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Inherent load measurement and component identification by multi-dimensional coded data in the component's subsurface region

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Abstract

In industrial production, the absence of component markings and unrecognized component failure can result in a lack of protection against product piracy and malfunctions of machinery and installations. A technique for storing data inherently in the subsurface region of the component was developed. Inherently stored data is highly resistant to external stresses and inseparably linked to the component. To evaluate the integrity of highly stressed components, material inherent sensors are induced in the subsurface region of the component to store the loading history. These techniques offer the potential for securely identifying and evaluating the status of components, and thus reducing failure costs.

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Keywords: Subsurface Modification; Heat Treatment; Piracy Protection; Load Sensor; Load History; Eddy-Current-Technology

1. Introduction

Advancing globalization generates growing problems in the field of product piracy. Product piracy is estimated to cost the German mechanical engineering and plant manufacturing sector 7.9 billion euros per annum [1]. Claims of liability and warranty, complex production processes and an increasing range of products require an unambiguous method of identifying components. The identification of components has to be non-falsifiable, inseparable from the component and easy to retrieve. Targeting a broad field of applications for marking and storing data in steel and light-

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metal material components, an innovative laser technology was developed to locally heat treat components. Using this technology, point-wise defined microstructural conditions can be specifically set in the component's subsurface region via tempering, hardening and dispersing. This multi-dimensional marking combined with coding (e.g. data-matrix-code) allows data to be stored within small spatial regions. In addition to established marking procedures: such as barcodes, a new multi-dimensional code was developed. This novel method for identifying parts provides components with a solid marking and a high degree of piracy protection.

While counterfeited components may lead to lower sales revenue and to the deterioration of the brand image, excessive loads can raise the probability of failure of safety critical components. The early detection of critical loads is needed in order to change overloaded components prior to failure. A suitable technique for storing critical component loads can help to prevent unexpected and expensive machine failures. Thus, a potential exists for simplifying maintenance regimes, and thus large cost savings. A new material integrated sensing concept was developed in order to detect and store locally applied stresses. This concept is based on global strain hardening of metastable austenitic materials and locally heat treating the formed martensite. With regard to the expected type and direction of the critical stress, the sensors can be specifically placed in selected regions of the component according to the given application. The sensors collect the load data inherent in the components subsurface region. The load data is available at any time and can, for instance, be read during a planned maintenance.

To be able to read the coded data and the loading history from the component's subsurface region, adapted non-destructive techniques were developed. By using high resolution eddy current array technology along with harmonic analysis of eddy current signals or induction thermography, it is possible to read out the local multistage changes of the microstructure. With these different techniques it is possible to either optimize the read out speed or signal quality depending on the specific application. In contrast to conventional marking techniques, it is also still possible to read out the component-inherent stored data even if the surface is painted or locally damaged.

2. Setting the reading markings and sensors in the component's subsurface region

The markings and the yield stress sensors were set in the subsurface region by an ytterbium high-power fiber laser using a focusing optical system. The laser used is characterized by a good beam quality (beam propagation ratio $M^2 < 1.1$) and a small focal spot size (≥ 15 µm), and thus, allows for a heat treatment in a well-defined volume. The power density of the laser radiation as well as the energy input into the component are given by the beam's power parameters, position of the component to focus and the emission duration. By modifying these parameters, it is possible to directly change the type of heat treatment and the volume of the modified microstructure. Furthermore, the surface finish of the component and the amount of reflected laser radiation are crucial for the introduced energy and the resulting microstructural changes.

Depending on the material and the selected laser parameters, the laser-induced local heat treatment causes local tempering or hardening. The microstructural changes produced in the area of the markings are accompanied by a change in the local material properties, such as the electrical conductivity, the magnetic material properties and the thermal conductivity. These different material properties can be detected by sensitive, non-destructive testing techniques: such as high-frequency eddy current array technology, harmonic analysis of eddy current signals and induction thermography. [2]

3. Piracy protection

Metallic components are currently marked by abrasive, surface-disfiguring procedures such as engraving techniques or by attaching labels with barcodes or RFID transponders. External mechanical and thermal stresses during the production and the usage phase can lead to the separation of those markings from the component or make them illegible. [2]

