Industrial Engineering Journal
ISSN: 0970-2555
Volume : 53, Issue 12, No.1, December : 2024

EVALUATION OF MAGNETOCRYSTALLINE ANISOTROPY ENERGY DENSITY CONSTANTS $K_0,K_1,K_2,K_3, K_4, K_5, K_6,K_7, K_8, K_9$ OF FERROMAGNETIC CRYSTAL ANISOTROPY ENERGY BALANCE AND CONTINUUM ANALYSIS OF PURE IRON AND ELECTRICAL STEELS BASED ON ELECTRICAL PROPERTIES & TEXTURE OF ϴ,α,ϒ, RANDOM IDEAL FIBERS

Sudhakar Geruganti PhD Research Scholar, orcid:0009-0000-0039-7536 SEST, The University of Hyderabad C.R. Rao Road, P.O. Central University, Gachibowli, Hyderabad 500046, Telangana (India). Email: 20etpm09@uohyd.ac.in
Gautam Jai Prakash Professor, SEST. The University of Hyderabad, Prof. C.R. Rao Road, P.O. Central University, Gachibowli, Hyderabad 500046, Telangana (India) Email: jaiprakashgautam@uohyd.ac.in
Nataraj M.V Research Associate, VIT University, Vellore (India) Email: natraj.dmrl@hotmail.com

Abstract:
Texture Factor, A* and Magnetic Crystalline Anisotropy Energy Density* $K_0,K_1,K_2,K_3, K_4, K_5, K_6,K_7, K_8, K_9$ 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 NTRODUCTION:

The Magneto Crystalline Anisotropy constants $K_0,K_1,K_2,K_3, K_4, K_5, K_6,K_7, K_8, K_9$ 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 factor constants$K_0,K_1,K_2,K_3, K_4, K_5, K_6,K_7, K_8, K_9$ values determines the preferred orientations of grains, the Overall Texture Factor is quantitative measurement of texture. Texture Factor is an important micro structural parameter which directly determines the anisotropy degree of most physical properties of a poly crystalline 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 texture S. The obtained information 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 $K_0,K_1,K_2,K_3, K_4, K_5, K_6,K_7, K_8, K_9$ values 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 material1.

Standard Equations:

$$E^*=K_0 + K_1 (\alpha_1\alpha_2+\alpha_2\alpha_3+\alpha_3\alpha_1) + K_2 (\alpha_1^2+\alpha_2^2+\alpha_3^2) + K_3 (\alpha_1\alpha_2\alpha_3) + K_4 (\alpha_1^2\alpha_2^2+\alpha_2^2\alpha_3^2+\alpha_3^2\alpha_1^2) ++K_5(\alpha_1^3+\alpha_2^3+\alpha_3^3)+K_6(\alpha_1^2\alpha_2\alpha_3+\alpha_2^2\alpha_3\alpha_1+\alpha_3^2\alpha_1\alpha_2)+K_7(\alpha_1^4+\alpha_2^4+\alpha_3^4)+K_8(\alpha_1^4\alpha_2^2+\alpha_2^4\alpha_3^2+\alpha_3^4\alpha_1^2)+K_9(\alpha_1^6+\alpha_2^6+\alpha_3^6)$$

$$E^*=K_+K_1(\sum\alpha_1\alpha_2)+K_2(\sum\alpha_1^2)+K_3(\prod\alpha_1)+K_4(\sum\alpha_1^2\alpha_2^2)++K_5(\sum\alpha_1^3)+K_6(\sum\alpha_1^2\alpha_2\alpha_3)+K_7(\sum\alpha_1^4)+K_8(\sum\alpha_1^4\alpha_2^2)+K_9(\sum\alpha_1^6)$$

$A^*=K_0 + K_1(\alpha_1\alpha_2+\alpha_2\alpha_3+\alpha_3\alpha_1)+K_2(\alpha_1^2+\alpha_2^2+\alpha_3^2)+K_3(\alpha_1\alpha_2\alpha_3)+K_4(\alpha_1^2\alpha_2^2+\alpha_2^2\alpha_3^2+\alpha_3^2\alpha_1^2)++K_5(\alpha_1^3+\alpha_2^3+\alpha_3^3)+K_6(\alpha_1^2\alpha_2\alpha_3+\alpha_2^2\alpha_3\alpha_1+\alpha_3^2\alpha_1\alpha_2)+K_7(\alpha_1^4+\alpha_2^4+\alpha_3^4)+K_8(\alpha_1^4\alpha_2^2+\alpha_2^4\alpha_3^2+\alpha_3^4\alpha_1^2)+K_9(\alpha_1^6+\alpha_2^6+\alpha_3^6)$

$A^*=K_+K_1(\sum\alpha_1\alpha_2)+K_2(\sum\alpha_1^2)+K_3(\prod\alpha_1)+K_4(\sum\alpha_1^2\alpha_2^2)++K_5(\sum\alpha_1^3)+K_6(\sum\alpha_1^2\alpha_2\alpha_3)+K_7(\sum\alpha_1^4)+K_8(\sum\alpha_1^4\alpha_2^2)+K_9(\sum\alpha_1^6)$

[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 REF1,we have E* = 0.355A* +(0.163 – 0.013A*)[wt%Si] -1.898
For Pure Iron, E* = 0.355A* -1.898

II. Calculate Manetic Anisotropy Constants E* of Pure Iron $K_0,K_1,K_2,K_3, K_4, K_5, K_6,K_7, K_8, K_9$ of Iron [ϴ ,α, ϒ, Random Fibres]and [ϴ ,α, ϒ Fibres]

2.1Calculate Manetic Anisotropy Constants E* of Pure Iron $K_0,K_1,K_2,K_3, K_4, K_5, K_6,K_7, K_8, K_9$ of Iron ϴ ,α, ϒ Fibres

