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Setting discrete yield-stress sensors for recording early component loading using eddy-current array technology and induction thermography

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Abstract

Problematic requirements, regarding the assessment of the integrity of highly loaded components require that modern methods be developed to record the component's loading history during its life cycle. New developments are moving towards a continuous monitoring of loading history using sensors as well as towards determing the material's or component's state during its service. This requires integrating the load sensors into the component in order to record the component's loading online. Based on the physical material properties of metastable austenitic steels, a novel design is developed for implementing local, component-inherent load sensors; so-called directionally-sensitive yield-stress sensors. The appropriate strengths and yield stresses, corresponding to the component loading to be monitored, can be specifically set by locally heat treating the selected, cold-worked sensor's region using a fibre-laser. Electromagnetic testing methods, such as eddy current technology and imaging induction thermography are developed to rapidly collect the technical data of such microstructures which possess modified physical material properties. The measuring technology is developed and adapted to the testing task via modelling. FEM computation are also performed both for describing the domain's scope and the eddy current distribution, as well as for simulating the magnetising processes as well as the chronological formation of temperature fields in the component's edge region.

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Keywords: Load sensor; yield-stress sensor; eddy-current technology; eddy-current array-technology; induction thermography; Villari effect

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1. Introduction

Precise knowledge about the state of mechanically or thermally loaded components can significantly contribute to increasing a plant's operating availability. Overloads, excessive wear or material fatigue can be detected prior to the occurrence of failure by means of recording the respective state of components, plants or machines. For this reason, it is necessary to locally record and store loadings in the component [1,2].

The vision of the Collaborative Research Centre CRC 653 “Gentelligent components' life cycle” consists of physically integrating the reproducible information and loading information from its life cycle into a component. Using the materials, technologies and processes developed in the CRC, the components can record, process and store loading information, such as operating forces, accelerations and temperatures, during their manufacturing and service phases, and communicate this information. This totality of information is inherently linked with the gentelligent (GI) component and is retrievable at any time. Following genetics, the GI component is, similar to a gene, furnished with the function of carrying its own component and manufacturing information for its entire life cycle.

An essential aim of the current research in fatigue is to develop methods and models to be able to predict the fatigue life of components. This is valid for both the component's design in terms of its structural durability, and also for monitoring components in service with the aim of estimating their residual operating lives [3,4,5]. The main concern is to determine the relationships between the type of loading, the loading direction and the resulting microstructural changes which can be measured using optical and electromagnetic methods [6]. Electromagnetic testing methods exploit the existing relationship between the mechanical properties and electromagnetic behaviour of metallic materials. Thus, both a change in the microstructure and also in the stress state leads to a change in the mechanical as well as the physical properties: such as electrical conductivity and magnetic permeability [7].

Quantitatively determining the magnetic parameters requires a laborious specimen preparation and a very time consuming measurement of the hysteresis loop. The magnetic-inductive testing method for the harmonic analysis of eddy-current signals has proven itself as a rapid measuring method for determining magnetic parameters since the higher order harmonics: in particular the 3rd harmonic, better reflect the microstructural and magnetic properties than the fundamental wave of the testing frequency. These harmonics describe the form of the magnetic hysteresis curve, whose non-linearity is caused by the material's magnetic properties [8].

The measuring principle of thermography using inductive excitation is, similar to the eddy-current testing, based on inducing high frequency eddy-currents and magnetic reversal losses into the edge region of components possessing electrically conductive and ferromagnetic material properties. Owing to the changed physical material properties, a change in the eddy-current and magnetic reversal processes occurs in material inhomogeneities subject to inductive excitation and therefore changes in the temperature ratios occur in these local regions [9,10].

In the current contribution, load sensitive specimens are combined into sensor fields and a method is developed and experimentally implemented to detect the loading magnitude and direction. Via global work-hardening and specific local heat treatment of the component's edge region, metastable austenite is developed into yield stress sensors possessing directionally dependent sensitivity. The examination will be performed in student's formula racing car of Leibniz Universität Hannover under real conditions. On exceeding the yield stress value, the loading stress stored in the components microstructure is recorded and is readable during the component's entire life cycle. Electromagnetic testing methods, such as eddy-current array technology and imaging induction thermography, are employed to rapidly collect the technical data of such microstructures which possess modified physical material properties.

