An Industry 4.0 example: real-time quality control for steel-based mass production using Machine Learning on non-invasive sensor data

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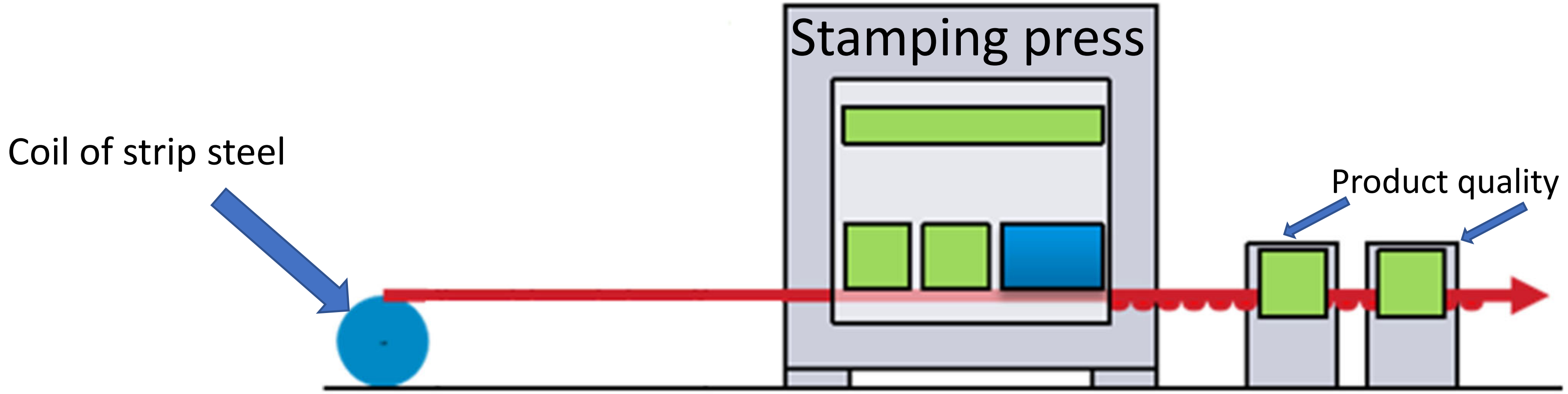
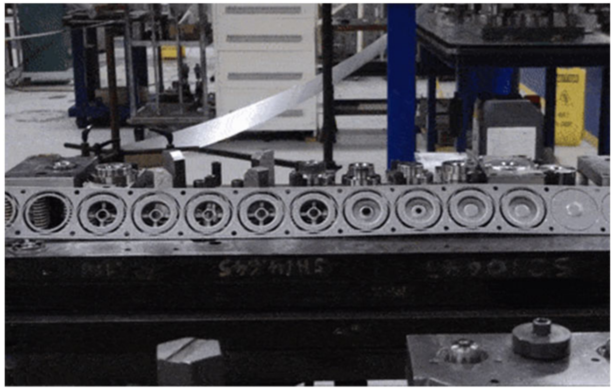
Problem overview



- Made out of steel coils that are up to a kilometre long
- Tens of thousands of products per day.
- Progressive stamping @ 180 strokes per minute.

Progressive stamping

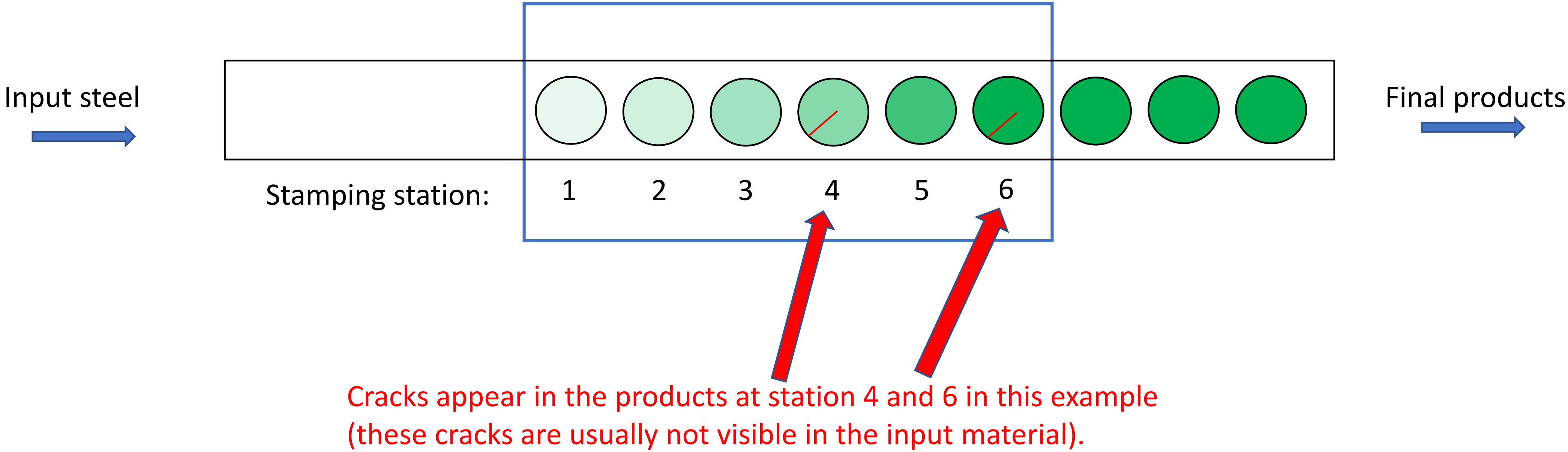


https://www.hudson-technologies.com/blog/progressive-die-stamping-overview/

- Material properties needs to conform to strict specification limits in order to be appropriate for the tooling

