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MODELLING THE EFFECTS OF RESIDUAL STRESSES ON ELECTRO-MAGNETIC PROPERTIES OF SUPER ALLOYS

Super Alloys, commonly used in safety-critical aerospace components, regularly impose problems when machined in drilling or milling processes, resulting in surface damages that facilitate cracks. Residual stresses are often induced to prevent crack mitigation, but national aviation agencies set high quality standards on them. Current methods are either destructive or impose safety risks for the employees. Eddy current methods, however, are fast and cheap non-destructive methods to receive information on metallic surfaces. They rely on electro-magnetic properties of the material. The influence of residual stresses on both permeability and conductivity are not yet fully understood. This article presents a simple model that describes the correlation between residual stresses and those aspects. At first, the dependency of permeability and conductivity on various metallurgical properties, such as grain size or orientation, is deduced. In a second step, the influence of residual stresses on these properties is shown. A third step combines both steps into a coherent and holistic model to describe the influence of residual stresses on the electro-magnetic properties of Super Alloys. This model will help establishing Eddy Current Testing in the product monitoring in the aerospace industry.

1. INTRODUCTION

Super alloys for the use in safety-critical aerospace components regularly undergo strong quality inspections, where residual stresses are commonly investigated. The current state of the art knows inspections methods that work by comparison, but no metrological methods that give a quantitative analysis of residual stresses. The present paper develops a model for an analytical grey-box approach to measuring residual stresses. It is based on Eddy Current Testing (ECT) systems that will be developed towards metrological features. ECT is chosen due to its ability to perform very fast (up to 2 GHz) measurements, to be mostly unaffected by dirt and other layers on the material and to be cheap and easy to implement. [1] Its general suitability to be used in automated processes makes it predestined for an integrated, in-situ 100% quality inspection for highly relevant safety critical parts,

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e.g. in the mobility sector where fatigue breaks may lead to personal damage. ECT systems are widely used for crack detection and finding of inserts. Although its feasibility to use it for finding residual stresses has been shown, it still requires long teaching processes. [17] [18] The model that was developed in this paper aims at supporting the applicability of ECT for quantitative residual stress measurements that can work with less or no teaching processes. It therefore analyses the correlation between residual stress induced material changes (e.g. grid distance deviation) and the electro-magnetic properties of the material on a physical and magneto-chemical way.

2. STATE OF THE ART

Residual stresses are internal mechanical stresses that exist without external impact in an isolated system, where those stresses are in a mechanical equilibrium. [2] While in some cases they are wanted, residual stresses mostly are inevitable concomitants to many production processes and might pose a threat to the fatigue life of oscillating structural components. Common methods to measure residual stresses are either only able to measure at the very surface (x-ray diffraction) or destructively (bore drill method). Other methods, such as ultrasonic or synchrotronic x-ray diffraction, are able to measure deeper into the material, but only give qualitative information about the residual stresses. [3] ECT systems can be used for residual stress testing as well, e.g. the 3MA system from the Fraunhofer IfZP, Germany. It uses a combination of different measurement technologies and needs to be calibrated with several positive parts. This calibration process is time consuming and thus expensive, especially for small batch sizes. [4] However, the physical correlations that ECT is based upon are very complex and not yet fully understood. ECT uses both electric as well as magnetic properties of the specimen. Residual stresses exert several influences on its material, grid distance deviation being one of the major effects. [5] Changes in both dimensions result in a shift of a point on the impedance plain, as illustrated in Fig. 1.

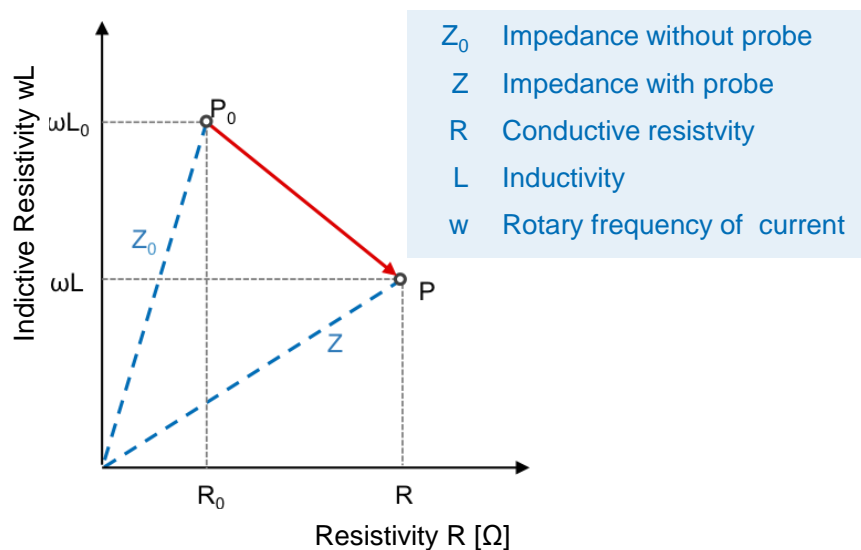


Fig. 1. Shift of the impedance vector due to changes in the electromagnetic properties

