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MAGNETIC ANISOTROPY CONSTANTS EVALUATION OF FOR ELECTRICAL STEELS BASED ON TEXTURE FACTOR FOR CUBE ϴ, GAMMA,RANDOM IDEAL FIBRES

Geruganti Sudhakar,Phd (Materials Engineering), School of Engineering Sciences and Technology, Hyderabad University,Hyderabad,India.
J.P.Gautam, Professor School of Engineering Sciences and Technology, Hyderabad University,Hyderabad,India. Email:20etpm09@uohyd.ac.in

1. ABSTRACT:

Texture Factor, A* and Magnetic Crystalline Anisotropy Energy Density*K_0, K1, K2, K3,K_4,K_5,K_6 Constants are important parameters for Electrical Steels. 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 Electrical Steels based on Texture Factor for Ideal fibers.

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

2. INTRODUCTION:

The Magneto Crystalline Anisotropy constantsK_0, K1, K2, K3,K_4,K_5,K_6 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. Texture factorconstantsK_0,K_1,K_2,K_3,K_4,K_5,K_6 values determines the preferred orientations of grains, the Overall Texture Factor is quantitative measurement of texture. 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, andshould 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 factorconstantsK_0, K1, K2,K_3values 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),Random Texture (T.F = 31.88) in the given material.

3. ESTIMATION OF MAGNETIC ANISOTROPY CONSTANTSK_0, K1, K2, K3,K_4,K_5,K_6CONSTANTS EVALUATION OF FOR ELECTRICAL STEELS:

Magneto Crystalline Anisotropy Energy is generally expressed by an expansion into direction cosines α_1, α_2, and α3of the magnetization with respect to the crystal axes.

$E^* = K_0 + K_1 (\sum\alpha^2_1 \alpha^2_2) + K_2 (\prod\alpha^2_1)+K_3 (\sum\alpha^2_1 \alpha^2_2)^2+ K_4 (\sum\alpha^2_1 \alpha^2_2)(\prod\alpha^2_1)+K_5(\sum\alpha^2_1 \alpha^2_2)^3+K_6(\prod\alpha^2_1)^2$[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	$1/\sqrt{2}$	$1/\sqrt{2}$	$1/\sqrt{2}$	$K_0+ K_1 /4$
[111]	54.7^0	54.7^0	54.7^0	$1/\sqrt{3}$	$1/\sqrt{3}$	$1/\sqrt{3}$	$K_0+ K_1 /3+ K_2 / 27$

From REF 1, we have

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

FOR **A* for Θ 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 ϒfibre<111>//ND is 38.68 => E* = -1.03608 [wt%Si] + 11.8334**
FOR **A* for Random Texture is 31.88 => E* = -0.82528 [wt%Si] + 9.4194**

$E^*= K_0 + K_1 (\sum\alpha^2_1\ \alpha^2_2) + K_2 (\prod\alpha^2_1) + K_3 (\sum\alpha^2_1\ \alpha^2_2)^2 + K_4 (\sum\alpha^2_1\ \alpha^2_2)(\prod\alpha^2_1) + K_5 (\sum\alpha^2_1\ \alpha^2_2)^3+ K_6 (\prod\alpha^2_1)^2$.....[I]

