On the Relation of Residual Magnetization and Applied Stress at Stress Concentration Zone

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Outline

- Introduction and Motivation
- Research Goals
- Magnetic Object Model
- Energy Minimization with Stress
- Experimental Setup
- Zero Field Measurements
- Discussion
- Summary

Introduction and Motivation

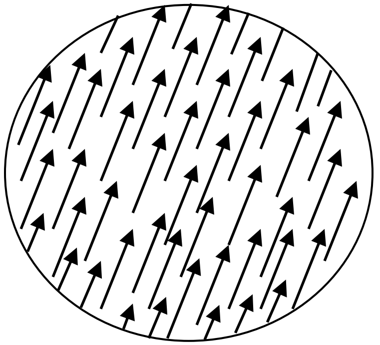
- Characterization of stress state is a key element in identifying the susceptibility of a material to various failure modes including:
  - Stress Corrosion Cracking
  - Potential for Plastic Deformation
  - Limited Ultimate Tensile strength
  - Fatigue Fracture Limits

Research Goals

- Develop method to identify effects of elastic stress and plastic deformation under near zero magnetization conditions on defects in steel.
- Investigate combined effects of stress and material properties such as grain size and microstructure on residual magnetization through modeling and direct laboratory measurements for validation.

Domain Configurations

Ferromagnetic Domains form in order to minimize total system energy.

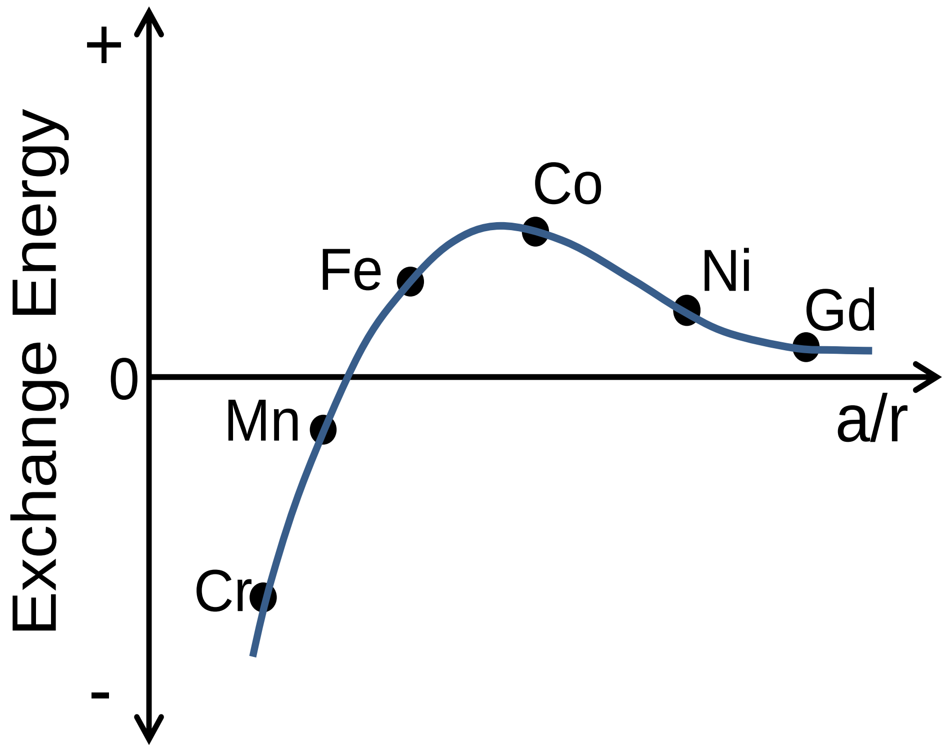


Energy terms include:

- Exchange Energy (Spin-Spin interaction)
- Magnetostatic Energy (Demagnetizing Fields)
- Crystallographic Anisotropy Energy
- Magnetoelastic Energy – Magnetostriction
- Domain Wall (DW) Energy

Shilling and Houze IEEE Trans Magn. 10, 195 (1974).

Exchange Energy



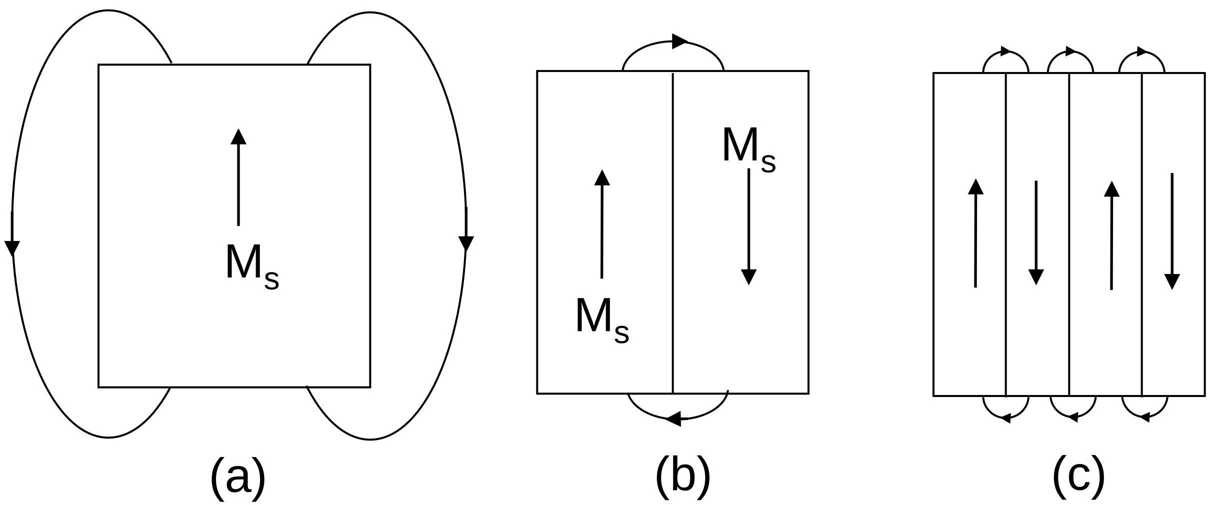
Bethe-Slater curve describes variations in exchange energy for increasing ratio of interatomic distance a radius of the 3d electron shell, r as a/r.

Magnetic Objects

- In polycrystalline steel single grains may be considered as regions exhibiting largely independent magnetic behavior (grain sizes ~ 5 to 50 μm in polycrystalline steels).
- Volumes of correlated domain behavior.
- Characterized by flux closure.
- Exhibit properties of a single Fe crystal.
- <u>Energy is minimized within a magnetic object.</u>
- How can this help us to understand magnetic behavior?

