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Effect of Magnetic Annealing on Magnetostriction of Grain-Oriented Electrical Steels

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A newly designed magnetic annealing apparatus was used for the treatment of Fe-3%Si steels. With the help of this device, the effect of magnetic annealing on magnetostriction was studied in a wide spectrum of external elastic stresses. It was shown that magnetostriction properties of Fe-Si steels were improved in the compressed state through magnetic annealing, while those in the unstressed state or under tension were found to be practically unchanged.

1. Introduction

Magnetostriction characteristics of grain-oriented (GO) Fe-3%Si steels are a serious problem of practical interest in connection with the noise generated by power transformer cores. At the same time the analysis of magnetostriction behavior is one of the basic methods for the analysis of magnetic domain structure (MDS) of these materials [1], because the magnetostriction change directly reflects the rearrangements of ferromagnetic domains during magnetization [2].

The magnetostriction properties of Goss-textured Fe-3%Si during magnetization as well as under external stress have been a subject of a large number of publications (refer to the review papers [1, 3] as well as [4-7]). It was shown that electrical steels are described by high magnetocrystalline anisotropy (close to that of the pure iron), so the degree of crystalline texture plays the most important role during the formation of MDS, magnetic and magnetostriction properties of the material, as well as the declination angles of the easy magnetization axes out of the sheet plane or the rolling direction.

Some indications were found in the literature [8-12], that magnetic annealing may essentially improve magnetic properties of Fe-Si alloys. However until this moment very limited information is available concerning the effect of magnetic annealing (MA) on the magnetostriction of grain-oriented silicon steels [6, 13-15], and sometimes no modifications of magnetostriction (in the unstressed state) are revealed after magnetic annealing [6]. It must be pointed out that very little information is available in the literature concerning the magnetic annealing effect on the stress-dependent magnetostriction of electrotechnical steels. At the same time the behavior of magnetostriction under compression and tension is the most interesting, both from the theoretical and practical points of view, because the magnetostriction can be much higher under compression than in the unstressed state due to the rearrangement of the magnetic domain structure [1, 4]. It can be mentioned also that in practice, a valuable portion of Fe-Si laminated steels is under a slight compressive stress in a transformer core [16].

The present paper reports the results on the effect of magnetic annealing in the high-level fields on the magnetostriction characteristics of grain-oriented electrical steels, in a wide spectrum of external stresses from compression to tension.

2. Materials and Experimental Methods

High-purity Fe-Si steels with different degrees of (110) [001] crystalline texture were studied in this work. The magnetization value in an external field of 1000 A/m (B_{10}) was used to estimate the degree of crystalline texture. All materials investigated were specially manufactured in the Electrical Steels Plant of the Pohang Iron & Steel Co., Ltd. The various types of electrical steels were prepared for the present study and presented in table 1.

In order to separate the effect of surface coating on magnetostriction, both bare materials (with the free metal surface) and industrial-coated samples were tested. Major attention was paid during the experiments to the industrial-coated samples, possessing some tensile stresses in the sheet plane, which increases the unidirectional magnetic anisotropy [1]. Coating removal was undertaken using the chemical methods [5, 17]. Experiments were performed using the standard magnetostriction samples (dimensions: $300 \times 30 \times 0.25$ -0.37 mm), cut along the rolling direction of the material.

Table 1. Characteristics of various types of the Fe-Si alloy.

TYPE	t (mm)	B10 (Tesla)	W17/50 (W/kg)	W15/50 (W/kg)	Hc (A/m)	COMMENTS
1	0.36	1.82~ 1.83	1.35~ 1.45	0.95~ 1.00	31~33	CGO, pronounced positive magnetostriction
2	0.36	1.84~ 1.85	1.45~ 1.55	1.03~ 1.08	32~33	CGO, slightly positive magnetostriction
3	0.26	1.94	1.06~ 1.09	0.82~ 0.84	26~27	Hi-B, high degree of texture, bare surface
4	0.29	1.89	1.07~ 1.08	0.70~ 0.80	25~26	CGO, negative magnetostriction

Prior to experiments, all samples were subjected to the stress-relief annealing (800 ℃ × 2 hrs, cooling with furnace) in the $H_2 + N_2$ protective atmosphere.