https://www.materials.sandvik/fr/products/strip-steel/strip-products/

Problem overview



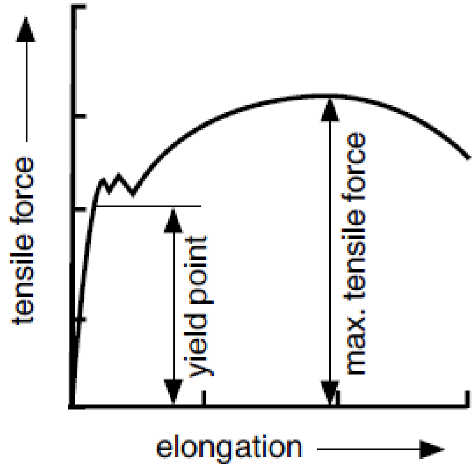
Consequences product faults:

- costly damage to tooling.
- production down time.
- When undetected: low quality products at final stage.

Hypothesis: the faults are caused by material that does not conform to specifications (e.g. too hard or brittle material)

Tensile tests of the material

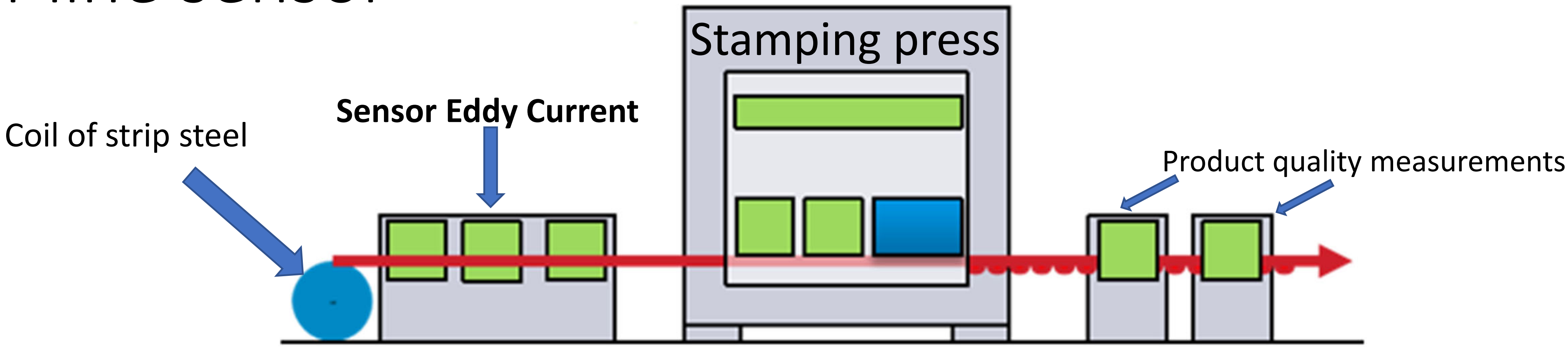
- Tensile tests on samples of the strip steel, covering only a small fraction of the coil
- Requires interpolation over large amount of steel
- **Not a solution for detecting quickly changing material properties**



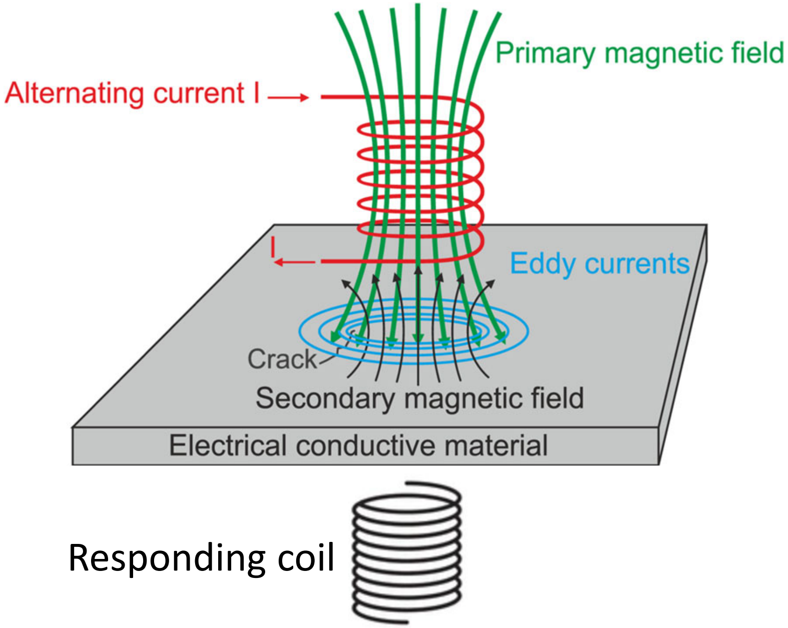
Goal of this work: predict yield strength and tensile strength for all material that is used in production, in order to prevent faults occurring in the press.

https://www.smalley.com/blog/tensile-strength-hardness-importance-tensile-strength-wave-spring-and-retaining-ring-design