2. Employing metastable CrNi steels as sensor materials

Metastable austenitic materials are frequently cited in the literature as suitable materials for sensors whose face-centred cubic lattice structure transforms under plastic deformation into a martensitic lattice by crystal lattice shearing [11, 12]. The austenitic steels, which are widely used in technical applications, have chrome and nickel contents ranging from 16 to 21% and from 9 to 16%, respectively. Owing to its ferromagnetic properties, the α’-martensite can be determined using non-destructive magneto-inductive measuring procedures [13, 14]. The suitability of the phase transformation in the CrNi steels to store static-cyclic overloading was investigated in preliminary tests. The specimens, made from materials: AISI 301, AISI 304 and AISI 316, were loaded in a tensile testing machine and stepwise plastically strained up to rupture within their reduced regions, see fig. 1a.

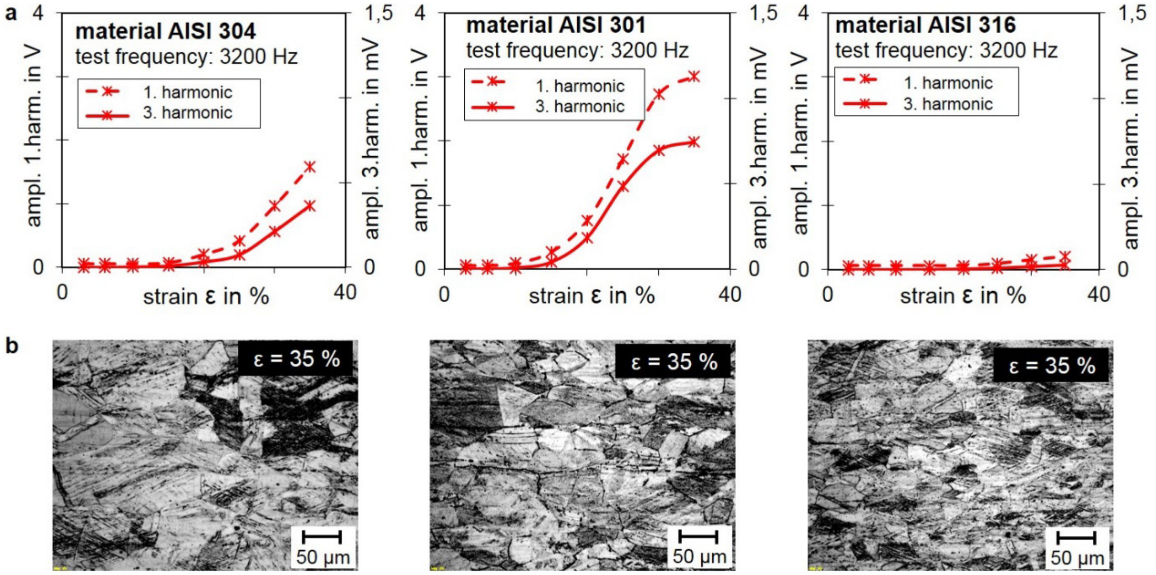

Fig. 1. (a) The 1^{rd} and 3^{th} harmonic amplitude values as a function of the plastic strain for different materials (b) microstructural changes.

Measured values integrated over the martensite's content, formed in the specimen's section, can be obtained using a probe which envelops the specimen or the component. Here, the high alloy material AISI 316, stabilised using titanium, exhibits only a slight tendency to form martensite. In contrast to this, the material AISI 301, possessing low contents of Ni, Cr and Mn, exhibit a highly metastable material condition with a pronounced tendency to form martensite, see fig. 1b.

3. Introduction of component-inherent load sensors

Based on the said physical material properties of metastable austenitic steels, a novel design was developed for implementing local, component-inherent load sensors; the so-called directionally-sensitive yield-stress sensors [12]. Combined with the structural material, the strength of the sensor material has to be matched via cold-working and martensite formation. Locally heat treating by introducing the energy in steps leads to stepwise tempering of the martensite in the austenitic matrix's microstructure and to the reduction of the strength and yield stress values.

