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Evaluation of the Effects of Pulsed Magnetic Field Treatment as a Nondestructive Treatment for Magnetic Materials

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Abstract
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Keywords
Barkhausen emission, Magnetic force microscopy, Magnetic hysteresis, Pulsed magnetic field processing, Stress relief

Disciplines
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Comments
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ABSTRACT

Pulsed magnetic treatment has been suggested as a nondestructive treatment of magnetic materials for reducing microscopic stress and strain in the materials. Systematic studies have been made to test the effect of pulsed magnetic field treatments in a variety of magnetic materials including bulk nickel and magnetic thin film samples. The treatment involves the application of a low frequency, periodic magnetic field superimposed with a high frequency pulse component followed by demagnetization. Equipment for applying the pulsed magnetic field treatment has been designed and constructed, together with computer software which was developed to allow complete control of the waveform, frequency and amplitude of the pulsed magnetic field profile. Various characterization techniques, including magnetic hysteresis, Barkhausen effect measurements and magnetic force microscopy, were used to test the effects of the pulsed magnetic field treatment. Present results indicate that the stress relief effect of the treatment on the samples, if there is any, is much weaker than claimed in previous studies.

Keywords: *pulsed magnetic field processing, stress relief, magnetic hysteresis, Barkhausen emission, magnetic force microscopy.*

INTRODUCTION

This paper presents results of a systematic study of the effects of the pulsed magnetic field treatment on a number of different magnetic specimens, including bulk samples and thin films, with a variety of chemical compositions. Pulsed magnetic field treatment has been proposed as a new nondestructive method of materials processing that can be applied to materials either immediately following initial fabrication or after service induced degradation has occurred. The treatment involves application of a pulsed magnetic field with a specific waveform to the materials at room temperature. There have been several claims that these treatments can relieve residual stress (Hochman et al., 1994), retard crack growth (Finkel, 1977; Baron, 1987), alter fracture and corrosion resistance, extend wear and fatigue lifetimes, reduce hysteretic energy losses and improve power conversion efficiency (Koepke, 2002). However, previous reports have been largely anecdotal. A systematic study of the effects was needed and this was the motivation of the present study.

There have been prior reports on the beneficial effects of the pulsed magnetic field treatment of metallic parts, including both magnetic and nonmagnetic materials. It has been claimed that pulsed magnetic field treatment can increase the life of metal parts by as much as 500%, with benefits found in all types of metal working from machining to grinding. Jablonowski (1987) claimed that there were a large number of instances where lifetimes of tool materials have been extended as a result of pulsed magnetic field treatment by industrial investigators of the technology. It was speculated that the increase in tool life was caused by changes in the dislocation density, residual stress level and the density of other discontinuities within the materials such as vacancies and interstitial pairs (Su et al., 1990). Despite the far reaching implications of these claims, there has not been any detailed study that confirms the beneficial effect of pulsed magnetic field treatment.

The pulsed magnetic field treatments reported in previous studies involved the application of magnetic fields consisting of a low frequency component (several hertz) superimposed with a higher frequency component (around 100 Hz). Field strengths with a typical amplitude of 23.8 to 39.8 kA/m (300 to 500 Oe) and cycle times of 100 to 1000 s were used and the treatment was usually followed by a demagnetization sequence. The effects of an alternating current magnetic field on material properties have been studied by Hockman et al. (1988), who claimed that the application of alternating current fields of 23.8 to 159.2 kA/m (300 to 2000 Oe) and at frequencies of 2 to 30 Hz could cause stress relief in carbon steels, high strength steels and cemented carbides. Fahmy et al. (1998) studied the effects of pulsed magnetic field treatment on the fatigue life of low carbon steels and concluded that the beneficial effects of the pulsed magnetic field treatment depend on demagnetization following the treatment. These results seem to suggest that the pulse amplitude, pulse frequency and duration of treatment are important parameters in determining the effects of pulsed magnetic field treatment on material properties.

The objective of this study is to determine if there is any noticeable beneficial effect of the pulsed magnetic field treatment on magnetic materials. To this end, a computer controlled system has been developed and this was used to treat various magnetic specimens having well characterized microstructures and properties. A range of characterization techniques were used to test the effects of the treatment, including magnetic hysteresis and Barkhausen effect measurements which are known to be sensitive to the microstructure and mechanical condition of magnetic materials. X-ray diffraction studies were conducted to detect any change in the stress level. The effect on a microscopic scale was tested using magnetic force microscopy by imaging magnetic domain structures before and after the treatment.