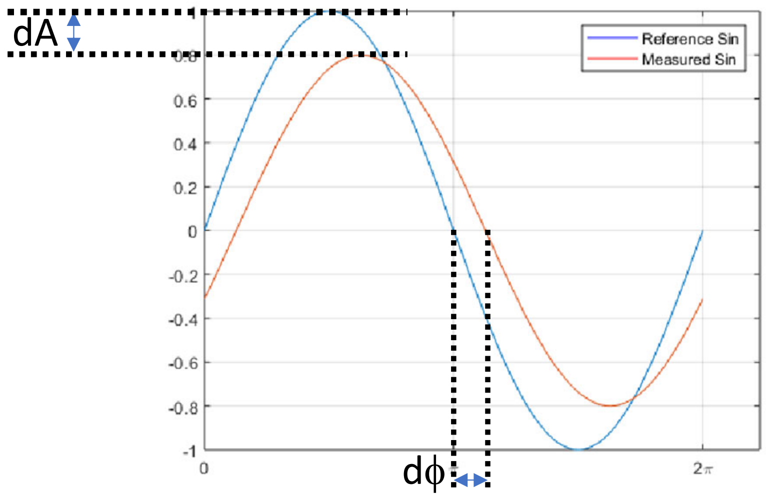
In-line sensor



Non-Destructive Testing (NDT)



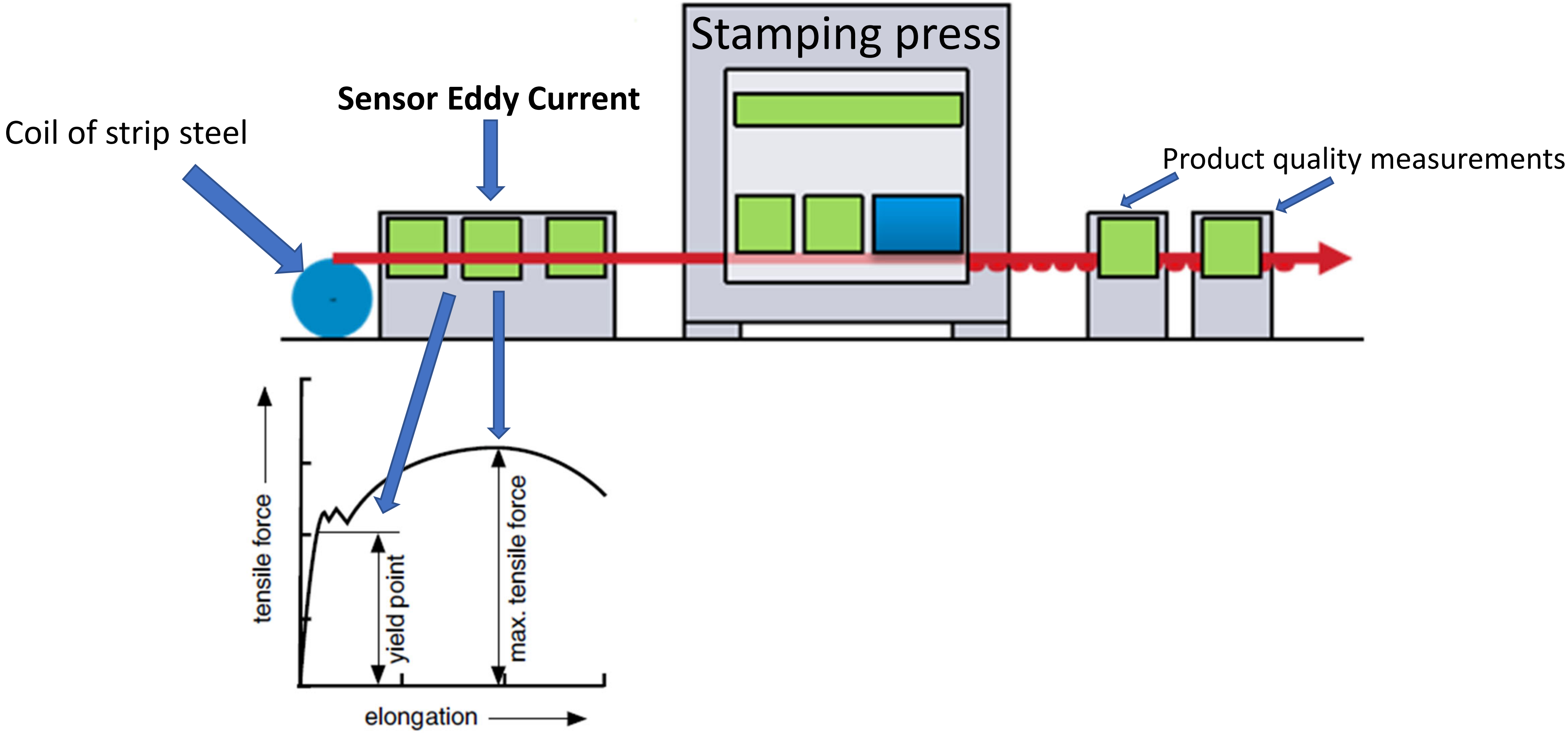
- 10 test frequencies, yields measurements $\boldsymbol{x} \in \mathbb{R}^{20}$