New developments integrate RFID chips right into cast or adaptive manufactured components itself. Thus, the RFID chips are protected against external influences in industrial environments and can be read without contact and non-optically. [3, 4]

With the newly developed method for component identification, the coded data is stored inherently in the subsurface region of the component by means of laser-induced stepwise defined, local changes in the microstructure of the basic material, without without introducing impurities into the component. Figure 1 outlines the reading and writing processes: First, data are transferred into a data matrix code and then gradually introduced into the component's subsurface region. To read the data, the component is scanned using high-resolution eddy current technology. The eddy current surface scan of the component is then decoded by software. The data, stored 3-dimensionaly throughout the depth and represented by the colors in figure 1, offer additional levels compared to the conventional 2-dimensional marking variant. In this way, the data density can be significantly increased.

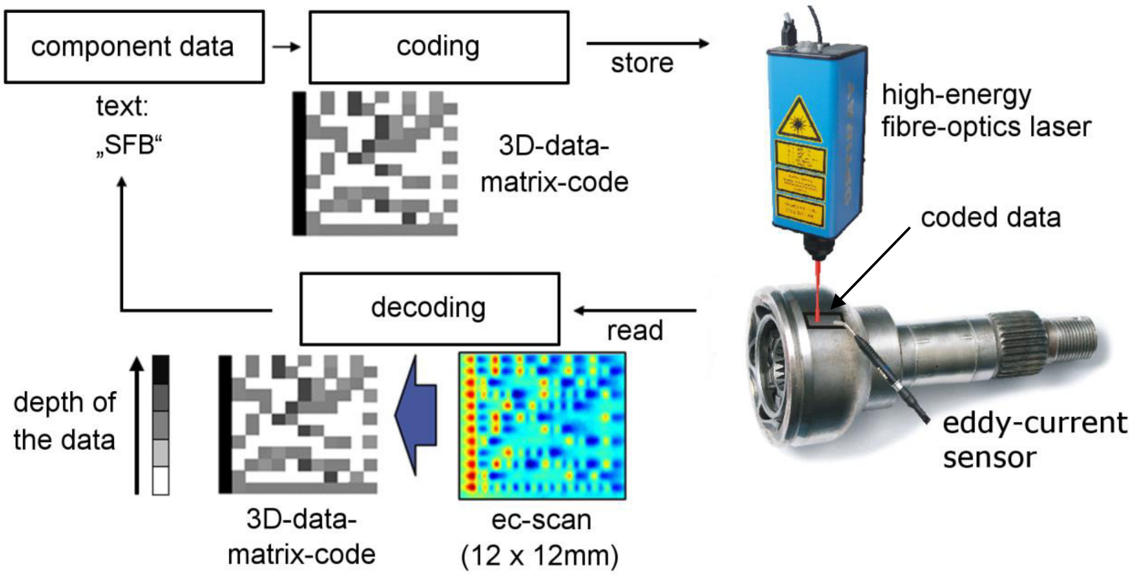

Fig. 1. Microstructure-based coded information storage, partly recompiled from [5].

Since these reading techniques do not rely on optical effects, markings can even be read out when the surfaces have been mechanically damaged, painted or coated. Only temperatures above several hundred degrees Celsius will change the microstructure of the steel components, therefore the markings are very robust with respect to temperature changes during the component's lifecycle.

Figure 2a presents a marking in the shape of the institute's logo. The logo was introduced into a component, which was made of C45 steel (material number 1.0503) using a laser beam power of 100 watts. The size of the logo is 12,5 x 9 mm. Through locally heating the material above its austenitizing temperature and subsequent cooling in air, the heated areas were hardened. A constant protective gas flow was supplied to avoid oxidation and surface decarburization during the hardening process. After its insertion, it was difficult to visually perceive the marking, but it was clearly readable with the high frequency eddy current technology

Next, as illustrated in figure 2b, the surface was completely covered with paint. Whereas the marking was no longer detectable with conventional optical reading methodologies, the logo was clearly revealed by the eddy current technique. The distance between the marking in the substrate and the eddy current sensor is, however, increased by the thickness of the painting. This increase in distance results in an impairment of the eddy currents forming in the component and thus a weakening of the secondary field, i.e. it lowers the measured signal's amplitude. However, the effect can easily be compensated by adjusting the signal's amplification.

