Industrial Engineering Journal
ISSN: 0970-2555
Volume : 52, Issue 8, No. 5, August : 2023

NOVEL METHOD OF K_0,K_1,K_2,K_3 CONSTANTS EVALUATION OF MAGNETO-CRYSTALLINE ANIOSOTROPY ENERGY DENSITY EQUATION OF ELECTRICAL STEEL BASED ON TEXTURE FACTOR FOR IDEAL FIBRES

Geruganti Sudhakar, orcid:0009-0000-0039-7536,Phd Research Scholar, Department of Material Engineering, School of Engineering Sciences andTechnology, University of Hyderabad,Hyderabad,India. Email :20etpm09@uohyd.ac.in

Abstract
Texture Factor, A* and Magnetic Crystalline Anisotropy Energy Density* K_0, K1, K2, K_3 Constants are important parameters for Pure Iron. While the former indicates volume density of crystals having preferred Orientation, latter indicates the easy and hard magnetization directions. Evaluation of these parameters for Pure Iron and Electrical Steel enables in reduction of core losses and improving the electrical energy efficiency in Transformers, Rotating Machines. In this research article, an attempt is made to compute Magneto-Crystalline Anisotropy Energy Density for pure iron based on Texture Factor for Ideal fibers.

Keywords: Texture Factor, Magnetic Crystalline Anisotropy Energy Density, Core losses

I. Introduction

The Magneto Crystalline Anisotropy constants K1, K2 values determine the extent to which a material is easily magnetizable. Their value depends on Chemical Composition, Crystal Structure, and Thermo-Mechanical Processing history of the given material. In material science, Texture Factor is an important microstructural parameter which directly determines the anisotropy degree of most physical properties of a polycrystalline material at the macro scale. Its characterization is thus of fundamental and applied importance, and should ideally be performed prior to any physical property measurement or modeling. Neutron diffraction is a tool of choice for characterizing crystallographic textures. The obtained information is representative of a large number of grains, leading to a better accuracy of the statistical description of texture.Texture factor constants K1, K2 , K3values determines the preferred orientations of grains, the Overall Texture Factor is quantitative measurement of texture. The value signifies extent of presence of standard texture viz. Cube Texture (T.F = 22.5), Goss Texture (T.F = 35.6), Gamma Texture (T.F = 38.68) in the given material.

1.1 STANDARD EQUATIONS:

$$\mathbf{E}^* = K_0 + K_1 (\sum\alpha^2_1 \alpha^2_2) + K_2 (\prod\alpha^2_1) + K_3 (\sum\alpha^2_1 \alpha^2_2)^2 + K_4 (\sum\alpha^2_1 \alpha^2_2)(\prod\alpha^2_1) + K_5 (\sum\alpha^2_1 \alpha^2_2)^3 + K_6)(\prod\alpha^2_1)^2 ;$$

$$A^* = K_0 + K_1 (\sum\alpha^2_1 \alpha^2_2) + K_2 (\prod\alpha^2_1) + K_3 (\sum\alpha^2_1 \alpha^2_2)^2 + K_4 (\sum\alpha^2_1 \alpha^2_2)(\prod\alpha^2_1) + K_5 (\sum\alpha^2_1 \alpha^2_2)^3 + K_6)(\prod\alpha^2_1)^2 ;$$

$$E^* = 0.355A^* + (0.163 - 0.013A^*)[wt\%Si] - 1.898$$

II. ESTIMATION OF MAGNETIC ANISOTROPY CONSTANTS K_0,K_1,K_2,K_3 CONSTANTS EVALUATION OF FOR ELECTRICAL STEELS:

Magneto Crystalline Anisotropy Energy is generally expressed by an expansion into direction cosines α_1, α_2,α_3 of the magnetization with respect to the crystal axes.

$$E^* = K_0 + K_1 (\sum\alpha^2_1 \alpha^2_2) + K_2 (\prod\alpha^2_1) + K_3 (\sum\alpha^2_1 \alpha^2_2)^2 \quad [\ I\ ];$$

[uvw]	a	b	c	α_1	α_2	α_3	E
<100>	0	90^0	90^0	1	0	0	K_0
<110>	45^0	45^0	90^0	$1/\sqrt{2}$	$1/\sqrt{2}$	0	$K_0 + K_1/4$
<111>	54.7^0	54.7^0	54.7^0	$1/\sqrt{3}$	$1/\sqrt{3}$	$1/\sqrt{3}$	$K_0 + K_1/3 + K_2/27$

Industrial Engineering Journal
ISSN: 0970-2555
Volume : 52, Issue 8, No. 5, August : 2023

