

# FIELD- AND STRESS-INDUCED MAGNETIC ANISOTROPY IN NANOCRYSTALLINE Fe-BASED AND AMORPHOUS Co-BASED ALLOYS

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For nanocrystalline alloy  $\text{Fe}_{73.5}\text{Cu}_1\text{Nb}_3\text{Si}_{13.5}\text{B}_9$  thermomechanical treatment was carried out simultaneously with nanocrystallizing annealing (1) or after it (2). It was shown that a change in magnetic properties for the case 1 is essentially greater than for the case 2. Complex effect of thermomagnetic and thermomechanical treatments on magnetic properties was studied in the above-mentioned nanocrystalline alloy as well as in the amorphous alloy  $\text{Fe}_3\text{Co}_{70.6}\text{Si}_{15}\text{B}_{9.4}$ . During the annealings both field and stress were aligned with the long side of the specimens. It was shown that the magnetic field, AC or DC, decreases an effect of loading. Moreover, the magnetic field, AC or DC, applied after stress-annealing can destroy the magnetic anisotropy already induced under load.

*Keywords:* Nanocrystalline and amorphous alloys; Induced magnetic anisotropy

## INTRODUCTION

Nanocrystalline Fe-based alloys are known as a unique magnetically soft material with a low coercive force, low magnetic losses, and high magnetic permeability, which is caused by very fine grain size (10–12 nm), random distribution of crystal axes of grains, and vanishing total magnetostriction. It was known that (Glazer *et al.*, 1991) using thermomechanical treatment, magnetic anisotropy of the easy-plane type characteristic of Co-based alloys (Nielsen *et al.*, 1985) may be

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obtained in the  $\text{Fe}_{73.5}\text{Cu}_1\text{Nb}_3\text{Si}_{13.5}\text{B}_9$  alloy. This work is a continuation of Glazer *et al.* (1991). Its aim is to study for Fe-based nanocrystalline alloy the effect of the conditions of thermomechanical and thermomagnetic treatments on the magnitude of induced magnetic anisotropy and to compare the data with those for Co-based amorphous alloy  $\text{Fe}_5\text{Co}_{70.6}\text{Si}_{15}\text{B}_{9.4}$ .

## EXPERIMENTAL

The method of rapidly quenching the melt onto a rotating copper drum was used to prepare amorphous ribbons of both Fe- and Co-based alloys of 20  $\mu\text{m}$  in thickness and 1 mm in width. In order to obtain a nanocrystalline state, the Fe-based ribbons were annealed in air at 530°C for 1 h. Below, we will call this treatment nanocrystallizing annealing (NCA). For both alloys the thermomechanical (TMechT), or thermomagnetic (TMT), or thermomechanomagnetic (TMechMT) treatment, that involve annealing and cooling of the sample under a tensile load, or in a magnetic field, or upon both factors, was carried out in a vertical tubular furnace; a load was fastened to the ribbon using a special clamp and removed after the termination of the treatment. The longitudinal magnetic field  $H = 400$  Oe, DC or AC, was created by coil wound around the furnace. For Fe-based material the treatment was performed using two regimes:

1. The NCA was carried out simultaneously with TMechT, or TMT, or TMechMT. An amorphous sample was subjected to NCA with a tensile load, or a magnetic field, or both a load and a magnetic field simultaneously.
2. NCA and TMechT, or TMT, or TMechMT were performed sequentially; the sample that was preliminarily annealed to obtain the nanocrystalline condition was then subjected to one of three treatments.

From a ribbon subjected to such a treatment, samples of 80–100 mm in length were cut from a portion that was located in the zone of the controlled uniform heating. Magnetic properties (hysteresis loops) were measured by the ballistic method in a field directed along the ribbon.

Similar to thermomagnetic treatment in transverse DC magnetic field the thermomechanical one increases the incline of the hysteresis loops;

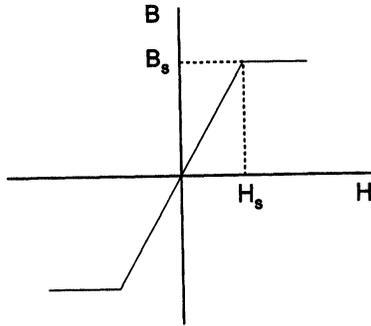


FIGURE 1 Appearance of the hysteresis loop for  $\text{Fe}_{73.5}\text{Cu}_1\text{Nb}_3\text{Si}_{13.5}\text{B}$ -specimens after stress- or field-treatment in transverse DC magnetic field.

with increasing load, the slope of the loop increases (Glazer *et al.*, 1991). The constant of induced magnetic anisotropy  $K_u$  was determined from a relation  $K_u = -0.5M_s H_s$  (see Fig. 1), where  $M_s$  is the saturation magnetization and  $H_s$  is the saturating field (in which saturation magnetization is reached). The error of measuring  $K_u$  was 5–7%.

## RESULTS AND DISCUSSION

The results of the investigations are shown in the figures and in the tables.