Magnetic annealing was undertaken using special apparatus designed to provide, if necessary, high magnetization values in the longitudinal direction of a magnetostriction sample. To meet the requirement, the sample was placed in the annealing furnace between two poles of the elongated-yoke electromagnet using extended pole caps (Fig. 1). During MA, the sample was supported by nonmagnetic clamps. Temperature uniformity along the sample was obtained using specially designed thin-walled extended pole caps. Unidirectional or alternating fields were applied at the annealing temperature (400-500 ℃) and samples were cooled to room temperature under the field. The cooling rate was limited by free cooling of the magnetic annealing furnace and was equal to ~1.5 ℃/min (at 350 ℃). The above mentioned design provides high magnetization values of the sample (close to the materials saturation, which was measured using the B-H curve tracer) and allows the application of a tensile stress in addition to the magnetic field.

To obtain very high magnetization of the sample during magnetic annealing, a special modification of the described apparatus was undertaken (Fig. 1). This implementation includes single-layer high-temperature solenoid (surrounding the sample and a portion of closure magnetic circuit) and high-power impulse current supply, providing current impulses with the maximum amplitude of ~200-300 A, (100 A × 3.5 ms), full impulse length 16 ms and f~1 Hz. Note that the current of 100 A through the solenoid induces a magnetic field of 250 Oe in the hot zone of the furnace. All MA treatments were undertaken along the rolling direction of the material and correspondingly, along the easy magnetization direction. Pure N_2 gas was used to maintain a protective atmosphere.

Each sample was subjected to the magnetic properties and magnetostriction testing before and after magnetic annealing. Such magnetic characteristics as core losses, coercive force, permeability were measured with the help of a fully-automatic magnetic tester using single-sheet Epstein apparatus. Magnetostriction measurements were performed with the help of semi-automatic apparatus for ac-field testing (50 or 60 Hz) with a quasi-closed magnetic circuit (permeameter) and a standard LVDT sensor of sample displacements (differential transformer). The application of the tensile and compressive stresses was undertaken using a pneumatic cylinder with a total mass of 100 g. This device allows simultaneous recording of the B-H and magnetostriction λ-H and λ-B loops. The magnetostriction was measured at the amplitudes of maximum magnetization of 0.7, 1.0, 1.2, 1.5, 1.7, 1.85 T and under the variety of external stresses from compression to tension (from −5 MPa to +3 MPa using steps 0.5 or 1 MPa), which allows the analysis of the magnetization process in its different stages.

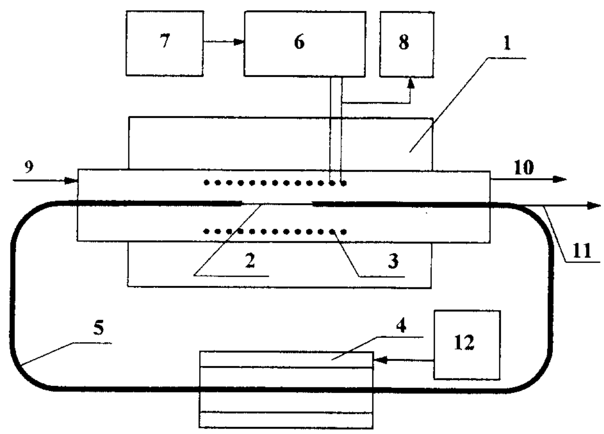


Fig. 1. Schematic drawing of magnetic annealing apparatus: 1-MA furnace; 2-sample; 3-impulse solenoid; 4-solenoid of electromagnet; 5-closure circuit of electromagnet; 6-impulse current supply; 7-synthesizer and controller; 8-impulses control system; 9-protection gas inlet; 10-protection gas outlet; 11-tension stress controller ; 12-dc-or ac-power supply.