From REF 1, we have E* = 0.355A* +(0.163 – 0.013A*)[wt%Si] -1.898

FOR A* for Ɵ fiber <100>//ND is 22.5 => E* = -0.5345 [wt%Si] + 6.0895
FOR A* for fiber <110>//ND is 35.6 => E* = -0.9406 [wt%Si] + 10.74
FOR A* for ϒ fibre <111>//ND is 38.68 => E* = -1.03608 [wt%Si] + 11.8334

$E^* = K_0 + K_1 (\sum\alpha^2_1 \alpha^2_2) + K_2 (\prod\alpha^2_1) + K_3 (\sum\alpha^2_1 \alpha^2_2)^2$ …. [I];

FOR [100] directions, $\alpha_1 = 1, \alpha 2 = 0, \alpha_3 = 0 \Rightarrow E = K_0$
⇨ FOR [100] directions , E* = 6.0895 => **K_0 = -0.5345 [wt%Si] + 6.0895**

FOR [110] directions, $\alpha_1 = 1/\sqrt{2}, \alpha 2 = 1/\sqrt{2}, \alpha_3 = 0$
FOR [110] directions, E* = -0.9406 [wt%Si] + 10.74
⇨ $E^* = -0.5345$ [wt%Si] + 6.0895 + $K_1/4 + K_3/16$
⇨ -0.9406 [wt%Si] + 10.74 = -0.5345 [wt%Si] + 6.0895 + K1/4+ $K_3/16$
⇨ 4.6505-0.4061[wt%Si] = $K_1/4 + K_3/16$
⇨ $4K_1 + K_3 = 74.408 - 6.4976$[wt%Si] ……[II]

FOR [111] directions, $\alpha_1 = 1/\sqrt{3}, \alpha 2 = 1/\sqrt{3}, \alpha_3 = 1/\sqrt{3}$
FOR [111] directions, E* = -1.03608 [wt%Si] + 11.8334
⇨ -1.03608 [wt%Si] + 11.8334 = $K_0 + K_1/3 + K_2/27 + K_3/9$
⇨ -1.03608 [wt%Si] + 11.8334 = -0.5345 [wt%Si] + 6.0895 + $K_1/3 + K_2/27 + K_3/9$
⇨ -13.54266[wt%Si] +155.0853 = $9K_1 + K_2 + 3K_3$
⇨ $9K_1 + K_2 + 3K_3 = -13.54266$[wt%Si] + 155.0853 ……[III]
⇨ $3(3K_1 + K_3) + K_2 = 155.0853 - 13.54266$[wt%Si]
⇨ Consider $3K_1 + K_3 = 50$ …… [IV]
⇨ $150 + K_2 = 155.0853 - 13.54266$[wt%Si]
⇨ **K_2 = 5.0853 - 13.54266[wt%Si] …..[V]**
FROM $4K_1 + K_3 = 74.408 - 6.4976$[wt%Si.[II], $3K_1 + K_3 = 50$ …… [IV] we have
⇨ $K_1 + 50 = 74.408 - 6.4976$[wt%Si]
⇨ **K_1 = 24.408 -6.4976[wt%Si]**
⇨ $3K_1 + K_3 = 50$
⇨ $K_3 = 50 - 3K_1$
⇨ $K_3 = 50 – 3*(24.408 - 6.4976$[wt%Si])
⇨ $K_3 = 50 – 73.224 + 19.4928$[wt%Si]
⇨ **K_3 =-23.224+ 19.4928[wt%Si]**
⇨ **K_0 = -0.5345 [wt%Si] + 6.0895**
⇨ $E^* = K_0 + K_1 (\sum\alpha^2_1 \alpha^2_2) + K_2 (\prod\alpha^2_1) + K_3 (\sum\alpha^2_1 \alpha^2_2)^2$
Substituting **K_0**, **K_1**, **K_2**, **K_3**
⇨ **E* = -0.5345 [wt%Si] + 6.0895 + (24.408 -6.4976[wt%Si])** $(\sum\alpha^2_1 \alpha^2_2)$ +**(5.0853 - 13.54266[wt%Si])** $(\prod\alpha^2_1)$ + **(-23.224+ 19.4928[wt%Si])** $(\sum\alpha^2_1 \alpha^2_2)^2$

⇨ **E* =-0.5345 [wt%Si] + 6.0895 + (13.126 - 1.98338[wt%Si])** $(\sum\alpha^2_1 \alpha^2_2)$ **– (28.7605)** $(\prod\alpha^2_1)$ + **(21.904 + 1.43592 [wt%Si])** $(\sum\alpha^2_1 \alpha^2_2)^2$

⇨ **E* = 6.0895 + (24.408)** $(\sum\alpha^2_1 \alpha^2_2)$ +**(5.0853)** $(\prod\alpha^2_1)$ **-23.224** $(\sum\alpha^2_1 \alpha^2_2)^2$ + [**-0.5345 [wt%Si] - 6.4976[wt%Si])** $(\sum\alpha^2_1 \alpha^2_2)$ **- 13.54266[wt%Si])** $(\prod\alpha^2_1)$**+19.4928[wt%Si])** $(\sum\alpha^2_1 \alpha^2_2)^2$]