$E^*=K_0 + K_1(\alpha_1\alpha_2+\alpha_2\alpha_3+\alpha_3\alpha_1)+K_2(\alpha_1^2+\alpha_2^2+\alpha_3^2)+K_3(\alpha_1\alpha_2\alpha_3)+K_4(\alpha_1^2\alpha_2^2+\alpha_2^2\alpha_3^2+\alpha_3^2\alpha_1^2)++K_5(\alpha_1^3+\alpha_2^3+\alpha_3^3)+K_6(\alpha_1^2\alpha_2\alpha_3+\alpha_2^2\alpha_3\alpha_1+\alpha_3^2\alpha_1\alpha_2)+K_7(\alpha_1^4+\alpha_2^4+\alpha_3^4)+K_8(\alpha_1^4\alpha_2^2+\alpha_2^4\alpha_3^2+\alpha_3^4\alpha_1^2)+K_9(\alpha_1^6+\alpha_2^6+\alpha_3^6)$

$E^*=K_+K_1(\sum\alpha_1\alpha_2)+K_2(\sum\alpha_1^2)+K_3(\prod\alpha_1)+K_4(\sum\alpha_1^2\alpha_2^2)++K_5(\sum\alpha_1^3)+K_6(\sum\alpha_1^2\alpha_2\alpha_3)+K_7(\sum\alpha_1^4)+K_8(\sum\alpha_1^4\alpha_2^2)+K_9(\sum\alpha_1^6)$

FOR E* for ϴ fiber <100>//ND => E*=6.0895
FOR E* for α fiber <110>//ND => E*=10.74
FOR E* for ϒ fibre <111>//ND => E*=11.8334
CASE 1: 6.0895 = $K_0 + K_2 + K_5 + K_7 + K_9$
CASE 2: 10.74= $K_0+0.5K_1 + K_2+0.25K_4+0.708K_5+0.5K_7 +0.25K_9$
CASE 3: 11.8334 = $K_0+K_1+K_2+0.192K_3+0.333K_4+0.576K_5 +0.576K_6+0.333K_7+0.111K_8 +0.099K_9$
CASE 1: $K_0 = K_2 = K_5 = K_7 = K_9 = 1.218$
CASE 2: $K_0+0.5K_1 + K_2+0.25K_4+0.708K_5+0.5K_7 +0.25K_9 = 10.74$
$0.5K_1 +0.25K_4 = 10.74$
$2K_1 +K_4 = 10.74$
$K_1 =13, K_4 =0.112$
$K_0+K_1+K_2+0.192K_3+0.333K_4+0.576K_5 +0.576K_6+0.333K_7+0.111K_8 +0.099K_9 = 11.8334$
$0.192K_3+0.576K_6+0.111K_8 = -4.86764$
$0.192K_3 = -2$; $0.576K_6 = -2$; $0.111K_8 = -0.86764$
$K_3 = -10.416$; $K_6 = -3.472$; $K_8 = -7.8165$
On Substitution in Main Equation,We Have
$E^*=K_+K_1(\sum\alpha_1\alpha_2)+K_2(\sum\alpha_1^2)+K_3(\prod\alpha_1)+K_4(\sum\alpha_1^2\alpha_2^2)++K_5(\sum\alpha_1^3)+K_6(\sum\alpha_1^2\alpha_2\alpha_3)+K_7(\sum\alpha_1^4)+K_8(\sum\alpha_1^4\alpha_2^2)+K_9(\sum\alpha_1^6)$

$\mathbf{E^*=1.218+13(\sum\alpha_1\alpha_2)+1.218(\sum\alpha_1^2)-10.416(\prod\alpha_1)+0.112(\sum\alpha_1^2\alpha_2^2)+1.218(\sum\alpha_1^3)-3.472(\sum\alpha_1^2\alpha_2\alpha_3)+1.218(\sum\alpha_1^4)-0.86764(\sum\alpha_1^4\alpha_2^2)+1.218(\sum\alpha_1^6)}$

CRYSTAL DIRECTION	MAGNETOCRYSTALLINE ALL ANISOTROPY ENERGY DENSITY FOR PURE IRON
[100] $\alpha_1 =1, \alpha_2 =0, \alpha_3=0$	$E^*_{[100]} = 6.0895$
[110] $\alpha_1 =1/\sqrt{2}, \alpha_2 =1/\sqrt{2}, \alpha_3=0$	$E^*_{[110]} = 10.74$
[111] $\alpha_1 =1/\sqrt{3}, \alpha_2 =1/\sqrt{3}, \alpha_3=1/\sqrt{3}$	$E^*_{[111]} =11.8334$

DISCUSSION: <100>//ND fibers have the lowest anisotropic strength because the flux lines are uniformly distributed in the plane of the rotated laminate, have a simple magnetization direction, and also have a cubic texture component rotated into a plane. In contrast, the α and <011>//ND ,<111>//ND fiber orientations have relatively high anisotropy properties and therefore the presence of particles is undesirable in electrical steels.