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IMPLEMENTATION OF THE PULSED MAGNETIC FIELD TREATMENT SYSTEM

A computer controlled magnetic processing system (Figure 1a) has been designed and constructed for generating pulsed magnetic fields with specific waveforms. The instrument consists of a signal generator that utilizes an arbitrary waveform generator to produce waveforms of any shape. A computer software package was developed which can be used to specify the waveform, amplitude and frequency of the applied field. This signal was amplified using a bipolar power supply which was connected to a solenoid that produced a pulsed magnetic field.

The pulsed magnetic field profile was comprised of a low frequency periodic carrier signal superimposed with a higher frequency component. A parameterization scheme for the pulsed magnetic field signal, as shown in Figure 1b, was devised to completely specify both the carrier signal and the high frequency component using five parameters. The computer software package developed for control and data logging (Figure 1c) accepted these parameters as inputs to generate the desired waveform. This allowed complete control of the field profile and facilitated the evaluation of the effects of different pulsed magnetic field waveforms on material properties.

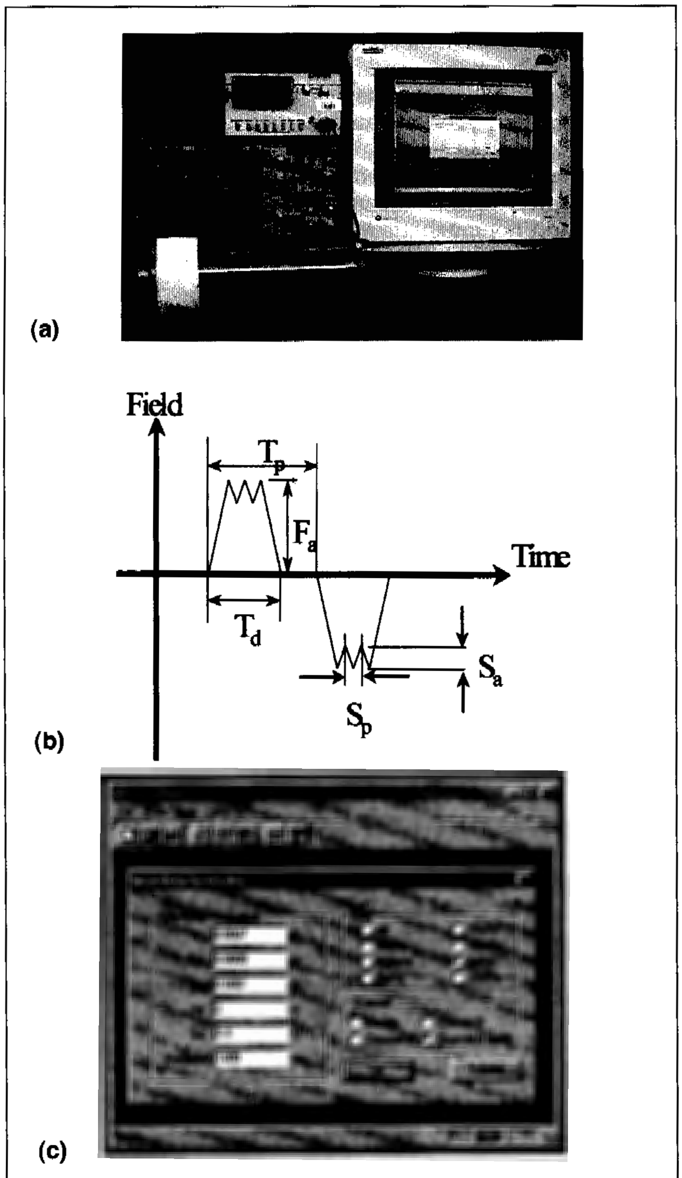


Figure 1 — The pulsed magnetic field treatment system: (a) the magnetic field profile is generated using a personal computer with a custom designed software package and is amplified to drive a solenoid; the applied field is measured using a Hall effect sensor with a gaussmeter and is displayed on the oscilloscope; (b) parameterized pulsed magnetic field signal — the input parameters T_p, T_d, F_a, S_p and S_a can be specified using the control and data logging software; (c) the main menu of the control software program.

