Final report

Consortional OTKA (K-111662 and K-111987) project
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ñOptimization of a magnetic hysteresis measurement-based nondestructive inspection method and its application in materials scienceò

The original objective of the research project is to improve an existing measurement method (MAT) by making it quantitative, based on electromagnetic field analysis, to analyze and improve the experimental conditions, to perform comparative tests and to make steps towards practical application. The project based on the cooperation of two institutions. The role of MTA EK, as main partner was to improve the experimental set-up based on the previouisly developed magnetic hysteresis measurement type nondestructive inspection method, and to perform measurements aimed practical application of the method. The role of BME HVT, as consortional partners was to develop custom-designed software capable to simulate the magnetic field in the arrangement of interest. The successful realization of the project goal was possible only by intensive cooperation of partners. During the project, according to the research plan, the following subjects were studied.

Simulation of the magnetic flux distribution in the investigated materials

The research work gathered round three main topics: i) implementation of a magnetic hysteresis model in the framework of the finite element method (FEM), ii) development of numerical techniques regarding the direct (forward) problem of the relevant electromagnetic theory, and iii) sensitivity analysis and optimization of the measurement method by numerical simulation.

We have chosen the Preisach hysteresis model for describing the behavior of ferromagnetic materials in the context of numerical field analysis, because this model is known to constitute the very basis of the measurement method MAT. The hysteresis model was implemented in Matlab. The vector extension of the Preisach model -- which is still a challenge in the community of computational electromagnetics -- was made by means of a plurality of scalar models, as following the method of Mayergoyz. Also an identification procedure of the Everett-table of the vector model was worked out based on the available scalar measurements. Successful tests have been made for various magnetization processes (e.g. in oscillating and rotating magnetic fields, respectively) using the vectorial model. The Matlab-model was built then into the FEM software Comsol Multiphysics. It was not only that the storage of the ñmagnetic historyò of the material had to be managed, but also convergence problems occurred during the nonlinear iteration close to saturation. After all, the combined FEM-Preisach algorithm was successfully tested and applied.

Next we focused on the development of the general field computational basis of MAT measurements, which is needed, on the one part, for determining the optimal configuration parameters of the measurement device, and, on the other part, for better evaluating the measured signals. This development includes advances in coil modeling, and material modeling in moving media, respectively.

A fast and memory efficient algorithm based on integral equations (IE) was developed, by which the field coupling of air-cored coils can be evaluated. Besides the piecewise constant basis functions used in the IE formulations, an improved scheme using global basis functions was introduced. The latter offers stronger numerical stability and better control over the convergence of the simulation. Further, an A-V formulation was applied with having current and charge densities on the wire surface as unknowns, which overcomes the limitation of the so-called thin-wire approximation, as it enables the unknowns to vary along the wire surface. As a result, the proximity effect, which that typically emerges when modeling dense windings, can be taken into account.

Our IE algorithm was later extended for heterogeneous media, and also coupled with finite elements through the concept of incident fields. We remark that other research fields, such as wireless power transfer (WPT), can benefit from this algorithm as well as from the computing experiences.

We have also investigated the effect of the reaction term caused by the motion-induced eddy-currents on the measured signal. By this we can tell whether and how the relative movement of the sensor and the material under test affects the measured signal, and, for instance, one can estimate the maximum allowable speed of the MAT sensor.

Although being quite different from a practical point of view, both the optimization of sensor configuration, and the reconstruction of local magnetic material characteristics from the measured signal, respectively, lead to a so-called inverse problem. This usually requires the solution of several direct problems. To avoid the computational burden, especially when there are several parameters to reconstruct or to optimize for (the ñcurse-of-dimensionalityò), one can use so-called surrogate models which approximate (interpolate) the output of the simulation, based on some pre-computed data.