2.2 Calculate Texture Factor constants $K_0,K_1,K_2,K_3, K_4, K_5, K_6,K_7, K_8, K_9$ of PureIron for ϴ ,α, ϒ Fibres

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

For Pure Iron,

$E^*_{PURE\ IRON}= 0.355A^*_{PURE\ IRON} -1.898$ [Si%=0]

$\Rightarrow 0.355A^*_{PURE\ IRON} = [E^*_{PURE\ IRON}+1.898]$

$\Rightarrow A^*_{PURE\ IRON} = [E^*_{PURE\ IRON}+1.898]/0.355$

=>SUBSTITUTING $E^*_{PURE\ IRON}=(1.218)+13(\sum\alpha_1\alpha_2)+1.218(\sum\alpha_1^2)-10.416(\prod\alpha_1^4)+(0.112)(\sum\alpha_1^2\alpha_2^2)+1.218(\sum\alpha_1^3)+ (-3.472)(\sum\alpha_1^2\alpha_2\alpha_3)+1.218(\sum\alpha_1^4)-0.86764(\sum\alpha_1^4\alpha_2^2)+1.218(\sum\alpha_1^6)$

=> We have **$A^*_{PURE\ IRON}= 8.777+36.619(\sum\alpha_1\alpha_2)+3.431(\sum\alpha_1^2)-29.34(\prod\alpha_1^4)+(0.3155)(\sum\alpha_1^2\alpha_2^2)+3.431(\sum\alpha_1^3)+ (-9.78)(\sum\alpha_1^2\alpha_2\alpha_3)+3.431(\sum\alpha_1^4)-2.444(\sum\alpha_1^4\alpha_2^2)+3.431(\sum\alpha_1^6)$**

CRYSTAL DIRECTION	TEXTURE FACTOR FOR PURE IRON
[100] $\alpha_1 =1,\alpha_2 =0, \alpha_3=0$	$A^*_{[100]} = 22.5$
[110] $\alpha_1 =1/\sqrt{2},\alpha_2 =1/\sqrt{2}, \alpha_3=0$	$A^*_{[110]} = 35.6$
111] $\alpha_1 =1/\sqrt{3},\alpha_2 =1/\sqrt{3}, \alpha_3=1/\sqrt{3}$	$A^*_{[111]} =38.68$

2.3 **Calculate Magnetic Anisotropy Constants E* of Pure Iron $K_0,K_1,K_2,K_3, K_4, K_5, K_6,K_7, K_8, K_9$ of Iron ϴ ,α, ϒand random Fibres**

$E^*=K_0 + K_1(\alpha_1\alpha_2+\alpha_2\alpha_3+\alpha_3\alpha_1)+K_2(\alpha_1^2+\alpha_2^2+\alpha_3^2)+K_3(\alpha_1\alpha_2\alpha_3)+K_4(\alpha_1^2\alpha_2^2+\alpha_2^2\alpha_3^2+\alpha_3^2\alpha_1^2)++K_5(\alpha_1^3+\alpha_2^3+\alpha_3^3)+K_6(\alpha_1^2\alpha_2\alpha_3+\alpha_2^2\alpha_3\alpha_1+\alpha_3^2\alpha_1\alpha_2)+K_7(\alpha_1^4+\alpha_2^4+\alpha_3^4)+K_8(\alpha_1^4\alpha_2^2+\alpha_2^4\alpha_3^2+\alpha_3^4\alpha_1^2)+K_9(\alpha_1^6+\alpha_2^6+\alpha_3^6)$

$E^*=K+K_1(\sum\alpha_1\alpha_2)+K_2(\sum\alpha_1^2)+K_3(\prod\alpha_1)+K_4(\sum\alpha_1^2\alpha_2^2)++K_5(\sum\alpha_1^3)+K_6(\sum\alpha_1^2\alpha_2\alpha_3)+K_7(\sum\alpha_1^4)+K_8(\sum\alpha_1^4\alpha_2^2)+K_9(\sum\alpha_1^6)$

FOR E* for ϴ fiber <100>//ND => E*=6.0895

FOR E* for α fiber <110>//ND => E*=10.74

FOR E* for ϒ fibre <111>//ND => E*=11.8334

$6.0895 = K_0 + K_2 + K_5 + K_7 +K_9$

$10.74= K_0+0.5K_1 + K_2+0.25K_4+0.7074K_5+0.5003K_7 +0.125K_8+0.25K_9$

$11.8334 = K_0+K_1+K_2+0.192K_3+0.333K_4+0.5772K_5+0.333K_6+0.333K_7+0.111K_8 +0.111K_9$

$9.4194=K_0+K_3+3(K_1+K_2+K_4 + K_5+K_6+K_7 ++K_8+K_9)$

case 1: $K_0 + K_2 + K_5 + K_7 +K_9 = 6.0895$;considering equal values for all constants we have

$K_0 = 1.2179; K_2 = K_5 = K_7= K_9 =1.2179$;.....(I)

case 2: $10.74= K_0+0.5K_1 + K_2+0.25K_4+0.7074K_5+0.5003K_7 +0.125K_8+0.25K_9$

$2K_1 +K_4+0.5K_8 = 26.1176$...(V)

2*12 +2+0.5*0.2352 =26.1176

$K_1 = 12;K_4 = 2;K_8 = 0.2352$ .....(II)

Case 3: $K_0+K_1+K_2+0.1924K_3+0.333K_4+0.5772K_5+0.333K_6+0.333K_7+0.111K_8 +0.111K_9 = 11.8334$

On Substitution of $K_0,K_1,K_2,K_4,K_5,K_7,K_8.K_9$

$0.1924K_3 +.333K_6 = -7.37447$....(VI)

Case 4: $K_0+K_3+3(K_1+K_2+K_4 + K_5+K_6+K_7 ++K_8+K_9)=9.4194$

$K_3+3K_6 = -49.13$ .....(VII)

Solving ....Equations (VI) and (VII)

We have $K_3=-23.6;K_6= -8.51$;

$E^*_{PURE\ IRON}=(1.218)+12(\sum\alpha_1\alpha_2)+1.218(\sum\alpha_1^2)-23.6(\prod\alpha_1^4)+(2)(\sum\alpha_1^2\alpha_2^2)++1.218(\sum\alpha_1^3)+ (-8.51)(\sum\alpha_1^2\alpha_2\alpha_3)+1.218(\sum\alpha_1^4)+0.2352(\sum\alpha_1^4\alpha_2^2)+1.218(\sum\alpha_1^6)$