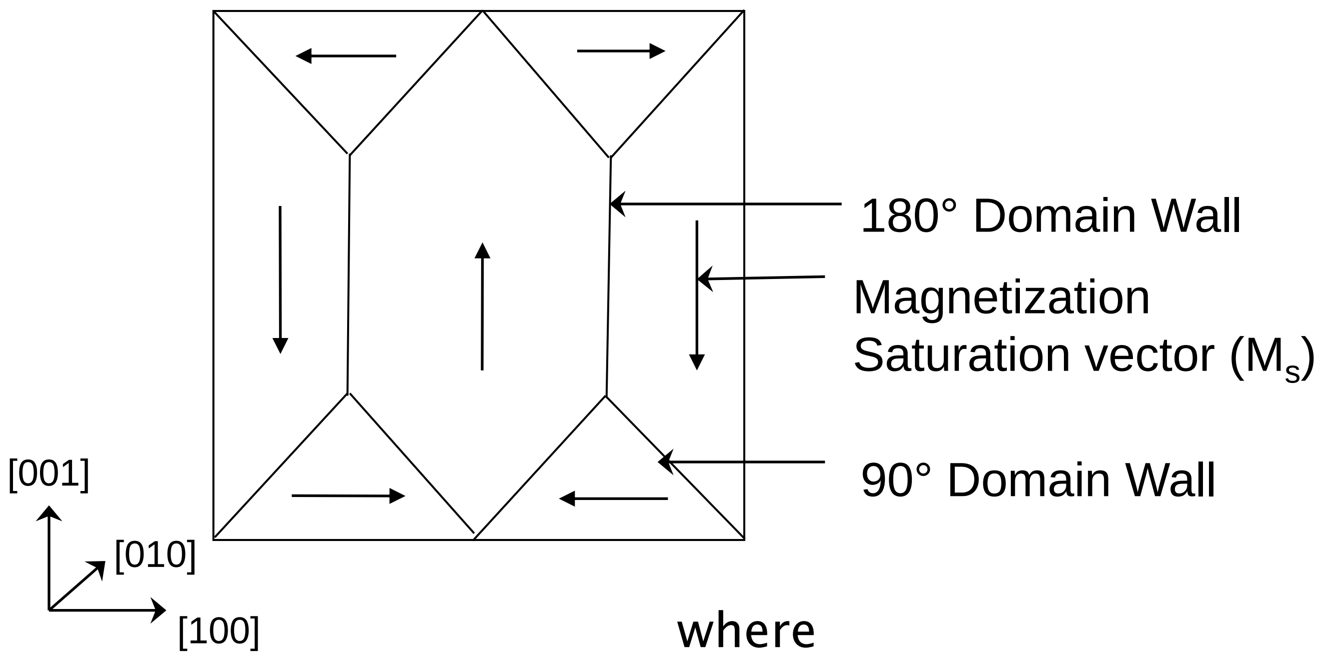
G. Berttoti IEEE Trans. Magn. **24,** 621 (1988).

Domain Wall Refinement



Domain wall refinement in a single ferromagnetic crystal.
a) Single domain in is spontaneously magnetized along easy axis.
b) Magnetostatic energy is reduced by splitting single domain into two domains.
c) Energy is further minimized if domains split into four.

Magnetostatic Energy Minimization



Total energy

$$E_T = E_{ex} + E_{ms} + E_K + E_{el} + E_\gamma$$

where

E_{ex} –Exchange Energy

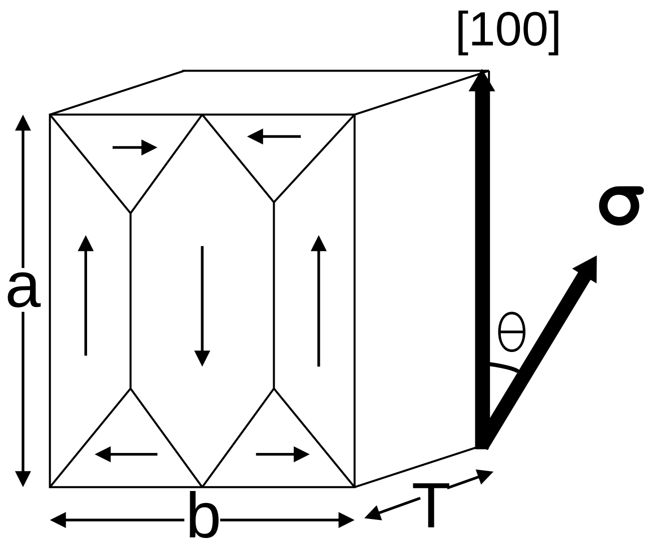
E_{ms} –Magnetostatic Energy

E_K –Anisotropy Energy

E_{el} –Magnetoelastic Energy

E_γ – Domain Wall Energy

Magnetoelastic Energy



$$E_{el} = -\frac{3}{2}\lambda_{100}\sigma\left(cos^2\theta V_{180^\circ} + sin^2\theta V_{90^\circ}\right)$$

$$V_{90^\circ} = \frac{Tb^2}{2n}$$ Volume of 90° domains

$$V_{180^\circ} = T\left(ab - \frac{b^2}{2n}\right)$$ Volume of 180° domains

$$E_{el} = -\frac{3}{4}\lambda_{100}\sigma Tb\left(a + \left(a - \frac{b}{n}\right)cos2\theta\right)$$

Where:

λ_{100} -saturation strain due to magnetostriction along the [100] direction ($2.07\text{x}10^{-5}$).

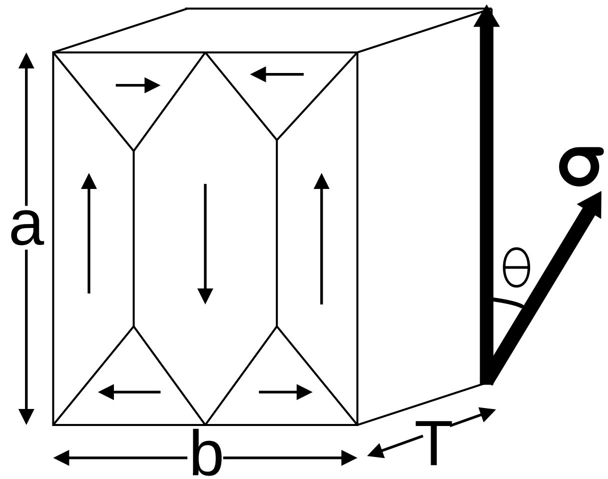
σ - applied stress

θ – angle of σ w.r.t. crystallographic [100] direction

n – is the number of 180° domain walls

T.W. Krause, L. Clapham, A. Pattantyus and D.L. Atherton, 'Investigation of the Stress-Dependent Magnetic Easy Axis in Steel Using Magnetic Barkhausen Noise',J. Appl. Phys. **79,** 4242 (1996).