- Very quick (2ms) contactless measurement

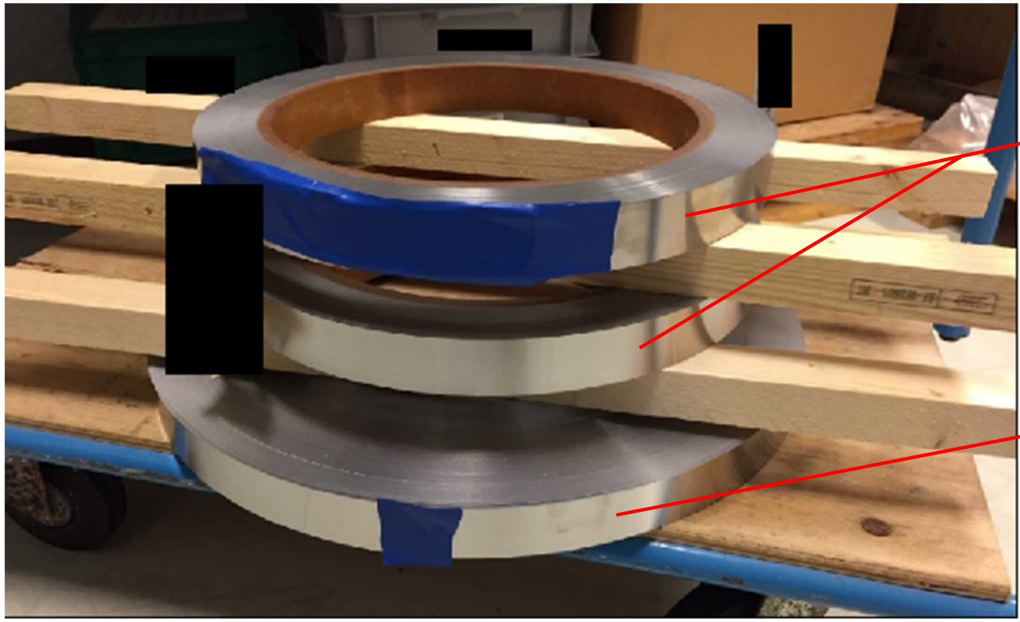
García-Martín, J.; Gómez-Gil, J.; Vázquez-Sánchez, E. Non-Destructive Techniques Based on Eddy Current Testing. *Sensors* **2011**, *11*, 2525-2565.

Goals



- Question 1: Can we predict material properties from the sensor measurements?
- Question 2: Can we prevent product faults using the inline sensor measurements?