FOR E* for ϴ fiber <100>//ND is 22.5 => E* = 6.0895

FOR E* for fiber <110>//ND is 35.6 => E* = 10.74
FOR E* for ϒ fibre <111>//ND is 38.68 => E* = 11.8334

CRYSTAL DIRECTION	MAGNETOCRYSTALLINE ALL ANISOTROPY ENERGY DENSITY
[100] $\alpha_1=1, \alpha_2=0, \alpha_3=0$	$E^*_{[100]} = 6.0895$
[110] $\alpha_1=1/\sqrt{2}, \alpha_2=1/\sqrt{2}, \alpha_3=0$	$E^*_{[110]} = 10.74$
[111] $\alpha_1=1/\sqrt{3}, \alpha_2=1/\sqrt{3}, \alpha_3=1/\sqrt{3}$	$E^*_{[111]} = 11.8334$
Random	$E^*_{[Random]} = 9.4194$

DISCUSSION:

<100>//ND fibers have the lowest anisotropic strength because the flux lines are uniformly distributed in the plane of the rotated laminate, have a simple magnetization direction, and also have a cubic texture component rotated into a plane. In contrast, the α and <011>//ND ,<111>//ND,Random fiber orientations have relatively high anisotropy properties and therefore the presence of particles is undesirable in electrical steels

2.4 Calculate Texture Factor constants $K_0, K_1, K_2, K_3, K_4, K_5, K_6, K_7, K_8, K_9$ of PureIron for ϴ ,α, ϒ,Random Fibres

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

For Pure Iron,

$E^*_{PURE\ IRON} = 0.355A^*_{PURE\ IRON} - 1.898$ [Si%=0]

$\Rightarrow 0.355A^*_{PURE\ IRON} = [E^*_{PURE\ IRON} + 1.898]$

$\Rightarrow A^*_{PURE\ IRON} = [E^*_{PURE\ IRON} + 1.898]/0.355$

=>SUBSTITUTING $E^*_{PURE\ IRON} = (1.218) + 12(\sum\alpha_1\alpha_2) + 1.218(\sum\alpha_1^2) - 23.6(\prod\alpha_1^4) + (2)(\sum\alpha_1^2\alpha_2^2) + +1.218(\sum\alpha_1^3) + (-8.51)(\sum\alpha_1^2\alpha_2\alpha_3) + 1.218(\sum\alpha_1^4) + 0.2352(\sum\alpha_1^4\alpha_2^2) + 1.218(\sum\alpha_1^6)$

=> We have **$A^*_{PURE\ IRON} = 8.77 + 33.802(\sum\alpha_1\alpha_2) + 3.431(\sum\alpha_1^2) - 66.478(\prod\alpha_1^4) + (5.6338)(\sum\alpha_1^2\alpha_2^2) + 1.218(\sum\alpha_1^3) + (-23.9718)(\sum\alpha_1^2\alpha_2\alpha_3) + 5.6338(\sum\alpha_1^4) + 0.6625(\sum\alpha_1^4\alpha_2^2) + 5.6338(\sum\alpha_1^6)$**

CRYSTAL DIRECTION	TEXTURE FACTOR FOR PURE IRON
[100] $\alpha_1=1, \alpha_2=0, \alpha_3=0$	$A^*_{[100]} = 22.5$
[110] $\alpha_1=1/\sqrt{2}, \alpha_2=1/\sqrt{2}, \alpha_3=0$	$A^*_{[110]} = 35.6$
[111] $\alpha_1=1/\sqrt{3}, \alpha_2=1/\sqrt{3}, \alpha_3=1/\sqrt{3}$	$A^*_{[111]} = 38.68$
Random	$A^*_{[111]} = 31.88$

2.5 Calculate Texture Factor constants $K_0, K_1, K_2, K_3, K_4, K_5, K_6, K_7, K_8, K_9$ of PureIron for ϴ ,α, ϒ,Random Fibres By General Approach

$A^* = K_0 + K_1(\alpha_1\alpha_2+\alpha_2\alpha_3+\alpha_3\alpha_1) + K_2(\alpha_1^2+\alpha_2^2+\alpha_3^2) + K_3(\alpha_1\alpha_2\alpha_3) + K_4(\alpha_1^2\alpha_2^2+\alpha_2^2\alpha_3^2+\alpha_3^2\alpha_1^2) + +K_5(\alpha_1^3+\alpha_2^3+\alpha_3^3) + K_6(\alpha_1^2\alpha_2\alpha_3+\alpha_2^2\alpha_3\alpha_1+\alpha_3^2\alpha_1\alpha_2) + K_7(\alpha_1^4+\alpha_2^4+\alpha_3^4) + K_8(\alpha_1^4\alpha_2^2+\alpha_2^4\alpha_3^2+\alpha_3^4\alpha_1^2) + K_9(\alpha_1^6+\alpha_2^6+\alpha_3^6)$

$A^* = K_+ K_1(\sum\alpha_1\alpha_2) + K_2(\sum\alpha_1^2) + K_3(\prod\alpha_1) + K_4(\sum\alpha_1^2\alpha_2^2) + +K_5(\sum\alpha_1^3) + K_6(\sum\alpha_1^2\alpha_2\alpha_3) + K_7(\sum\alpha_1^4) + K_8(\sum\alpha_1^4\alpha_2^2) + K_9(\sum\alpha_1^6)$

FOR A*=22.5 for ϴ fiber <100>//ND
FOR A* =35.6for fiber <110>//ND
FOR A*=38.68 for ϒ fibre <111>//ND
FOR A*=31.88 for Random Fibre

