Stress analysis of specimen with a reinforced thin layer

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Abstract. The paper presents an analysis of the stress state in the tensile test sample. The test sample has a hardened surface layer with chemic heat treatment – cementation. The analysis was carried out for various thicknesses of the reinforced cemented layer. If the whole thickness of the material is not cemented, the fracture is near the grip section of the specimen. The analysis results explain the cause of this fracture.

1. Introduction
The surface of components or tools is very often adjusted using processes such as heat-treatment or chemical-heat treatment [1]. The treatments change the properties of material. Surface of the material usually become more hardened [2]. In the case of intricately shaped parts of the component, the interaction between treated surface and deeper tough interior material may affect a reduction in the overall strength of the component [3, 4]. To achieve the most efficient properties of the component appropriate to industry [5], there is necessary to propose a correct ratio between thicknesses of the hardened surface layer and interior non-treated material [6]. The ratio could be determined using the program SYSWELD, but in the case of complex-shaped component, the generation of the model is accompanied by complications [7].

The paper focuses on stress distribution in components loaded to tension, which surface is heat-treated or chemical-heat treated. The components are made of chromium-manganese steel 16CrMn5 with the adjusted surface layer. The objective of the paper is to examine the stresses in the component during constant loading with changing the thickness of the adjusted material.

The analysis of the heat transfer in the program Ansys Workbench was performed to determine the shapes of adjusted material, transition area and material that is not affected by carburization process [8].

In the process of carburization, the temperature distribution described by the differential equations for thermal conduction (1) and diffusion (2) control the thickness of the adjusted layer [9, 10]:

\[
\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2}
\]  

(1)

\[
\frac{\partial T}{\partial t} = D \frac{\partial^2 T}{\partial x^2}
\]

(2)

where \(\alpha\) is thermal conduction coefficient and \(D\) is diffusion coefficient.
The differentiation between partial differential equations (1) and (2) is solely based on the usage of specific constants. It means, that the mathematical formulation of carbon atoms absorption into steel procedure is similar to the process of heat conduction. Therefore, the geometric shape of a model (carburized and non-carburized material) was determined from the simulation of heat conduction. Subsequently, this analysis was connected to a static analysis of specimen loaded to tension with defined geometry (Figure 1). Different material properties were assigned to treated surface and interior part of the specimen, which correspond to the carburized and non-carburized steel 16CrMn5.

Figure 1. Specimen shape.

2. Model preparation

The content of the alloying elements in the specimen made of Chromium-Manganese steel 16CrMn5 is given in Table 1. Selected mechanical properties of 16CrMn5 steel in carburized and non-carburized state are in Table 2.

Table 1. Content of Chromium-Manganese 16CrMn5 steel.

| Chemical element | Amount (%) | Tolerance (%) |
|------------------|------------|---------------|
| Chromium (Cr)    | 0.80–1.10  | 0.05          |
| Manganese (Mn)   | 1.00–1.30  | 0.05          |
| Sillicon (Si)     | 0.40       | 0.03          |
| Sulphur (S)       | < 0.035    | 0.005         |

Table 2. Mechanical properties of 16CrMn5 steel.

|                        | Non-carburized specimen | Carburized specimen |
|------------------------|-------------------------|---------------------|
| Yield strength (MPa)   | 710                     | 1000                |
| Ultimate strength (MPa)| 780                     | 1300                |
| Young modulus $E$ (GPa)| 200                     | 220                 |

Another properties of Chromium-Manganese steel, which are assumed in the simulation are:

- thermal expansion coefficient $10^{-6}$ (K$^{-1}$)
- thermal conductivity $41$ (W m$^{-1}$K$^{-1}$)
- specific heat capacity $460$ (J kg$^{-1}$K$^{-1}$)

For both types of materials were defined corresponding curves on $\sigma$ - $\varepsilon$ graph in the Material Data of software Ansys Workbench (Figure 2).
For tensile test simulation of the specified specimen shape (Figure 1) modeled using CAD programs [11, 12] was created the temperature-dependent material model (figure 3) in the following steps. The heat conduction simulation determined temperature limits at which material has various mechanical properties [13]. At a temperature not exceeding 24.3 °C, the specimen has the mechanical properties of non-carburized steel. The properties of carburized steel were assigned to the material with temperatures more than 24.5 °C. The transition area, which was identified at temperatures between 24.3 °C and 24.5 °C, had mechanical properties determined by program ANSYS Workbench. The program determined them in pursuance of input values, which were specified for both materials.

![Stress vs. Strain Graph](image1)

**Figure 2.** Curves for carbonized and non-carbonized type of material on σ - ε graph.

![Temperature vs. Young Modulus Graph](image2)

**Figure 3.** Relation between temperature and Young modulus.

3. **Stress distribution analysis**

The first assessed specimen was composed solely of non-treated steel. The loading force was 20 000 N. The maximal stress occurs in the narrowest part of the specimen (figure 4).