Additional Energy Terms



Energy of 180° DWs

$$E_\gamma = \gamma_{180^\circ} A_{180^\circ}$$

Energy of 90° DWs

$$E_\gamma = \gamma_{90^\circ} A_{90^\circ}$$

Area of 180° DWs

$$A_{180^\circ} = T\left(an - b\right)$$

Area of 90° DWs

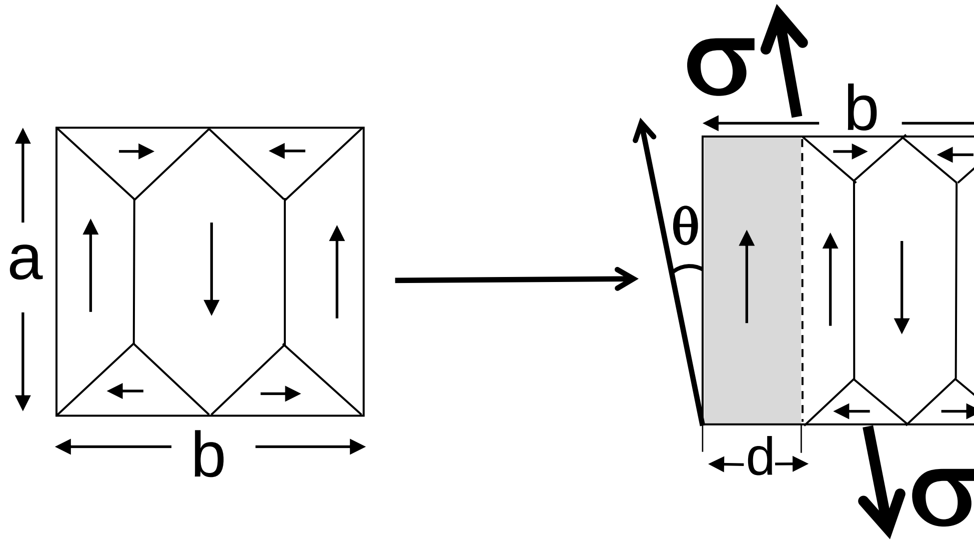
$$A_{90^\circ} = T\sqrt{a^2 + b^2}$$

Energy of Magnetic Object under uniaxial stress

$$E = \frac{3}{4}\lambda_{100}\sigma Tb\left(a + \left(a - \frac{b}{n}\right)cos2\theta\right) + \gamma_{180^\circ}T\left(an - b\right) + \gamma_{90^\circ}T\sqrt{a^2 + b^2}$$

T.W. Krause and A.A. Samimi, 'Micromagnetic Techniques', Vol. 17, Nondestructive Evaluation and Quality Control, American Society of Metals, 40 pgs., In Press.

Total Energy under Formation of Magnetic Moment



Magneto-static energy per unit area (d<<a)[1]

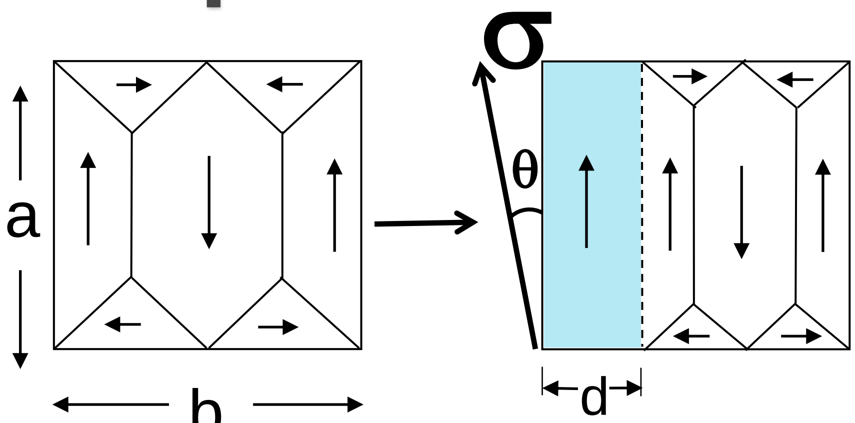
$$E_{ms} = \frac{M_s^2}{2\mu_0} a,$$

Total energy becomes:

$$E_T = 1.810^5 M_s^2 T d^2 - \frac{3}{4}\lambda_{100}\sigma T(b-d)\left(a + \left(a - \frac{(b-d)}{n}\right)cos2\theta\right)$$
$$+ \gamma_{180^\circ} T\big(an - (b-d)\big) + \gamma_{90^\circ} T\sqrt{a^2 + (b-d)^2},$$

[1]S. Chikazumi and S.H. Charap, *Physics of Magnetism*, Krieger, Florida, 1964.

Stress Dependence



Stress dependence of pole width d (change in domain wall energy is negligible).

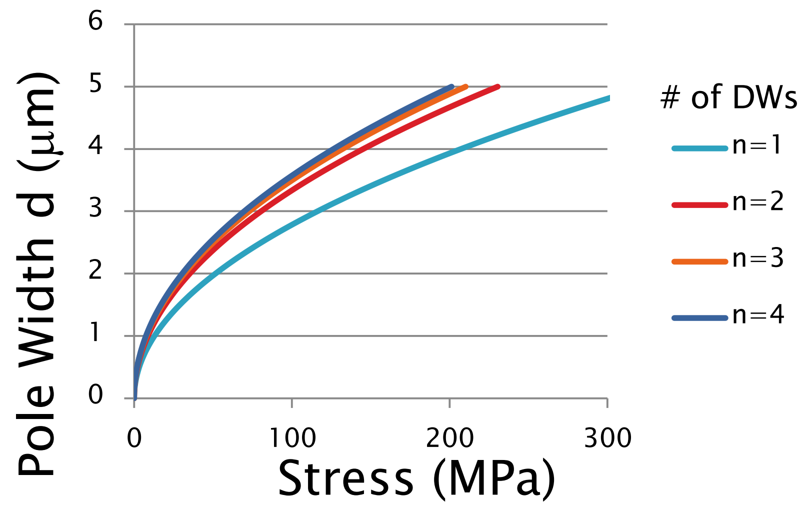
$$\sigma = \frac{1.4410^5 M_s^2 d^2}{\lambda_{100}(b-d)\left(a+\left(a-\frac{(b-d)}{n}\right)cos2\theta\right)}$$

