J Mater Sci (2006) 41:7380–7386
DOI 10.1007/s10853-006-0805-1

Effects of Co, Mo, and Ni on magnetic properties in 3Si–0.1Sn–0.08Sb alloyed non-oriented electrical steels

Sam K. Chang

Received: 8 August 2005 / Accepted: 6 December 2005 / Published online: 20 September 2006

Abstract With the addition of Co, Mo and Ni to high-alloyed non-oriented electrical steels with 3Si–0.1Sn–0.08Sb, Ni increased grain size more than Co and Mo. A very low level of core loss ($W_{15/50}$ = 2.2 W/kg) and high magnetic induction (B_{50} = 1.7 T) were obtained in the Ni added steel. However, Co and Mo deteriorated the magnetic properties substantially. With respect to the texture effect on magnetic properties, core loss decreased and magnetic induction increased proportionally to texture factor (ratio of the sum of cube and Goss texture to γ fiber), while correlations of anisotropies of core loss and magnetic induction to the texture factor appeared parabolic.

Introduction

Electrical steels are used as core materials for electrical products such as transformers, motors, and generators and thus require high magnetic induction and low core energy loss at use. There are two types of electrical steels, grain-oriented (GO) and non-oriented (NO). GO steels are grain-oriented in a specific direction consisting mainly of Goss orientation of (110)[001] which is very favorable to magnetic properties of induction and core loss, and are thus used mainly for transformer cores. Manufacture of GO steels consists of complicated processes and there are many difficulties associated with controlling Goss orientation. In contrast, NO steels do not require a unidirectional orientation because they are used for electrical rotary devices such as motor cores. The control of unidirectional oriented-grains is not necessary for NO steels, and thus the manufacturing processes of NO steels are comparatively simple and economical. Recently NO steels have been developed so that magnetic properties were greatly improved, with the result that core loss can decrease as low as 2.5 W/kg at $W_{15/50}$ during commercial production.

In the present work, the author attempted to develop advanced non-oriented electrical steels having extremely low core loss, together with high magnetic induction to substitute for grain oriented steels which are expensive and difficult to manufacture. In order to gain high magnetically efficient steels, it is necessary to add large quantity of silicon and special elements in non-oriented steels. The reference steel was designed with 3Si–0.1Sn–0.08Sb. Some special elements such as cobalt, molybdenum and nickel were added to maximize magnetic properties. Silicon is used as a main element in electrical steels because it has high electrical resistivity and is effective in magnetizing steels. Tin and antimony were proven effective in decreasing core loss and increasing magnetic flux density [1]. Such trial chemistries for non-oriented steels have never been investigated to substitute for grain oriented steels, nor have additional elements of cobalt, molybdenum and nickel to non-oriented steels been tested. Although these elements are known to have lower electrical resistivity than silicon and similar magnetic anisotropies to silicon, their effects on magnetic properties were not proven and so must be investigated as well as further evaluation of its relationship with texture is required.

S. K. Chang (✉)
Graduate Institute of Ferrous Technology, POSTECH,
Pohang 790-784, Korea
e-mail: c3k@postech.ac.kr

Experimental procedure

Four steels were melted in a 30 kg vacuum furnace and their chemical compositions are shown in Table 1. Steel A is a reference material and the other three alloys are compared with it to evaluate the effects of each element on magnetic properties. Ingots were hot rolled to a thickness of 2.6 mm, cold rolled to 0.35 mm, and annealed at 1,000 °C for 2 min in an oxidation free atmosphere.

Magnetic properties were measured by the single sheet test method. Texture measurements were performed at the surface of the annealed specimens. The (110), (200), and (211) pole figures were measured to a maximum tilt angle of 75° by X-ray diffractometer by using Cu Kα radiation. The ODFs were presented as a plot of constant ϕ_2 section with intensity contours defining Euler angles of ϕ_1, ϕ, and ϕ_2 in the Euler space. Crystallographic textures were analyzed from the ODFs by using software [2]. Quantitative texture analysis was carried out to calculate volume fractions of ideal components of all possible crystallographic orientations. The intensities of the ODFs within 15° from the exact point of each texture in the Euler space were integrated [3]. The texture effect was evaluated as a texture factor expressed as a ratio of the sum of volume fractions of cube and Goss textures to volume fraction of γ fiber, to weigh texture effectiveness on magnetic induction and core loss.