3. Experimental Results and Discussion

Let us first report the results on magnetic annealing of conventional grain-oriented electrical steels (CGO-grade) under the unidirectional magnetic field. Typical modification of ac-magnetostriction after MA and stress-relief annealing (SRA) for the material with a pronounced positive magnetostriction is presented in Fig. 2 and Fig. 3. MA in this case was undertaken in accordance with the following regime: 450 ℃, 2 hrs + cooling with furnace under high dc-magnetic field (close to the material's saturation). After magnetic properties and magnetostriction testing, samples were subjected to SRA in the same annealing conditions as previous MA, but without application of the magnetic field. It can be seen from Fig. 2 a-b that the MA doesn't noticeably change the magnetostriction characteristics of the material in the unstressed state and under tensile stresses of 1 and 2 MPa.

However the application of a compressive stress along the rolling direction of the material makes the difference in magnetostriction properties before and after magnetic annealing clearly visible. It should be noted that the mentioned difference in properties is more serious under a small applied magnetic field (maximum magnetization of 1.0 T at 50 Hz, Fig. 2a) than under high ac-fields (B_m = 1.85 Tesla, Fig. 2b). It is also noteworthy that the effect of MA is more pronounced for larger compressive stresses than for a small ones (Fig. 2).

Reannealing of the samples without the field (SRA) recovers the initial level of properties almost reversibly (marked by a double-head arrow in Fig. 2a and Fig. 2b). The reversibility of the MA effect for this industrial-coated material is more evidenced from Fig. 3, where ac-magnetostriction in the compressed state ($\sigma_c = -2$ MPa) is plotted against the peak induction in an external ac-field (50 Hz-excitation). The double-head arrow in Fig. 3 points out a remarkable decrease of magnetostriction after MA and its return to the initial position by SRA. It can be mentioned that the relative improvement of the magnetostriction properties is much more serious for small values of B_{max} (below 1.5 Tesla, see Fig. 3), which indicates serious changes of the magnetic domain structure.

Let us discuss briefly the above presented data in terms of magnetic annealing theory. It is known [8, 11, 18], that the effect of magnetic annealing in Fe-Si alloys is caused, first of all, by the preferred orientation of the symmetry axes of local magnetic inhomogeneities under the applied field. These inhomogeneities may be considered basically as the local dispersed areas, ordered by *B*2 and $D0_3$-structures, in the matrix, depleted by Si. These structural defects are in fact magnetically anisotropic and may be subjected to MA (for instance, by means of the directional ordering mechanism, [19]).

Preferred orientation of the anisotropy axes of local inhomogeneities will result, in our case, in some increase of unidirectional magnetic anisotropy along the rolling direction of the electrical steel sheet. For the materials with a pronounced positive magnetostriction, this last factor means the increase of volume fraction of 180°-domain walls, initially oriented along the rolling direction of the material, and it can be assumed that the relative volume fraction of 90°-walls of the magnetic domains will be decreased in the demagnetized state and upon MDS rearrangement under the magnetic field. In this case, the application of an external compressive stress will cause another rearrangement of MDS in the state after MA, as compared to that in the initial state of material. It can be assumed that the appearance of the transversal domain structure will be suppressed after MA due to the decrease of the number of the nucleation points for such a reorientation of the MDS. For the materials with initially positive magnetostriction characteristics, this modification of MDS must lead to a decrease of the positive magnetostriction, especially under the compressive stress, which was indeed observed in our experiments (Fig. 2). Also, the above described mechanism lets us assume that the magnetostriction must be more seriously suppressed for the lower alternating magnetic fields, because in this case much less volume of the material is subjected to magnetization, which allows to exclude from the magnetization process the areas