Another advantage of this technology is that slight mechanical damage of the component's surface does not lead to an unrecognizable readout as demonstrated in figure 2c. Due to the local heat treatment, the markings are stored both on the surface but also in deeper subsurface layers. Thus, if only the component's surface is damaged, the markings are still legible. Yet, the damage of the surface has an influence on the eddy current and distorts the measuring signal. By using an appropriate test frequency and phase rotation, the distortion can be filtered out.

Finally, the component was heated to 500 °C in a shielding gas atmosphere, held at this temperature for thirty minutes and then quenched in air. As demonstrated in figure 2d, the marking can still be read out clearly. For a heat treatment at a temperature of 600 °C and a holding period of 30 minutes the marking were no longer clearly legible. This is attributed to diffusion processes which significantly change the microstructure that had resulted from the local hardening. As a result of this homogenization, the differences in the magnetic and electrical properties between the marking and the base material disappear.

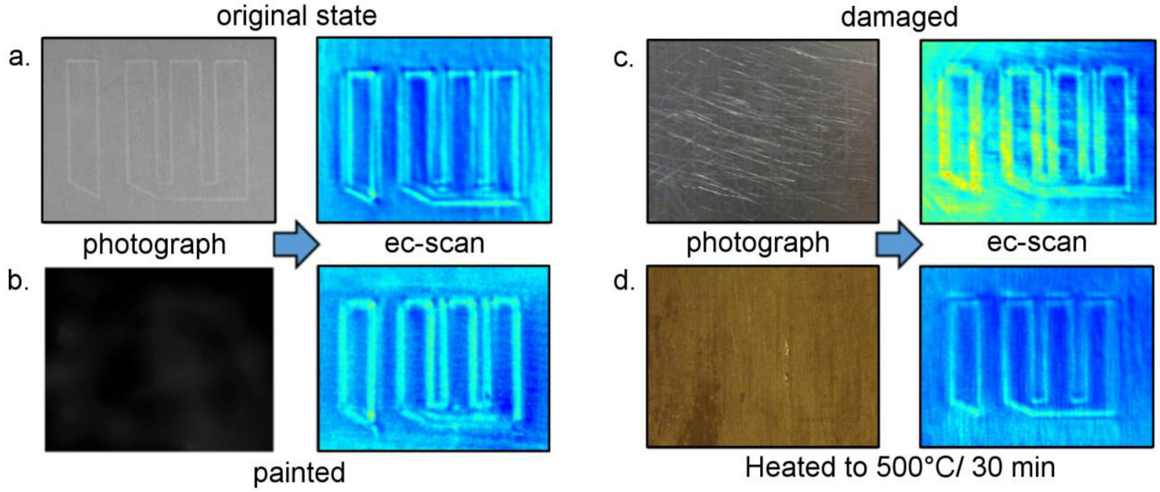

Fig. 2. Readout of an inherent marking (12,5 x 9 mm) by eddy current (ec) technology under validating conditions.

4. Non-directional load measurement

An evaluation of the component's integrity can be carried out by detecting the load-induced microstructural changes during the usage phase. In particular critical loads, which are higher than the expected operational loads and therefore might lead to material damage or fatigue, must be detected reliably otherwise component failures or malfunctions might occur. To address this problem, a component's load history can inherently be stored in the material permitting the integrity of the component to be evaluated. Using this approach, no additional electronic devices are required during the use phase to save the loading history. External read out technology is only needed to monitor the loading history of the component during maintenance. The inherent sensors do not require additional space and are robust with respect to the operating mechanical and thermal loads.