EXPERIMENTAL STUDIES OF THE EFFECTS OF PULSED MAGNETIC FIELD TREATMENT

The effects of pulsed magnetic field treatment were examined using a number of magnetic specimens whose microstructures and properties were well characterized. These included:

- cold drawn plain carbon steel (AISI 1020)
- cold worked and heat treated nickel samples
- magnetic thin films with high levels of residual stress.

Study on Cold Worked Steel

The effect of pulsed magnetic field treatment on cold drawn plain carbon steel (AISI 1020) samples was tested and compared with that of thermal annealing. Five samples were cut from a cold drawn steel bar using an electrical discharge machine. Plastic deformation in the samples was characterized using X-ray diffraction. Barkhausen effect measurements were made on each of the samples using a surface sensor with the magnetic field applied along and perpendicular to the long axis of the original steel bar. One sample (A) was kept in the cold worked state. Another sample (B) was annealed at 773 K (932 °F) for 1 h in a furnace to relieve the residual stress. Three other samples (C to E) were subjected to pulsed magnetic field treatment for various periods of time (5, 10 and 30 min). X-ray diffraction and Barkhausen effect measurements were repeated on the samples after the thermal and magnetic treatments.

The X-ray diffraction spectra of samples B and D, which were subjected to thermal annealing and magnetic field treatment, respectively, are shown in Figure 2 for comparison. In the as received condition, both samples showed broad diffraction lines which are indicative of the presence of nonuniform strain due to the cold

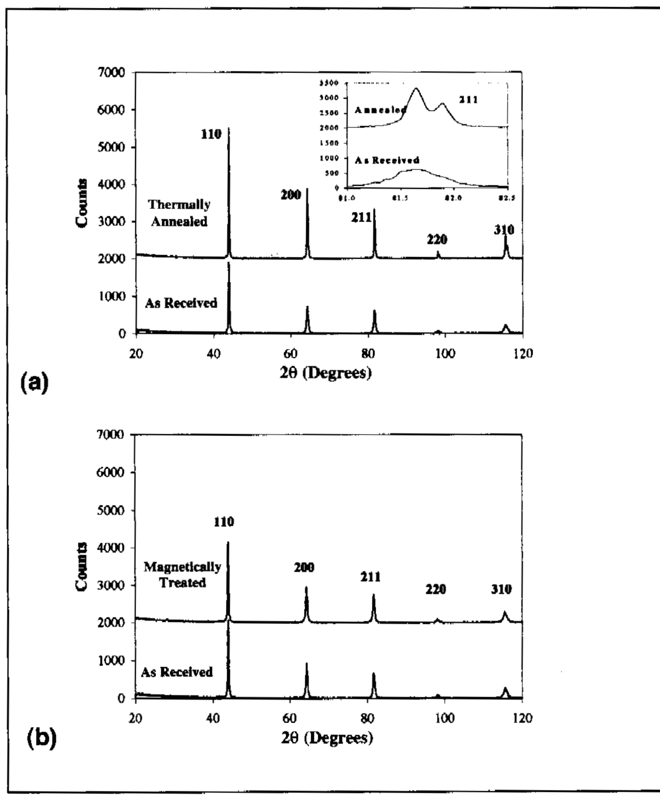


Figure 2 — X-ray diffraction spectra of: (a) the 1020 steel sample B before and after thermal annealing (the inset shows the K_α doublets of the α-Fe [211] peak after thermal annealing); (b) the 1020 steel sample D before and after pulsed magnetic treatment.

Table 1 Results of Barkhausen effect measurements made on the samples cut from a 1020 steel bar before and after thermal annealing and pulsed magnetic field treatments; $V_{//}$ and $V_{\perp}$ are the root mean square Barkhausen effect signal voltages (in millivolts) with the magnetizing field applied parallel and perpendicular to the long axis of the original steel bar, respectively