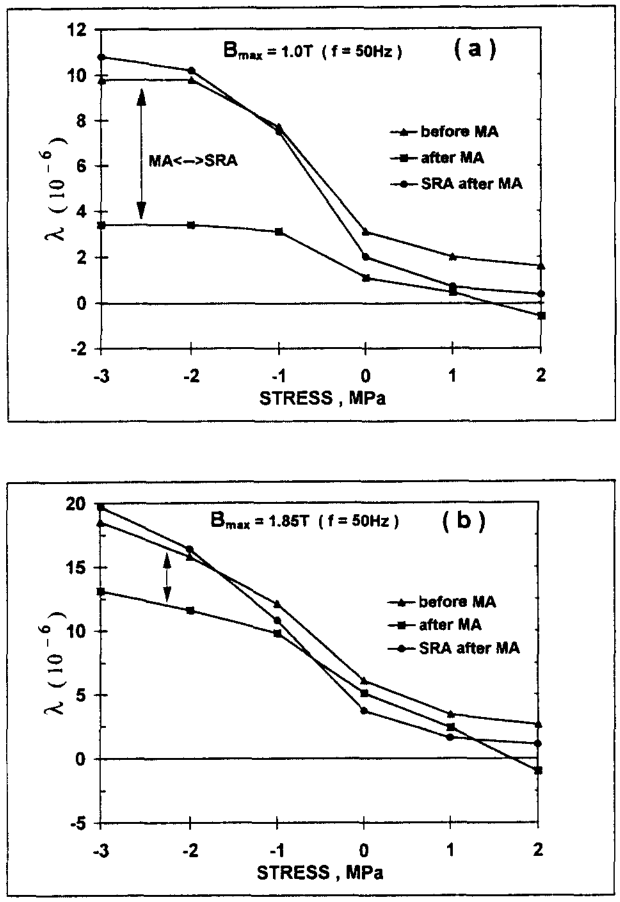


Fig. 2. Magnetostriction behavior of industrial-coated Fe-Si alloy (type 1) under external stress at maximum magnetization of 1.5 T (a) and 1.85 T (b).

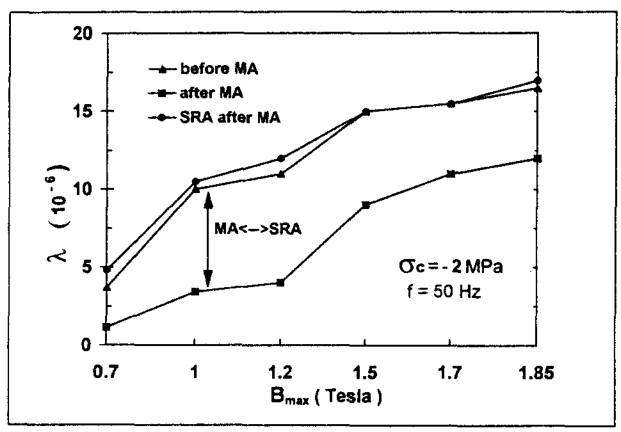


Fig. 3. Reversible modification of magnetostriction after MA for industrial-coated Fe-Si alloy (type 1) under compression of 2 MPa.

with an increased volume fraction of low-mobile 90°-domain walls. In accordance with that, Fig. 3 demonstrates a much more pronounced MA effect for the low values of B_{max}.

These last results forced us to bring the following question into consideration: is MA effective for the improvement of λ at very high levels of B_{max} or not? In order to verify this, experiments with the high-permeability electrical steels (Hi-B grade) were undertaken. Stress-dependent behavior of magnetostriction of the Hi-B material (type-3) for a high magnetic flux density (1.95 T, 50 Hz-excitation) is presented in Fig. 3. MA was undertaken according to the following regime: 440 ℃, 1.5 hrs + cooling with furnace under dc-field. It can be seen that MA causes serious large decrease of the magnetostriction under an external compressive stress of 2 and 3 MPa, which may be important from the practical point of view. At the same time the comparison of Fig. 3 and Fig. 2b allows us to assume that the degree of crystalline texture, and correspondingly the character of initial magnetic domain structure of the material are very important for the efficiency of magnetic annealing. Indeed, different grades of electrical steels, tested in this work, demonstrated different sensitivity to the MA treatment and sometimes very complex modification of λ was registered after MA in the unidirectional magnetic field (for instance, for the materials of the type-4).