While changes in the magnetic properties (e.g. inductivity) result in a shift of the imaginary part of the impedance, a change in conductivity will result in a shift of the real part of it. ($P_0 \rightarrow P$) [6] ECT systems are able to measure those changes in impedance in a quantitative way. However, the connection between the mechanical deviations that are induced by residual stresses and the shift in electromagnetic properties are not yet investigated to full extent. The major characteristics that determine the electromagnetic properties of a material are its conductivity σ_L and its (relative) permeability μ_r . As many of these correlations are investigated on an atomic level only, the model will use both white- and black-box approaches, resulting in a so called grey-box model. [7] Detailed information on the magneto-chemical and quantum physics that this paper builds upon can be found in [8],[9],[10],[11],[12] and [15]. Residual stresses σ_E lead to a deviation of the grid distances that in turn lead to shifts in the magnetisation curves and the electron mobility [6],[8],[9]. Fig. 2 shows the influence of compressive and tensile residual stresses on the magnetisation curve.

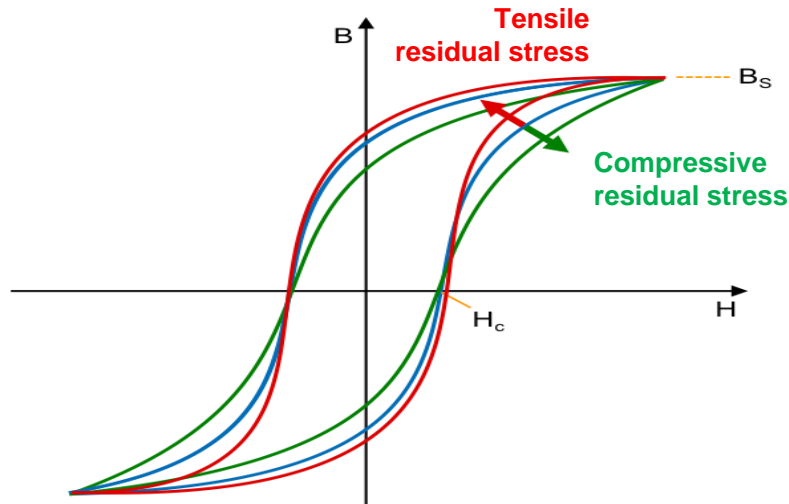


Fig. 2. Altering of the hysteresis curve due to tensile or compressive residual stresses

Equation (1) describes the basic correlation between the conductivity and the electron mobility.

$$\sigma_L = n \times e \times \mu_e \quad (1)$$

where: σ_L - Conductivity, n - Electron density e - Electron charge μ_e - Electron mobility

3. MODEL DEVIATION

The general model's architecture consists of different layers, where each subordinate layer describes its superior model in more detail. Fig. 3 shows the model with its three

layers. Note that the second layer consists of two parallel layers that are shown as being subordinate for the sake of an easy depiction.

