) under tensile deformation with the amount of strain $\Lambda > 0.55$ (fig. 1).

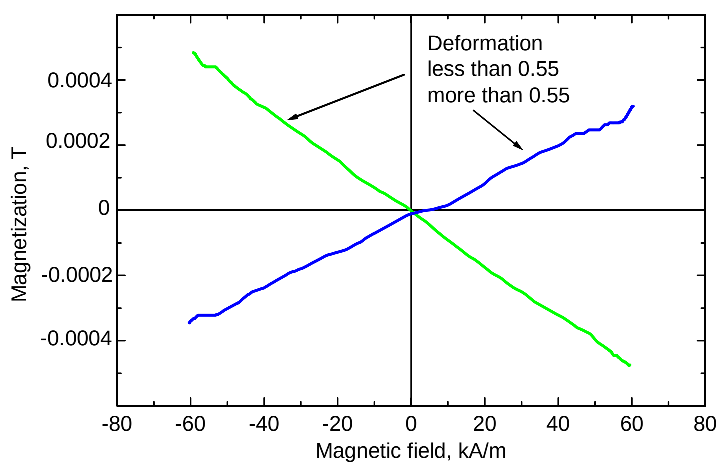
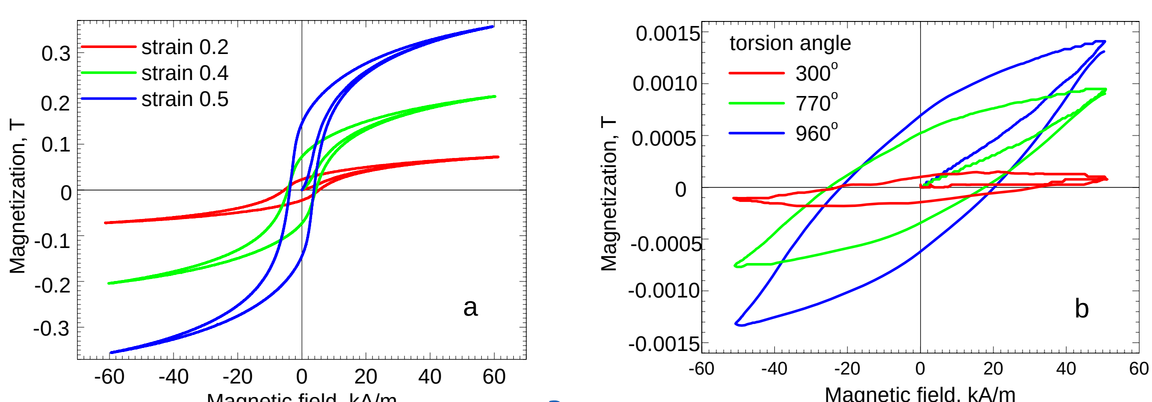


Fig. 1. Magnetization reversal curves for steel 30G21Kh13

Samples of two-phase ($\gamma+\varepsilon$) steel 05G20S2 display paramagnetic properties after heat treatment, their magnetic susceptibility being equal to 6.2×10^{-3}. The behaviour of the magnetization curves for steel 05G20S2 (fig. 2) changes essentially as the amount of both tensile and torsional strain increases, namely, magnetization grows, implying the formation of ferromagnetic α'-martensite, and the trend is toward greater magnitudes of the coercive force and residual induction. It is obvious from fig.1 that, at comparable amounts of strain, much



more α'-martensite is formed in the specimen bulk in tension, than in torsion. This is attributable to the nonuniform distribution of shearing strain in the specimen cross section in torsion tests (there is no deformation in the central part, whereas on the specimen surface deformation attains maximal values).

Figure 3 shows H_c and J_{max} as functions of the amount of strain for steel 05G20S2. The magnitude of J_{max} monotonically increases as the amount of strain grows, whereas the coercive force decreases, and it attains 27.4 kA/m thus approaching the value of the anisotropy field for iron. Apparently, this magnitude of the coercive force and the behaviour of its strain dependence are due to the fact that, in the early stages of deformation of the 05G20S2 steel, the state of the ferromagnetic phase inclusions is close to single-domain because of their high dispersivity. As the amount of strain increases, the ferromagnetic particles grow in size, they transform into a multidomain state, and the coercive force is diminished.