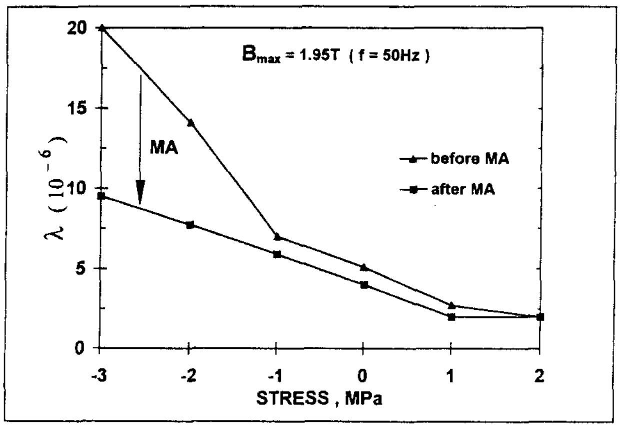


Fig. 4. MA effect on magnetostriction of Fe-Si alloy (Hi-B, type 3) with bare surface conditions.

It is also very important that the modification of MA conditions (for example, the decrease of the sample magnetization during MA up to the certain level of I_{max}) may essentially increase the magnetostriction characteristics of Fe-Si alloys, as it was demonstrated in our previous paper [20]. It was shown in [20], that this behavior may be caused by the stabilization (during MA) of the specific magnetic domain structure with the enhanced fraction of supplementary magnetic domains with the magnetization vectors, located in the transversal direction [1, 2, 21-24]. In this case the material will be characterized by the enhanced fraction of 90°-domain walls in the structure, which increases the magnetostriction. Stabilization of the supplementary domain structure may take place due to the effects of self-magnetic annealing in the field of the magnetic domain or due to interaction of magnetostriction distortions of magnetic domains with the base metal-insulating coating interface [20] (for the samples with the coated surface conditions).

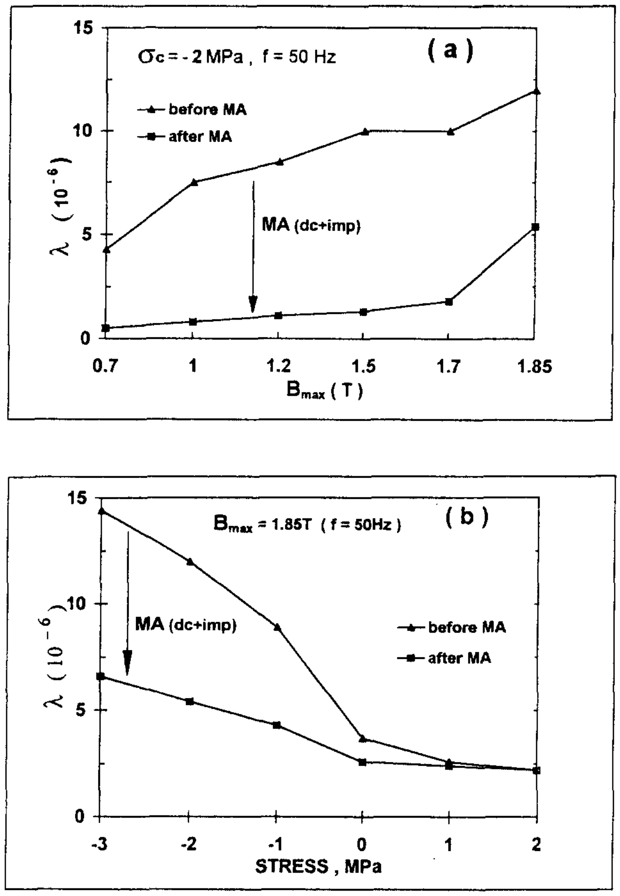
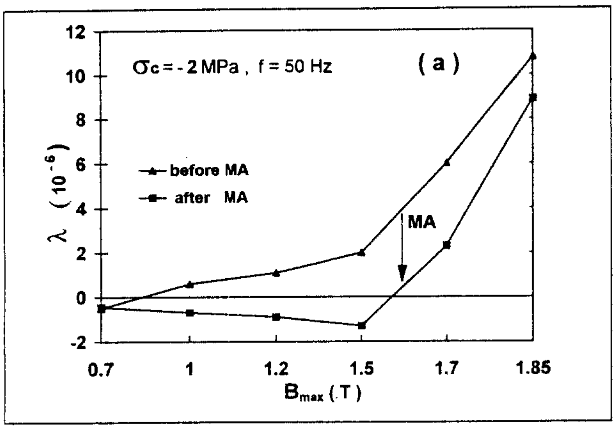


