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Real-Time Microstructure Characterization using Eddy Current-based Soft Sensors

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Summary:

Non-destructive testing methods enable not only quality assurance but also material characterization. This is often done in offline application or as an intermediate step, in-line applications in close integration with manufacturing processes are more complex. By using a model integrated into a soft sensor on top of eddy current impedance measurement, we show that it is possible to obtain useful material data using comparatively simple sensor hardware in real time.

Keywords: eddy current, material characterization, in-process measurement, soft sensors, process technology

Introduction

In advanced manufacturing processes, often not only the shape but some microstructural properties of the workpiece are critical quality targets. The use of eddy-current measurement even for minor microstructural changes has previously been demonstrated [1]. To allow for in-process control of such properties, they must be measured in real time and with sufficiently low latency in often adverse conditions, such as in close proximity to tools, hot workpieces, cooling media, etc. It is rarely possible to suppress or control for all of these interferences. Hence, a form of sensor data processing is desired that transforms measured signals to useful outputs that are less sensitive to disturbances. The use of model-based soft sensors is one way to achieve this. This article presents a design of a soft sensor based on an eddy current system and shows its implementation in real-time application. Additionally, we briefly discuss practical use of this system in a tangential profile ring rolling process [2,3].

Measurement Hardware

Eddy current measurements were carried out using the analog frontend of an *EddyCation* testing system coupled with custom signal processing software. A two-coil probe with separate transmitter and receiver coils was used in conventional transformatoric setup. Both coils were housed in a 10 mm ferrite core as a field guide, which was then mounted in the mechanical support structure (see figure 1). An otherwise identical second probe without the mounting parts was used for testing and evaluation.

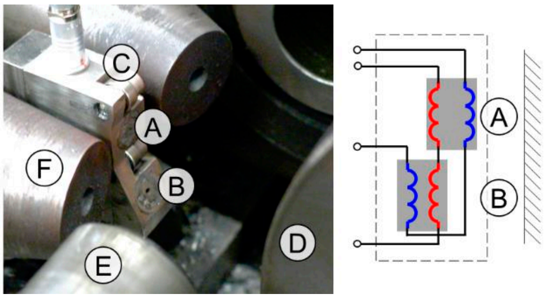

Fig. 1. Sensor head integrated in ring rolling machine (left) and schematic (right). A: Main probe, B: drift subtraction probe, C: support rollers, D: Main roll, E: mandrel, F: stabilization rolls. Shaded area indicates coils sharing one ferrite core.

Signal Processing

The transmission coil was excited using wideband pseudorandom white noise. The received signal was evaluated in the range from 1 kHz to 20 kHz, corresponding to the pass-band of the frontend filters. By transformation to frequency space and complex division, the forward transfer function H is obtained directly.

This transfer function was then modeled using a simplified lumped-element model [4]. The elements of this model are shown in figure 2. An analytical expression for the transfer function of this model can be found and while it contains many terms, the mathematical complexity is manageable. It was found that only three probe (constructive) parameters (inductivities, resistances) and three material-related parameters (ideal transformer coupling, loss resistance) are sufficient to describe the resulting transfer function.

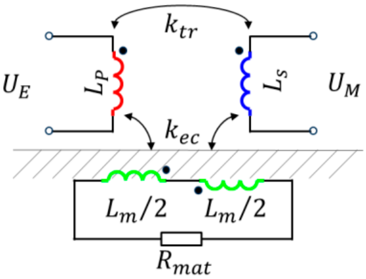

Fig. 2. Proposed equivalent lumped element model for the electro-magnetic interactions. U_E: transmitted voltage, U_M: response voltage, L_P, L_S,: probe inductivities, k_{tr}, k_{ec}: ideal transformer coupling factors, L_m: fictional ring current inductivity, R_{mat}: material loss resistance

Then, a fit is performed to find material parameters that describe the currently measured transfer function by minimizing the weighted sum of the absolute differences between measured and predicted transfer function in frequency domain. To ensure real-time applicability, the optimization must take at most as much time as the next data acquisition, ideally with constant (predictable) time lag. This is implemented by using a continuously running random gradient descent method which can be interrupted at any time. Since the current best prediction is continuously refined, this method converges quickly, but at the same time is capable of following changes in the measured signal with low response time.

Results

The presented sensor system was evaluated both in off-line and in-line application. It could be shown that using this model approach, it is possible to characterize both ferromagnetic and non-ferromagnetic materials as well as materials that exhibit a phase transformation without adjustments to signal conditioning.

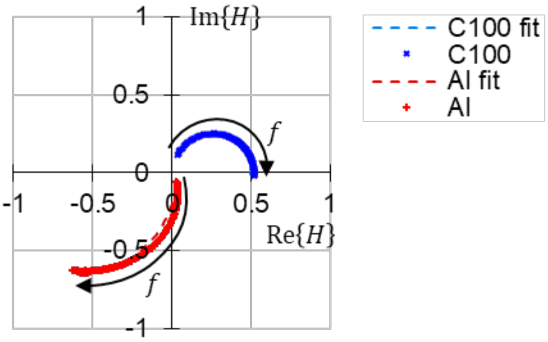

Fig. 3. Comparison of as-measured transfer function and fitted values for aluminum and ferritic C100 steel samples. Both acquired with identical device settings.

In the fully integrated application, ring rolling experiments were carried out. Figure 4 shows one result. It was found the loss resistance parameter correlates well with the total accumulated strain, including the recovery and recrystallization once forming is finished but the workpiece is still hot. Similarly, the transformatoric parameter k_{tr} relates to the permeability and magnetic domain size. This is especially interesting in this application as it also identifies the formation of bainite (which has smaller magnetic domains compared to ferrite) at around 400°C in the rest phase.

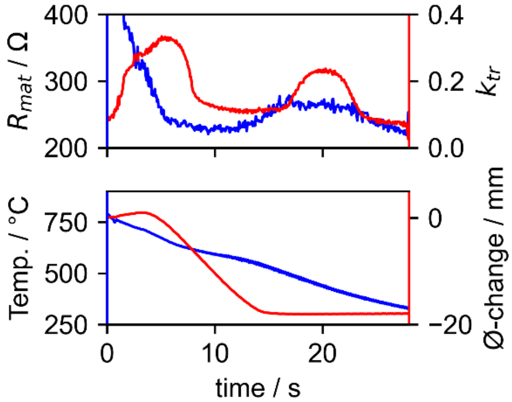

Fig. 4. Model parameters fitted in real-time during forming process (top) and process conditions (bottom).

Additional data processing can be used to identify and correlate the equivalent model's parameters to physical quantities such as concrete values of permeability, grain size, equivalent strain, etc.

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