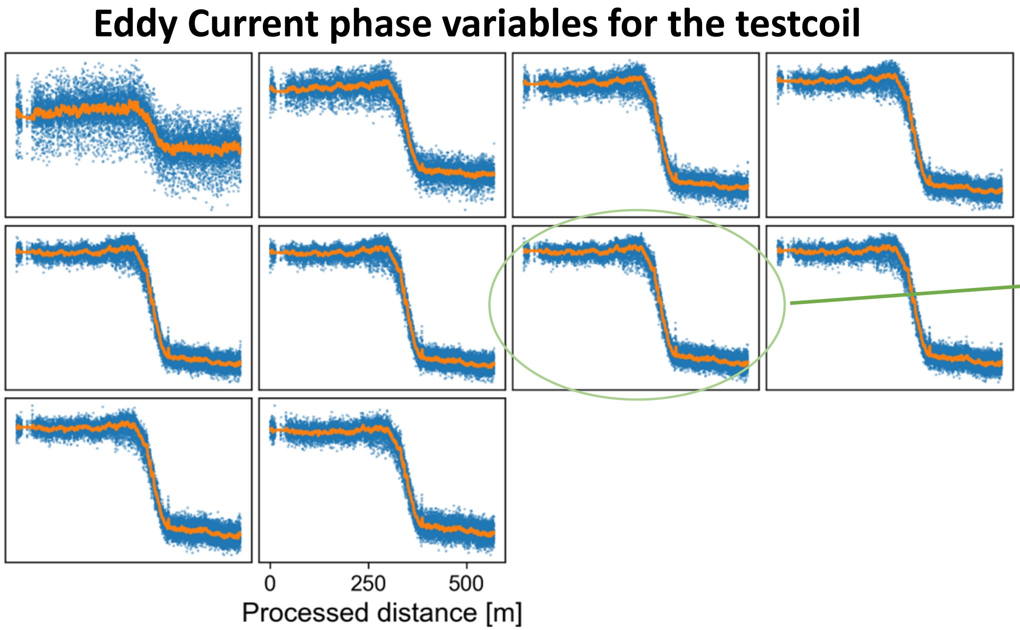
Dataset: measurements on outlier coil

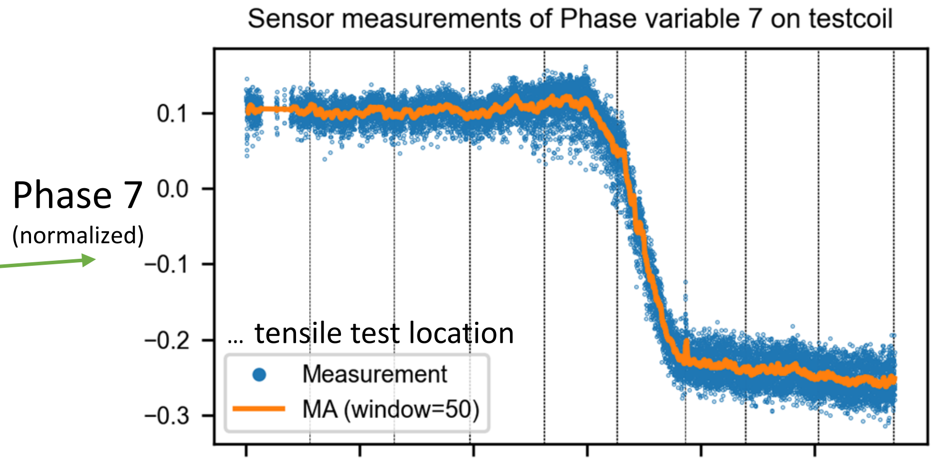


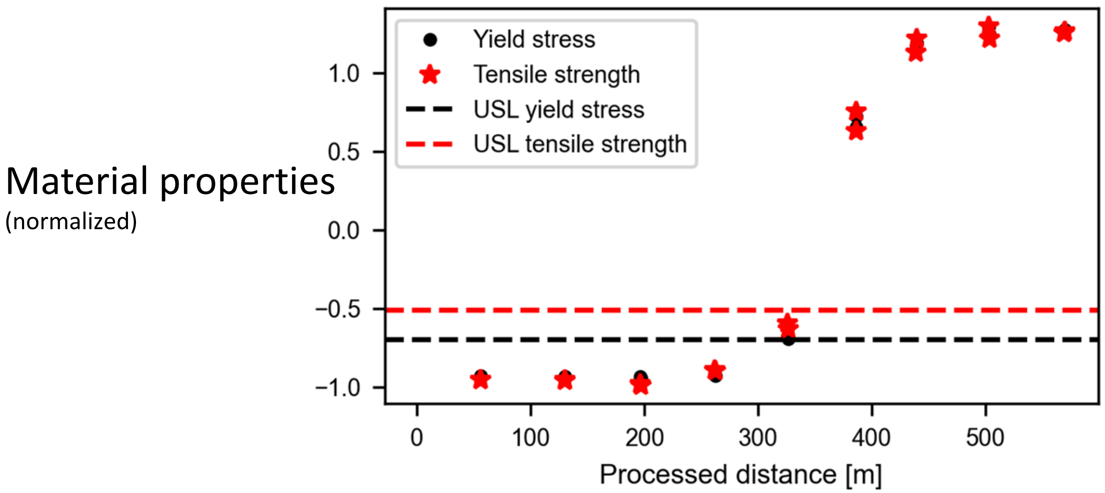
Coils rejected halfway due to cracks in products

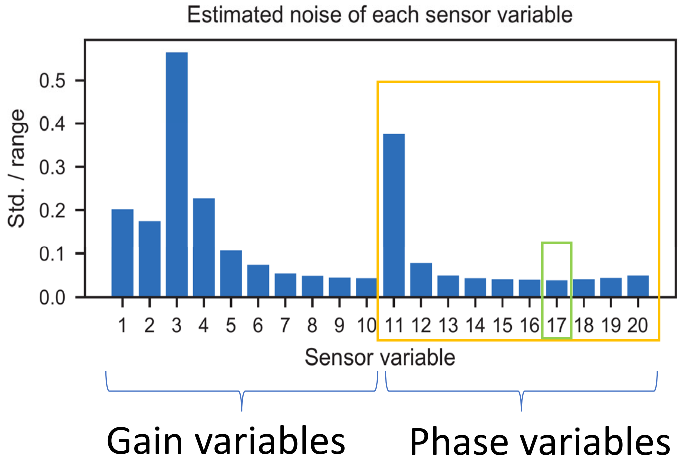
Coil rejected preventively and labeled “testcoil”.
-> Measure this coil with the sensor and take 9 tensile tests over the full length of the coil.

