Load Sensitive Control Arm based on Martensitic Phase Transformation

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Summary: In this paper, a new technology for a novel material inherent load sensor for sheet metal components of metastable austenitic steel is presented. The new technology is based on load induced martensite formation and is investigated in the Collaborative Research Centre (CRC) 653. The sensors are small areas in the sheet metal material, which have been plastically deformed by means of stamping. Due to this, residual stress remains within the material assisting the formation of martensite if mechanical load is applied to the component. The martensite content correlates with the magnitude of the load and can be measured by means of eddy-current testing. The aim is to expand the possibilities of load and damage detection especially for security-relevant components.

For demonstration, a control arm made of metastable austenitic stainless steel EN 1.4301 (X5CrNi8-10) is being investigated. In the frame of this paper, the results of numerical analyses to determine adequate positions for implementing the load sensors are presented. Therefore, a mathematical model was developed that considers formation of martensite in the FE-simulation and allows for computer-aided design of the sensors. The basic idea of the CRC 653, the principle of the load sensor, the development of the mathematical model and results of the numerical investigations are presented.

Keywords: Metal forming, Sensor, Finite element method (FEM).

1. Gentelligent Components

The presented investigations are a work of the subproject S2 of the Collaborative Research Centre (CRC) 653 “Gentelligent Components in Their Lifecycle – Utilization of Inheritable Component Information in Product Engineering”. The term gentelligent (GI) is composed of the words “genetic” and “intelligence”. The aim of this coordinated research program is the use of bionic principles in production processes. Bionic principles in this case are the capabilities of passing information to following generations and of continuous learning during production and lifecycle. The aim is to make components capable to communicate, to store data and to pass information to the following generations. By means of these properties, an assessment of a product’s lifecycle will become feasible and thus make the difference between a state-of-the-art-component and a next-generation component – the gentelligent (GI) component (Fig. 1).

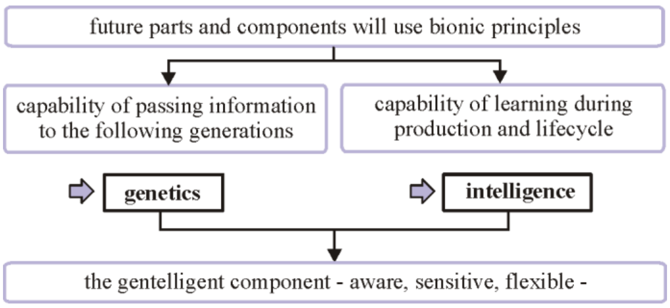

Figure 1. Principles of biology and their use for gentelligent components.

The aim is to utilize these novel characteristics in fields of product identification, protection against plagiarism, construction planning and production technology. Within the scope of the subproject S2, a new technology for GI-components is being developed that allows to detect and to prove overload of a component by means of changes in the microstructure of the component’s material. In this regard, a classification of the level of mechanical forces as wells as their directions are goals of the subproject. Fields of application are security-relevant parts.

2. State of the Art

Metastable austenitic Cr-Ni steels, e.g. X5CrNi18-10 (1.4301, AISI304) which was used in this research, are resistant to corrosion and provide a high formability. Depending on the specific alloy composition, they feature high creep strength at high temperatures as well as considerable durability at low temperatures. In unformed state, Cr-Ni steels show a metastable austenitic structure at room temperature [1]. With a sufficient amount of energy applied to the material thermally or by mechanical load, a partial transformation of austenite to the stable martensite lattice occurs. Three types of phase transformations are known for X5CrNi18-10: the transformation of austenite to ε martensite (a metastable intermediate stage); the transformation of ε martensite to α’-martensite, a stable body-centred cubic lattice (bcc) [2]; and third the direct transformation of austenite to α’-martensite [3] (figure 1). Moreover, a simultaneous formation of α’- and ε-martensite can occur. As ε martensite is an intermediate stage, less activation energy is required for a transformation of ε-martensite to α’ martensite than for a transformation of austenite to α’-martensite. The formation of α’ martensite is assisted by tensile stress, whereas low temperatures and compressive stress support the formation of ε martensite [2; 4]. Hence, residual stress within the material (e.g. due to forming) can assist the phase transformation. This effect can be used to lower the threshold for external forces at which the martensite formation is initiated. For this purpose, the material is locally deformed by a forming process and defined initial martensite content is set. If mechanical load is applied to the material afterwards, a change of α’-martensite content occurs. This can be measured by the non-destructive eddy current testing due to different magnetic properties of austenite and α’-martensite and conclusions concerning the magnitude of load can be drawn.

3. Inherent Load Sensor in CrNi-Austenites

The aim of the subproject S2 of the CRC 653 is a novel material load sensor based on load induced formation of martensite to detect and to prove overload during the lifecycle of the component (Fig. 2). The effect of load induced martensite formation can be locally increased by means of metal forming (compare chapter 2). Caused by mechanical load, the austenitic face-centred cubic (fcc) lattice partially changes into a body-centred cubic (bcc) α'-martensitic lattice. Thus, load sensitive stampings can be implemented to components of metastable austenitic steels as inherent load sensors.