For nanocrystalline alloy Fig. 2 shows the variation of the constant of induced magnetic anisotropy depending on the load during TMechT at  $530^\circ\text{C}$  for 1 h according to regimes 1 and 2 (curves 1 and 2, respectively). It can be seen that, first, the magnitude of  $K_u$  induced by TMechT increases with increasing load, the magnitude of  $K_u$  after TMechT by regime 1 is substantially larger than that obtained after treatment by regime 2. The times for reaching maximum  $K_u$  upon treatment by regimes 1 and 2 are also substantially different. When TMechT is performed at  $530^\circ\text{C}$   $K_u$  reaches its maximum in a few minutes if TMechT is combined with NCA, but only in more than 1 h if TMechT follows NCA. It was noted also that ribbons treated by regime 1 increase in length. The larger the load, the greater the elongation; at maximum loads it reaches 13–15 mm, which is equal to about 15% of the gage length of the ribbon. The elongation occurs in approximately the same

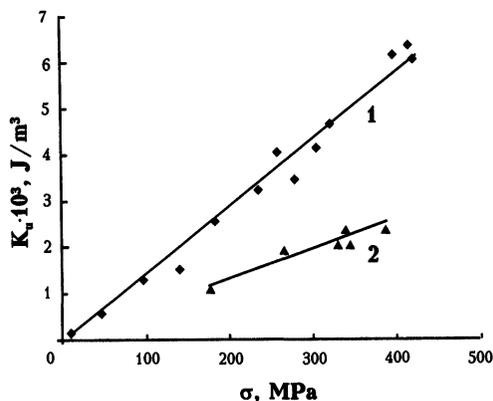


FIGURE 2 Variation of the constant of induced magnetic anisotropy  $K_u$  depending on the load during TMechT; (1) regime 1: TMechT is combined with NCA (530°C, 1 h); (2) regime 2: TMechT (530°C, 1 h) follows NCA (530°C, 1 h).

TABLE I  $K_u$  values for nanocrystalline specimens subjected to TMechT or TMechMT

Load at TMechT or TMT, MPa	7	30	50	100	150	215
$K_u$ after TMechT, J/m <sup>3</sup>	110	285	500	1120	1620	2300
$K_u$ after TMechT in DC H, J/m <sup>3</sup>	95	260	465	1030	1580	2230
$K_u$ decrease, %	-14	-9	-7	-3	-3	-3
$K_u$ after TMechT in AC H, J/m <sup>3</sup>	85	250	445	1080	1630	2260
$K_u$ decrease, %	-23	-12	-11	-4	+0.5	-2

time, in which  $K_u$  reaches its maximum value, i.e. in a few minutes. No elongation was observed when treating ribbons by regime 2.

The Table I shows the  $K_u$  behavior for Fe-based specimens subjected to NCA simultaneously with TMechT in a magnetic field, AC or DC, at 530°C for 1 h. In addition, the percent of the  $K_u$  value decrease after TMechMT is shown in comparison with that after TMechT. One can see that the magnetic field decreases an effect of loading to 50 MPa; the less the load, the more the decrease. At loads more than 50 MPa the change of  $K_u$  is less than 5% which is within the error of measuring  $K_u$ .

Figure 3 shows the hysteresis loops of Fe-based specimens subjected to NCA at 530°C for 1 h under load  $\sigma = 30$  MPa. Cooling of specimens after this treatment proceeded in different ways: under load  $\sigma = 30$  MPa (a); without anyload (b); without anyload in longitudinal DC (c) or AC (d) magnetic field  $H = 400$  Oe. Co-based amorphous specimens were subjected to analogous treatment, what means annealing at 300°C for 1 h

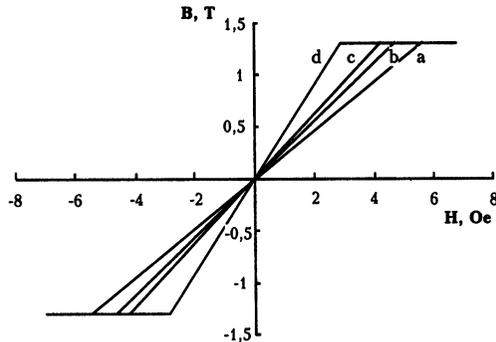


FIGURE 3 Hysteresis loops after 1 h annealing under load  $\sigma = 30$  MPa at temperature  $T = 530^\circ\text{C}$  followed by cooling under the load (a), without any load (b), without any load in magnetic DC (c) and AC (d) field  $H = 400$  Oe.

TABLE II  $K_u$  magnitudes for nanocrystalline and amorphous specimens subjected to stress-annealing followed by cooling in different conditions

Cooling mode after stress-annealing for alloys	$K_u$ , J/m <sup>3</sup>		$K_u$ decrease, %	
	Fe-based	Co-based	Fe-based	Co-based
Under load	285	280		
Without any load	240	240	-16	-14
Without any load in DC field	220	170	-23	-39
Without any load in AC field	150	130	-47	-54

under load  $\sigma = 600$  MPa and cooling: under load  $\sigma = 600$  MPa (a), without any load (b); without any load in longitudinal DC (c) or AC (d) magnetic field  $H = 400$  Oe.

The Table II shows the values of  $K_u$  after different coolings for both alloys. Also, it shows a percent of  $K_u$  decrease after cooling without any load and in magnetic fields in comparison with  $K_u$  after cooling under load. It is seen that after cooling without any load  $K_u$  decreases by 16% for Fe-based and 14% for Co-based alloys, and after cooling in a magnetic field much larger, particularly in AC one. It means that cooling in magnetic field can destroy magnetic anisotropy induced under load.

## CONCLUSION

1. The magnitude of the constant of induced magnetic anisotropy that can be obtained by TMechT increases with increasing tensile stresses.

2. The combined effect of NCA and TMechT, all other conditions being the same, produces a greater induced anisotropy than that obtained when TMechT follows NCA.
3. Magnetic field can interfere with the induction of magnetic anisotropy during stress-annealing and destroy the already stress-induced one.

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### ***References***

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