$22.5 = K_0 + K_2 + K_5 + K_7 + K_9$

$35.6 = K_0 + 0.5K_1 + K_2 + 0.25K_4 + 0.7074K_5 + 0.5003K_7 + 0.125K_8 + 0.25K_9$

$38.68 = K_0 + K_1 + K_2 + 0.192K_3 + 0.333K_4 + 0.5772K_5 + 0.333K_6 + 0.333K_7 + 0.111K_8 + 0.111K_9$

$31.88 = K_0 + K_3 + 3(K_1 + K_2 + K_4 + K_5 + K_6 + K_7 + +K_8 + K_9)$

case 1: $K_0 + K_2 + K_5 + K_7 + K_9 = 22.5$;considering equal values for all constants we have $K_0 = K_2 = K_5 = K_7 = K_9 = 4.5$ .....(I)

case 2: $35.6 = K_0 + 0.5K_1 + K_2 + 0.25K_4 + 0.7074K_5 + 0.5003K_7 + 0.125K_8 + 0.25K_9$

$0.5K_1 + 0.25K_4 + 0.125K_8 = 20.04$

$4K_1 + 2K_4 + K_8 = 160.32$ ...(V)
$4*35 + 2*10 + 0.32 = 160.32$
$K_1 = 35; K_4 = 10; K_8 = 0.32$ .....(II)
$K_0+K_1+K_2+0.192K_3+0.333K_4+0.5772K_5+0.333K_6+0.333K_7+0.111K_8 +0.111K_9 = 38.68$
On Substitution of $K_0,K_1,K_2,K_4,K_5,K_7,K_8.K_9$
We Have $0.192K_3 + .333K_6 = -13.2454$ ....(VI)
$K_0+K_3+3(K_1+K_2+K_4+K_5+K_6+K_7++K_8+K_9)=31.88$
$K_3+3K_6 = -162.58$ .....(VII)
Solving ....Equations (VI) and (VII)
We have $K_3=13.2245; K_6= -60$;
Substituting in Texture Factor Equation, We have
$A^*=K_0 +K_1(\sum\alpha_1\alpha_2)+K_2(\sum\alpha_1^2)+K_3(\prod\alpha_1)+K_4(\sum\alpha_1^2\alpha_2^2)++K_5(\sum\alpha_1^3)+K_6(\sum\alpha_1^2\alpha_2\alpha_3)+K_7(\sum\alpha_1^4)+K_8(\sum\alpha_1^4\alpha_2^2)+K_9(\sum\alpha_1^6)$
$A^*=K_+K_1(\sum\alpha_1\alpha_2)+K_2(\sum\alpha_1^2)+K_3(\prod\alpha_1)+K_4(\sum\alpha_1^2\alpha_2^2)++K_5(\sum\alpha_1^3)+K_6(\sum\alpha_1^2\alpha_2\alpha_3)+K_7(\sum\alpha_1^4)+K_8(\sum\alpha_1^4\alpha_2^2)+K_9(\sum\alpha_1^6)$
$A^*_{PURE\ IRON}=4.5+35(\sum\alpha_1\alpha_2)+4.5(\sum\alpha_1^2)+13.2245(\prod\alpha_1^4)+10(\sum\alpha_1^2\alpha_2^2)+4.5(\sum\alpha_1^3)-60(\sum\alpha_1^2\alpha_2\alpha_3)+4.5(\sum\alpha_1^4)+0.32(\sum\alpha_1^4\alpha_2^2)+4.5(\sum\alpha_1^6)$

CRYSTAL DIRECTION	TEXTURE FACTOR FOR PURE IRON
[100] $\alpha_1 =1, \alpha_2 =0, \alpha_3=0$	$A^*_{[100]} = 22.5$
[110] $\alpha_1 =1/\sqrt{2}, \alpha_2 =1/\sqrt{2}, \alpha_3=0$	$A^*_{[110]} = 35.6$
[111] $\alpha_1 =1/\sqrt{3}, \alpha_2 =1/\sqrt{3}, \alpha_3=1/\sqrt{3}$	$A^*_{[111]} =38.68$
Random	$A^*_{[111]} =31.88$

III. Calculate Magnetic Anisotropy Constants$K_0,K_1,K_2,K_3, K_4, K_5, K_6,K_7, K_8, K_9$ of E* of Electrial Steels $K_0,K_1,K_2,K_3, K_4, K_5, K_6,K_7, K_8, K_9$ [ϴ ,α, ϒ, RandomFibres] and [ϴ ,α, ϒ Fibres]

3.1 Calculate Manetic Anisotropy Constants E* of Electrical Steels $K_0,K_1,K_2,K_3, K_4, K_5, K_6,K_7, K_8, K_9$ of Iron ϴ ,α, ϒ ,Random Fibres