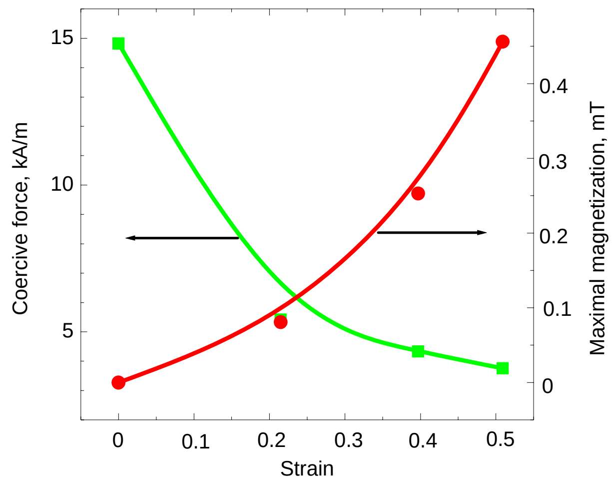


Fig. 3. The effect of tensile strain on the magnetic characteristics of steel 05G20S2

The magnetic characteristics of structural steels and alloys vary considerably under plastic deformation, and this leads to the evolution of the microstructure (change in the effective grain size, higher dislocation density, etc.) [3]. In the deformation of metastable steels and alloys, one more essential contribution to the change of magnetic properties is added, and it is related to the occurrence of ferromagnetic α′-martensite in the austenitic or two-phase (γ + ε) nonmagnetic matrix, which amounts to several tens percent. An earlier high-precision magnetic analysis of the steels under study showed that in uniaxial tension tests the formation of the first portions of strain-induced α′-martensite amounting to 0.5-2.5 % occurs at stresses close to conventional yield strength $\sigma_{0.2}$ [4]. By the instant of fracture, the maximum quantity of the α'-phase exceeds 40 % for the 05G20S2 steel.

Specimens made of steel 03G21Kh13 have fairly high magnetization as early as in the initial state (fig. 4), and it can be related to the presence of about 4 % of δ-ferrite in the specimen structure, see the table. In tension, owing to the formation of the ferromagnetic α′-martensite in the steel under study, its magnetization monotonically increases with an increase in the amount of strain. In torsion, however, the magnitude of J_{max} is stabilised upon reaching the amount of strain Λ>0.5 (fig. 5).

The magnitude of the coercive force for the 03G21Kh13 steel monotonically increases with an increase in the amount of strain both in tension and in torsion (fig. 5), but at large strains (Λ>0.5) it remains stable up to the instant of fracture. Thus, the behaviour of the $H_c(\Lambda)$ curve is essentially different from that for the 05G20S2 steel, where the magnitude of the coercive

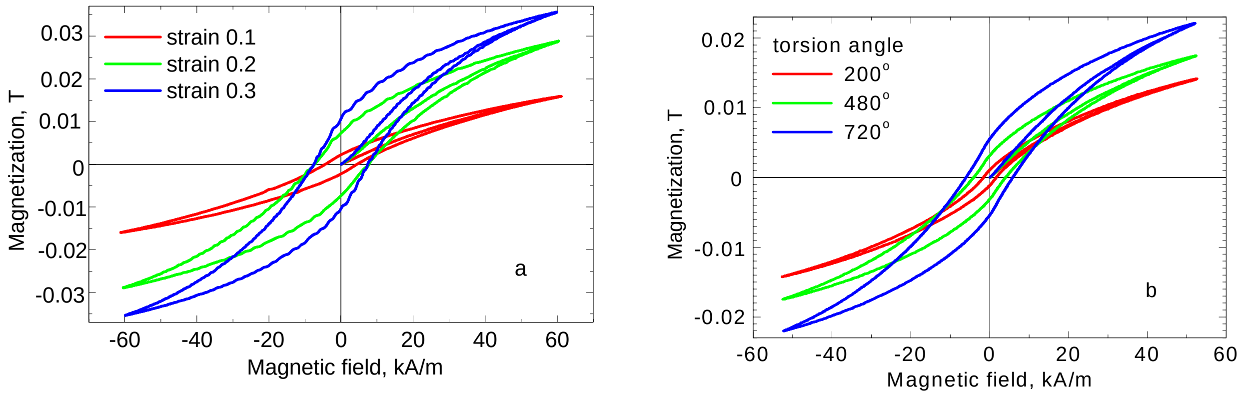


Fig. 4. Magnetic hysteresis loops for steel 03G21Kh13 in tension (a) and in torsion (b)