Results

Microstructure

Table 2 shows the grain size of annealed steels. Steel D containing Ni revealed larger grains than Co and Mo bearing steels which exhibit comparatively larger than the reference steel A.

Magnetic properties and anisotropy

Core loss and magnetic flux density are shown in Table 3. Steel containing Ni showed the lowest core loss of 2.2 W/kg but Mo bearing steel showed the highest core loss, 2.4 W/kg. However, magnetic flux density is inverse to core loss, that is, Ni-steel showed the highest level of 1.68 T but Mo-steel the lowest level of 1.65 T. Of note, a core loss of 2.2 W/kg in non-oriented steels is an extremely low level which has never been obtained. Therefore, Ni is very effective in lowering core loss and increasing magnetic induction but Mo is ineffective in improving core loss and magnetic induction. Regarding magnetic anisotropies, Mo-steel exhibited the lowest anisotropies of both core loss and magnetic induction, which is an inverse result to that of Mo, which is ineffective for reducing core loss and increasing magnetic induction. Regarding magnetic anisotropies, Ni-steel is next to the Mo-steel and better than Co bearing and reference steels.

Texture

Figure 1 shows the ODF maps of annealed steels. The ODF contours exhibit no difference among the steels, A, B, and C but show a distinct difference between these steels and Ni-steel. Ni-steel represents strong intensities at certain textures which are subject to be analyzed by calculating the volume fractions quantitatively using software. The results of the calculated volume fractions of texture components from the ODFs are shown in Table 4. First of all, regarding the textures influencing significantly the magnetic properties, cube, Goss, and γ fiber textures are mainly discussed. The volume fractions of cube texture (001)(100) and Goss texture (110)(001) in Ni-steel are a bit more than both Co-steel and Mo-steel as though the quantity is small. On the other hand, γ fiber (ϕ_1 = 0–90°, ϕ = 55°, and ϕ_2 = 45°) shows high volume fractions more than 30% for all steels. Ni-steel reveals noticeably lowest γ fiber in volume fraction, compared to Co and Mo bearing steels. Therefore, it is obvious that Ni element is more effective in reducing γ fiber than Co or Mo element. All steels show strong orientations of (323) and (211) . Other orientations which appeared conspicuously are (116), (611), (001)[120], and (001)[110]. The (211) orientation is the most dominant and the volume fractions are ranged from about 15–20%, followed by (323) orientation, which was between about 10 and 14%. Ni-steel, in particular,

Table 1 Chemical compositions (wt %) of test steels

Steel	C	Mn	Si	Al	Sn	Sb	Co	Mo	Ni
A	0.0058	0.308	2.90	1.52	0.101	0.078			
B	0.0042	0.309	2.91	1.52	0.103	0.078	0.050		
C	0.0039	0.310	2.90	1.52	0.104	0.077		0.053	
D	0.0035	0.309	2.92	1.51	0.105	0.078			0.054

Table 2 Grain size of annealed steels

Steel	Mean grain size (μm)	Number of grains
A	103.1	152
B	114.9	136
C	111.6	140
D	123.0	127

Table 3 Core loss and magnetic flux density of test steels

Steel	Core loss			Anisotropy	Magnetic induction			Anisotropy
	$W_{15/50}$ (W/kg)			(%)	B_{50} (T)			(%)
	W_L^a	W_T	Mean	ΔW^c	B_L^b	B_T	Mean	ΔB^d
A	2.046	2.453	2.249	9.0	1.707	1.635	1.671	2.2
B	2.150	2.549	2.352	8.5	1.697	1.627	1.662	2.1
C	2.258	2.548	2.402	6.0	1.681	1.623	1.652	1.8
D	2.039	2.402	2.221	8.2	1.706	1.644	1.675	1.9