	Sample A	Sample B	Sample C	Sample D	Sample E
Condition	as received	as received	as received	as received	as received
$V_{//}$	546.4 ± 5.0	548.6 ± 7.6	537.7 ± 4.0	526.9 ± 6.9	536.7 ± 2.4
$V_{\perp}$	587.2 ± 6.2	592.2 ± 6.3	583.2 ± 4.5	586.0 ± 1.2	599.5 ± 6.6
Treatment	kept in the as received condition	annealed at 773 K (932 °F) for 1 h	magnetically treated for 5 min	magnetically treated for 10 min	magnetically treated for 30 min
$V_{//}$	546.4 ± 5.0	634.3 ± 0.8	539.7 ± 3.2	534.8 ± 1.9	533.4 ± 0.5
$V_{\perp}$	587.2 ± 6.2	565.9 ± 4.2	577.8 ± 7.9	562.1 ± 2.2	601.0 ± 2.5

work. After annealing, the diffraction peaks of sample B became sharper and the K_{α} doublets of the α-Fe (211), (220) and (310) peaks became resolvable (inset of Figure 2a). The full width half maximum of the diffraction lines was also found to be smaller after annealing. These changes are attributed to the recovery of the cold worked structure of the sample by annealing and a reduction in the residual stress level. Conversely, the diffraction peaks of sample D remained broad after the pulsed magnetic field treatment. The full width half maxima of the peaks after the treatment are within 5% of those found in the cold worked X-ray diffraction spectrum, showing that the pulsed magnetic treatment did not affect the plastic strain in the sample.

The root mean square values of the Barkhausen effect signal measured with the applied field along ($V_{//}$) and perpendicular to ($V_{\perp}$) the long axis of the original steel bar are shown in Table 1. All samples exhibited similar root mean square values of Barkhausen effect signals in the as received condition. Thermal annealing caused $V_{//}$ to increase but $V_{\perp}$ to decrease substantially. These changes can be explained by the fact that the Barkhausen effect signal measured with field along the stress axis increases with tensile stress and decreases with compressive stress for materials with positive magnetostriction such as plain carbon steels. The residual stress induced by cold working was compressive along the long axis of the steel bar but tensile in the perpendicular direction. Thermal annealing reduced the residual stress levels, causing opposite changes of the Barkhausen effect signals in the two orthogonal directions. In contrast, the Barkhausen effect signals remained unchanged within the experimental errors for the samples subjected to pulsed magnetic field treatment (such as samples C, D and E), suggesting little or no effect of the magnetic treatment on residual stress.

Study on Nickel

Nickel was used because it was speculated that a pulsed magnetic field may exhibit a stronger effect in nickel than in other ferrous alloys such as steel for two reasons. First, nickel has higher magnetostriction constants ($\lambda_{100} = 45.9 \times 10^{-6}$, $\lambda_{111} = 24.3 \times 10^{-6}$) than iron ($\lambda_{100} = 20.7 \times 10^{-6}$, $\lambda_{111} = -21.2 \times 10^{-6}$). Therefore, if a pulsed magnetic field could affect the mechanical properties via magnetoelastic coupling, the effect should be more profound in nickel than in iron. Second, the shear stress exerted by a 180 degree magnetic domain wall (lying in the [112] plane) on a screw dislocation along the [110] direction is 1.3 kg/mm^2 (1849 lb/in.^{2}) according to Trauble (1967), which is larger than the critical resolved shear stress of nickel (0.7 kg/mm^2 [993.5 lb/in.^{2}] at 300 K [80 °F]), according to Hassen (1958). This suggests that the interaction between the stress field of a moving domain wall and that of a dislocation may be of sufficient magnitude to move a free dislocation and induce changes in dislocation density or structure.

Four cold worked nickel bars of dimensions 38.1 by 9.5 by 9.5 mm (1.5 by 0.4 by 0.4 in.) were used. In order to produce a series of samples with different number densities of dislocations, the samples were subjected to various heat treatments (Table 2). Hysteresis loops were measured using a hysteresis graph and magnetic force microscopy images were obtained from the samples at the same magnetic state (at remanence) before and after the pulsed magnetic field treatment.