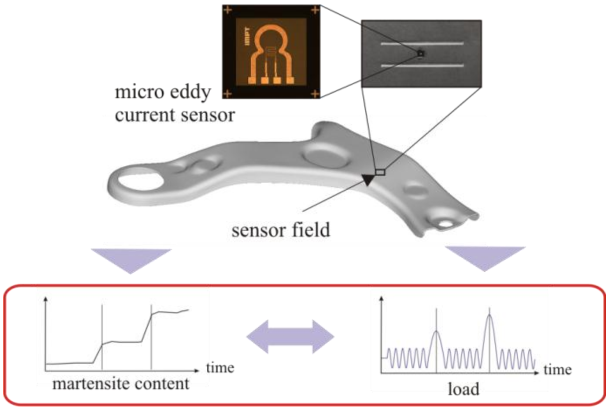

Figure 2. Detection of overload by means of phase transformation.

While austenite shows antiferromagnetism, α'-martensite has ferromagnetic properties. This disparity is used in eddy-current testing systems for non destructive measurement of the martensite fraction in the material. By means of changes of the martensite content, conclusions on the mechanical load applied to the component during operation can be drawn. Overload can be detected and it can be checked if the component needs to be replaced or not. A novel micro eddy current sensor is used for the non destructive testing. The micro eddy current sensor was developed within the subproject S1 of the CRC 653.

To implement a load sensitive stamping in the material, a defined initial α'-martensite fraction is produced in the material by means of stamping. By means of arrangement of the stamping dies, combined sensor fields can be realized to allow for classification of both level of forces and the corresponding direction. For this purpose, stiffening ribs are implemented next to the load sensitive stamping. This way, a local work hardening of the material is reached leading to a heterogen distribution of stress in the material that depends on the direction of force.

In actual work, a control arm of a passenger car made of metastable austenitic stainless steel EN 1.4301 is investigated (Fig. 2) to identify adequate positions to implement the sensors.

4. Development of a Material Model

To investigate the martensite formation caused by forces applied to the material, a mathematical model was developed at the IFUM. This material model is based on the models of Ludwigson [5] and Tsuta [6]. It was made up by Springub [4] and enhanced to a multiaxial formulation by Weilandt [7]. The calculation is carried out incrementally and is based on the equation:

$$\left(\frac{\partial f^{\alpha'}}{\partial \varphi}\left(f^{\alpha'}, T, \varphi, \underline{\underline{\Sigma}}\right)\right) = \left(1 - f^{\alpha'}\right) \cdot \frac{C \cdot \varphi^{-1}}{1 - A \cdot e^{D + \frac{B}{T[K]}} \cdot \varphi^{-C}} + E \cdot \left(1 + f^{\alpha' F}\right) \cdot \frac{e^{G - T[K]}}{1 + e^{G - T[K]}} \cdot \sqrt{\varphi} \cdot \left(1 + H \cdot signum\left(\frac{\sigma_2}{\sigma_1}\right) + H \cdot signum\left(\frac{\sigma_3}{\sigma_2}\right) + H \cdot signum\left(\frac{\sigma_1}{\sigma_3}\right)\right)$$

A - H	= material parameters
T	= temperature
φ	= true strain
$f^{\alpha'}$	= initial martensite fraction
σ_1 - σ_3	= principal stresses

The material parameters A to H are determined by experimental tensile and deep drawing tests. These parameters are batch-independent for each type of steel and they have to be determined only once. The temperature T, the true strain φ, the initial martensite content $f^{\alpha'}$ and the influence of the principal stresses σ_1, σ_2 and σ_3 on the phase transformation is taken into consideration. The equation was implemented into the commercial finite element software Abaqus by means of a subroutine. It is being used for numerical investigations on the martensite formation in sheet metal components.

5. Numerical Investigations

A successful implementation of load sensitive stampings into sheet metal components can be reached only if the forming process to manufacture the component is known in detail. In this regard, the local true strain, the local martensite fraction as a result of the forming process as well as the local sheet thickness of the control arm must be taken into consideration to reach a defined sensitivity of the stampings. Hence, the process parameters related to manufacturing a load sensitive control arm are different to a state-of-the-art-process (Fig. 3).

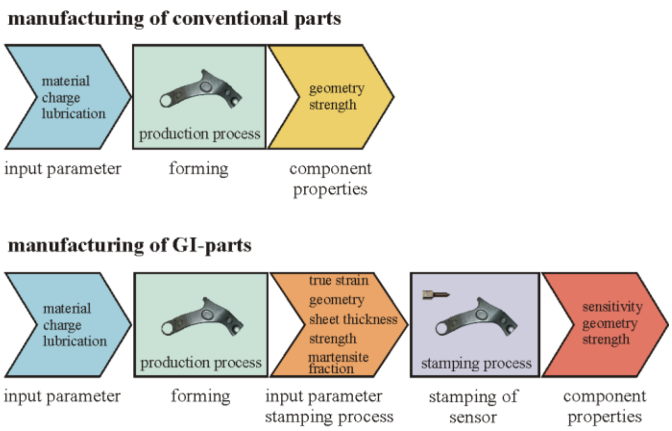

Figure 3. Comparison of process parameters.