Fig. 5. The effect of MA in the combined field on ac-magnetostriction of industrial-coated Fe-Si alloy (type 1): a-amplitude dependence of λ in the compressed state; b-stress-dependent magnetostriction at B_m = 1.85 T.

How to avoid the negative influence of special effects during MA and to increase the uniformity and efficiency of magnetic annealing for Fe-Si alloys? There are several ways to do this and the efficiency of one of them was verified in the present work with respect to the industrial Fe-Si materials. It was assumed that the application of a short impulses of high-level magnetic field during MA will destroy the structure of supplementary magnetic domains due to the inertial character of the domain wall movement.

The impulses of a high magnetic field (400-600 Oe) were applied in the present work simultaneously with the application of the dc-field at a high temperature. Samples were annealed under these conditions for a specified time and then cooled down to room temperature under the combined (dc + impulse) field. Fig. 5 presents the results on the effect of such magnetic annealing on magnetostriction of the Fe-Si alloy with a pronounced positive magnetostriction (the same material as presented in Fig. 2-3 for MA under the dc-field). Magnetic annealing (Fig. 5) was undertaken in accordance with the following regime: 450 ℃, 1 hr + furnace cooling. It can be seen from Fig. 5, that the material behavior obeys the same regularities as described before for MA in the high dc-fields. However, the comparison of Fig. 2b, Fig. 3 and Fig. 5 allows us to conclude that MA in the combined (dc + impulse) field is essentially more effective than that without the superimposed impulse field. It can be seen from the comparison of Fig. 3 and Fig. 5a, that the sharp increase of magnetostriction (starting at B_{max} = 1.2 T for the material after MA in dc-field) has been shifted to much higher values of B_{max} = 1.7 T after MA in the combined (dc + impulse) field. These last results indicate that the nucleation centers for the formation of the supplementary magnetic domain structure has been suppressed more effectively in the combined field. In accordance with this, Fig. 5b demonstrates a more pronounced difference of magnetostriction under compression for the states before and after magnetic annealing.



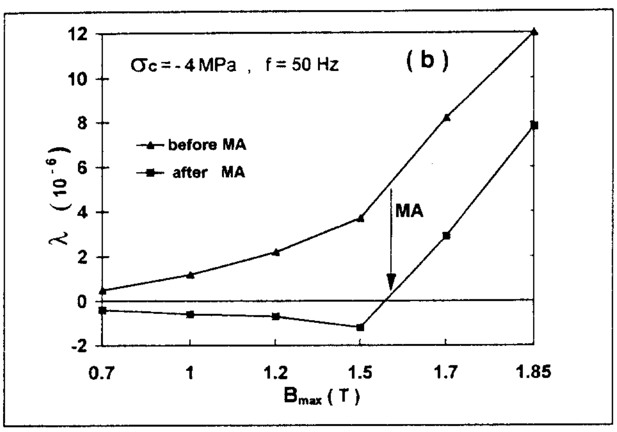


Fig. 6. Effect of MA in the combined (dc + impulse) field on magnetostriction of Fe-Si material (type 2) under compressive stress of 2 MPa (a) and 4 MPa (b).