The following simulations were performed on specimens with the carburized surface layer. The model preparations consist of the increasing thickness of the hardened layer in simulation of heat conduction. The specimens were loaded to force from 20 kN to 30 kN. In each figure of the specimen model, the red colour represents carburized material, green colour illustrates the transition area and the blue colour introduces non-carburized steel. Firstly, the specimen with a 0.2 mm thick carburized surface layer was assessed (figure 5).
In the case of the specimen with a 0.2 mm thick carbonized layer, the maximal stress appears throughout the length of the narrowest part of the specimen. Figure 6 shows the stress state at the time of 1.7 s, which corresponds to the loading force of 27 kN. The increase of loading force effect to the gradual spread of stress from the narrowest part to the head of the specimen.

Secondly, the carburized layer was 1.2 mm thick at the narrowest part of the specimen. Figure 7 shows the geometry model obtained from the simulation of heat conduction.
In comparison to previous one, the maximal stress in specimen reinforced with 1.2 mm thick carburized layer exceeds into deeper location of specimen in the narrowest specimen part. In addition, stress at the head of specimen increase. Figure 8 shows the stress distribution in the specimen at loading force 27 kN.

![Figure 8](image)

**Figure 8.** Stress distribution in specimen carburized over the entire cross-section.

Finally, the last specimen has carburized material over the entire cross-section. Non-carburized material was located only at head part of specimen. The thickness of the carburized material at the roundings of specimen was 0.7 mm (Figure 9).

![Figure 9](image)

**Figure 9.** The model of specimen with non-carburized material located only in head of specimen.

Figure 10 shows the stress distribution in the specimen at a loading force 27 kN. The stress concentrations occur at the rounding regions of specimen, which result to premature failure of specimen.

![Figure 10](image)

**Figure 10.** Stress distribution in specimen with non-carburized material only in head of specimen.
4. Conclusion
The simulation confirmed the experimental results, which resulted in breakage of the specimen at the rounding regions. The case for breakage of the specimen is the insufficient depth of the hardened layer at the head part of the specimen.

5. References
[1] Domanski T, Sapietova A and Sága M 2017 Application of Abaqus software for the modeling of surface progressive hardening Procedia Engineering 177 64–69
[2] Zavodska D, Tillova E, Guagliano M, Kucharikova L and Chalupova M 2017 Fatigue Resistance of Self-hardening Aluminium Cast Alloy 33rd Danubia Adria Symposium on Advances in Experimental Mechanics (DAS) Materials Today: Proceedings 4 6001–6006
[3] Wilczyński M and Domek G 2019 Influence of tension layer quality on mechanical properties of timing belts MATEC Web of Conferences 254 05010
[4] Zaušková L, Czán A, Šajgalík M, Drbúl M and Ryšavá Z 2017 Triaxial measurement of residual stress after high feed milling using X-ray diffraction Procedia Engineering 192 982–987
[5] Grega R, Krajňák J, Žuľová L, Fedorko L and Molnár V 2017 Failure analysis of driveshaft of truck body caused by vibrations Engineering Failure Analysis 79 208–215
[6] Belan J, Kucharikova L, Tillova E and Vaško A 2017 The influence of applied heat-treatment on IN 718 fatigue life at three point flexural bending Metalurgija 56 167–170
[7] Piekarska W, Kubiak M and Žmindák M 2017 Issues in numerical modeling of phase transformations in welded joint Procedia Engineering 177 141–148
[8] ANSYS 2009 ANSYS Workbench User’s guide Available: https://www.researchgate.net/file.PostFileLoader.html?id=5444928ed2fd647d5f8b46b7&assetKey=AS:272120486006786@1441889987511
[9] Markoš P 2017 Computer modelling: Heat conduction equation (in Slovak) Available: <http://davinci.fmph.uniba.sk/~markos/prednasky/poc-fyzika-difuzia.pdf>
[10] Paliesková J, Pajtášová M, Feriancová A, Ondrušová D, Holcová K, Vavro J Jr and Mojumdar S C 2015 Thermal properties of fillers based on organoclays in the polymeric materials Journal of Thermal Analysis and Calorimetry 119 939–43
[11] Kuric I 2011 New methods and trends in product development and planning Journal of Manufacturing Engineering 9 453–456
[12] Macko M, Tyszczuk K, Šmigielski G, Flizikowski J and Mroziński A 2018 The use of CAD applications in the design of shredders for polymers MATEC Web of Conferences 157 02027
[13] Leitner B 2011 The least squares method in a parametric identification of the large crane system 15th International Conference on Transport Means Transport Means – Proceedings of the International Conference pp 42–45

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