Example: For a 50 μm cubic grai with n=2 180° DWs at 231 MPa

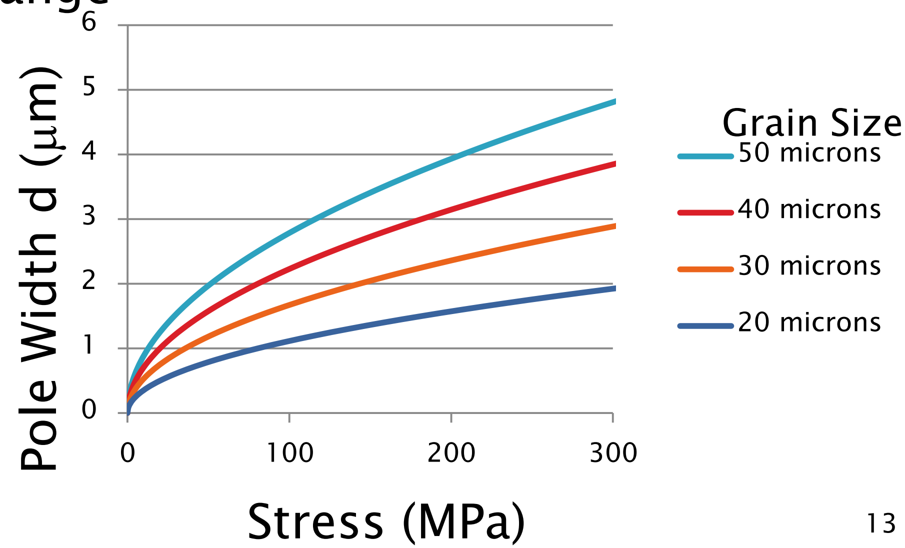
$E_{el}=E_{ms}=0.624\ nJ/m^3$

$E_{\gamma 180^o}=0.0044\ nJ/m^3$

$E_{\gamma 90^o}=\ 0.0027\ nJ/m^3$

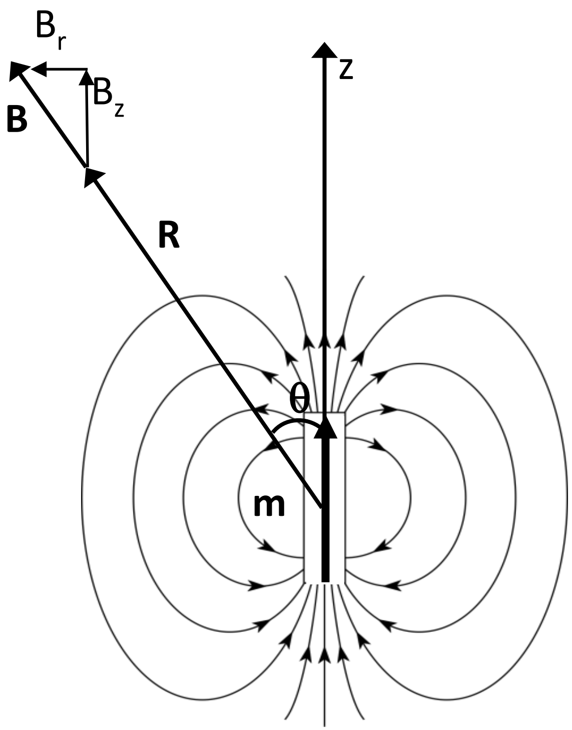


Surface Pole width versus Stress at 50 μm Grain Size



Surface Pole Width versus Stress for Various Grain sizes

Magnetic Dipole Moment



Magnetic dipole moment becomes:

$$m = (TcM_s)a,$$

which leads to magnetic field components:

$$B_r = \frac{\mu_0 m}{4\pi}\left(\frac{3\sin 2}{\theta 2R^3}\right)$$

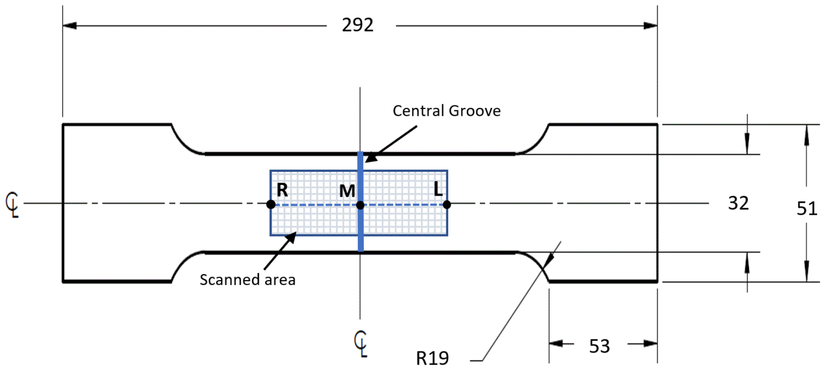
Radial field component sensed by tangential magnetic measurements.

$$B_z = \frac{\mu_0 m}{4\pi}\left(\frac{3cos^2\theta - 1}{R^3}\right)$$

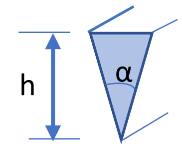
In-line magnetic field component sensed by normal magnetic component measurements.

P. Lorrain, D.R. Corson and F. Lorrain, Electromagnetic Fields and Waves, 3rd Ed., W.H. Freeman and Company, New York, 1988, P 340.