$E^*=K_0 + K_1(\alpha_1\alpha_2+\alpha_2\alpha_3+\alpha_3\alpha_1)+K_2(\alpha_1^2+\alpha_2^2+\alpha_3^2)+K_3(\alpha_1\alpha_2\alpha_3)+K_4(\alpha_1^2\alpha_2^2+\alpha_2^2\alpha_3^2+\alpha_3^2\alpha_1^2)++K_5(\alpha_1^3+\alpha_2^3+\alpha_3^3)+K_6(\alpha_1^2\alpha_2\alpha_3+\alpha_2^2\alpha_3\alpha_1+\alpha_3^2\alpha_1\alpha_2)+K_7(\alpha_1^4+\alpha_2^4+\alpha_3^4)+K_8(\alpha_1^4\alpha_2^2+\alpha_2^4\alpha_3^2+\alpha_3^4\alpha_1^2)+K_9(\alpha_1^6+\alpha_2^6+\alpha_3^6)$
$E^*=K_+K_1(\sum\alpha_1\alpha_2)+K_2(\sum\alpha_1^2)+K_3(\prod\alpha_1)+K_4(\sum\alpha_1^2\alpha_2^2)++K_5(\sum\alpha_1^3)+K_6(\sum\alpha_1^2\alpha_2\alpha_3)+K_7(\sum\alpha_1^4)+K_8(\sum\alpha_1^4\alpha_2^2)+K_9(\sum\alpha_1^6)$
FOR E* for ϴ fiber <100>//ND => E*=6.0895 - 0.5345Si
FOR E* for α fiber <110>//ND => E*=10.74- 0.9406Si
FOR E* for ϒ fibre <111>//ND => E*=11.8334 - 1.03608Si
$6.0895 - 0.5345Si= K_0 + K_2 + K_5 + K_7 + K_9$
$10.74- 0.9406Si = K_0+0.5K_1 + K_2+0.25K_4+0.7074K_5+0.5003K_7 +0.125K_8+0.25K_9$
$11.8334 - 1.03608Si = K_0+K_1+K_2+0.192K_3+0.333K_4+0.5772K_5+0.333K_6+0.333K_7+0.111K_8 +0.111K_9$
$9.4194-0.25144Si=K_0+K_3+3(K_1+K_2+K_4+K_5+K_6+K_7++K_8+K_9)$
case 1: $K_0 + K_2 + K_5 + K_7 + K_9 = 6.0895 - 0.5345Si$;considering equal values for all constants we have
$K_0 = 1.2179 - 0.5345; K_2 = K_5 = K_7= K_9 =1.2179$;.....(I)
case 2: $10.74- 0.9406Si = K_0+0.5K_1 + K_2+0.25K_4+0.7074K_5+0.5003K_7 +0.125K_8+0.25K_9$
$2K_1 + K_4+0.5K_8 = 26.1176$...(V)
$2*12 +2+0.5*0.2352 =26.1176$
$K_1 = 12; K_4 = 2; K_8 = 0.2352$ .....(II)
Case 3: $K_0+K_1+K_2+0.1924K_3+0.333K_4+0.5772K_5+0.333K_6+0.333K_7+0.111K_8 +0.111K_9 = 11.8334 - 1.03608Si$
On Substitution of $K_0,K_1,K_2,K_4,K_5,K_7,K_8.K_9$

$0.1924K_3 + .333K_6 = -7.37447$....(VI)

Case 4: $K_0+K_3+3(K_1+K_2+K_4+K_5+K_6+K_7++K_8+K_9)=9.4194 - 0.25144Si$

$K_3+3K_6 = -49.13$ .....(VII)

Solving ....Equations (VI) and (VII)

We have $K_3=-23.6; K_6= -8.51$; Adjusting Silicon Content for Electrical Steels we have $K_0 =1.218 - 0.5345Si$; $K_4 =2 -1.6244Si$; $K_6 = -8.51+1.6506Si$

$$E^*_{ELECTRICAL\ STEELS}=(1.218 - 0.5345Si)+12(\sum\alpha_1\alpha_2)+1.218(\sum\alpha_1^2)-23.6(\prod\alpha_1^4)+(2 -1.6244Si)(\sum\alpha_1^2\alpha_2^2)++1.218(\sum\alpha_1^3)+ (-8.51+1.6506Si)(\sum\alpha_1^2\alpha_2\alpha_3)+1.218(\sum\alpha_1^4)+0.2352(\sum\alpha_1^4\alpha_2^2)+1.218(\sum\alpha_1^6)$$

CRYSTAL DIRECTION	MAGNETOCRYSTALLINE ALL 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	$E^*_{RANDOM} = 9.4194 -0.25144$[wt%Si]

S.NO.	Standard Crystallographic Directions	Magneto-Crystalline Anisotropy Value E* For Pure Iron	Magneto-Crystalline Anisotropy Value E*	Magneto-Crystalline Anisotropy Value E* for Fe-0.51%Si	Magneto-Crystalline Anisotropy Value E* for Fe-1.38%Si	Magneto-Crystalline Anisotropy Value E* for Fe-2.8%Si	Magneto-Crystalline Anisotropy Value 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
4.	Random	$E_{[Random^*]} = +9.4194$	$E^*_{[111]} = -0.25144$ [wt%Si] + 9.4194	9.2917	9.0724	8.71537	8.6148

DISCUSSION:

<100>//ND fibers have the lowest anisotropic strength because the flux lines are uniformly distributed in the plane of the rotated laminate, have a simple magnetization direction, and also have a cubic texture component rotated into a plane. In contrast, the α and <011>//ND .<111>//ND,Random fiber orientations have relatively high anisotropy properties and therefore the presence of particles is undesirable in electrical steels.

3.2 Calculate Texture Factor constants $K_0, K_1, K_2, K_3, K_4, K_5, K_6, K_7, K_8, K_9$ of Electrical Steels for ϴ ,α, ϒ,Random Fibres

$A^*=K_0 + K_1(\alpha_1\alpha_2+\alpha_2\alpha_3+\alpha_3\alpha_1)+K_2(\alpha_1^2+\alpha_2^2+\alpha_3^2)+K_3(\alpha_1\alpha_2\alpha_3)+K_4(\alpha_1^2\alpha_2^2+\alpha_2^2\alpha_3^2+\alpha_3^2\alpha_1^2)++K_5(\alpha_1^3+\alpha_2^3+\alpha_3^3)+K_6(\alpha_1^2\alpha_2\alpha_3+\alpha_2^2\alpha_3\alpha_1+\alpha_3^2\alpha_1\alpha_2)+K_7(\alpha_1^4+\alpha_2^4+\alpha_3^4)+K_8(\alpha_1^4\alpha_2^2+\alpha_2^4\alpha_3^2+\alpha_3^4\alpha_1^2)+K_9(\alpha_1^6+\alpha_2^6+\alpha_3^6)$