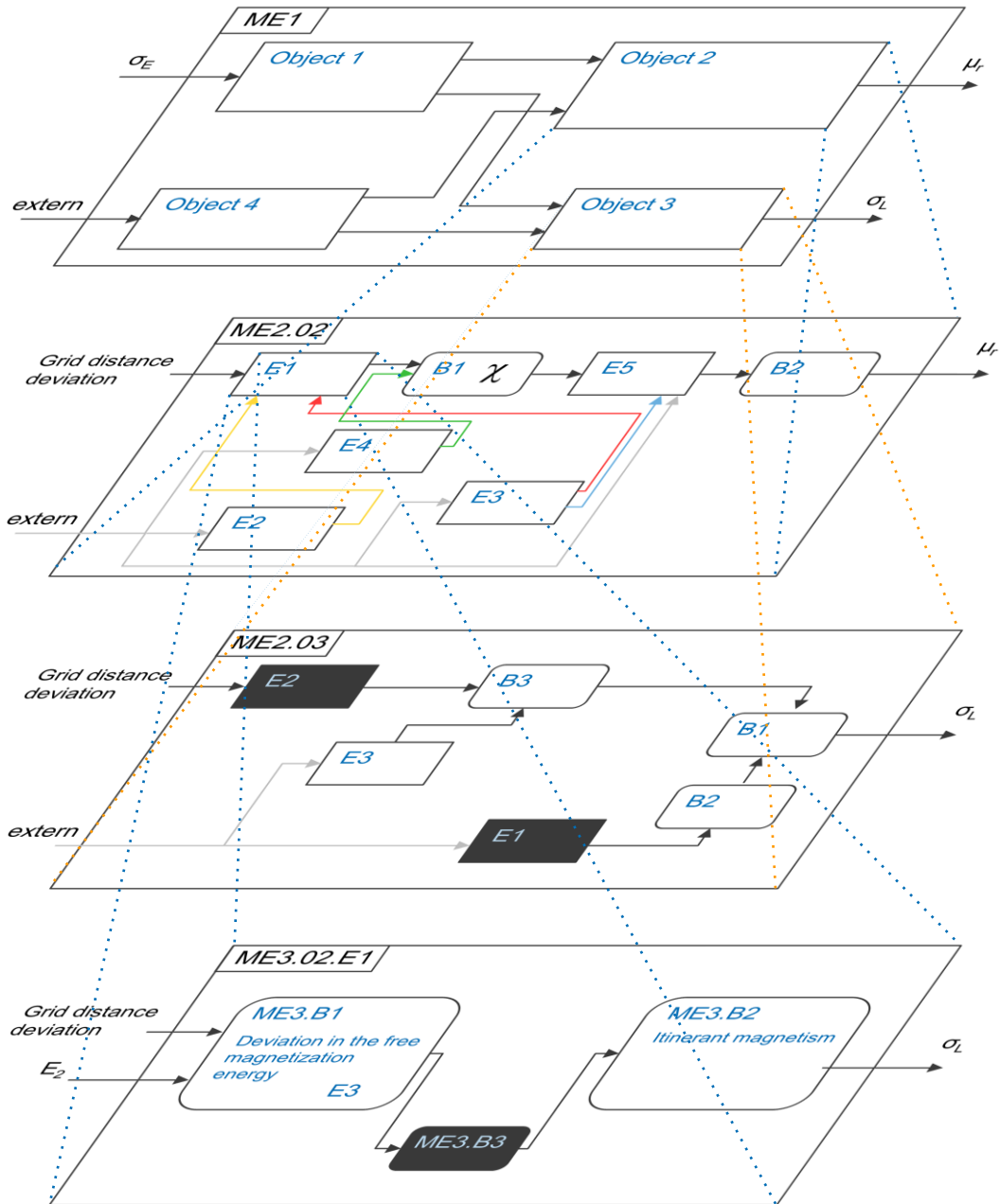


Fig. 3. Model of the effects of residual stresses on electromagnetic properties

Each layer consists of objects (awkward boxes), relations (rounded boxes) and connections (arrows). Objects may either exert direct influence, or by an interposed relation box. In the nomenclature, layers are described as MEx, with x being the order of the layer, while objects are described as Ex and relations as Bx.

The first layer is a relation layer and describes the general connection between the subordinate layers as well as the input and output parameters of the model. The input parameters are residual stresses and external influences, with the latter describing all other influences on the output parameters that are either known or unknown. It can be seen that residual stresses exert influence on both permeability and conductivity; therefore the first layer describes the transformation of residual stresses and external influences into changes of permeability and conductivity. While object 1 describes the resulting effects of residual stresses (e.g. a deviation in grid distances), object 4 summarizes all other effects. At this point, further development needs to identify and analyse other major influence factors that affect the impact of residual stresses on the eddy current signals. Object 2 describes the transformation of the effects of residual stresses – grid distance deviation – into a change of permeability, while object 4 can be seen as the disturbing factor. Object 3 does the same as object 2, only for changes in conductivity. As these latter two objects are complex, they are described in more detail on the second layer.