Measurements on testcoil

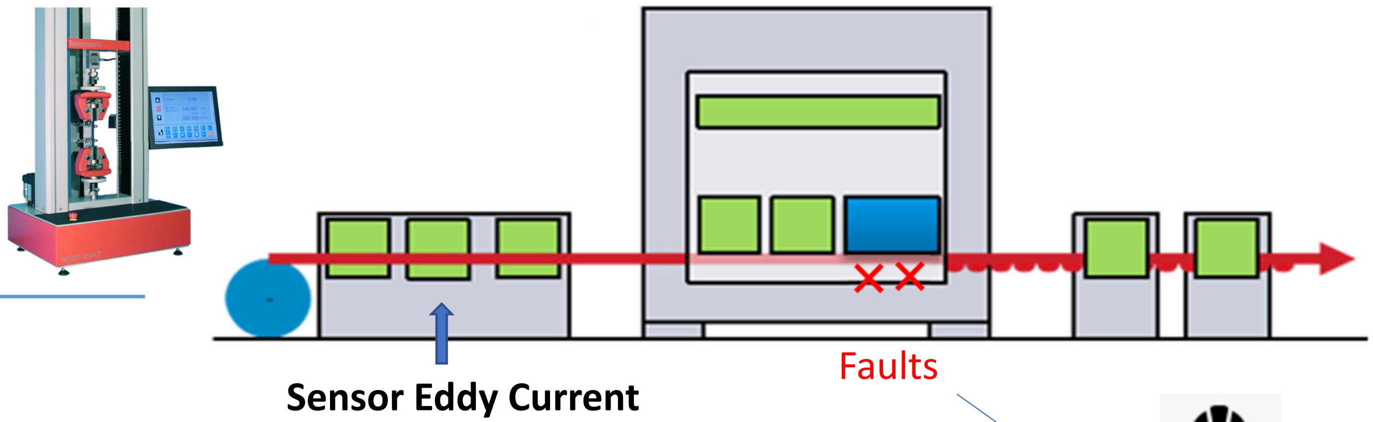








Measurements production coils

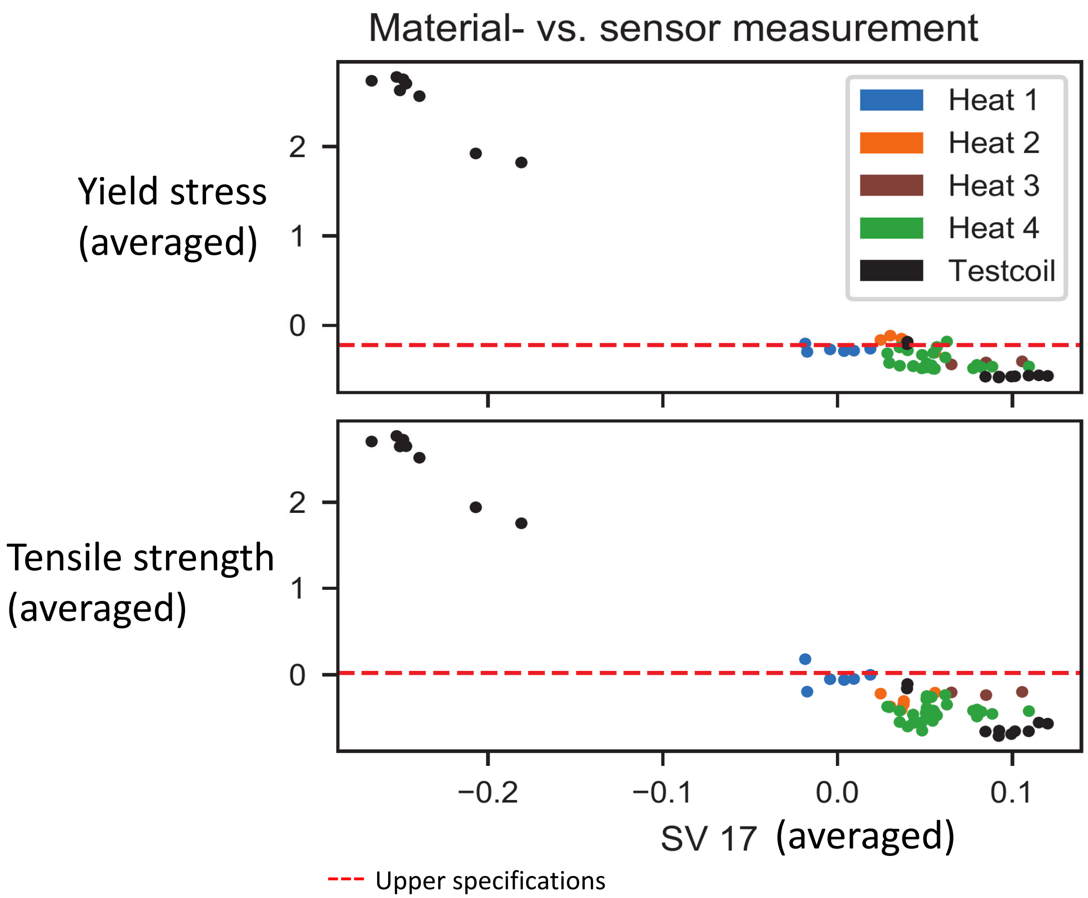


For 40 production coils:

- Tensile test samples at start of the coil
- Eddy Current measurements while producing with the coil
- The product faults occurring by producing with these coils were logged by the operators

Operator reports the time of faults in the production logbook. In 16 consecutive cases, the measurement ID of the steel was recovered.

Tensile tests and Eddy Current



Predicting material properties from Eddy Current

Fit *Partial Least Squares* regression model relating sensor data $\boldsymbol{X} \in \mathbb{R}^{N\times 20}$ to material properties $\boldsymbol{Y} \in \mathbb{R}^{N\times 2}$.

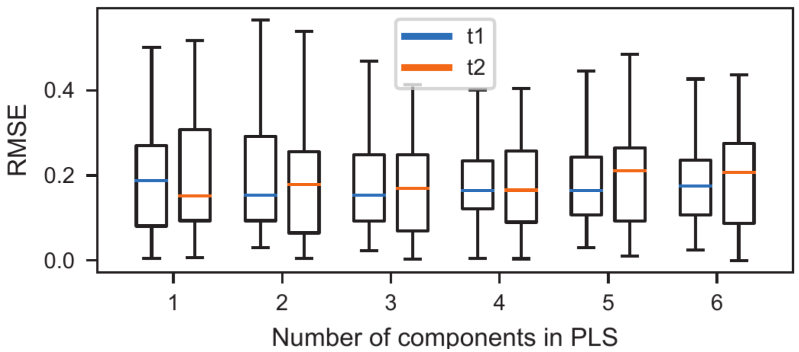
Model assumption:

$$\boldsymbol{X} = \boldsymbol{T}\boldsymbol{P}^{\boldsymbol{T}} + \boldsymbol{E}\,,$$
$$\boldsymbol{Y} = \boldsymbol{U}\boldsymbol{Q}^{\boldsymbol{T}} + \boldsymbol{F}\,.$$