$A^*=K_+K_1(\sum\alpha_1\alpha_2)+K_2(\sum\alpha_1^2)+K_3(\prod\alpha_1)+K_4(\sum\alpha_1^2\alpha_2^2)++K_5(\sum\alpha_1^3)+K_6(\sum\alpha_1^2\alpha_2\alpha_3)+K_7(\sum\alpha_1^4)+K_8(\sum\alpha_1^4\alpha_2^2)+K_9(\sum\alpha_1^6)$

FOR A*=22.5 for ϴ fiber <100>//ND

FOR A* =35.6for fiber <110>//ND

FOR A*=38.68 for ϒ fibre <111>//ND

FOR A*=31.88 for Random Fibre

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

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

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

$(0.355 - 0.013[wt\%Si])A^* =(1.218 - 0.5345Si-0.163[wt\%Si] +1.898)+12(\sum\alpha_1\alpha_2)+1.218(\sum\alpha_1^2)-23.6(\prod\alpha_1^4)+(2 -1.6244Si)(\sum\alpha_1^2\alpha_2^2)+1.218(\sum\alpha_1^3)+ (-8.51+ 1.6506Si) (\sum\alpha_1^2\alpha_2\alpha_3)+ 1.218(\sum\alpha_1^4)+ 0.2352(\sum\alpha_1^4\alpha_2^2)+ 1.218(\sum\alpha_1^6)$

$(0.355 - 0.013[wt\%Si])A^* =(3.116 - 0.3715[wt\%Si])+12(\sum\alpha_1\alpha_2)+1.218(\sum\alpha_1^2)-23.6(\prod\alpha_1^4)+(2 - 1.6244Si)(\sum\alpha_1^2\alpha_2^2)++1.218(\sum\alpha_1^3)+ (-8.51+1.6506Si) (\sum\alpha_1^2\alpha_2\alpha_3)+ 1.218(\sum\alpha_1^4)+ 0.2352(\sum\alpha_1^4\alpha_2^2)+ 1.218(\sum\alpha_1^6)$

$A^*_{ELECTRICAL\ STEELS}=K_0+K_1(\sum\alpha_1\alpha_2)+K_2(\sum\alpha_1^2)+K_3(\prod\alpha_1)+K_4(\sum\alpha_1^2\alpha_2^2)++K_5(\sum\alpha_1^3)+K_6(\sum\alpha_1^2\alpha_2\alpha_3)+K_7(\sum\alpha_1^4)+K_8(\sum\alpha_1^4\alpha_2^2)+K_9(\sum\alpha_1^6)$

Assuming $P=(0.355 - 0.013[wt\%Si])$;

$K_0=(3.116 - 0.3715[wt\%Si])/P$

$K_1=12/P$

$K_2=1.218/P$

$K_3= -23.6/P$

$K_4= (2 -1.6244Si)/P$

$K_5 =1.218/P$

$K_6 =(-8.51+1.6506Si)/P$

$K_7=1.218/P$

$K_8=0.2352/P$

$K_9=1.218/P$

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	direction <100>	$\alpha_1=1$, α2=0, $\alpha_3=0$	22.5 ϴ fibre <100>//ND	≈22.5	≈22.5	≈22.5	≈22.5
2	direction <110>	$\alpha_1=1/\sqrt{2}$, α2=1/√2, $\alpha_3=0$	35.6 fibre //ND	≈35.6	≈35.6	≈35.6	≈35.6
3	direction <111>	$\alpha_1=1/\sqrt{3}$, α2 =1/√3, $\alpha_3=1/\sqrt{3}$	38.68 ϒ fibre <111>//ND	≈38.68	≈38.68	≈38.68	≈38.68
4.	Random	$\alpha_1=1$, α2=1, $\alpha_3=1$	31.88	≈31.88	≈31.88	≈31.88	≈31.88

3.3 Calculate Manetic Anisotropy Constants E* of Electrical Steels K_0,K_1,K_2,K_3, K_4, K_5, K_6,K_7, K_8, K_9 of Iron ϴ ,α, ϒ Fibres

Industrial Engineering Journal
ISSN: 0970-2555
Volume : 53, Issue 12, No.1, December : 2024

$E^*=K_0 + K_1(\alpha_1\alpha_2+\alpha_2\alpha_3+\alpha_3\alpha_1)+K_2(\alpha_1^2+\alpha_2^2+\alpha_3^2)+K_3(\alpha_1\alpha_2\alpha_3)+K_4(\alpha_1^2\alpha_2^2+\alpha_2^2\alpha_3^2+\alpha_3^2\alpha_1^2)++K_5(\alpha_1^3+\alpha_2^3+\alpha_3^3)+K_6(\alpha_1^2\alpha_2\alpha_3+\alpha_2^2\alpha_3\alpha_1+\alpha_3^2\alpha_1\alpha_2)+K_7(\alpha_1^4+\alpha_2^4+\alpha_3^4)+K_8(\alpha_1^4\alpha_2^2+\alpha_2^4\alpha_3^2+\alpha_3^4\alpha_1^2)+K_9(\alpha_1^6+\alpha_2^6+\alpha_3^6)$

$E^*=K_+K_1(\sum\alpha_1\alpha_2)+K_2(\sum\alpha_1^2)+K_3(\prod\alpha_1)+K_4(\sum\alpha_1^2\alpha_2^2)++K_5(\sum\alpha_1^3)+K_6(\sum\alpha_1^2\alpha_2\alpha_3)+K_7(\sum\alpha_1^4)+K_8(\sum\alpha_1^4\alpha_2^2)+K_9(\sum\alpha_1^6)$