FOR [100] directions,α_1 =1, α2 =0, α_3=0
⇨ $E^*= K_0= -0.5345\ \text{[wt\%Si]} + 6.0895$
FOR [110] directions, α_1 =1/√2, α2 =1/√2, α_3=0
⇨ $E^*=-0.5345\ \text{[wt\%Si]} +6.0895 + K_1/4 + K_3/16 + K_5/64$
⇨ $-0.9406\ \text{[wt\%Si]} + 10.74 =-0.5345\ \text{[wt\%Si]} + 6.0895 + K_1/4 + K_3/16+ K_5/64$
⇨ $(-0.4061\text{[wt\%Si]} +4.6505)*64= 16K_1+4K_3+K_5$
⇨ $16K_1+4K_3 + K_5 = 297.632-25.9904\text{[wt\%Si]}$.....[II]
FOR [111] directions, α_1 =1/√3, α2 =1/√3, α_3=1/√3
⇨ $-1.03608\ \text{[wt\%Si]} + 11.8334 =-0.5345\ \text{[wt\%Si]}+6.0895 + K_1/3 + K_2/27+ K_3/9+ K_4/81+K_5/27+K_6/729$
⇨ $27(9K_1+ K_5 + 3K_3) + (9K_4+ 27K_2 + K_6)= 4187.3031-0.50158\text{[wt\%Si]}*729$
⇨ $27(150) + 137.3031 = 4187.3031-365.65182\text{[wt\%Si]}$
⇨ $(9K_1+ K_5 + 3K_3) = 150 -13.54266\text{[wt\%Si]}$;….[III]
⇨ $(9K_4+ 27K_2 + K_6) = 137.3031$
⇨ $(9*3+ 27*4+2.3031) =137.3031$
⇨ $K_2 =4;K_4 = 3;K_6 =2.3031$ ….[IV]

For Random Fibre,α_1 =1, α2 =1, α_3=1
$E^*_{\text{random}} = K_0+ 3K_1 + K_2 + 9K_3 + 3K_4 + 27K_5+ K_6$
$-0.82528\ \text{[wt\%Si]} + 9.4194 = -0.5345\ \text{[wt\%Si]} + 6.0895 + 3K_1 + K_2 + 9K_3 + 3K_4 + 27K_5+ K_6$
$=>3K_1 + K_2 + 9K_3 + 3K_4 + 27K_5+ K_6= -0.82528\ \text{[wt\%Si]} + 11.8334 + 0.5345\ \text{[wt\%Si]} - 6.0895$
$=> 3K_1 + 9K_3 + + 27K_5= -0.29078\text{[wt\%Si]} + 3.3299 - K_2 -3K_4 - K_6$
$=>3K_1 + 9K_3 + + 27K_5= -0.29078\text{[wt\%Si]} + 3.3299 -4 -3*3-2.3031$ from ….[IV]
$=>3K_1 + 9K_3 + + 27K_5= -0.29078\text{[wt\%Si]} -11.9732$ ….[V]
=>Solving the equations simultaneously :https://www.wolframalpha.com/calculators/system-equation-calculator
$16K_1+4K_3 + K_5 = 297.632-25.9904\text{[wt\%Si]}$
$(9K_1+ K_5 + 3K_3) = 150 -13.54266\text{[wt\%Si]}$
$3K_1 + 9K_3 + + 27K_5 = -11.9732-0.29078\text{[wt\%Si]}$
⇨ $K_1= 24.877 -2.0108948\text{[wt\%Si]},K_3= -26.507074 +1.628524\text{[wt\%Si]};K_5= 5.6281272 -0.33017818\text{[wt\%Si]}$
⇨ $K_0 = -0.5345\ \text{[wt\%Si]} + 6.0895;K_1 = 24.877 -2.0108948\text{[wt\%Si]}, K_2 =4;K_3 = -26.507074 +1.628524\text{[wt\%Si]}; K_4 = 3; K_5 = 5.6281272 -0.33017818\text{[wt\%Si]}; K_6 =2.3031$
⇨
⇨ $E^*= K_0 + K_1 (\sum\alpha^2_1\ \alpha^2_2) + K_2 (\prod\alpha^2_1) + K_3 (\sum\alpha^2_1\ \alpha^2_2)^2 + K_4 (\sum\alpha^2_1\ \alpha^2_2)(\prod\alpha^2_1) + K_5 (\sum\alpha^2_1\ \alpha^2_2)^3+ K_6 (\prod\alpha^2_1)^2$

$E^*= -0.5345\ \text{[wt\%Si]} +6.0895 +[24.877 -2.0108948\text{[wt\%Si]}](\sum\alpha^2_1\ \alpha^2_2)+ 4(\prod\alpha^2_1)+ [-26.507074 +1.628524\text{[wt\%Si]}](\sum\alpha^2_1\ \alpha^2_2)^2+3(\sum\alpha^2_1\ \alpha^2_2)(\prod\alpha^2_1) +[5.6281272 -0.33017818\text{[wt\%Si]}](\sum\alpha^2_1\ \alpha^2_2)^3$