It should be noted that the yield stress values R_{p0} of the cold-worked matrix microstructure has a maximum of 1100 MPa. Lower yield stress values R_{p1} and R_{p3} are set by means of increasing the tempering condition of the martensite, see fig. 2. On exceeding a specified yield stress due to the loading stress, the sensor again forms martensite due to the plastic deformation. In this way, the criterion for assessing the loading stress is given by the change in the locally set yield stress; due to the plastic deformation and the newly formed martensite, with respect to the set reference values. Thus, the loading record is obtained using the so-called yield-stress sensors which can be employed within a broad temperature range up to about 300 °C and the level of martensite formation is not known to depend on material, temperature or load [15, 16].

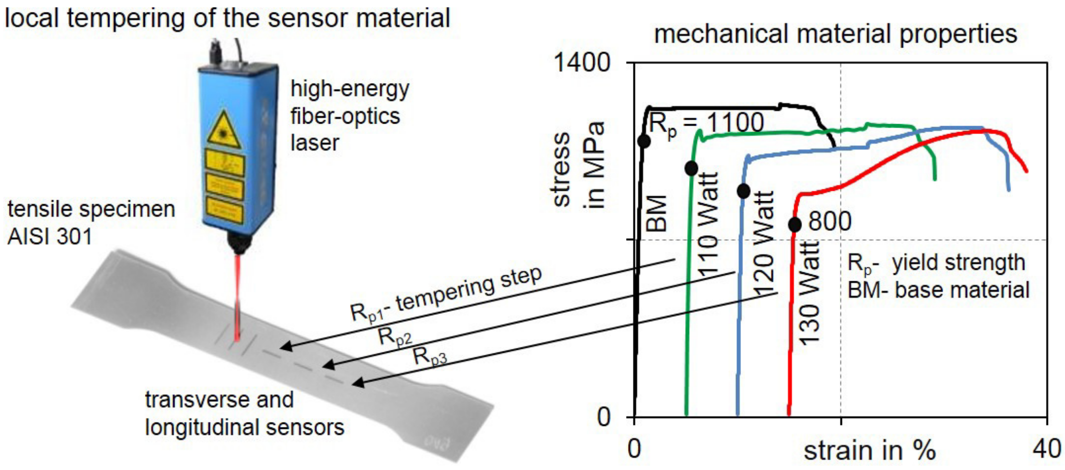

Fig. 2. Adaptation of the sensor strength to the component's loading stresses.

4. Design of a EC sensor array for pictorially recording local material properties

High resolution eddy-current sensor arrays (ECA) were designed to determine the phase changes from metastable austenite to martensite in austenitic materials subject to plastic deformation. Instead of scanning the surface using a single sensor, several sensors were combined into a sensor array, see fig. 3.

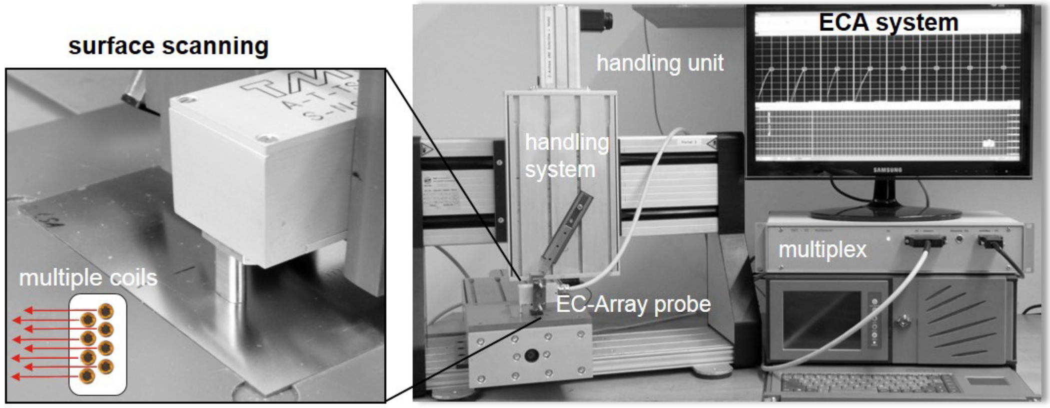

Fig. 3. EC sensor array for pictorially recording local material properties.