Experiment: Sample Parameters



Geometry of specimen and scanned area



α=15°
h = 0.1, 0.2 and 0.3 mm

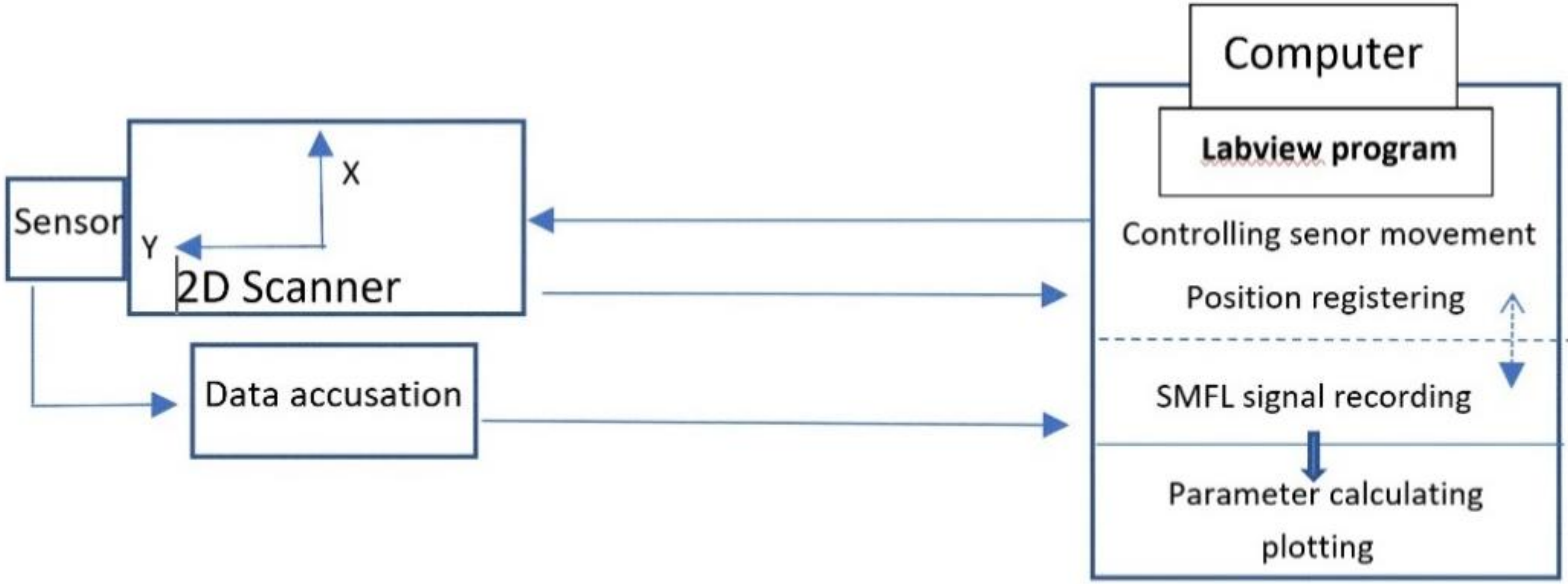
Geometry of groove

Chemical and Mechanical Properties of 1.9 mm thick 1015 Steel Sample

Chemical Composition Max.%				Mechanical Properties (MPa)		
C	Mn	P	S	σys	σuts	% ε
0.15	0.6	0.03	0.035	321	372	>25

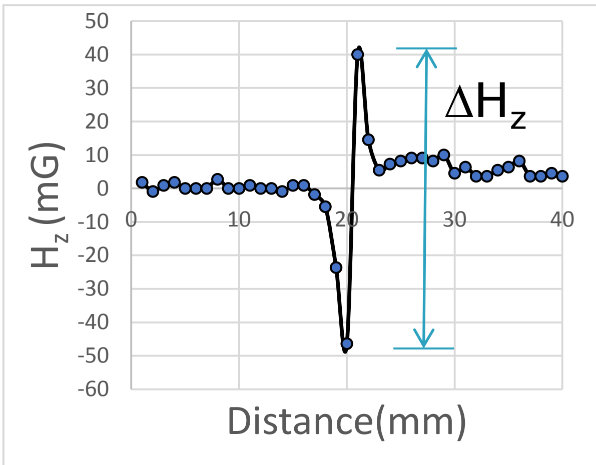
Samples were demagnetized by AC while on tensile machine, using a U-shaped probe (Parker Research). Horizontal 20 KN tensile testing machine manufactured by Monsanto Instruments (Tensometer 20) was used for applying force with loading speed of 2 mm/min.

Scanning System

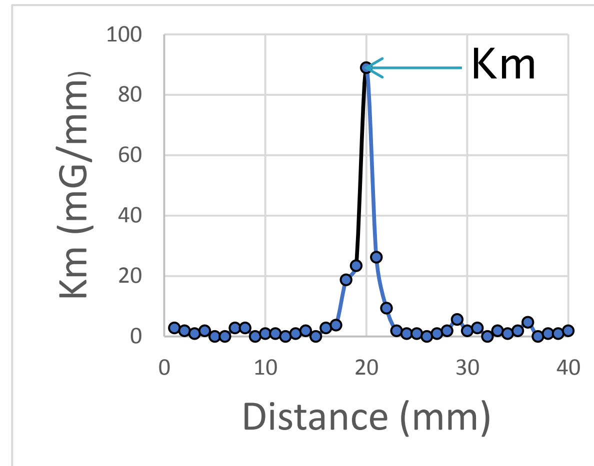


- Self magnetic flux leakage (SMFL) Scanning system .
- XY translation system is controlled by stepper motors (Arrick Robotics)
- Magnetic sensor – Honeywell 3-Axis (HMC 5883L) AMR sensor with 4.5 milliGauss (mG) resolution and ±8 Gauss range.
- 3 SMFL signal components measured over sample surface simultaneously.
- Lift-off value kept at 1 mm using a protective plastic cover on sensor.
- A I2C/SPI Interface Device (National Instruments USB-8451) was used as data acquisition device and data was recorded using a LabView program.