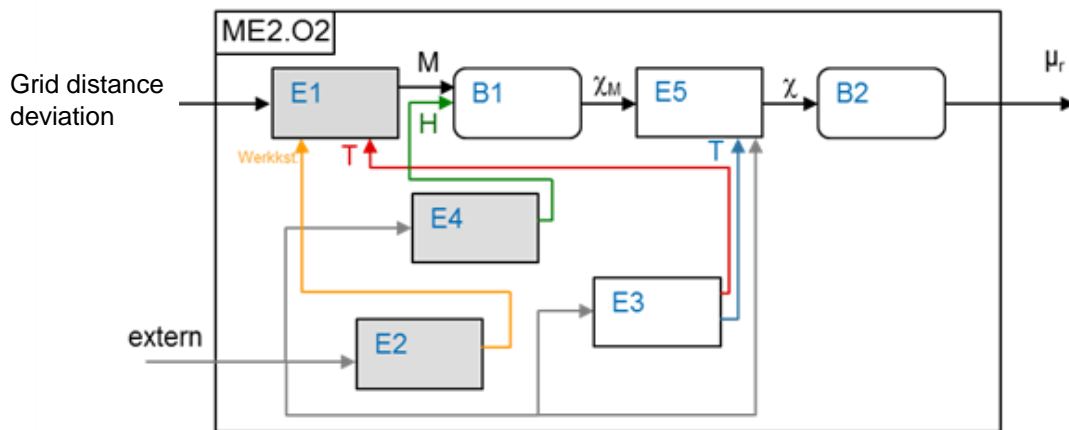


Fig. 4. First descriptive layer: Permeability

Fig. 4 shows the first of the two second layers, which describes the connection between grid distance deviation and the relative permeability. E1 describes the correlation between the grid deviation and the magnetisation. The correlation can be ascribed to the inverse magnetostrictive effect [14],[16]. The magnetisation M, together with the magnetic field strength H (output E4), influences B1 that results in the magnetic susceptibility χ according to (2):

$$\chi = \frac{\delta M}{\delta H} \tag{2}$$

The susceptibility influences B2 as a direct link to the permeability, as seen in (3):

$$\mu_r = 1 + \chi \tag{3}$$

where: μ_r - Relative permeability, χ - Susceptibility

The object E3 exerts an additional influence on E1 as well as on E5. It contains the influence of the materials' temperature on both the magnetisation and the susceptibility. The temperature influences the probability of an electron to be in a discrete state of the system, according to the Fermi-Dirac-Statistic (4):

$$f(E)_i = \left[\exp\left(\frac{E_i - \eta}{k_B \cdot T}\right) + 1 \right]^{-1} \quad (4)$$

where: E- Energy, η - Chemical potential, k_B - Boltzman constant T- Temperature

Therefore, an increase of the temperature increases the probability to be in a discrete state of the system and thus also influences magnetisation. The influence of the temperature on the susceptibility is given by the Curie Law (5):

$$\chi = \frac{C}{T} \quad (5)$$

where: χ - Susceptibility, C- Curie-Constant, T- Temperature

These relations describe the most important relations between residual stresses, permeability and disturbance values. Albeit electromagnetism is very complex, so that future research needs to investigate how other disturbances will exert influence on those properties.

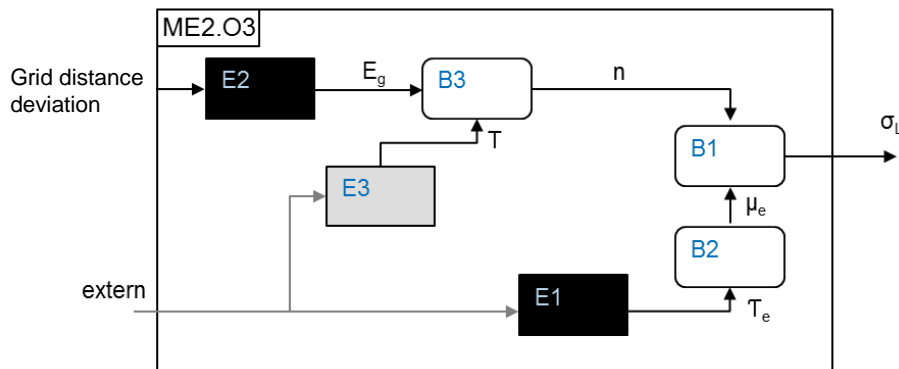


Fig. 5. Second descriptive layer: Conductivity

Fig. 5 shows the second descriptive layer that explains the correlation between grid distance deviations and the electric conductivity σ_L . The conductivity is depending on the two varying quantities n (electron density) and the electron mobility μ_e , as given in (1). This is constituted in B1. The electron mobility μ_e can be derived from the mean impact time τ_e in B2 from (6) as follows:

$$\mu_e = e \times \frac{\tau_e}{m_e} \quad (6)$$

where: μ_e - Electron mobility, e - Electron charge, τ_e - Mean impact time, m_e - Electron mass
The mean impact time τ_e is influenced by the intermittency of the grid structure, as proposed by [13]. However, this correlation cannot yet be determined via formula and hence needs to be furtherly investigated.