Table 2 Preparation and heat treatment conditions for the nickel samples

Sample	Heat Treatment
1	kept in the as received cold worked condition
2	annealed in vacuum at 673 K (752 °F) for 1 h and then furnace cooled
3	annealed in vacuum at 973 K (1292 °F) for 1 h and then furnace cooled
4	annealed in vacuum at 1273 K (1832 °F) for 1 h and then furnace cooled

As shown in Table 3, the magnetic loop properties such as coercivity and remanent induction were found to be invariant after the treatment for all samples. The magnetic force microscopy images of the samples in general show a large scale domain structure (tens of micrometers), which is probably related to the grain structure, and a fine scale (approximately 1 to 2 µm [3.9×10^{-5} to 1×10^{-4} in.]), complex domain pattern. An example is given in Figure 3a, which shows the domain structure of the nickel sample annealed at 973 K (1292 °F) before the pulsed magnetic field treatment. The magnetic force microscopy image obtained after the treatment exhibits similar features (Figure 3b). Similarly, no significant change in the domain structure was observed in the other samples after the pulsed magnetic field treatment. Since dislocations are pinning sites for domain walls, it was expected that any change in the dislocation density or residual stress level would be accompanied by a change in the domain pattern. The persistence of the fine scale, complex domain pattern seems to indicate that the treatment had a negligible effect on the dislocation density and structure in the nickel samples.

Study on Magnetic Thin Films

An extensive study of the effects of the pulsed magnetic field treatment was made on thin magnetic FeAlSi(N) films, which were deposited by radio frequency diode sputtering onto a Si (100) substrate using Ar + N_2 plasma with 3% partial pressure nitrogen in the sputtering gas. This material was of interest because it has a high level of compressive residual stress in the as deposited state along with a well characterized microstructure. It was also discovered in previous studies that there was a close relationship between the sample's hysteresis loop properties such as coercivity and film stress (Snyder et al., 2001), which can be used to assess the pulsed magnetic field treatment through the magnetic hysteresis measurement.

One FeAlSi(N) film sample was subjected to pulsed magnetic field treatment and the other sample was thermally annealed at 623 K (662 °F) for 2 h in a quartz tube back filled with 0.7 Pa (5 millitorrs) of argon gas. The film microstructure was characterized using X-ray diffraction and transmission electron microscopy. Hysteresis loops were measured using a vibrating sample magnetometer with the magnetizing field applied in the sample plane. Film stress was determined by measuring the curvature of the film substrate combination using an atomic force microscope. Magnetic domain structure was imaged using magnetic force microscopy. After the magnetic and thermal treatments, X-ray diffraction, vibrating sample magnetometer, magnetic force microscopy and curvature measurements were repeated on the samples.

Table 3 Magnetic hysteresis properties of the nickel samples before and after pulsed magnetic field treatment

Sample	Heat Treatment	Coercivity (A/m [Oe])		Remanent Induction*	
		Before Treatment	After Treatment	Before Treatment	After Treatment
1	as received	1081 ± 16 (13.58 ± 0.2)	1112 ± 16 (14 ± 0.2)	2492 ± 60	2509 ± 6
2	annealed at 763 K (752 °F)	1083 ± 22 (13.6 ± 0.28)	1183 ± 23 (15 ± 0.29)	2311 ± 96	2545 ± 5
3	annealed at 973 K (1292 °F)	612 ± 58 (7.7 ± 0.7)	721 ± 22 (9 ± 0.28)	2688 ± 25	2746 ± 20
4	annealed at 1273 K (1832 °F)	219 ± 34 (2.75 ± 0.4)	259 ± 24 (3.3 ± 0.3)	1144 ± 26	1016 ± 48

*Measurements are given in gauss (G); 1 G = 1×10^{-4} T.

It was found in the transmission electron microscopy and X-ray diffraction studies that the as deposited films consist of 100 nm (3.9×10^{-6} in.) diameter body center cubic grains. As shown in Figure 4, the hysteresis loops measured before and after pulsed magnetic field treatment are essentially the same. Hysteresis loop properties such as coercive force, remanent magnetization and maximum magnetic susceptibility remained unchanged after pulsed magnetic field treatment (Table 4). These magnetic properties had been found to be dependent on the film stress in a previous study (Snyder et al., 2001). In the as deposited state, the sample had a highly compressive residual stress which induced a strong magnetic anisotropy normal to the sample plane. This stress induced anisotropy contributed to the curved high field portion (5 kA/m [62.8 Oe] $< H <$ 50 kA/m [628 Oe]) of the hysteresis loop, which corresponded to rotation of the out of plane domain magnetization component towards the sample plane under the applied magnetic field. The similar loop shape obtained after treatment indicates that the sample still possessed a strong out of plane anisotropy maintained by a high film stress.