The materials with a slight positive magnetostriction (type-2) were found to demonstrate almost equal regularities, as the described above. Magnetic annealing of these materials was undertaken using the following regime: 450 ℃, 70 min + cooling with furnace under the combined field. Amplitude dependencies of magnetostriction for industrial-coated Fe-Si steel (type 2) in the compressed state are presented in Fig. 6 a-b. It can be seen that the magnetostriction characteristics have been decreased throughout the spectrum of applied magnetic fields. The comparison of Fig. 6a and Fig. 6b indicates that the relative effect of MA is more serious under the higher compressive stress (4 MPa). The magnetostriction demonstrates the definite shift from a positive λ values (in the initial state) to the negative ones after magnetic annealing (Fig. 6), which indicates serious rearrangement of the magnetic domain structure. The mentioned shift is observed for this material for relatively small exciting ac-fields (i. e. below $B_{max} \approx 1.5$ T, Fig. 6).

Materials with negative magnetostriction characteristics in the initial state (type 4) were also found to demonstrate serious magnetostriction modifications after MA in the combined field. Magnetic annealing in this case was performed using the following regime: 450 ℃, 30 min + cooling with furnace under (dc + impulse) field. However, the behavior of this material after MA in the combined field is still more complicated as compared with the above mentioned materials. Table 2 presents peak-to-peak λ-values for the material with the negative magnetostriction (type 4) in its initial state and in the state after magnetic annealing (sign ± for the λ-values indicates, that the shape of the magnetostriction loop is rather complicated and the data can not be definitely determined as either positive or negative values). A noticeable decrease of λ can be mentioned for the compressed state of the material (Table 1), but maximal improvement of magnetostriction was observed at the intermediate compressive stresses (−3 and −2 MPa), which may be explained by the addition to the anisotropy energy [20]. Complete analysis of the magnetostriction behavior of this material after magnetic annealing needs serious additional investigation, including the Fourier analysis of the magnetostriction signal. However the fact that the improvement of magnetostriction was realized for sufficiently high values of the peak induction (B_{max} = 1,85 T, Table 1) seems to be promising from the practical point of view.

Table 2. Magnetostriction of the Fe-Si alloy (type 4) before and after MA in the combined magnetic field (dc + impulse).

EXTERNAL STRESS (MPa)	λ (10^{-6}) at B_m = 1.85 T		
	BEFORE MA	AFTER MA	Δ, %
−4	±2.8	±2.1	−25 %
−3	±3.1	±1.9	−39 %
−2	±3.2	±1.8	−44 %
0	−2.7	−2.6	~=
+2	−2.8	−2.8	=

In consequence it can be said that, in spite of some quantitative variations and several peculiarities, all materials studied in this work were found to obey some common regularities in their behavior, which allows the formulation of generalized conclusions.

4. Conclusions

The new design of the magnetic annealing apparatus, tested in the present work, allows remarkable modification of the magnetostriction characteristics of grain-oriented Fe-3%Si electrical steels along the rolling direction of the material.

Magnetic annealing allows significant improvement of the magnetostriction characteristics of industrial Fe-3%Si alloys in the compressed state of material (at least in the region from −5 MPa to −0.5 MPa). The effect of magnetic annealing is more pronounced for low and intermediate magnetic flux densities.

Magnetostriction characteristics of grain-oriented electrical steels in the unstressed state and under external tension do not demonstrate serious modifications after magnetic annealing.

Simultaneous application of unidirectional and pulsating fields increases the efficiency of magnetic annealing and provides a more stable positive effect.

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