[a] W_L is longitudinal core loss and W_T is transverse core loss

[b] B_L and B_T are longitudinal and transverse magnetic induction, respectively

[c] ΔW is core loss anisotropy expressed as $|(W_L - W_T)/(W_L + W_T)|$

[d] ΔB is magnetic induction anisotropy expressed as $|(B_L - B_T)/(B_L + B_T)|$

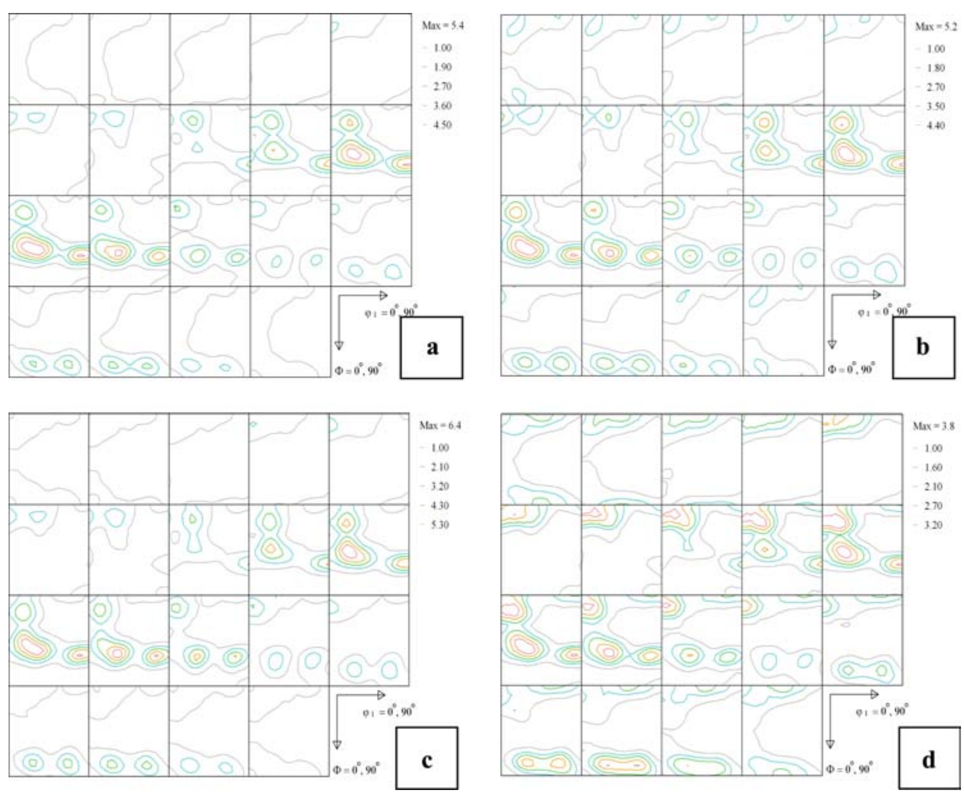

Fig. 1 ODFs of annealed steels

showed that (611) and (001)[110] orientations were stronger than other steels.

Texture factors for the four steels are shown in Fig. 2 and are expressed as a rate of the sum of cube texture and Goss texture to γ fiber in order to ascertain effectiveness of the former two textures against the γ fiber. This is because cube and Goss textures are favorable but γ fiber is unfavorable to magnetic induction and core loss. Steel containing Ni showed the highest texture factor and Co-steel showed the lowest. The large texture factor means that useful textures for magnetic properties are much and thus can increase magnetic induction and decrease iron loss. As though it was verified experimentally that Ni enhanced cube and Goss texture and lowered iron loss, it is hardly