Related studies have shown that lower yield stress values can be set by means of controlled heat treatment of martensite-hardened austenitic materials. Figure 3 depicts lower yield stress values $\sigma_{y1}\ldots\sigma_{y3}$ which are set by increasing the tempering condition of the martensite. The yield strength of the base material of 1100 MPa was lowered stepwise down to 800 MPa by using laser beam powers of 110 to 130 watt. [6]

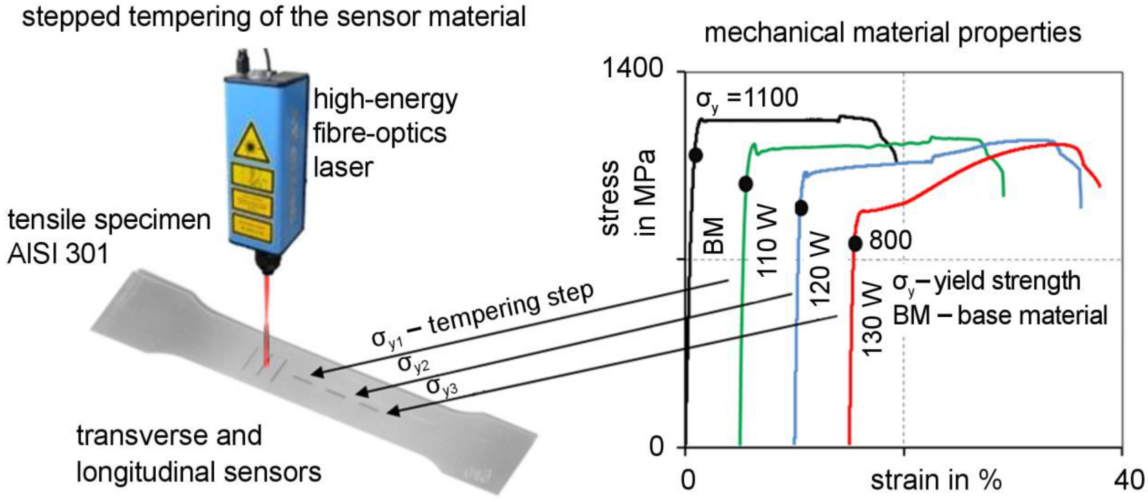

Fig. 3. Adaptation of the sensor strength to the component's loading stresses [6].

Based on the new technical capabilities, a multi-sensor concept for load sensors was designed and developed. This multi-sensor system enables both a differentiated collection of the component's load level and information regarding the loading direction and the type of load. To sensitively detect overloading, the local martensitic constituents of the metastable austenitic sensor materials are tempered. This results in regions which have a lower yield strength than the surrounding areas. The yield strength can be set individually depending on the application. Usually stresses occurring during the use phase are below the yield strength of the substrate and thus within the elastic range. If the yield strength of the inherent sensors is exceeded, local changes in the microstructure occur; i.e martensite is formed, which remains after the external stress has been removed. These changes in the microstructure increase the local yield strength, in a way that a re-load of equal strength does not necessarily lead to a further formation of martensite. Only a stress above the actual yield stress results in martensite formation. This change in the microstructural properties can be detected by eddy current technology and read out whenever required. [2, 6, 7, 8]

Preliminary studies have shown that these yield stress sensors and markings introduced by local heat treatment, do not weaken the component. Failures in tensile tests on samples with areas modified by local heat treatment occurred independent of these areas. [2]

In figure 4, three circular sensors are depicted. These were introduced into the component using different laser beam powers. The left graph shows the eddy current-surface-scan prior to any component loading. The right graph depicts the scan after statically loading to a stress of 1000 MPa and subsequent unloading. After loading, a significant change in the eddy current signal in the loading direction is observed. Due to the locally-induced phase transformation formation, the signal approaches the level of the surrounding martensitic structure. Thus, the circular yield stress sensors indicate both the strength and the direction of loading. [2, 7]