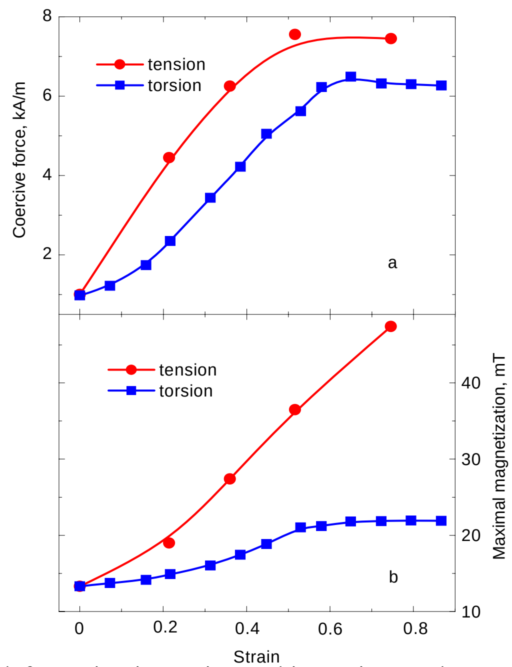


Fig. 5. The effect of deformation in tension and in torsion on the coercive force (a) and maximal magnetization (b) of steel 03G21Kh13

force tends to decrease with a rise in plastic strain. Different behaviours of the coercive force varying with the amount of accumulated strain for steels 05G20S2 and 03G21Kh13 is attributable to a larger fraction and higher dispersivity of α'-martensite in the structure of the 05G20S2 steel. For example, after tension with a degree of specific elongation of 30 %, the contents of nonmagnetic ε-martensite in steels 05G20S2 and 03G21Kh13 is practically the same (about 50 %), whereas the amount of α'-martensite makes 26 % in the former steel and 8 % in the latter one, that is, about three times less [4]. And, in view of the peculiarities of the formation of α'-martensite inside the intersecting plates of the ε-phase [5], it is possible to infer that the greater volume of the α'-phase in the 05G20S2 steel is accompanied by higher dispersivity.

Superposition of the tension stress-strain curves and the curves showing the amount of α'-martensite and maximal magnetization as dependent on the amount of accumulated strain for the 05G20S2 and 03G21Kh13 steels (fig. 6), together with the identical variation trend of these parameters, is one more evidence to the fact that increasing saturation magnetization in steels with metastable austenite is caused by the growing strain-induced α'-martensite

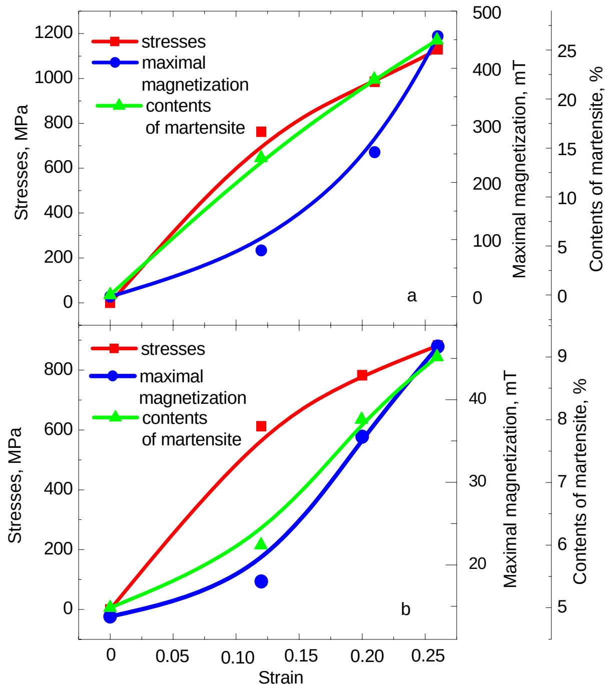


Fig. 6. Stress-strain curves, deformation dependences of maximal magnetization and contents of strain-induced martensite for steels 05G20S2 (a) and 03G21Kh13 (b)

contents in the structure. Besides, at amounts of strain Λ>0.1, a more intensive increase in magnetization is noted in the steels under study.