In case of the control arm presented in this work, the process to manufacture the component results in an inhomogeneous degree of deformation the material. Thus, the sheet thickness and the local content of martensite are inhomogeneous too and were determined experimentally. The results is depicted in Fig. 4.

As the formation of martensite causes an increase of the flow stress of the material, variable martensite content across the control arm causes an inhomogeneous strength of the component. This must be taken into consideration during development of the load sensors to be implemented as it has an impact on a) the sensor itself and b)on the strength properties of the component.

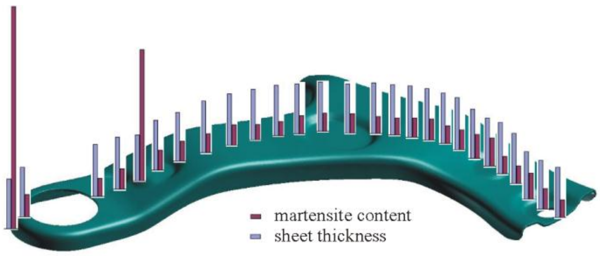

Figure 4. Local martensite content and local sheet thickness of the control arm as a consequence of the forming process.

In this regard, the yield stress level of the control arm was determined for relevant areas based on the martensite content measured in these areas. This was done by experimental testing of flat tensile specimens that were elongated continuously while the martensite content was measured. It was found, that a content of martensite similar to the control arm corresponds to a yield stress level of 475 MPa. Hence, if external forces cause a local stress above this level, a plastic deformation will occur. Below this threshold only elastic deformation will occur in the relevant areas. Based on this result, the scenario of component damaging that is to be detected by means of the novel load sensor was investigated in an FE-simulation. For this reason, a numerical model of the control arm was built up using the software Abaqus and a virtual test force was applied to the control arm afterwards. The mounting position of the real control arm in the passenger car of its origin is depicted in Fig. 5.

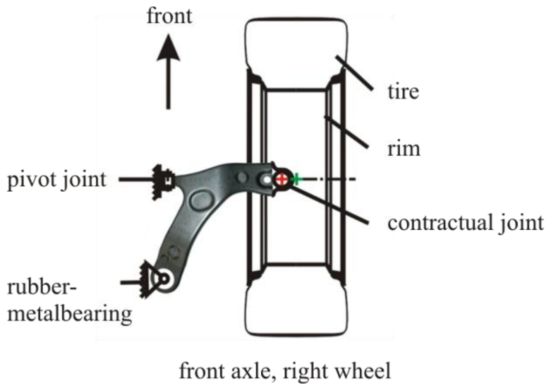

Figure 5. Mounting position of the control arm in the vehicle.

According to this arrangement, a virtual test force in longitudinal direction was applied to the contractual joint of the wheel. The other two ends of the component that are mounted to the car where set to be fix. This scenario corresponds to overriding e.g. a kerb. The resulting stress and strain and the corresponding deformation of the component were calculated. This way, adequate positions on the control arm to implement the load sensitive stampings and sensor fields were determined (Fig. 6).

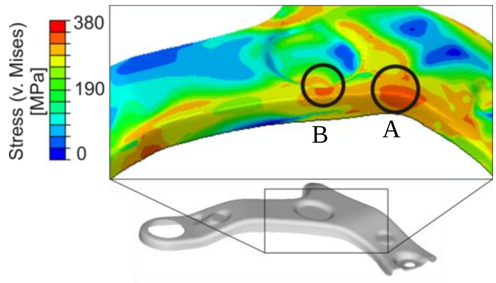

Figure 6. Virtual determination of adequate positions to implement load sensitive stampings.

Based on the resulting stress according to v. Mises, suitable positions that are restricted to the centre of the control arm were found. In this area, two positions are eligible (Fig. 6). In position ‘A’, an increase of the martensite content will occur for elastic deformation of the control arm whereas in position ‘B’ an increase of the content of martensite will not occur until the control arm is plastically deformed. Hence, in a change of the martensite content in position B would indicate a damage of the component. In the reality, this might impact the driving safety of the passenger car or lead to an increase of fuel consumption.

6. Future Prospects

In further work, the load sensitive stampings e.g. the sensor fields will be implemented into the control arm experimentally. By means of a servo hydraulic testing machine, test forces will be applied to the component. It will be investigated, to what extent the load applied to the component can be classified by means of the martensite content and if the measured values correspond to computed values based on the material model.

Acknowledgements

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