The sensor field's focusing and the operating range of the coil is locally adjusted by means of austenitic and ferritic shielding. The parallel operation of several sensors in a sensor field is conducted via a handling system and a multiplexer. The measured values of the detected, location dependent eddy-current signals are prepared and analysed as scan images. By means of specifically optimising the test parameters and evaluating selected phases of the eddy-current signals, it is feasible to separate the measured and spurious effects. For suitable test parameters, parts of the useful signal, possessing information about the material's condition, occur in the Y-components of the eddy-current signal.

To adjust and test the directionally sensitive yield-stress sensors, specimens of the metastable austenitic material AISI 301 were cold-worked and tempered along 2 lineal patterns in the longitudinal and transverse directions using 3 steps of different laser powers, see fig. 4.

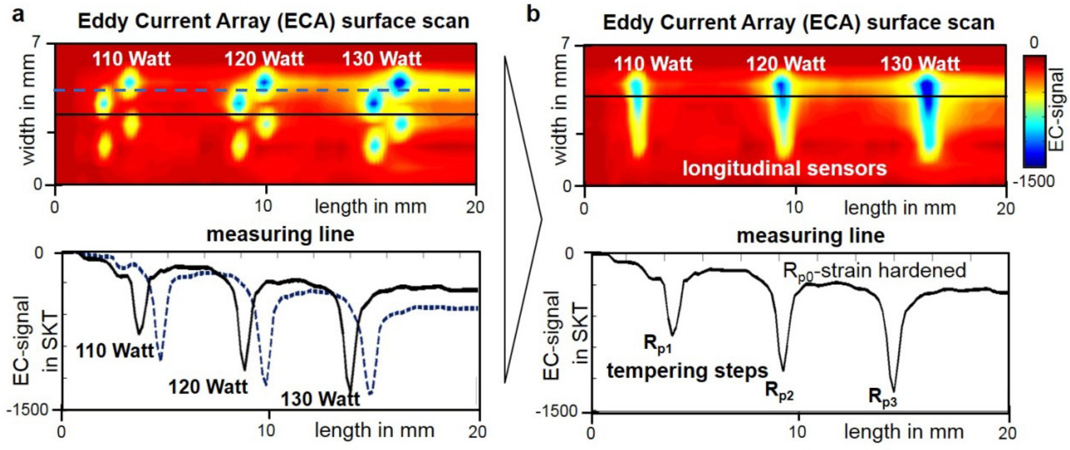

Fig. 4. (a) Eddy-current surface scan (b) graphic off-set of the EC measured value.

Owing to the intense focusing of the laser, a material transformation is readily obtained in a narrow and thin edge zone for low laser powers and energy-input per unit run length. With increasing laser power, the transformation zone varies in width and depth from 0.4 to 0.6 mm and from 0.2 to 0.4 mm, respectively.