We have implemented a sparse grid surrogate model for the purpose in collaboration with CEA, which applies a hierarchical set of basis functions in each of the n dimensions of the problem, and a sparse tensor product to define the set of n-dimensional basis functions. For smooth functions to be interpolated (which smoothness can usually be assumed for the response of electromagnetic models), the loss of interpolation accuracy of sparse grids compared to full grids is far less that the gain in the reduction of sample number needed. We remark that we also demonstrated the performance of the sparse grid surrogate models on another nondestructive testing method, the magnetic flux leakage technique.

Another important issue of the measurement method is the quantification of uncertainty. The source of the latter can be manufacturing, material imperfection, air gap, contamination, etc. For this purpose, the electromagnetic simulation tool based on IE was coupled with a stochastic method that quantitatively determines the contribution of each uncertain design variable to the output uncertainty in terms of Sobolô indices. A generalized polynomial chaos expansion, which is a state-of-art surrogate modeling method, was used to reduce the computational cost involved by these stochastic simulations.

The effects of geometry parameters of the probe on the measured signal, as well as that of the air gap have also been investigated by direct finite element simulations. Via these simulations we aimed at, i) obtaining better knowledge about the penetration of the magnetic field into the ferromagnetic material, ii) clarifying the role of the air gap between the magnetizing yoke and the sample on the measured magnetic characteristics, and iii) determine the optimal size, shape and material of the magnetizing yoke for a given application.

Application of the simulation for solving practical problems in nondestrive detection of artifial slots in ferromagnetic plates

The observed structure consists of a probe (coils wound on a yoke) above a plain metallic workpiece (sheet). The conducting sheet can be layered, and may be damaged: it can contain a defect (crack, notch) opening onto the backside (other side than the probe). Our aim was to find the optimal yoke geometry, where the relative difference in the measured parameter between the damaged and the undamaged case is the highest. In particular, we investigated how the distance between the yoke's two supports, and the inevitably presenting air gaps between the interfaces alter the results. Here, by result, we mean magnetic flux induced in the cross section of the yoke, placed above the workpiece. These data were collected by systematic numerical simulations (parametric sweep). To compare the results obtained with and without the defect, we took the relative difference of the calculated fluxes.

Single, double and triple layer configurations were considered, where the magnetization takes place by an attached magnetizing yoke from the top of the layers, while the slot is located on the bottom side. The size of the magnetizing yoke was changed and the influence of this modification was studied on the detectable flux. The size of the slot and the thickness of the air gap, which exists between the magnetizing yoke and plateôs surface were also taken into account.

We found that the air gap, which is inevitable in all such types of experiments, has the most significant influence on the magnetic flux, while other parameters (such as the distance between yoke legs) have much weaker effect. Evidently, the examiner tries to keep the air gap as small as possible during the measurement to avoid this unwanted effect, provided he/she can get control on it. At least, it is important to keep the air gap constant in order to perform reliable and reproducible measurements.

The simulation also revealed that the flux change remains well measurable even for a relative large air gap (like 20 or 25 εm), despite the fact that the flux itself decreases rapidly with increasing air gap. For instance, when supposing 20 or 25 εm air gap between the yoke and plate (which is quite normal in the measurement praxis) in the single layer configuration, a relative flux change as high as about 3% is expected. This difference is large enough to get acceptable sensitivity in a MAT measurement. However, if double or triple layer configurations are considered, the available maximum flux change is significantly less than in the single layer case. For instance, in the triple layer configuration supposing a 20 εm air gap between yoke and plate, the calculated flux change is less than 1%, which makes the reliability of measurement questionable in this case.

Unlike the air gap, other parameters, e.g. the size of the yoke, are more-or-less the examinerôs choice. Simulations can help to optimize the measurement configuration to get as high sensitivity in the local wall thinning inspection as possible. For example, the flux change caused by plate thinning (slot) has a definite local maximum as function of the yoke size. This means one can optimize the size of the yoke for detecting the presence of the slot. Obviously, the optimal distance of yoke legs is smaller than slot width in a single layer configuration, while it becomes larger in the double and triple layer configurations. Therefore in the practical application, where the defect size is usually not known in advance, choosing a larger magnetizing yoke might yield better results. Moreover, the change in the magnetic flux due to the slot does not seem to be very sensitive to the choice of the yokeôs size (10% or less), which underlines the reliability of the measurement.