Table 4 Texture volume fractions of annealed steels

Texture	Orientation	Euler angles	Texture volume fraction (%)			
		$g = [\phi_1\ \phi\ \phi_2]$	Steel A	Steel B	Steel C	Steel D
Cube	(001)[100]	[0 0 0]	2.1	2.4	2.2	2.7
Goss	(110)[001]	[90 90 45]	2.8	1.8	1.6	2.1
γ fiber	(111)	[0 55 45]	7.6	6.7	7.6	6.0
	(111)	[30 55 45]	12.3	12.2	13.9	9.2
	(111)	[60 55 45]	7.7	6.8	7.7	6.1
	(111)	[90 55 45]	12.3	12.2	13.9	9.2
	Total		39.9	37.9	43.1	30.5
Other	(211)	[73 66 63]	16.8	17.4	20.3	15.0
Dominant	(323)	[23 50 56]	12.2	11.9	13.6	9.5
Textures	(116)	[0 13 45]	6.3	6.6	6.3	8.9
	(001)[110]	[0 0 45]	2.7	3.0	2.8	4.5
	(611)	[48 81 81]	8.2	8.7	8.5	11.3
	(001)[120]	[0 0 63]	5.7	6.9	6.6	7.9
Texture factor (%) = (Cube + Goss)/γ			12.3	11.1	8.8	15.7

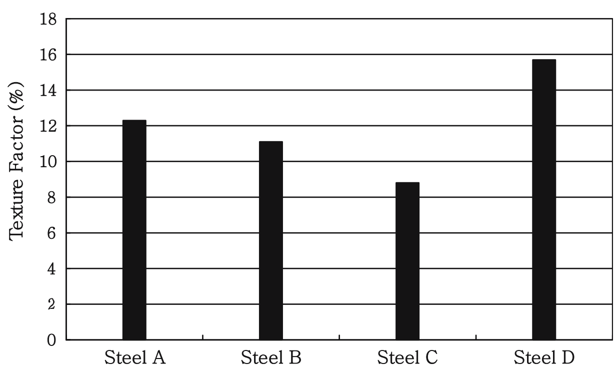

Fig. 2 Texture factors of annealed steels

explained how Ni element plays a role in developing such textures but this is subject to investigate in future.

Misorientation and CSL boundaries

The misorientation is calculated between each pair of orientations randomly chosen from the ODFs. In calculation of grain boundary character distribution from the ODFs, it is assumed that grains have random spatial correlation in the software and better statistical results in the misorientation calculation can be obtained because a large number of grain pair is chosen to 1,000. Figure 3 shows misorientation angles of annealed steels. Misorientation angles of all steels were equally distributed in the same manner and show a major portion of misorientation between 35° and 55°, showing a peak between 40° and 50°. Ni added steel shows misorientation angles dominantly at 35–45°, which is slightly low in comparison with the other steels. For high angle boundaries with misorientation angles larger than 15°, Ni-steel showed the accumulative frequency of 97.2%, which is higher than the Co-steel and the Mo-steel having about 95%. This means that larger grains provide larger misorientation because Ni-steel exhibited larger grains than the Co-steel and Mo-steel, as mentioned above. It is obvious that Ni element is less effective on the restriction of the grain growth than Co and Mo.

The CSL boundary distribution was calculated by the same manner as the misorientation. Figure 4 shows CSL boundaries for the annealed specimens. The CSL boundaries larger than $\sum = 19b$ are very low frequency and thus negligible in the figure. The Ni-steel showed less frequency for $\sum = 1$ and $\sum = 3$ boundaries than Co-steel and Mo-steel. However, CSL boundaries larger than $\sum = 5$ differ little among four steels. This result is in accordance with the above mentioned misorientation for which the Ni-steel has comparatively less frequency in low angle grains but more frequency in high angle grains than the other steels.