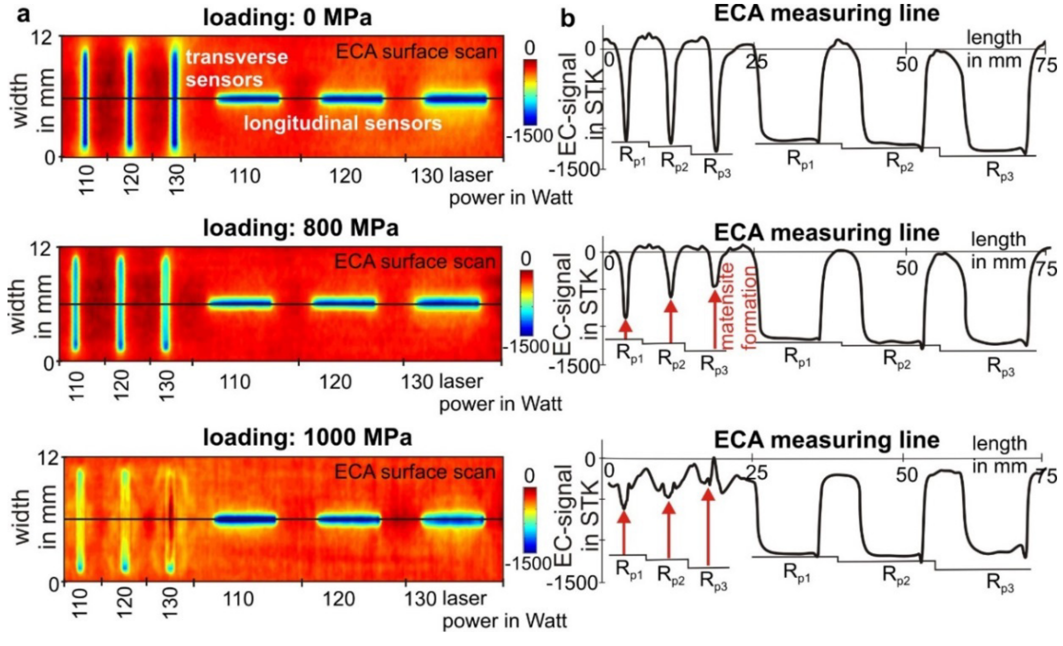

Fig. 5. Sensitivity of the load sensors in the longitudinal and transverse layout regarding plastic deformation and martensite formation: (a) surface scan; (b) EC signal amplitude.

A program written in Matlab was employed to evaluate the data obtained with the aid of the eddy-current technology. Using this program, the sensor off-set can be corrected and the measured values graphically represented. On the left of figure 5, an eddy-current scan is depicted which was measured using an array off-set of 1 mm. The EC signal amplitude permits the position of the individual sensors to be detected. If the measuring points are displaced about the sensor distance, then a clear image of the tag results which the resolution of the individual sensors reflects, see fig. 4b.

For a linear layout, the load sensors exhibit different sensitivities regarding the plastic deformation and martensite formation for pronounced normal stresses in the longitudinal and transverse directions, see Fig. 5. Subject to loading in the longitudinal direction, the linear sensors in parallel alignment lie in the force path and the load is essentially transmitted by the adjacent higher strength sensor material. On loading the linear sensors in the transverse direction, the force flows across the width of the loading sensor and, for loading stresses above the yield stress, plastic deformation occurs and martensite is newly formed in the linear region.

4.1. Influence of plastic deformation on the microstructure and hardness profile in the region of heat treatment

In contrast to the austenite, martensite is a hard and brittle material phase and has been investigated by means of hardness testing along the transverse specimens in the longitudinal and transverse directions. The distance between the measuring points was 0.1 mm, see Fig. 6.

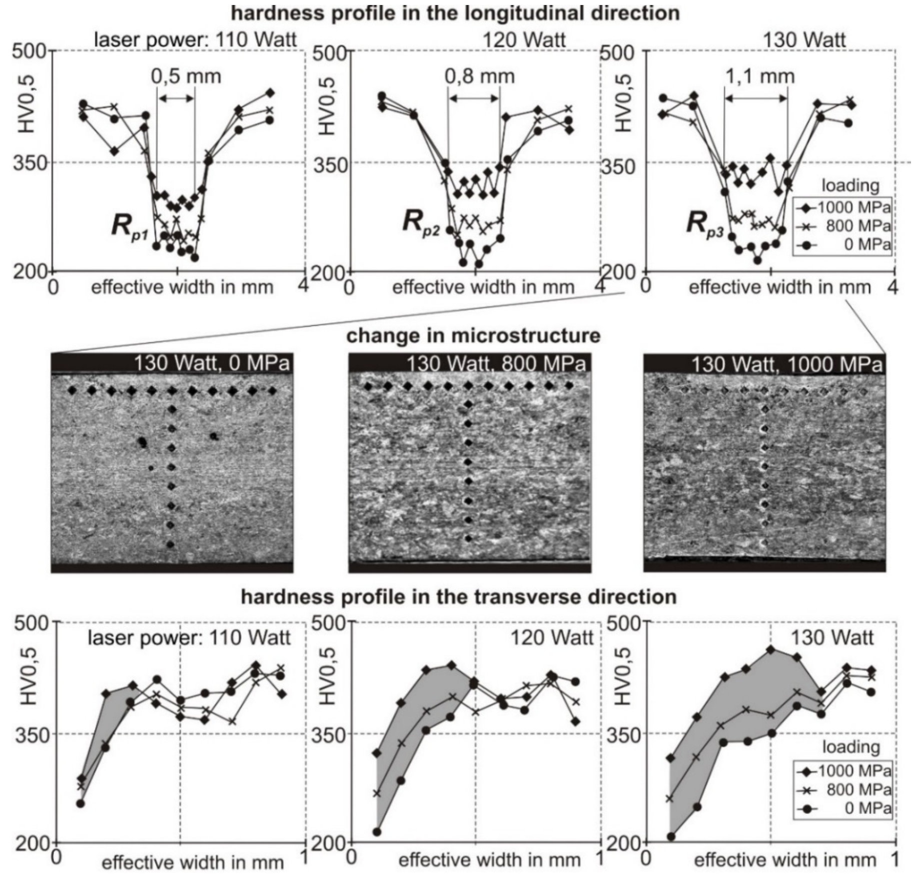

Fig. 6. (a) Influence of plastic deformation on the change in microstructure (b) hardness profile (c) in the region of heat treatment.