$E^*= -0.5345\ \text{[wt\%Si]} +6.0895 +[24.877 -2.0108948\text{[wt\%Si]}](\sum\alpha^2_1\ \alpha^2_2)+ 4(\prod\alpha^2_1)+ [-26.507074 +1.628524$[wt%
$[5.6281272 -0.33017818\text{[wt\%Si]}](\sum\alpha^2_1\ \alpha^2_2)^3 +(2.3031)(\prod\alpha^2_1)^2$ …[VI]

⇨ **$E^* = 6.0895 + 24.877(\sum\alpha^2_1\ \alpha^2_2) + 4(\prod\alpha^2_1) - 26.507074(\sum\alpha^2_1\ \alpha^2_2)^2 + 3(\sum\alpha^2_1\ \alpha^2_2)(\prod\alpha^2_1) + 5.6281272(\sum\alpha^2_1\ \alpha^2_2)^3 + (2.3031)(\prod\alpha^2_1)^2 + [-0.5345\ [wt\%Si] - 2.0108948[wt\%Si])\ (\sum\alpha^2_1\ \alpha^2_2) + 1.628524[wt\%Si](\sum\alpha^2_1\ \alpha^2_2)^2) + 5.6281272[wt\%Si](\sum\alpha^2_1\ \alpha^2_2)^3]$**

⇨ **$E^* = E^*_{IRON} + E^{**}$**

⇨ **Where $E^*_{IRON} = 6.0895 + 24.877(\sum\alpha^2_1\ \alpha^2_2) + 4(\prod\alpha^2_1) - 26.507074(\sum\alpha^2_1\ \alpha^2_2)^2 + 3(\sum\alpha^2_1\ \alpha^2_2)(\prod\alpha^2_1) + 5.6281272(\sum\alpha^2_1\ \alpha^2_2)^3 + (2.3031)(\prod\alpha^2_1)^2$**

⇨ **$E^{**} = [-0.5345\ [wt\%Si] - 2.0108948[wt\%Si])\ (\sum\alpha^2_1\ \alpha^2_2) + 1.628524[wt\%Si](\sum\alpha^2_1\ \alpha^2_2)^2) + 5.6281272[wt\%Si](\sum\alpha^2_1\ \alpha^2_2)^3]$**

⇨ **Above is the Standard Magnetic –Crystalline Anisotropy Energy Density Equation for Electrical Steel**

⇨ **Magneto-Crystalline EnergyDensity Equation of Electrical Steel in terms of 7 constants.**

CRYSTALLOGRAPHIC DIRECTION	MAGNETO-CRYSTALLINE ANISOTROPY ENERGY DENSITY
[100] $\alpha_1 = 1, \alpha_2 = 0, \alpha_3 = 0$	**$E^*_{[100]} = 6.0895 - 0.5345\ [wt\%Si]$**
[110] $\alpha_1 = 1/\sqrt{2}, \alpha_2 = 1/\sqrt{2}, \alpha_3 = 0$	**$E^*_{[110]} = 10.74 - 0.9406\ [wt\%Si]$**
[111] $\alpha_1 = 1/\sqrt{3}, \alpha_2 = 1/\sqrt{3}, \alpha_3 = 1/\sqrt{3}$	**$E^*_{[111]} = 11.8334 - 1.03608\ [wt\%Si]$**
Random, $\alpha_1 = 1, \alpha_2 = 1, \alpha_3 = 1$ [Assumed]	**$E^*_{random} = 9.4194 - 0.82528\ [wt\%Si]$**

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]	$E^*_{[111]} = 11.8334$	$E^*_{[111]} = -1.03608\ [wt\%Si] + 11.8334$	11.3049992	10.4036096	8.932376	8.517944
4	Random	$E^*_{random} = 9.4194$	$E^*_{random} = -0.82528\ [wt\%Si] + 9.4194$	8.9985072	8.2805136	7.108616	6.778504

⇨ 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 ,randomfiber orientations have relatively high anisotropy energy and as such, the occurrence of these components in electrical steels is undesirable.