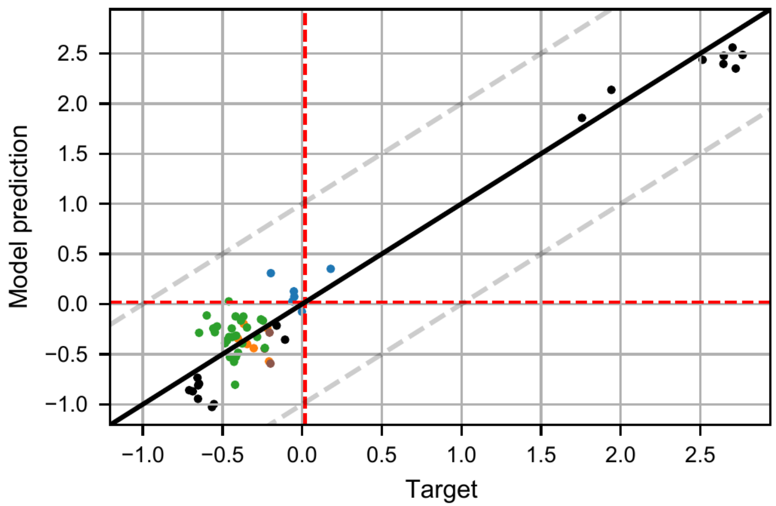
Optimization: find loadings $\boldsymbol{P}$ and $\boldsymbol{Q}$ so that the covariance between latent variables $\boldsymbol{T}$ and $\boldsymbol{U}$ is maximum.