Signal Analysis



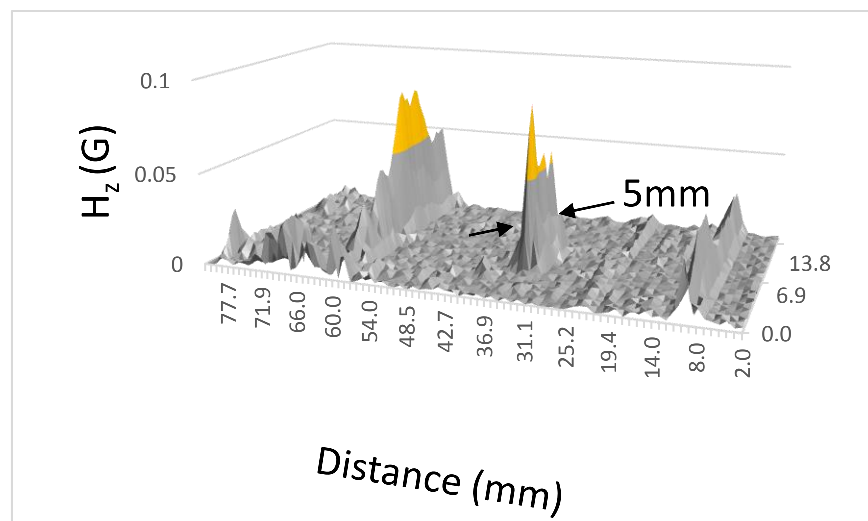
ΔH_z Definition



Km definition

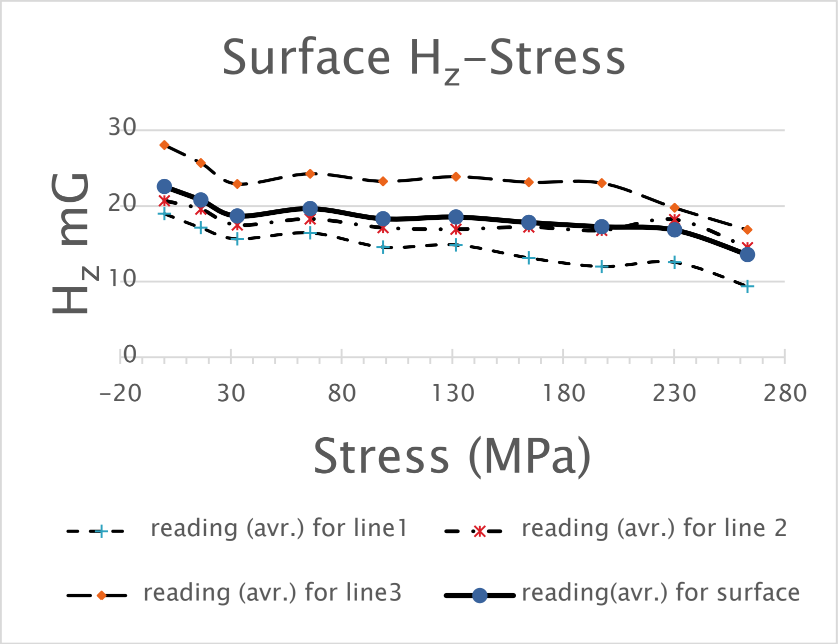
$$\text{Km}=\frac{|dH_z|}{dx}$$

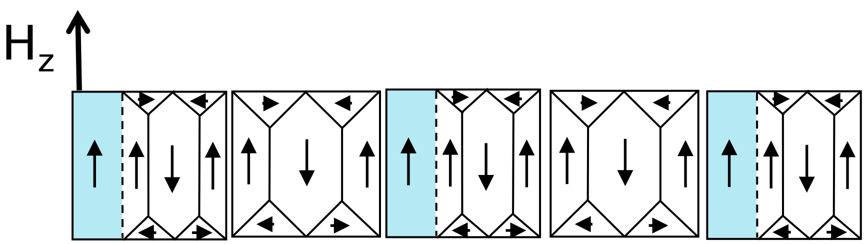
Surface plot of Km factor for sample with three grooves



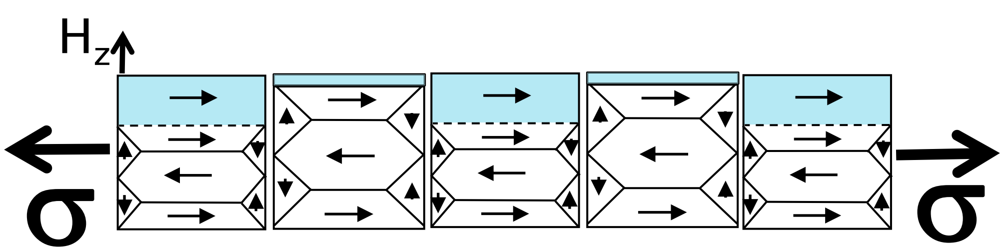
No Defect Sample Response

Changes in normal component H_z of SMFL with applied stress for un-grooved sample.



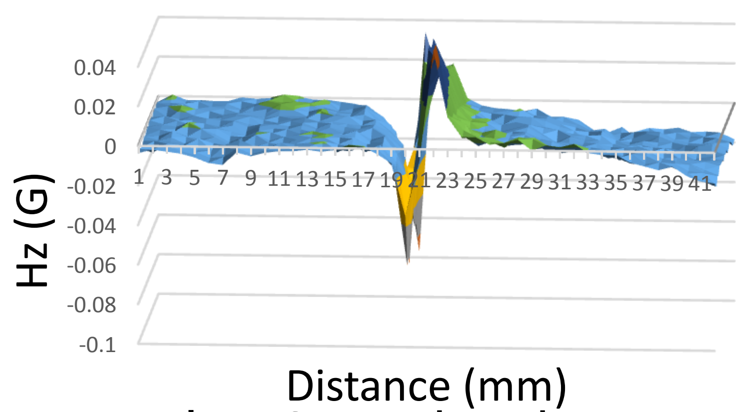


Normal H_z SMFL distribution – No Groove and No Stress

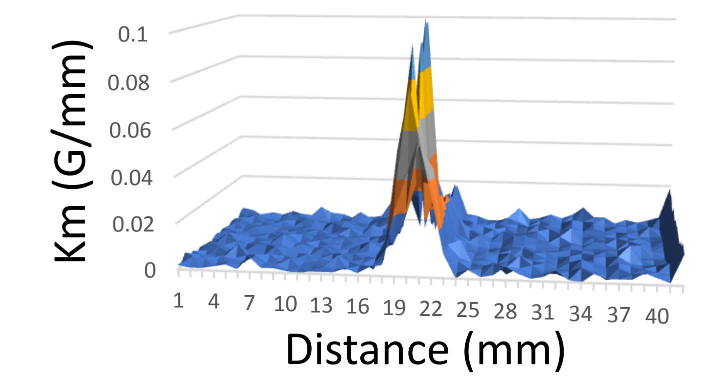


Normal H_z SMFL reduced with Stress (aligns with σ)