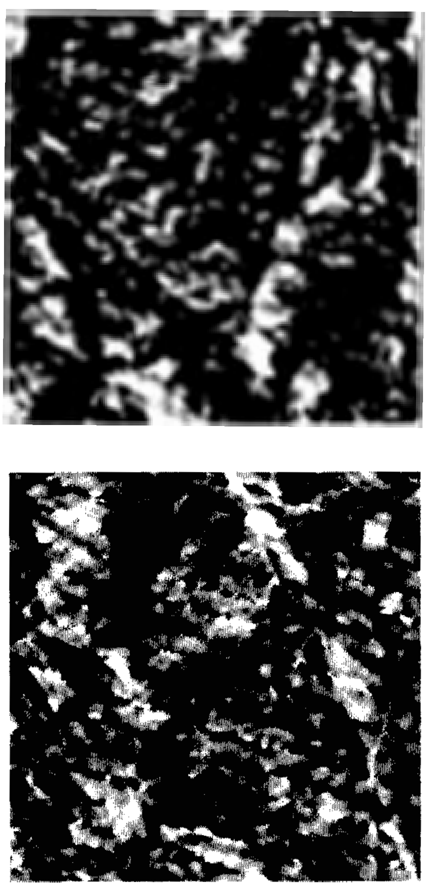


Figure 3 — Magnetic force microscopy images showing the magnetic domain structure in the nickel samples (heat treated at 973 K [1292 °F]) in the remanent state: (a) before pulsed magnetic field treatment; (b) after pulsed magnetic field treatment.

In contrast, the thermally annealed sample exhibited significantly different magnetic properties with a narrower hysteresis loop (Figure 4), lower coercivity, higher remanence and higher susceptibility (Table 4). The change in magnetic properties of the annealed sample was attributed to relief of film stress during thermal annealing. This was confirmed by the results of the film stress measurements (Table 4) and the X-ray diffraction studies (Table 5). The position and the width of the body center cubic peaks in the X-ray diffraction spectra remained unchanged after pulsed magnetic field treatment, while the body center cubic peaks of the thermally annealed sample shifted to higher 2θ values. This indicates that the lattice strain and hence the residual stress became lower after thermal annealing but were not altered by the pulsed magnetic field treatment.

Results obtained in the magnetic force microscopy studies also indicated a much greater effect on the domain structure caused by thermal annealing than by pulsed magnetic field treatment. The magnetic force microscopy images in Figures 5a and 5b show strikingly similar domain patterns in the remanent state before and after the magnetic treatment. This indicates the presence of strong pinning sites for magnetic domain walls, which continued to exist after the pulsed magnetic field treatment. These pinning sites are probably the amorphous secondary phase formed at the grain boundaries, as observed in the transmission electron microscopy study, or other structural discontinuities such as dense dislocation clusters. The present result shows that the pulsed magnetic field treatment was unable to remove these microstructural discontinuities. On the other hand, the annealed sample exhibited a wider and more regular stripe domain pattern (Figure 5c), which is attributed to reduced out of plane magnetic anisotropy as a result of the reduced residual

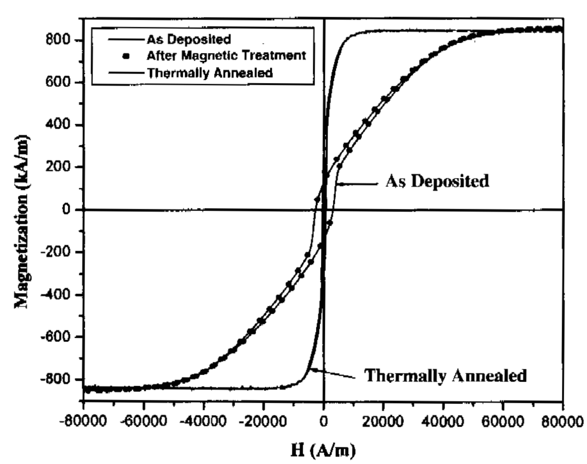


Figure 4 — Hysteresis loops measured from a thin FeAlSi(N) film sample before and after pulsed magnetic field treatment and after thermal annealing at 623 K (662 °F) for 2 h under an inert gas atmosphere.