B3 gives the electron density, which can be deduced from (3), as described in [8], and can be formulated in (7):

$$n = C \times \exp\left(-\frac{E_g}{2 \times k_B \times T}\right) \quad (7)$$

where: n - Electron density, C - Max. number of electrons in conduction band, E_g - Electron energy between conduction and valence band, k_B - Boltzmann-constant, T - Temperature

The objects E1 and E2 are hence modelled as black boxes, whose content are not yet understood and where further research is suggested. Future work will focus on these aspects in order to improve the model.

4. CONCLUSION

Eddy Current Testing was identified as a promising method to investigate residual stresses in metallic materials in a fast and efficient manner. Albeit many scientific and commercially available systems make use of eddy currents for comparing, qualitative investigations, the proposed model gives evidence that a quantitative, absolute measurement with little to no teaching is viable. As the electromagnetic relations behind the process are very complex, a three-layer model was developed to describe the relevant relations and put them into dependence to each other. In the present model, the focus was put onto the relations between grid distance deviations that were induced by residual stresses and the two most important electromagnetic properties, conductivity and permeability. It was shown that although it is possible to identify relations and intermittent formulae, at this point it is not yet possible to create a fully white-box analytical model that describes the relation between the residual stress level and the changes in the impedance vector. Future work on that model will therefore focus on the black boxes that were outlined in chapter 3.

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REFERENCES

- [1] SADEK H.M., 2006, *NDE technologies for the examination of heat exchangers and boiler tubes*, Insight 48, 181-183.
- [2] SCHOLTES B., 1990, *Eigenspannungen in mechanisch randschichtverformten Werkstoffzuständen*, Dissertation, University of Karlsruhe.

- [3] WITHERS P.J., BADESHIA, H.K., 2001, *Residual stress part 1*, Materials Science and Technology, 17, 355-365.
- [4] SZIELASKO K., 2009, *Entwicklung messtechnischer Module zur mehrparametrischen elektromagnetischen Werkstoffcharakterisierung*, Dissertation, Universität des Saarlandes.
- [5] ROHRBACH C., 1989, *Handbuch für Spannungsanalyse*, VDI-Verlag, Düsseldorf.
- [6] STROPPE H., 2011, *Wirbelstrommaterialprüfung*, Castell-Verlag GmbH, Wuppertal.
- [7] KICILLOF N., 2007, *Achieving both model and code coverage with automated gray-box testing*, ACM, London.
- [8] HORNOGEN E., 2008, *Aufbau und Eigenschaften von Keramik-, Metall- und Verbundwerkstoffen*, Springer Verlag, Berlin.
- [9] SCHÖNEKESS H., 2009, *Bestimmung statischer und dynamischer Zugspannungen in Stahlverseilungen mittels Wirbelstrom-Multisensoren zu einer Sensordatenfusion*, Dissertation, Universität Kassel.
- [10] PEITER A., 1992, *Handbuch Spannungs Messpraxis*, Vieweg + Teubner Verlag, Wiesbaden.
- [11] FEISTE K.L., 2003, *Entwicklung der Harmonischen-Analyse von Wirbelstromsignalen zur Charakterisierung mechanischer Kugelgraphitgusseigenschaften*, Dissertation, Universität Hannover.
- [12] LUEKEN H., 1999, *Magnetochemie Eine Einführung in Theorie und Praxis*, Teubner Verlag, Leipzig.
- [13] VINARICKY E., 2001, *Elektrische Kontakte, Werkstoffe und Anwendungen*, Springer Verlag, Berlin und Heidelberg.
- [14] BOZORTH R., 1951, *Ferromagnetism*, Van Nostrand.
- [15] M'SAOUBI R., OUTEIRO, J.C., CHANDRASEKARAN H., DILLON O.W., JAWAHIR I.S., 2008, *A Review of Surface Integrity in Machining and its Impact on Functional Performance and Life of Machined Products*, Int. J. Sustainable Manufacturing, 1/1/2, 2008.
- [16] CULLITY B.D., 1972, *Introduction to Magnetic Materials*, Hoboken.
- [17] MEKHLOUF S., ZERGOUG M., 2009, *Residual Stress Analysis in the Titanium by Eddy Current Method*, 5th International Workshop NDT in Progress.
- [18] GABI Y., WOLTER B., 2014, *Electromagnetic Examination of Hardened Depth of Steel Using 2D Nonlinear Hysteresis FEM Analysis*, 11th European Conference on NDT, Prague.