Surface Scan for 0.3mm Deep Groove

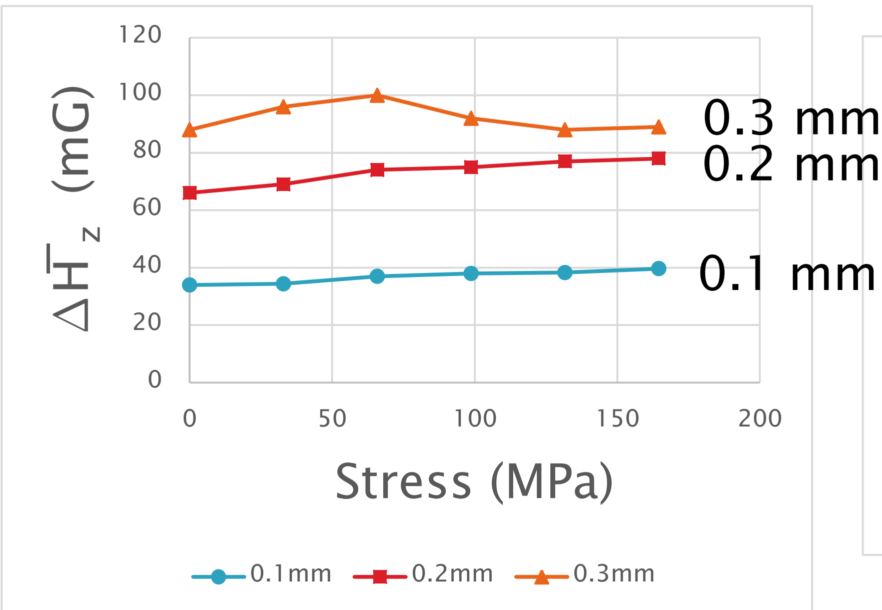


Normal H_z SMFL distribution

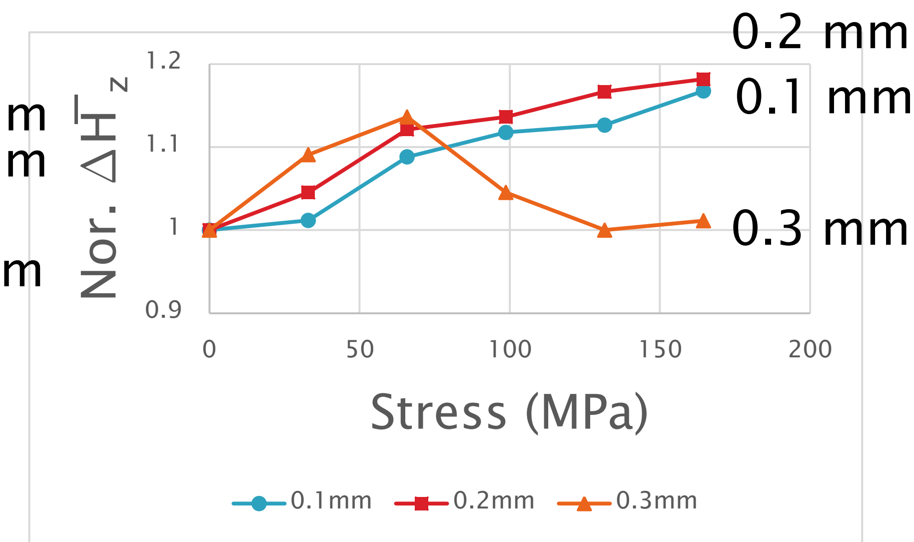


Km distribution

Change in ΔH_z with Stress over Grooves

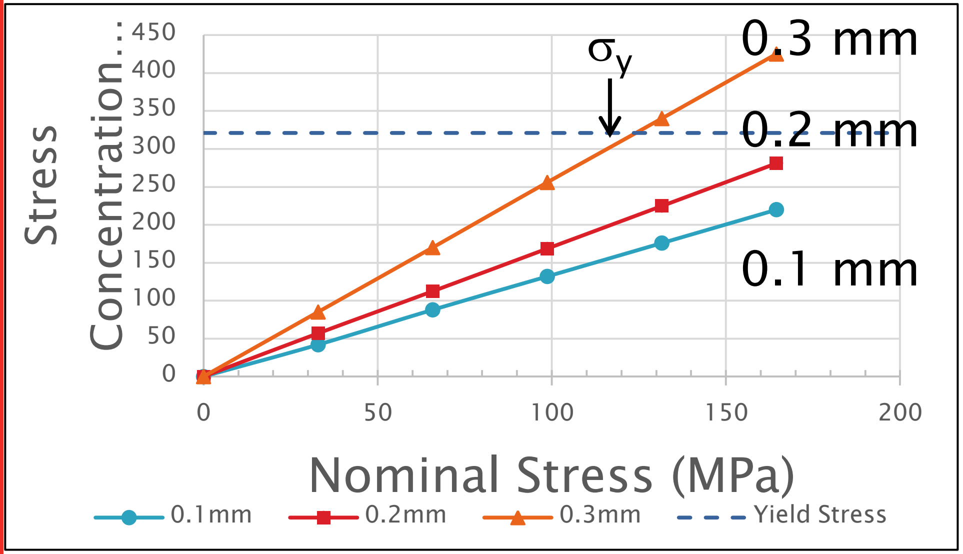


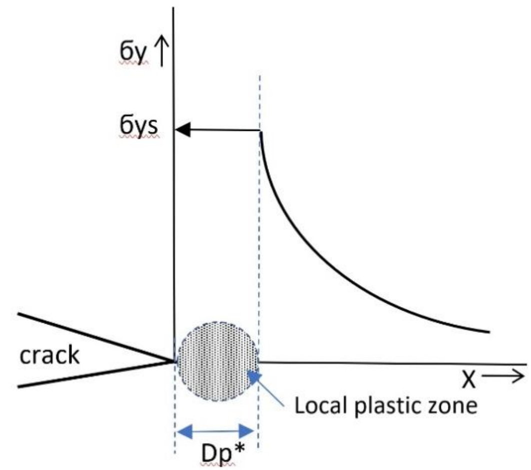
$\overline{\Delta H}_z$ with applied stress for samples with 0.1, 0.2 and 0.3 mm deep



Normalized $\overline{\Delta H}_z$ with applied stress for samples with 0.1, 0.2 and 0.3 mm deep grooves.