3. ESTIMATION OF TEXTURE FACTOR CONSTANTS$K_0, K_1, K_2, K_3, K_4, K_5, K_6$ FOR ELECTRICAL STEELS

$A^* = K_0 + K_1 (\sum\alpha^2_1\ \alpha^2_2) + K_2 (\prod\alpha^2_1) + K_3 (\sum\alpha^2_1\ \alpha^2_2)^2 + K_4 (\sum\alpha^2_1\ \alpha^2_2)(\prod\alpha^2_1) + K_5 (\sum\alpha^2_1\ \alpha^2_2)^3 + K_6 (\prod\alpha^2_1)^2$ …..[V]

From REF 1, we have

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

⇨ **$E^* = -0.5345\ [\text{wt\%Si}] + 6.0895 + [24.877\ -2.0108948[\text{wt\%Si}]](\sum\alpha^2_1\ \alpha^2_2) + 4(\prod\alpha^2_1) + [-26.507074\ +1.628524[\text{wt\%Si}]]\ (\sum\alpha^2_1\ \alpha^2_2)^2 + 3(\sum\alpha^2_1\ \alpha^2_2)(\prod\alpha^2_1) + [5.6281272\ -0.33017818[\text{wt\%Si}]](\sum\alpha^2_1\ \alpha^2_2)^3 + (2.3031)(\prod\alpha^2_1)^2$from …..[VI]**

⇨ **$(0.355 - 0.013[\text{wt\%Si}])\ A^* = [-0.6975[\text{wt\%Si}] + 7.9875 + [24.877\ -2.0108948[\text{wt\%Si}]](\sum\alpha^2_1\ \alpha^2_2) + 4(\prod\alpha^2_1) + [-26.507074\ +1.628524[\text{wt\%Si}]]\ (\sum\alpha^2_1\ \alpha^2_2)^2 + 3(\sum\alpha^2_1\ \alpha^2_2)(\prod\alpha^2_1) + [5.6281272\ -0.33017818[\text{wt\%Si}]](\sum\alpha^2_1\ \alpha^2_2)^3 + (2.3031)(\prod\alpha^2_1)^2$**

⇨ Comparing with Standard Equation [V] we have,

⇨ **$A^* = K_0 + K_1 (\sum\alpha^2_1\ \alpha^2_2) + K_2 (\prod\alpha^2_1) + K_3 (\sum\alpha^2_1\ \alpha^2_2)^2 + K_4 (\sum\alpha^2_1\ \alpha^2_2)(\prod\alpha^2_1) + K_5 (\sum\alpha^2_1\ \alpha^2_2)^3 + K_6 (\prod\alpha^2_1)^2$ ..[VI]**

⇨ $K_0 = \dfrac{[-0.6975[\text{wt\%Si}] + 7.9875]}{(0.355 - 0.013[\text{wt\%Si}])}$; $K_1 = \dfrac{[24.877\ -2.0108948[\text{wt\%Si}]]}{(0.355 - 0.013[\text{wt\%Si}])}$; $K_2 = \dfrac{4}{(0.355 - 0.013[\text{wt\%Si}])}$;

⇨ (0.355– 0.013[wt%Si])(0.355– 0.013[wt%Si])(0.355– 0.013[wt%Si])

⇨ $K_3 = \dfrac{(-26.50707074 + 1.628524[\text{wt\%Si}])}{(0.355 - 0.013[\text{wt\%Si}])}$; $K_4 = \dfrac{3}{(0.355 - 0.013[\text{wt\%Si}])}$; $K_5 = \dfrac{(5.6281272 - 0.33017818[\text{wt\%Si}])}{(0.355 - 0.013[\text{wt\%Si}])}$

⇨ (0.355– 0.013[wt%Si])(0.355– 0.013[wt%Si])(0.355– 0.013[wt%Si])

⇨ $K_6 = \dfrac{(2.3031)}{(0.355 - 0.013[\text{wt\%Si}])}$.