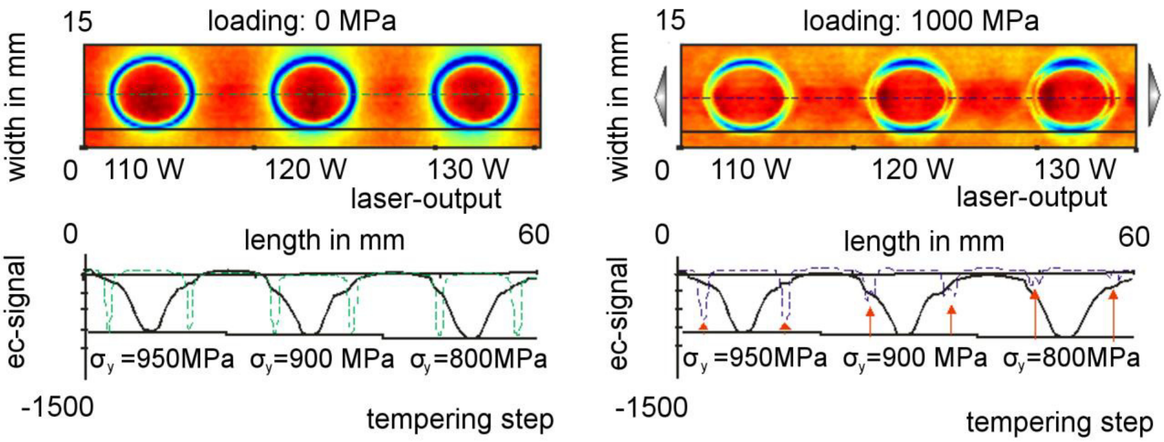

Fig.4. Detecting the components loading using directionally sensitive yield stress sensor, partly recompiled from [2].

In the multi-sensor concept using circular or line sensors, it is necessary to introduce a separate sensor to store each load level. In the next stage of development, more tempering steps were combined into a single line sensor. The sensor depicted in Figure 5, is only 6 mm long and includes 5 tempering steps (laser beam powers: 100 to 140 watts). At a stress of 700 MPa, the signal from line sensor, which was pre-treated at 140 watts, changes as shown in the second graph in figure 5. At a stress of 900 MPa, the sections 2 (130 watts) and 3 (120 watts) also respond. The 4th section (110 watts) responds at a stress of 1100 MPa, while the 5th (100 watts) indicates that that the stress was below its critical level.

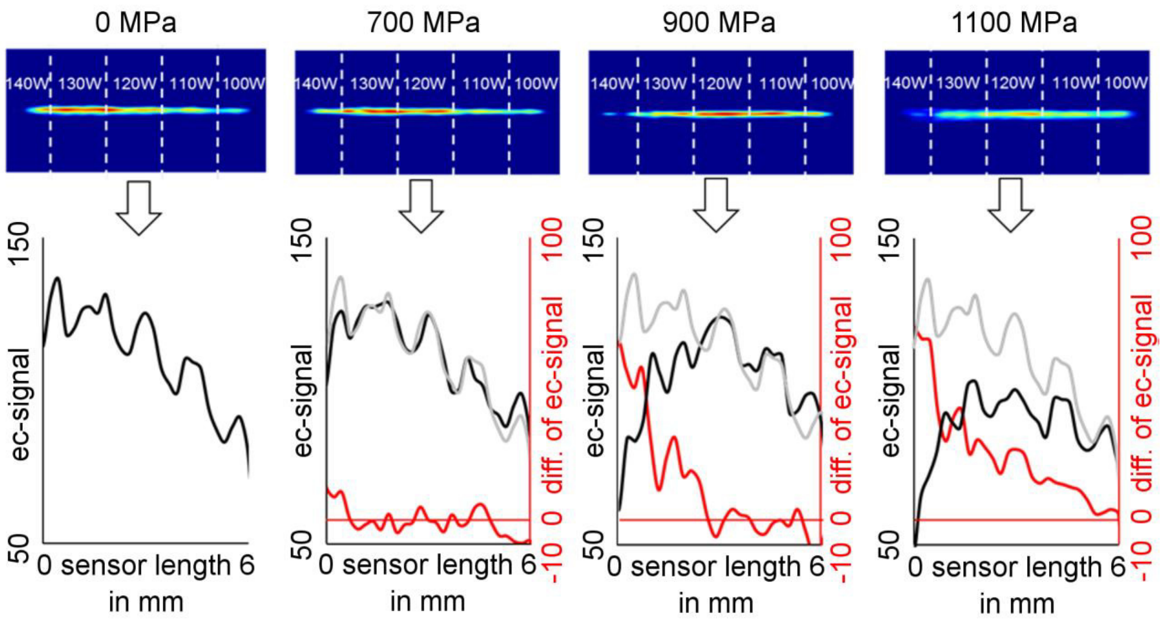

Fig. 5. Multistage inherent loading sensor.

With this approach an increase in the density of the stored load data is possible. Using more finely graded laser powers and hence a finer associated gradation of the tempering states, even smaller separation between the measurable stress levels is conceivable.

Acknowledgments

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