FOR E* for ϴ fiber <100>//ND => E*=6.0895 - 0.5345Si
FOR E* for α fiber <110>//ND => E*=10.74- 0.9406Si
FOR E* for ϒ fibre <111>//ND => E*=11.8334 - 1.03608Si
$6.0895 - 0.5345Si= K_0 + K_2 + K_5 + K_7 +K_9$
$10.74- 0.9406Si = K_0+0.5K_1 + K_2+0.25K_4+0.7074K_5+0.5003K_7 +0.5K_8+0.25K_9$
$11.8334 - 1.03608Si = K_0+K_1+K_2+0.192K_3+0.333K_4+0.576K_5+0.576K_6+0.333K_7+0.111K_8 +0.099K_9$

$\mathbf{E^*_{ELECTRICAL\ STEELS}=(1.218 - 0.5345Si)_+13(\sum\alpha_1\alpha_2)+1.218(\sum\alpha_1^2)-10.416(\prod\alpha_1^4)+(0.112-1.6244Si)(\sum\alpha_1^2\alpha_2^2)+1.218(\sum\alpha_1^3)+ (-3.472+1.6506Si)(\sum\alpha_1^2\alpha_2\alpha_3)+1.218(\sum\alpha_1^4)-0.86764(\sum\alpha_1^4\alpha_2^2)+1.218(\sum\alpha_1^6)}$

CRYSTAL DIRECTION	MAGNETOCRYSTALLINE ALL 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]

S.NO.	Standard Crystallographic Directions	Magneto-Crystalline Anisotropy Value E* For Pure Iron	Magneto-Crystalline Anisotropy Value E*	Magneto-Crystalline Anisotropy Value E* for Fe-0.51%Si	Magneto-Crystalline Anisotropy Value E* for Fe-1.38%Si	Magneto-Crystalline Anisotropy Value E* for Fe-2.8%Si	Magneto-Crystalline Anisotropy Value 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

3.4 Calculate Texture Factor constants $K_0, K_1, K_2, K_3, K_4, K_5, K_6, K_7, K_8, K_9$ of Electrical Steels for ϴ ,α, ϒ Fibres

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

$E^*_{ELECTRICAL\ STEELS}=(1.218 - 0.5345Si)_+13(\sum\alpha_1\alpha_2)+1.218(\sum\alpha_1^2)-10.416(\prod\alpha_1^4)+(0.112-1.6244Si)(\sum\alpha_1^2\alpha_2^2)+1.218(\sum\alpha_1^3)+ (-3.472+1.6506Si)(\sum\alpha_1^2\alpha_2\alpha_3)+1.218(\sum\alpha_1^4)-0.86764(\sum\alpha_1^4\alpha_2^2)+1.218(\sum\alpha_1^6)$

$\mathbf{(0.355 - 0.013[wt\%Si])A^*_{ELECTRICAL\ STEELS} = (3.116 - 0.6975[wt\%Si])_+13(\sum\alpha_1\alpha_2)+1.218(\sum\alpha_1^2)-10.416(\prod\alpha_1^4)+(0.112-1.6244Si)(\sum\alpha_1^2\alpha_2^2)+1.218(\sum\alpha_1^3)+ (-3.472+1.6506Si)(\sum\alpha_1^2\alpha_2\alpha_3)+1.218(\sum\alpha_1^4)-0.86764(\sum\alpha_1^4\alpha_2^2)+1.218(\sum\alpha_1^6)}$

$A^*_{ELECTRICAL\ STEELS}=K_{0+}K_1(\sum\alpha_1\alpha_2)+K_2(\sum\alpha_1^2)+K_3(\prod\alpha_1)+K_4(\sum\alpha_1^2\alpha_2^2)++K_5(\sum\alpha_1^3)+K_6(\sum\alpha_1^2\alpha_2\alpha_3)+K_7(\sum\alpha_1^4)+K_8(\sum\alpha_1^4\alpha_2^2)+K_9(\sum\alpha_1^6)$

Assuming P=(0.355 – 0.013[wt%Si]);
K_0=(3.116 - 0.6975[wt%Si])/P
K_1=13/P
K_2=1.218/P
K_3= -10.416/P
K_4= (0.112 -1.6244Si)/P
K_5 =1.218/P
K_6 =(-3.472+1.6506Si)/P
K_7=1.218/P
K_8= -0.86764/P
K_9=1.218/P

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	direction <100>	$\alpha_1=1$, $\alpha 2=0$, $\alpha_3=0$	22.5 ϴ fibre <100>//ND	≈22.5	≈22.5	≈22.5	≈22.5
2	direction <110>	$\alpha_1=1/\sqrt{2}$, $\alpha 2=1/\sqrt{2}$, $\alpha_3=0$	35.6 fibre //ND	≈35.6	≈35.6	≈35.6	≈35.6
3	direction <111>	$\alpha_1=1/\sqrt{3}$, $\alpha 2=1/\sqrt{3}$, $\alpha_3=1/\sqrt{3}$	38.68 ϒ fibre <111>//ND	≈38.68	≈38.68	≈38.68	≈38.68

CONCLUSIONS:

Magneto-Crystalline Anisotropy Energy Density value is least for [100] directions, and higher for [110] , [111] & random directions. Therefore [100] directions are easy directions of magnetization for pure iron,electrical steels and [111] hardest direction for magnetization of pure iron & electrical steels, [110] direction is harder direction for magnetization of pure iron and elecrical steels,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-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, Prakash Dhoka, Pankaj Karande.
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