USE OF BARKHAUSEN NOISE IN INSPECTION OF THE SURFACE CONDITION OF STEEL COMPONENTS

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• Barkhausen noise
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BACKGROUND

• Material properties can be measured destructively or non-destructively
• Destructive methods are not applicable to quality control
  ◦ non-destructive methods are preferred
• Non-destructive testing methods: visual inspection, ultrasonics, acoustic emission, magnetic methods etc.
• Barkhausen noise (BN) is an intriguing technique for ferromagnetic materials
  ◦ Fast, low costs, simple equipment
BARKHAUSEN NOISE – ORIGIN

• The specimen is placed in an external, varying magnetic field
  ◦ Magnetic domain wall movements
  ◦ The walls get trapped behind pinning sites
  ◦ Rapid and stochastic movements caused by walls breaking out of the pinning sites
• Rapid movements of the domain walls cause a noise-like signal
• Wall movements are influenced by material properties

![Diagram](image.png)
BARKHAUSEN NOISE SIGNAL

--- Barkhausen noise  --- Applied magnetic field

Applied magnetic field

Barkhausen noise

Time (relative)

-1500 -1000 -500 0 500 1000 1500
-1000 -500 0 500 1000
-300 -200 -100 0 100 200 300
BARKHAUSEN NOISE – LITERATURE

• BN has been shown to be very sensitive to microstructure and material properties: residual stress, hardness, etc.
• Some feature is calculated from the BN signal and compared to the material property studied
  - RMS, peak height, width and position
• Results are usually only qualitative

Figure from Sorsa (2013)
BARKHAUSEN NOISE – APPLICATIONS

• Material characterisation
  ◦ Quality control
• Case depth evaluation
  ◦ Remaining layer thickness
• Grinding burn detection
  ◦ Soft spot detection
BN STUDIES – RESEARCH PROBLEM

• Changes in material properties cumulate to the BN signal.
  ◦ How to distinguish the influence of different factors?
• Interactions between material properties and BN are complex.
• Stochastic phenomenon
  ◦ Only averaged properties are reproducible.
• Indirect measurement
  ◦ Models are needed
  ◦ Significance of calculated features?
BN STUDIES – APPROACH

• Mathematical models used for describing the interactions between material properties and BN
  ◦ Residual stress, hardness
• Identification of the model divided into 4 steps
  ◦ Feature generation
  ◦ Feature selection
  ◦ Model identification
  ◦ Model validation
BN STUDIES – APPROACH: STEP 1

• Feature generation
  ◦ BN signal is useless by itself
  ◦ Information needs to be converted into useful form
  ◦ Calculation of features with different mathematical operations
    - Statistical
    - RMS, BN energy and entropy
    - Factors
    - Features from BN profile
  ◦ Produces a big set of features (about 150)
BN STUDIES – APPROACH: STEP 2

• Feature selection
  ◦ The most significant features are case-dependent
  ◦ Automatic procedures are needed
  ◦ Deterministic methods
    - Stepwise selection (forward-selection, backward-elimination and their combinations)
    - May not lead to optimal solution
  ◦ Stochastic methods
    - Simulated annealing, genetic algorithms
    - Reported to give better results
BN STUDIES – APPROACH: STEP 3

• Model identification
  ◦ Usually carried out simultaneously with feature selection
• Different model structures can be used
  ◦ MLR, PLSR, PCR, ANN ...
• Model is identified with the training data set
• In BN studies, the number of data points is limited
  ◦ Cross-validation methods are used (efficient data usage)
BN STUDIES – APPROACH: STEP 4

• Model validation
  ◦ Prediction models are useless if they are valid only for the data they were trained with.
  ◦ Models must be validated with an independent testing data set
  ◦ Validation should also include validation of the selected features with expert knowledge
BN STUDIES – RESULTS

- Material characterisation: prediction of residual stress
- All studies carried out in cooperation with the Department of Materials Science, Tampere University of technology

<table>
<thead>
<tr>
<th>Study</th>
<th>Feature selection</th>
<th>Modelling technique</th>
<th>Reference</th>
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<tbody>
<tr>
<td>1</td>
<td>Manual</td>
<td>MLR</td>
<td>Sorsa et al. (2012a)</td>
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<td>2</td>
<td>Forward-selection</td>
<td>MLR</td>
<td>Sorsa et al. (2012b)</td>
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<td>3</td>
<td>GA</td>
<td>MLR</td>
<td>Sorsa et al. (2013a)</td>
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<tr>
<td>4</td>
<td>Preselection + GA</td>
<td>Nonlinear regression</td>
<td>Sorsa et al. (2014)</td>
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<td>5</td>
<td>Preselection + exhaustive</td>
<td>ANN</td>
<td>Sorsa et al. (2013b)</td>
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BN STUDIES – RESULTS: STUDY 1

Data set 1
Data set 2
Perfect fit

Predicted residual stress vs. Measured residual stress

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<tr>
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<th>Training</th>
<th>Validation</th>
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<tbody>
<tr>
<td>R</td>
<td>0.85</td>
<td>0.91</td>
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<td>RMSEP</td>
<td>57.68 MPa</td>
<td>139.37 MPa</td>
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BN STUDIES – RESULTS: STUDY 2

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<td>RMSEP</td>
<td>53.11 MPa</td>
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**BN STUDIES – RESULTS: STUDY 3**

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<td>RMSEP</td>
<td>75.62 MPa</td>
<td>93.80 MPa</td>
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</table>

- **Predicted residual stress [MPa]**
- **Measured residual stress [MPa]**

- **Training**
- **External validation**
- **Perfect fit**
BN STUDIES – RESULTS: STUDY 4

<table>
<thead>
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<td>RMSEP</td>
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BN STUDIES – RESULTS: STUDY 5

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<td>51.1 MPa</td>
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- **R**
- **RMSEP**

b) RBF
BN STUDIES – RESULTS: CONCLUSIONS 1/2

- Feature selection
  - Manual selection
    - Reasonable results but not as good as with other methods
    - Features based on expert knowledge
  - Deterministic methods
    - Efficient
    - Good results but not as good as with stochastic methods
  - Stochastic methods
    - Best results
    - Computationally expensive
BN STUDIES – RESULTS: CONCLUSIONS 2/2

• Model structures
  ◦ Linear / MLR
    - Not as good results as with nonlinear
    - Robust
    - Main interactions
    - Computationally efficient
  ◦ Nonlinear regression
    - Not as good results as with ANN
    - Computationally expensive
    - More robust than ANN
  ◦ ANN
    - Best results
    - Computationally expensive
    - Risk of overfitting
SUMMARY

• BN is a non-destructive testing method suitable for ferromagnetic materials
  ◦ Sensitive to many material properties
  ◦ Indirect measurement → models are needed
• Evaluation of material properties with mathematical models
  ◦ 4 steps: feature generation, feature selection, model identification, model validation
• Results illustrated with residual stress predictions
  ◦ Reasonable results
REFERENCES

THANK YOU FOR YOUR ATTENTION!!