Finally, it was found that the flux change is roughly proportional with the size of the slot. Notably this correlation, which agrees with our expectations, gives rise to methods for estimating the size of the defect from the measured signal.

A sensitivity analysis of the studied nondestructive testing setup was also performed. This analysis also showed that the air gap has the largest impact on the measured signal ï in accordance with our expectation. Other parameters have several order of magnitude lower indices. The uncertainty of the yoke position seems to be the less important parameter and the other three parameters (permeability of the plate, permeability of the core and thickness of plate) have similar impact on the output variance when the yoke is close to the slot, while far from it the effect of the depth of the plate reduces and the permeability of the core is becoming the most important factor.

We made also the experimental verification of simulation results in another system, where a slot is located in a single sheet arrangement. The results of both the simulation and of the experimental measurement showed nearly linear correlations between the evaluated parameters and the cross section of the slots. This was true both for the case when depth of a given slot was fixed and its width was modified, and also when width of a given slot was fixed and its depth was varied. However, the slopes were significantly different. Consequently we can conclude that depth of the slot has a larger influence on the measurable signal than its width, considering the same slot volume.

The results of simulation can be used successfully for determining the optimal parameters of the actual measurement arrangement of the Magnetic Adaptive Testing method. On the other side, result means also the verification of the simulation.

Comparison of MAT and other methods in nondestructive evaluation

In this area an important tasks of the project was to perform comparative measurements on the same sample series by method suggested by us (MAT) and by the Magnetic Flux Leakage (MFL) method, which is known in the literature as a possible method for detecting local wall thinning. To make the comparison even more complex, another method, called Metal memory method (MMM) was also applied. For comparative measurements three plates were prepared and investigated. One of them contained a slot in the middle. Measurements were performed from the top side.

Based on the results of our measurements, we concluded, that MAT seemed to be the most effective way for detection of an artificial slot from the top size of two or three layer systems. This method resulted the highest sensitivity in all cases, and it was able to detect the slot even in the third plate, in contrast to MFL method.

Study of correlation between magnetic parameters, determined by MAT, and structural characteristics of cast iron

Cast irons are one of important structural materials; they are used in many areas of industry. Our research within the project aimed to find correlation of nondestructively determinded magnetic parameters and destructively measured parameters, which characterize the structural degradation of the material. In one measurement series of flake graphite cast iron samples having different chemical compositions and different heat treatments were studied, which process generated different material behaviour. Results of the magnetic tests were compared with the destructive mechanical measurements of Brinell hardness and linear correlation with low scatter of points was found between them. The length of graphite particles and the pearlite volume of samples were also determined by metallographic examination and these parameters were compared with the magnetic parameters. It was shown that linear correlation existed between the magnetic quantities and the graphite length in the investigated cast iron. Numerical expression was determined between magnetic characteristics and relative pearlite content, which does not depend on the detailed experimental conditions any more. This expression can be generally applied for determination of the pearlite values in any cast iron with the two-components metal matrix made up from the pearlite and ferrite only.

Our results reflect another important feature of MAT, too. Namely its multiparametric character. Made *one single measurement* on the investigated sample a *big data pool* is generated. The MAT method looks for those magnetic descriptors of the varied structural properties, which are best adapted to the investigated property and to the investigated material, such a way a complex characterization of material becomes possible. As an example, tensile tests of plastically deformed steel specimens were performed in order to investigate the relation between variation of magnetic characteristics and residual plastic strain. It was shown that an efficient combination of the MAT parameters yields a reliable and unambiguous correlation with residual strain of the specimens even though all relations between the strain and each of the individual MAT-parameters were non-monotonous.

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We have disseminated the results of the project on several international scientific conferences, and published them in numerous high quality journal papers.