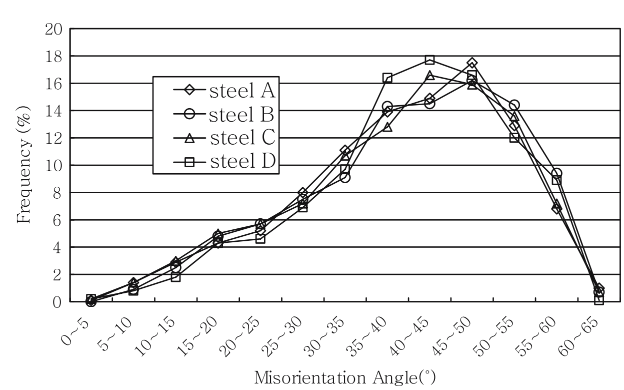

Fig. 3 Misorientation angles of annealed steels

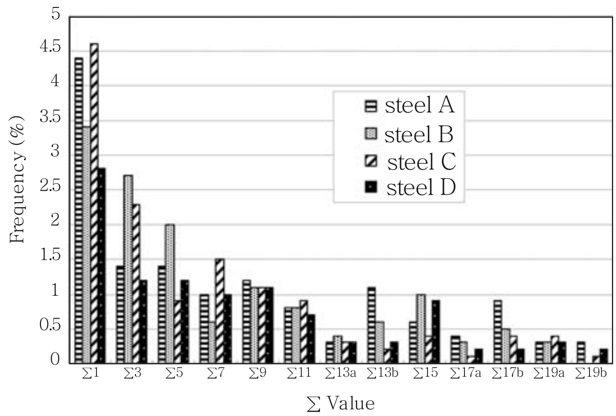

Fig. 4 CSL boundaries of annealed steels

Discussion

Effects of Co, Mo, and Ni on magnetic properties

Reference steel A, bearing high alloys of 2.9% Si, 1.5% Al, 0.1% Sn, and 0.078% Sb, shows a high level of magnetic induction and low core loss which is close to the level of magnetic properties of grain oriented electrical steel. Moreover, addition of Co, Mo and Ni elements to this steel has a great effect on magnetic properties and texture. Of the four test steels, steel D, containing Ni, had the best magnetic flux density and core loss, which proves that Ni was more effective in improving magnetic properties than Co and Mo. Co and Mo added steels revealed lower magnetic induction and higher core loss than even the reference steel. Sn and Sb elements contained in the reference steel already proved favorable to the magnetic properties [1], but the addition of Co and Mo to the reference steel is unfavorable and instead deteriorates the magnetic properties. Co, Mo, and Ni have similar electrical resistivity, but when these elements are added to steel, their chemical behaviors would react differently in steel and thus also affect magnetic properties in a different manner. That is, Co and Mo form chemical compounds such as carbide precipitates, while Ni does not form carbides and thus does not hinder magnetization. Therefore, Ni is presumably effective on permeability and eddy current because of free carbides compared to the other elements. Co and Mo bearing steels showed smaller grain size than the Ni bearing steel, as seen in Table 2. In general, larger grains show higher magnetic induction and larger core loss because movement of magnetic domains is more freely active in larger grains and thus permeability increases as energy loss increases. Shimanaka et al. [4] reported that core loss in non-oriented electrical steels decreased with an increase of grain size up to 100 μm and thereafter increased. Their steels showed core loss of only about 3 W/kg for 2.8% Si steel without special elements such as Sn, Sb, Co, Mo, or Ni, but our Ni added steel revealed a much lower core loss of 2.2 W/kg. Therefore, the fact that Ni added steel has even larger grains but shows lower core loss than other steels is a new result which is quite different from findings to date.

Correlation of texture with magnetic properties

Magnetic properties are concomitant with crystal texture [1], that is, cube and Goss texture are favorable to magnetic properties but γ fiber is unfavorable. The texture factor [1] was introduced to evaluate favorable textures over unfavorable ones and was expressed as a ratio of the sum of cube and Goss texture volumes to γ fiber volume. The Ni added steel exhibited a high texture factor compared to other steels. The Co or Mo added steel exhibited a lower texture factor than the reference steel, because Co and Mo form carbides and thus presumably hinder the development of cube and Goss texture. Correlations of texture factor with both magnetic flux density and core loss are shown in Fig. 5. The magnetic flux density increases proportionally with texture factor, consistent with previous work [1] which shows a steeper slope than the present slope (Fig. 5a). On the other hand, core loss also decreases proportionally with texture factor, which is identical to earlier results, which showed a steeper slope than the present slope (Fig. 5b). The previous steel did not contain Co, Mo, or Ni. These results on the relationship between texture factor and magnetic properties prove that magnetic induction and core loss are directly related to texture factor, and addition of Co, Mo, or Ni makes texture factor rather less sensitive to magnetic properties.