It can be seen that the hardness values change depending on the introduced stresses σ_{tens}, which correspond to the yield stresses R_{p1}, R_{p2} and R_{p3}. Since the yield stress was exceeded, a fraction of the austenite was transformed into martensite during the subsequent plastic deformation. Subject to the plastic deformation, a pronounced change in the hardness values is obtained in the highly tempered material regions using a laser power of 130 W because here, a large effective depth and width occurs. The difference in hardness between the substrate material or rather the undeformed region is approximately 200HV0.5.

5. Development of induction-thermography for characterising local material properties

Analogous to the eddy-current technology, a pictorial recording method of the temperature fields on the component's surface was developed by employing inductively excited thermography using pulse excitation to locally assess the material properties in the component's edge zone adjacent the yield-stress sensors, see Fig. 7.

By implementing a controlled pulse to operate the HF generator, it is possible to locally introduce high energies and develop temperatures over a short time, to increase the dynamic and sharpness of the temperature field as well as to lower the global heating of the component. Moreover, apart from the spatial analysis of the temperature field, the procedure also permits time and frequency range analyses of the temperature-time profile to be employed, see Fig. 9a. In practice, an excitation and delay period of 50 ms has proved to be expedient. This corresponds to an impulse excitation frequency of 10 Hz and a duty factor of 50%. The profile of the temperature curve at an image point depends on the eddy-current distribution at the observed location in the component. The eddy-current distribution is mainly determined by the material properties, the excited region's distance from the inductor as well as the geometry of the component.

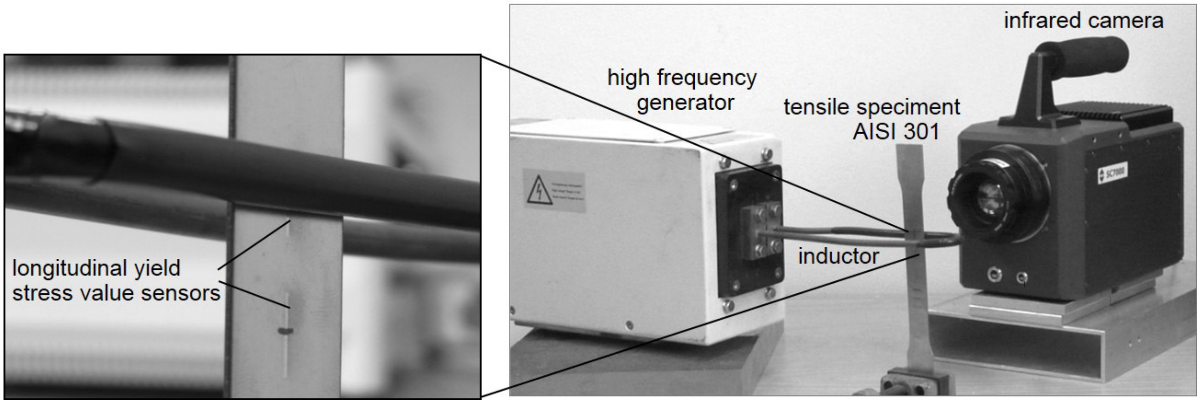

Fig. 7. Material characterisation from yield-stress sensors using induction-thermography.

The investigations depicted in Fig. 8a, present the resulting temperature distribution as a function of the tempered martensite. A significant change in temperature is observed in the region of 110 W where the influence of the heat treatment on the microstructure's condition or the electrical conductivity and the material's magnetic properties is a maximum. In order to raise the emittivity of the polished metallic specimens, a further series of specimens were coated using a graphite spray, see Fig. 8b below.