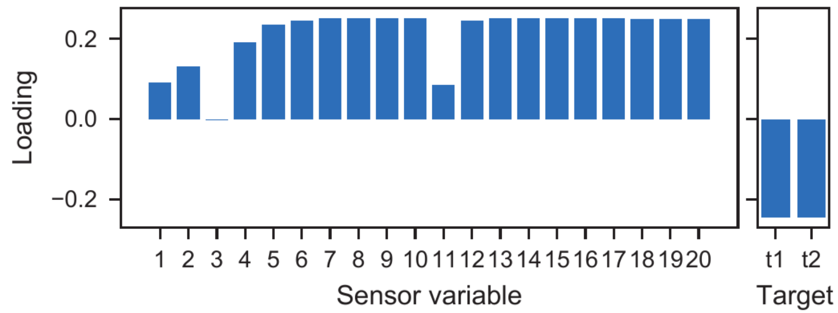
Partial Least Squares results

Average cross validation RMSE

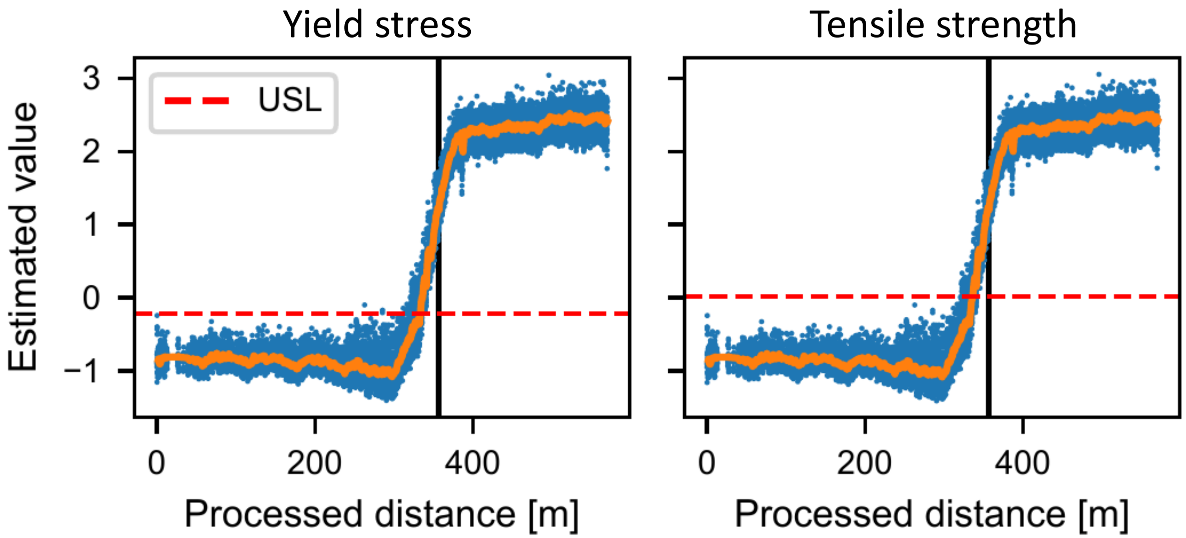


Tensile strength: Model vs. target

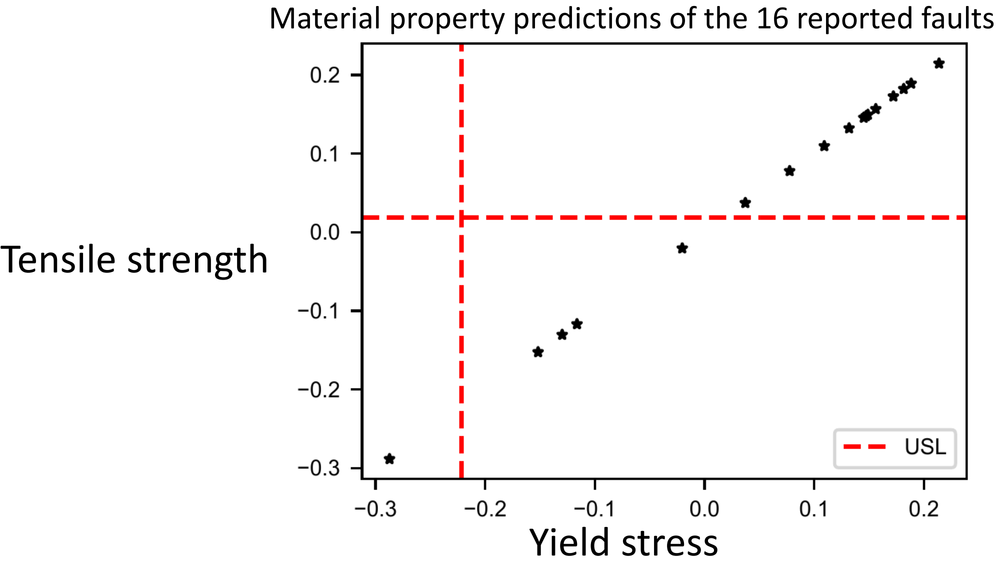


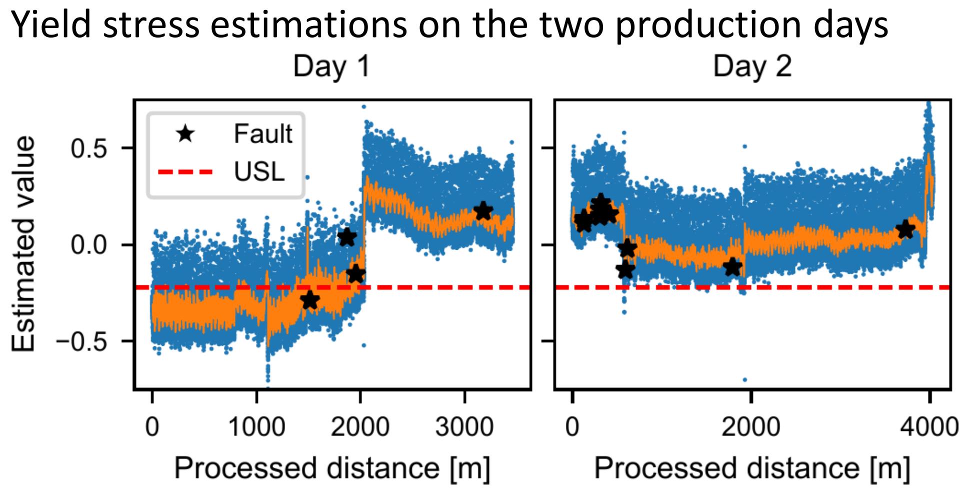


Model predictions on testcoil



Predicting faults from Eddy Current measurements

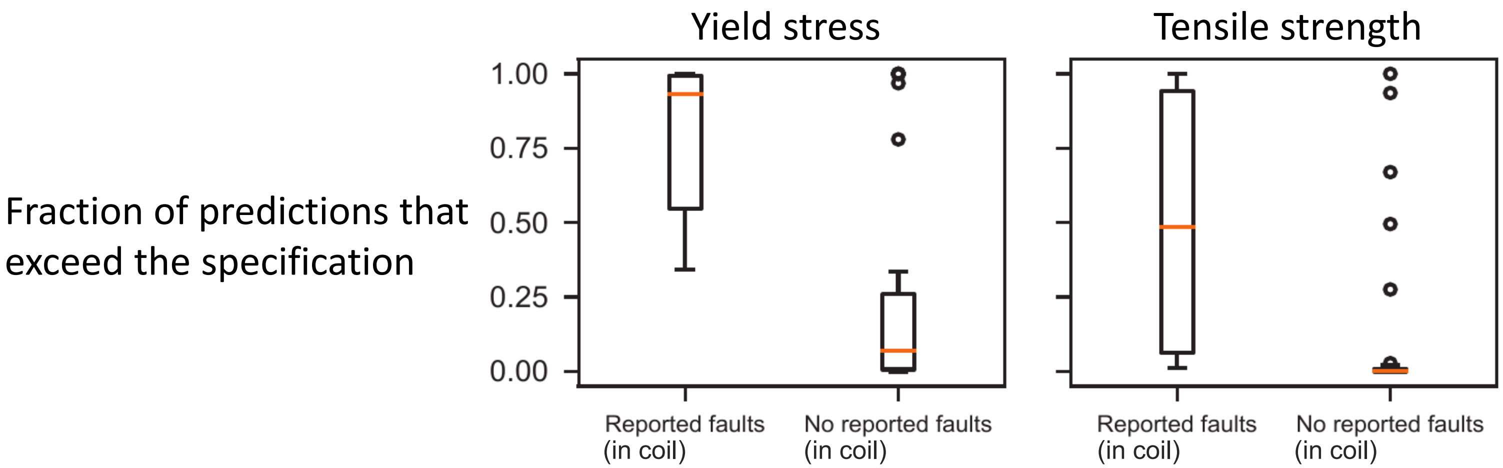




- Of the 16 reported faults, 15 exceed the specification limit of yield stress.
- Supervised training of a fault classifier yielded an average ROC of 0.58.

Are coils with reported faults different?

- Compute of the 40 coils the fraction of predictions exceeding the specifications.
- Compare these fractions between coils with reported faults to coils without reported faults.



A large percentage of predictions exceeding the specifications is a risk factor for product faults.

Conclusion and future work

- Developed real-time material property estimation based on inline sensor measurements.
- Preventive production stops in case of changing material properties.
- A large fraction of estimated out of specification material is a risk factor for faults.

Future work

- Measure more data of deviating material to validate the model further.
- Future aim: Optimize the machine settings for the real-time measured material to obtain the least faults and highest product quality.