In consideration of the linear relationship between texture factor and magnetic properties, further investigation of the relationship between texture factor and magnetic anisotropy is required, because magnetic properties show a difference along angles from the rolling direction of materials [5]. Figure 6 shows the relationship between texture factor and magnetic anisotropy. Correlations of texture factor with anisotropies of magnetic induction (Fig. 6a) and core loss (Fig. 6b) are rather parabolic but are opposite to each other; that is, the former relationship is positive parabolic but the latter negative parabolic. The data

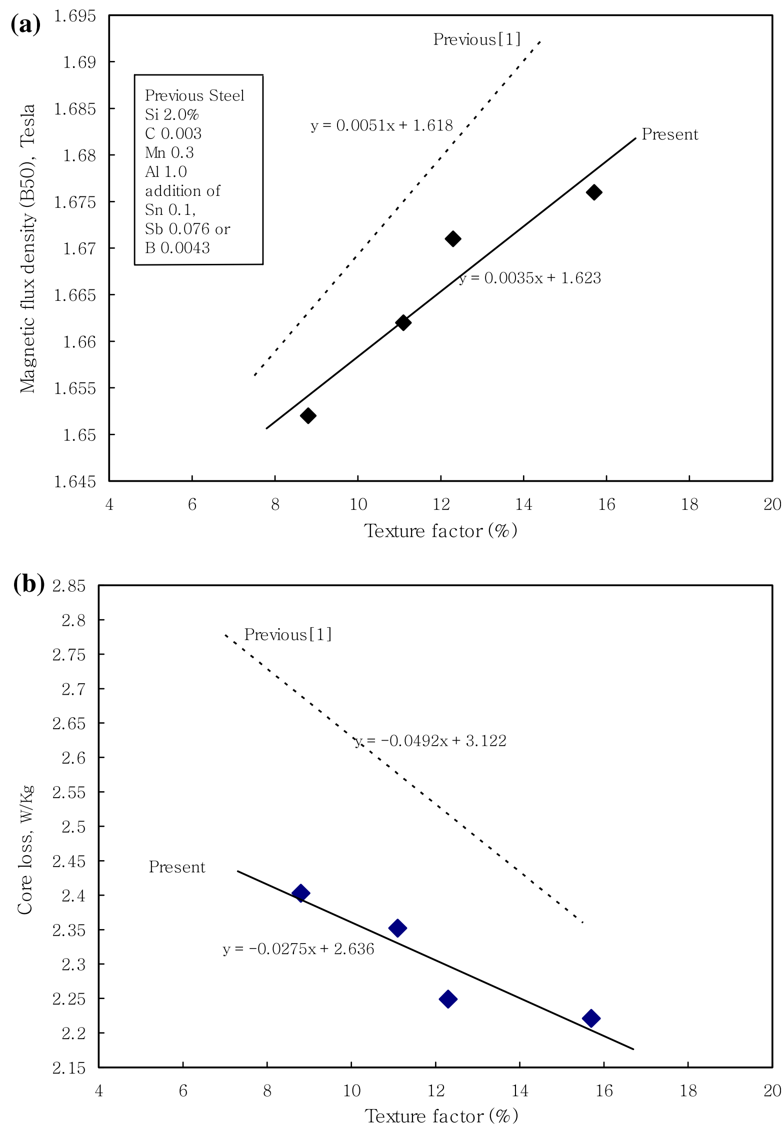

Fig. 5 Correlation of texture factor with (**a**) magnetic flux density and (**b**) core loss

plotted in Fig. 6a, b showed that, as texture factor exceeds about 13%, magnetic induction anisotropy decreases and core loss anisotropy increases again; a result which requires further investigation.