⇨ (0.355– 0.013[wt%Si])

S.NO.	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	70.31882	65.572791	60.4095874	58.8453626
3.	K_2	11.7928	11.867323	14.914243	15.637216
4.	K_3	-75.69952	-71.974448	-68.886389	-67.950842
5.	K_4	8.8446	8.9004924	11.185682	11.727912
6.	K_5	16.096395	15.34769839	14.7634284	14.5869719
7.	K_6	6.7899997	6.832908087	7.2288135	7.34875

⇨ **ABOVE IS STANDARD EQUATION FOR TEXTURE FACTOR FOR ELECTRICAL STEELS IN TERMS OF 7 CONSTANTS**

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

$A^* = 22.5 + 70.31882(\sum\alpha^2_1\ \alpha^2_2) + 11.7928\ (\prod\alpha^2_1) - 75.69952(\sum\alpha^2_1\ \alpha^2_2)^2 + 8.8446(\sum\alpha^2_1\ \alpha^2_2)(\prod\alpha^2_1)$ $+16.096395(\sum\alpha^2_1\ \alpha^2_2)^3 + 6.7899997(\prod\alpha^2_1)^2$ ……[1]

$A^* = 22.5 + 65.572791\ (\sum\alpha^2_1\ \alpha^2_2) + 11.867323\ (\prod\alpha^2_1) - 71.974448(\sum\alpha^2_1\ \alpha^2_2)^2 + 8.9004924(\sum\alpha^2_1\ \alpha^2_2)(\prod\alpha^2_1) + 15.34769839(\sum\alpha^2_1\ \alpha^2_2)^3 + 6.832908087(\prod\alpha^2_1)^2$ …… [2]

$A^* = 22.5 + 60.4095874\ (\sum\alpha^2_1\ \alpha^2_2) + 14.914243\ (\prod\alpha^2_1) - 68.886389(\sum\alpha^2_1\ \alpha^2_2)^2 + 11.185682(\sum\alpha^2_1\ \alpha^2_2)(\prod\alpha^2_1) + 14.7634284(\sum\alpha^2_1\ \alpha^2_2)^3 + 7.2288135(\prod\alpha^2_1)^2$ …… [3]

$A^* = 22.5 + 58.8453626\ (\sum\alpha^2_1\ \alpha^2_2) + 15.637216(\prod\alpha^2_1) - 67.950842(\sum\alpha^2_1\ \alpha^2_2)^2 + 11.727912\ (\sum\alpha^2_1\ \alpha^2_2)(\prod\alpha^2_1) + 14.5869719\ (\sum\alpha^2_1\ \alpha^2_2)^3 + 7.34875\ (\prod\alpha^2_1)^2$ …… [4]

S.NO	TEXTURE FACTOR, A*	ELECTRICAL STEELS Fe + 0.51%[wt%Si]	ELECTRICAL STEELS Fe + 1.38% [wt%Si]	ELECTRICAL STEELS Fe + 2.8% [wt%Si]	ELECTRICAL STEELS Fe + 3.2%[wt%Si]
1.	22.5 for ϴ<100>fibre	22.5	22.5	22.5	22.5
2.	35.6 for <110>fibre	35.5999	34.6346	33.5276	33.1923
3.	ϒ fibre<111>//ND is 38.68	38.6799	38.6245	36.2284	35.8393
4.	Random fibre is 31.88	31.8800447	31.2379	38.064	39.4964

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 Electrical Steels and [111] hardest direction for magnetization of Electrical Steels, [110] direction is harder direction for magnetization of Electrical Steels. Texture Factor Equation results are consistent and conforms with the standard results

REFERENCES:

1.Through process texture evolution and magnetic properties of high Si non-oriented electrical 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,PrakashDhoka,PankajKarande, SiddharthJabade,Marek Iwaniec https://doi.org/10.3390/ma15072630
3.Texture Control and Manufacturing in Non-Oriented Electrical Steel LeoKestens[1]and SigridJacobs[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]
DOI10.1088/0031-8949/11/6/010
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 texturesVincent Kloseka
CEA, IRAMIS, Laboratoire Léon Brillouin, 91191 Gif-sur-Yvette Cedex, France