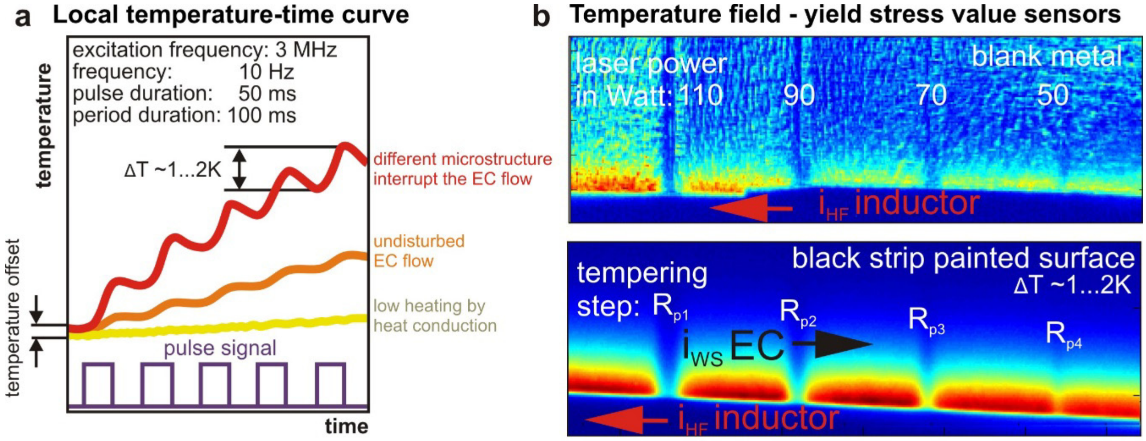

Fig. 8. (a) Temperature profiles as a function of the excitation and pulse duration (b) the resulting temperature distribution as a function of the tempered martensite.

5.1. Simulation-aided tuning of the measuring technology

To qualify a suitable, locally high-resolving electromagnetic measuring technology with respect to the testing task: to non-destructively characterise local material properties in the component's edge region, suitable modelling and simulation computations are employed for the domain's scope and the eddy current distribution in the component and the sensor range. In order to obtain the most realistic representation of the developing field, eddy-current and temperature distributions in the edge region, a high resolution is required by means a fine mesh possessing a correspondingly high number of nodal points. During the simulation, consideration is given to the geometry and material size effects as well as to the excitation and testing frequencies.

Three tagging regions were specified in the edge zone of a ferromagnetic steel component possessing different fractions of austenite and a relative permeability of μR = 150. Similar to eddy-current testing, an eddy-current is generated from a high test frequency of several 100 kHz principally in the components edge zone. As a consequence of the austenite's lower electrical conductivity and permeability, the eddy-current penetration is larger in the region of the tagging than in the untreated edge zone regions.

Using FEM computations, it was verified that, at high-frequency inductive component excitation, the eddy-current density and the elevation in temperature in the tagging is more weakly developed than in the undisturbed component edge zones.

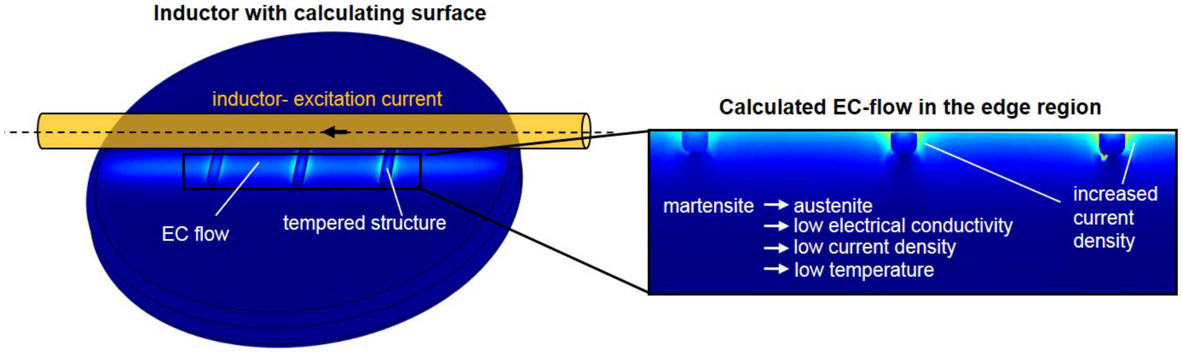

Fig. 9. Simulation computations to describe the formation of fields, EC-distribution and the magnetising processes in the component's edge region.