Conclusions

The effects of Co, Mo, and Ni addition to high-alloyed non-orientation steels with 2.9Si–0.1Sn–0.08Sb on magnetic properties and texture are as follows:

(1) Ni bearing steel exhibits a larger grain size than Co or Mo added.
(2) Ni addition substantially decreases core loss to 2.22 W/kg at $W_{15/50}$ and increases magnetic flux density to a high level of 1.68 T at B_{50}, while Co and Mo increase core loss and decrease magnetic flux density.
(3) Volume fractions of cube and Goss textures are similar for all steels, but γ fiber volume is lower in Ni-steel than other steels. Thus texture factors which show the extent of favorable textures is much high in Ni-steel, compared with Co and Mo added steels.
(4) Magnetic flux density increases proportionally with texture factor and core loss also decreases linearly, but the relationships of magnetic induction anisotropy and core loss anisotropy with texture factor are positive and negative parabolic, respectively.

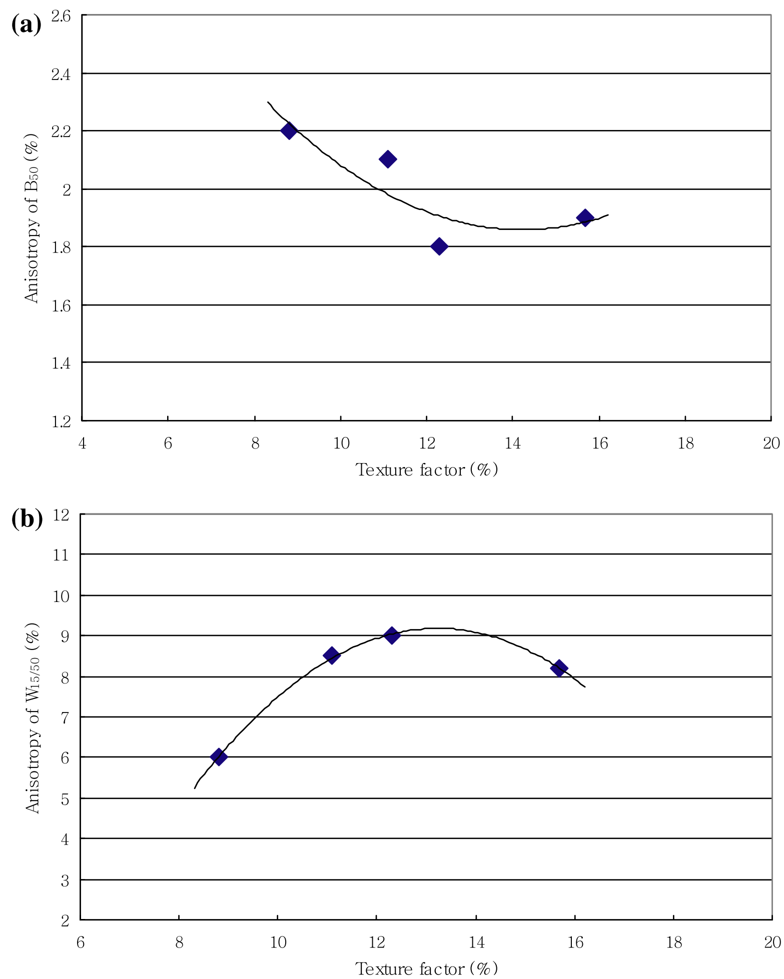

Fig. 6 Correlation of texture factor with (**a**) magnetic induction anisotropy and (**b**) core loss anisotropy

References

1. Chang SK, Huang WY (2005) ISIJ Int 45:918
2. Texture measurement software, Res-Mat Co, McGill University
3. Liu WC, Morris JG (2004) Met Mat Trans A 35A:265
4. Shimanaka H, Ito Y, Matsumura K, Fukuda B (1982) J Magn Magn Mater 26:57
5. Birsan M, Szpunar JA (1996) J Appl Phys 80:6915