⇨ **$E^* = E^*_{IRON} + E^{**}$**

Industrial Engineering Journal
ISSN: 0970-2555
Volume : 52, Issue 8, No. 5, August : 2023

⇨ **E** =[-0.5345 [wt%Si] -6.4976[wt%Si])** $(\sum\alpha^2_1\ \alpha^2_2)$ **- 13.54266[wt%Si])** $(\prod\alpha^2_1)$ **+19.4928[wt%Si])** $(\sum\alpha^2_1\ \alpha^2_2)^2$]

⇨ **Above Equation is very important Magneto-Crystalline Energy Density Equation for Electrical Steels**

CRYSTALLOGRAPHIC DIRECTION	MAGNETO-CRYSTALLINE ANISOTROPY ENERGY DENSITY
[100] α_1 =1,α_2 =0, α_3=0	**$E^*_{[100]}$ = 6.0895 - 0.5345 [wt%Si]**
[110] α_1 =1/√2,α_2 =1/√2, α_3=0	**$E^*_{[110]}$ = 10.74 - 0.9406 [wt%Si]**
[111] α_1 =1/√3,α_2 =1/√3, α_3=1/√3	**$E^*_{[111]}$ =11.8334 -1.03608 [wt%Si]**

S.NO.	Standard Crystallographic Directions	Magneto-Crystalline Anisotropy Values ,E* For Pure Iron	Magneto-Crystalline Anisotropy Values ,E*	Magneto-Crystalline Anisotropy Values ,E* for Fe-0.51%Si	Magneto-Crystalline Anisotropy Values ,E* for Fe-1.38%Si	Magneto-Crystalline Anisotropy Values ,E* for Fe-2.8%Si	Magneto-Crystalline Anisotropy Values ,E* for Fe-3.2%Si
1	[100]	$E^*_{[100]}$ = 6.0895	$E^*_{[100]}$ = -0.5345 ([wt%Si])+6.0895	5.816905	5.35189	4.5929	4.3791
2	[110]	$E^*_{[110]}$ = 10.74	$E^*_{[110]}$ = -0.9406 [wt%Si] + 10.74	10.260294	9.441972	8.10632	7.73008
3	[111]	$E^*_{[111]}$ = 11.8634	$E^*_{[111]}$ = -1.03608 [wt%Si] + 11.8634	11.3349992	10.4336096	8.962376	8.547944

2.1 Discussion

From Ref[1],The <100>//ND fibre accounts for the lowest anisotropy energy since the flux lines, distributed homogenously in a plane of the rotating laminated sheet, have an easiest magnetization direction with the in-plane rotated cube texture components. On the contrary, the ϒ and the <011>//ND fiber orientations have relatively high anisotropy energy and as such, the occurrence of these components in electrical steels is undesirable.

III. ESTIMATION OF TEXTURE K_0, K1,K2,K3 CONSTANTS FOR ELECTRICAL STEELS

⇨ E* = 0.355A* + (0.163 – 0.031A*)[wt%Si] -1.898 FROM REF 1,

⇨ **$A^* = K_0 + K_1 (\sum\alpha^2_1\ \alpha^2_2) + K_2 (\prod\alpha^2_1) + K_3 (\sum\alpha^2_1\ \alpha^2_2)^2$**

⇨ **[0.355 – 0.031[wt%Si]**]A* =-0.163[wt%Si] + 1.898 **-0.5345 [wt%Si] + 6.0895 + (24.408 - 6.4976[wt%Si])** $(\sum\alpha^2_1\ \alpha^2_2)$ +(**5.0853 - 13.54266[wt%Si])** $(\prod\alpha^2_1)$+**(-23.224+ 19.4928[wt%Si])** $(\sum\alpha^2_1\ \alpha^2_2)^2$

Industrial Engineering Journal
ISSN: 0970-2555
Volume : 52, Issue 8, No. 5, August : 2023

⇨ **[0.355 – 0.031[wt%Si]**]A* = **-0.6975[wt%Si] + 7.9875 + (24.408 -6.4976[wt%Si])** $(\sum\alpha^2_1\ \alpha^2_2)$ **+(5.0853 - 13.54266[wt%Si])** $(\prod\alpha^2_1)$ **+ (-23.224+ 19.4928[wt%Si])** $(\sum\alpha^2_1\ \alpha^2_2)^2$

⇨ $\mathbf{A^* = K_0 + K_1\ (\sum\alpha^2_1\ \alpha^2_2) + K_2\ (\prod\alpha^2_1) + K_3\ (\sum\alpha^2_1\ \alpha^2_2)^2}$