Table 4 Positions (2θ) and widths (Δθ) of the body center cubic peaks in the X-ray diffraction spectra for the FeAlSi(N) thin film sample before and after the pulsed magnetic field treatment and after thermal annealing (positions and widths are in degrees)

Peak	Before Pulsed Magnetic Field Treatment		After Pulsed Magnetic Field Treatment		After Thermal Annealing	
	Peak Position	Peak Width	Peak Position	Peak Width	Peak Position	Peak Width
(110)	44.03	0.63	44.03	0.62	44.62	0.64
(211)	81.69	0.96	81.74	1.08	82.48	1.33
(220)	97.81	1.70	97.81	1.71	98.99	1.88

Table 5 Magnetic hysteresis properties of the FeAlSi(N) thin film sample before and after pulsed magnetic field treatment and after thermal annealing

Sample Condition	Film Stress (MPa [psi])	Coercivity (A/m [Oe])	Remanent Magnetization (kA/m [G])	Hysteresis Loss (J/m³)
as deposited	-1284 ± 28 (-186 228 ± 4061)	2897 ± 134 (36.4 ± 1.68)	139 ± 7 (139 ± 7)	4328 ± 36
after magnetic treatment	-1276 ± 30 (-185 068 ± 4351)	2929 ± 121 (36.8 ± 1.5)	136 ± 5 (136 ± 5)	4531 ± 30
after thermal annealing	-204 ± 10 (-29 588 ± 1450)	590 ± 16 (7.4 ± 0.2)	288 ± 11 (288 ± 11)	1389 ± 19

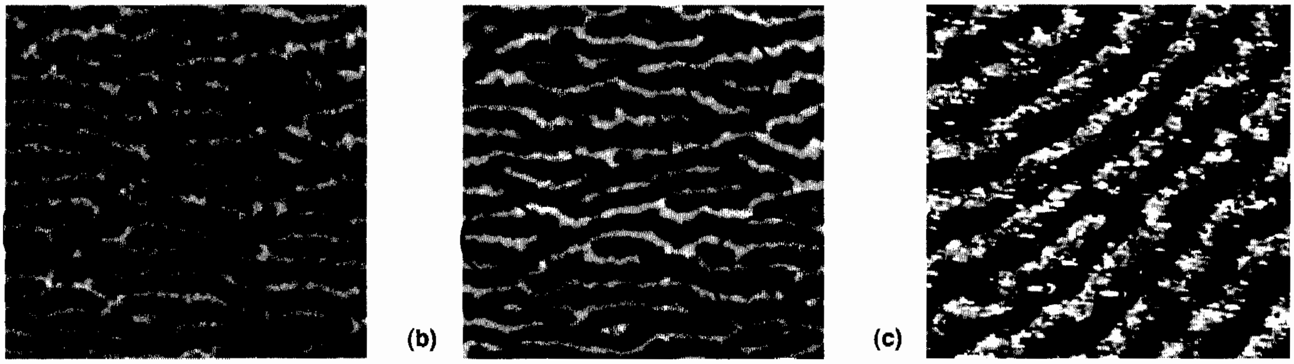
(a) (b) (c)


Figure 5 — Magnetic force microscopy images showing the magnetic domain structure in the remanent state of the FeAlSi(N) film sample: (a) before pulsed magnetic field treatment; (b) after pulsed magnetic field treatment; (c) after thermal annealing at 623 K (662 °F) for 2 h under an inert gas atmosphere. Note the strikingly similar domain patterns (the circled regions) in (a) and (b).

stress level after thermal annealing. The domain pattern was also found to be less repetitive after the sample was magnetized over a hysteresis cycle, indicating that domain wall pinning was weaker in the thermally annealed state than in the as deposited state.

CONCLUSION

Wide ranging and systematic studies were made to investigate the effects of the pulsed magnetic field treatment on various magnetic samples with well characterized structures and properties. A magnetic processing system has been designed and constructed for applying pulsed magnetic field treatments to materials. A software package was developed which allowed complete computer control of the pulsed magnetic field profile. The effects of the magnetic treatment were tested by measuring the magnetic properties and stress states of the samples before and after the treatment and compared to property changes caused by thermal annealing. The present investigation, using a range of characterization methods on a number of different specimens, both bulk samples and thin films, and with a variety of chemical compositions, was unable to detect any effect of the pulsed magnetic field treatment on the magnetic properties or the stress state of the samples.

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