It should be noted that magnetic analysis methods are applicable for diagnosing cracking in metastable austenitic steels. In this case, the formation of ferromagnetic strain-induced martensite is localized within the plastic zone at the tip of a fatigue crack, which is not always detected visually. The amount of the deformational α'-phase noted on the fracture surface of G20-type steels under cyclic stressing making $\sigma<\sigma_{02}$, according to the data found in [6], is nearly twice its content on the fracture surfaces obtained in static tests.

An important aspect in the diagnostics of the microstructural state of structural steels working under sustained mechanical loads is the estimation of the degree of cumulative damage. According to the concept outlined in [1], the value of the damage parameter ω for structural steels and alloys is ω=0 in the initial state, and it attains the limiting value ω = 1 immediately before fracturing. The calculation of ω made for the 03G21Kh13 steel after different amounts of torsional strain has shown that the values of the coercive force on the major magnetic hysteresis loop and the maximal magnetization from cumulative damage vary in the same manner as from the degree of plastic strain attained (compare figs 5 and 7).

It has been found that, in torsion, the range of monotonically rising values of J_{max} and H_c falls inside the interval of strains $0<\Lambda<0.6$, and this corresponds to $0<\omega<0.7$, which is limiting cumulative deformational damage for articles, constructions and engineering structures in long-term use. This bears witness to considerable potentialities of magnetic techniques of testing and diagnostics of both the attained amount of plastic strain and the degree of accumulated damage as applied to metastable austenitic steels.

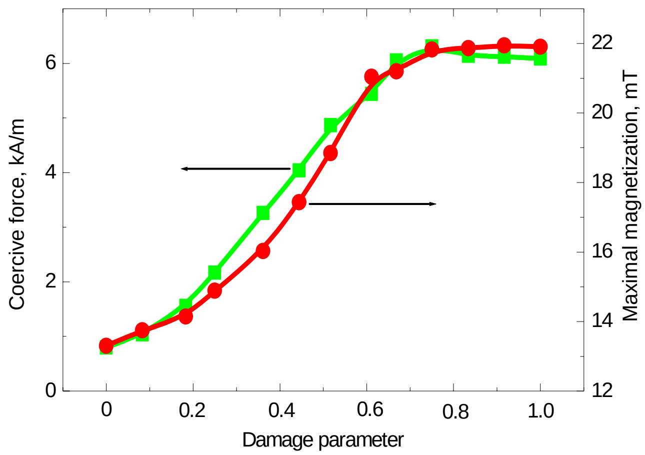


Fig. 7. Magnetic characteristics of steel 05G21Kh13 as functions of the damage parameter in torsion

3. Conclusion

It is established on the basis of the investigation conducted that the formation of ferromagnetic strain-induced α'-martensite in Fe-Mn-Cr and Fe-Mn steels with the structure of metastable austenite under applied loads leads to a substantial change in the complex of their magnetic characteristics. This makes it possible to use magnetic methods of nondestructive testing for expeditious diagnostics of the phase composition of metastable steels, accumulated amount of plastic strain and deformational damage. Different behaviours of such magnetic characteristics as saturation magnetization and the coercive force governed by the amount of plastic strain makes it possible to determine the history of stressing (to differentiate the scheme of deformation – by uniaxial tension or torsion).

It has been revealed that the coercive force shows counter behaviours as the amount of strain grows for steels 03G21Kh13 and 05G20S2, and this may be related to different intensities of the development of deformational martensitic transformations. It has been established that, under conditions of uniaxial tension, upon reaching the amount of strain $\Lambda > 0.55$, the 30G21Kh13 steel with the structure of stable austenite transforms from the diamagnetic state to the paramagnetic one.

The work has been partly supported by the Russian Foundation for Basic Research "Ural", grant 04-01-96110.

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