⇨ **K_0 = -0.6975[wt%Si] + 7.9875 ; K_1 = (24.408 -6.4976[wt%Si]) ; K_2 = (5.0853 - 13.54266[wt%Si]); K_3 = (-23.224+ 19.4928[wt%Si])**
[0.355 – 0.031[wt%Si]] [0.355 – 0.031[wt%Si]] [0.355 – 0.031[wt%Si]] [0.355 – 0.031[wt%Si]]

S.NO.	TEXTURE FACTOR CONSTANTS	Fe + 0.51%Si	Fe + 1.38%Si	Fe + 2.8%Si	Fe + 3.2%Si
1.	K_0	22.5	22.5	22.5	22.5
2.	K_1	62.1899	49.45651	23.171961	14.13479
3.	K_2	-5.370018	-43.57046	-122.424116	-149.53562
4.	K_3	-39.15997	11.773954	116.91215	153.0608

⇨ $\mathbf{A^*_{0.51\%Si} = 22.5 + 62.1899\ (\sum\alpha^2_1\ \alpha^2_2) - 5.370018(\prod\alpha^2_1) - 39.15997(\sum\alpha^2_1\ \alpha^2_2)^2}$
⇨ $\mathbf{A^*_{1.38\%Si} = 22.5 + 49.45651\ (\sum\alpha^2_1\ \alpha^2_2) - 43.57046\ (\prod\alpha^2_1) + 11.773954\ (\sum\alpha^2_1\ \alpha^2_2)^2}$
⇨ $\mathbf{A^*_{2.8\%Si} = 22.5 + 23.171961\ (\sum\alpha^2_1\ \alpha^2_2 - 122.424116\ (\prod\alpha^2_1) + 116.91215\ (\sum\alpha^2_1\ \alpha^2_2)^2}$
⇨ $\mathbf{A^*_{1.38\%Si} = 22.5 + 14.13479\ (\sum\alpha^2_1\ \alpha^2_2) - 149.53562\ (\prod\alpha^2_1) + 153.0608\ (\sum\alpha^2_1\ \alpha^2_2)^2}$

S.NO.	CRYSTALLOGRAPHIC DIRECTIONS	DIRECTIONAL COSINE RELATIONSHIP	TEXTURE FACTOR FOR A* IDEAL FIBER	TEXTURE FACTOR FOR $A^*_{0.51\%Si}$	TEXTURE FACTOR FOR $A^*_{1.38\%Si}$	TEXTURE FACTOR FOR $A^*_{2.8\%Si}$	TEXTURE FACTOR FOR $A^*_{3.2\%Si}$
1	<100>direction	α_1 =1, α2 =0, α_3=0	22.5 Θ fibre <100>// ND	22.5	22.5	22.5	22.5
2	<110>direction	α_1 =1/√2, α2 =1/√2, α_3=0	35.6 fibre <110>// ND	35.6	35.6	35.6	35.6
3	<111> direction	α_1 =1/√3, α2 =1/√3, α_3=1/√3	38.68 ϒ fibre <111>// ND	38.68	38.68	38.68	38.68

5. Conclusions

Magneto-Crystalline Anisotropy Energy Density value is least for [100] directions, and higher for [110] & [111] directions. Therefore [100] directions are easy directions of magnetization for pure iron and [111] hardest direction for magnetization of pure iron, [110] direction is harder direction for

magnetization of pure iron. Texture Factor Equation results are consistent with the standard results and conforms to the value of ideal fibres.

REFERENCES:

1. **Through process texture evolution and magnetic properties of high Si non-orientedelectrical steels Jurij J. Sidor, Verbeken, Kim,Pablo Rodriguez Calvillo, Edgar Gomes, Juergen Schneider, https://doi.org/10.1016/j.matchar.2012.06.006**

2. Manufacturing of Pure Iron by Cold Rolling and Investigation for Application in Magnetic Flux Shielding Nitin Satpute,Prakash Dhoka,Pankaj Karande, Siddharth Jabade, Marek Iwaniec https://doi.org/10.3390/ma15072630

3. Texture Control and Manufacturing in Non-Oriented Electrical Steel Leo Kestens[1]and Sigrid Jacobs[2] DOI: 10.1155/2008/173083

4**.** The Magneto crystalline Anisotropy Constants of Iron and Iron-sil icon Alloys Björn Westerstrand[1], Per Nordblad[1] and Lars Nordborg[1] doi 10.1088/0031-8949/11/6/010

5. Mehdi, Mehdi, "Texture Evolution of Non-Oriented Electrical Steels during Thermomechanical Processing" (2019). Electronic Theses and Dissertations. 7648. https://scholar.uwindsor.ca/etd/7648

6. Crystallographic textures Vincent Kloseka CEA, IRAMIS, Laboratoire Léon Brillouin, 91191 Gif-sur-Yvette Cedex, France