Stress Concentration at Groove Tip

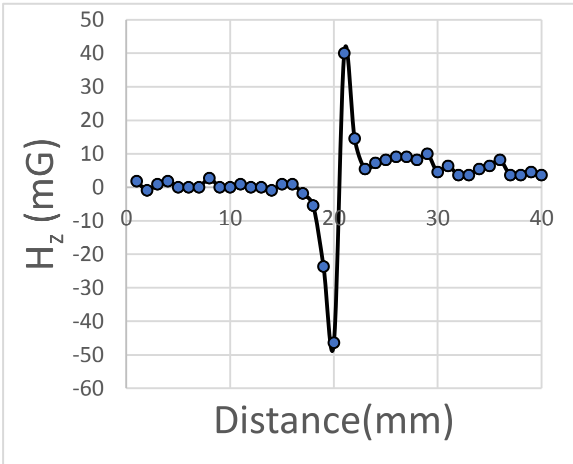


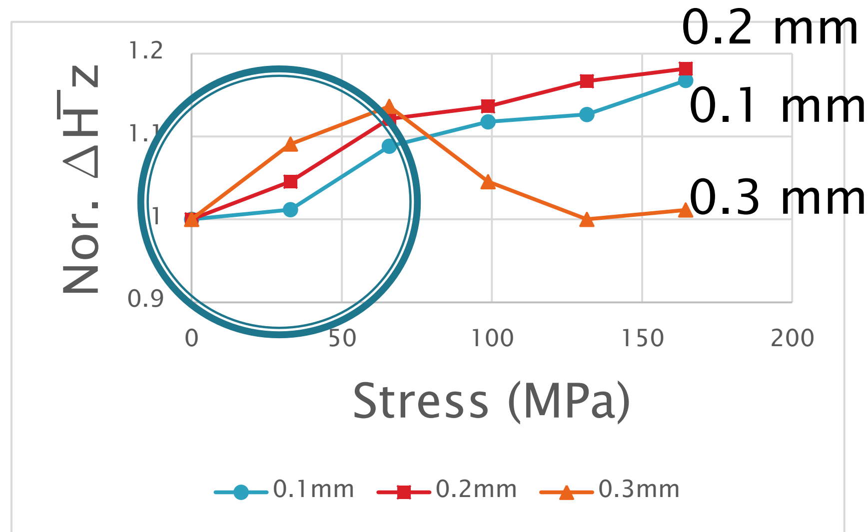


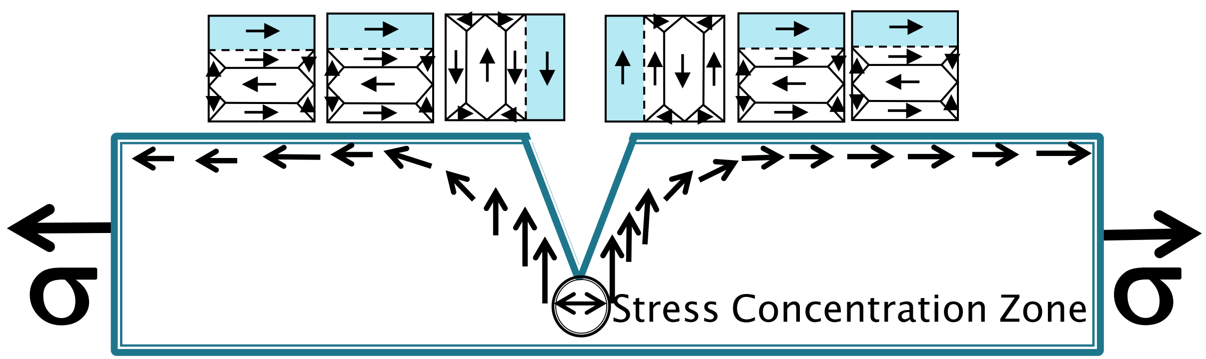
Change in stress concentration at 0.05 mm under the tip of the groove with applied stress for samples with 0.1, 0.2 and 0.3 mm deep groove.

Simplified model for formation of local plastic zone at crack tip.

Discussion: Elastic Range

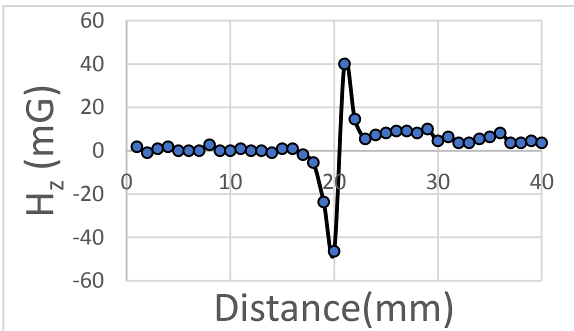


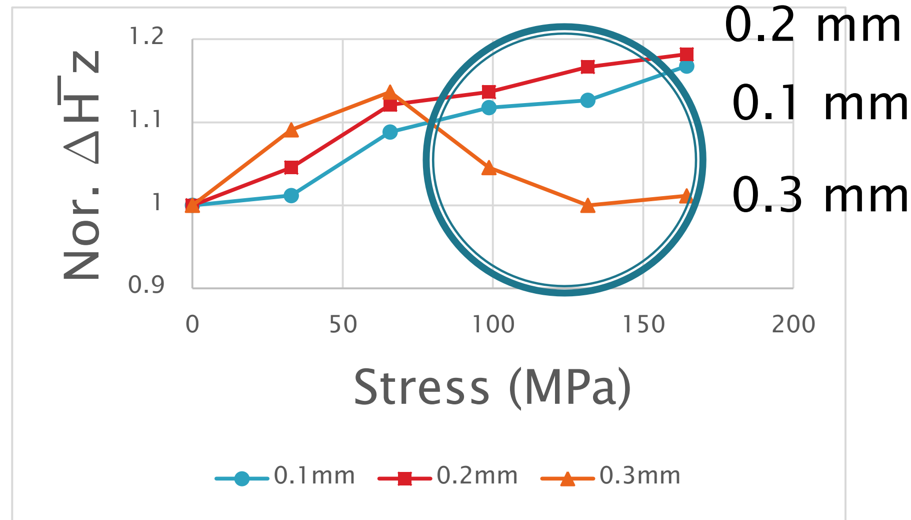


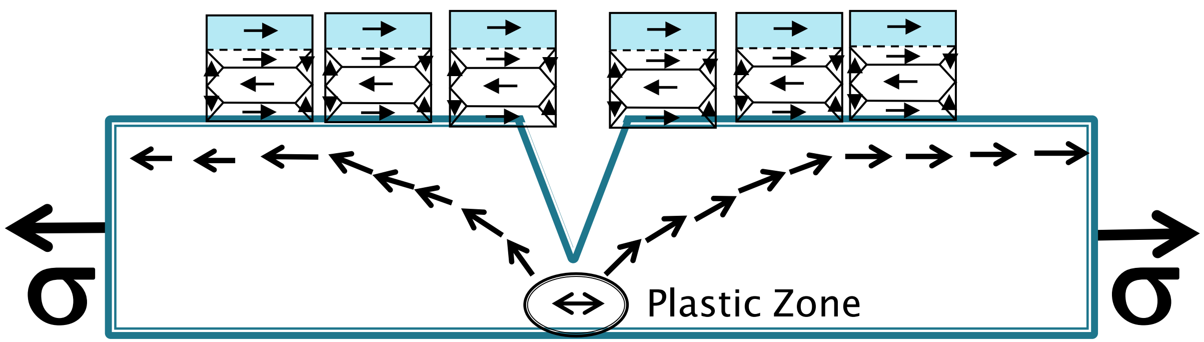


Normal H_z SMFL increases with stress concentration at defect (aligns with σ) until yield point.

Discussion: Plastic Range







Beyond yield no additional growth in perpendicular moments occurs and moments are reoriented in direction of applied stress. Defect signal returns to its initial size.

Summary

- Work examined influence of applied stress on normal component of self magnetic flux leakage (SMFL) signals and its gradient at transverse grooves.
- SMFL signals are the result of combined effects of different elastic and plastic deformation mechanisms at the groove root, which contribute to its magnetic signature.
- Normal component of SMFL signal (ΔH_z) and its gradient (Km) increases with stress level up to local yielding.
- Local plastic deformation limits further change in magnetic properties and SMFL signals.
- Results are explained in terms conversion of magnetoelastic energy ⇔ magnetostatic surface pole energy on magnetic objects, which are detected by magnetic sensor in near zero field.

Acknowledgements

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Questions?