6. Technical application in student's formula racing car

A concluding test and qualification of the loading-sensor's elements are performed on a demonstration component model subject to actual loading conditions in one of the Hanover University student's formula racing cars; Fig. 10. The trust rod, made of metastable austenite, was chosen as the sensor component. By means of local tempering, the martensite was transformed into metastable austenite having lower yield stress values. On exceeding these specified yield stress values by the loading stresses, martensite was newly formed. On exceeding the yield stress values due to the extreme component loading, local flow processes are stored in the directionally sensitive yield-stress sensors. The actual cyclic loading in the thrust rod can also be detected as measured data by means of the higher order harmonics using a wide-range eddy-current coil via changes in the magnetic properties corresponding to the Villari-Effect.

Following its successful integration into the racing car, the loading data can, in this way, be recorded and stored during the race. Thus a GI-component can, when required, actively request an inspection, or a system of planned maintenance can access the component's data and thereby specify an appropriate maintenance time-limit and the required measures to be taken.

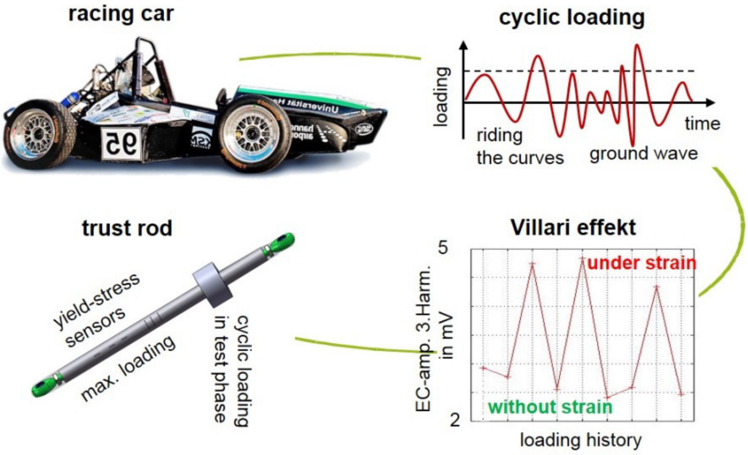

Fig. 10. Technical application in industrial demonstration-models.

7. Conclusions

Non-destructively characterising local material inhomogeneities using high resolution eddy-current technology and inductive excitation thermography in the region of load sensors is a new and technically interesting field of application of component edge region analysis. Here, the objective focuses on both a rapid data-collection measuring technology using a high resolution as well as the assessment and pictorial representation of material properties.

Investigations of the loading have shown that, on exceeding the local yield stress of the directionally sensitive lineal sensors, martensite is formed due to the loading stresses producing plastic deformation. In this way, local yield stress value sensors, as directionally sensitive threshold value sensors, present new opportunities for collecting loading histories with regard to the occurring loading stresses and loading scenario via the reformation of martensite in the corresponding yield stress value sensor region, Fig. 5.

The local reformation of martensite is, according to the locally specified yield stress value, a measure for the component's enduring loading and can be verified by means of a suitable, high resolving eddy-current sensor technology and inductively excited thermography, Fig. 4 – Fig. 8.

The measured results of the eddy-current testing regarding the phase transformation in the locally tempered regions were confirmed by the results of the hardness testing combined with the microstructural analysis. In contrast to the austenite, martensite is a hard and brittle material phase and has been investigated by means of hardness testing along the transverse specimens in the longitudinal and transverse directions, Fig. 6.

To adapt the thermography method, which employs pulse inductive component excitation, to the testing task, fundamental investigations were carried out via modelling, FEM computational simulations and parameter analyses. Owing to the changed physical material properties, a change in the eddy-current and magnetic reversal processes occurs in material inhomogeneities subject to inductive excitation and therefore changes in the temperature ratios occur in these local regions. This temperature change in the sensor's region is recorded using a thermal camera and, via an image analysis, can be used to rapidly recognise component identification and to assess yield-stress sensors.

The testing methods presented here; eddy-current array-technology and induction thermography using pulse excitation were employed and tested within the scope of the CRC 653 to carry out investigations on demonstration components.

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