STRESS ANALYSIS IN CYLINDRICAL SPECIMENS MADE FROM 34CrMo4 USING DIC

Michaela Štamborská[1)], Monika Losertová[1)], Vratislav Mareš [2)], Lukáš Horsák[2)]*
[1)] VŠB – Technical university of Ostrava, Faculty of Metallurgy and Materials Engineering, Department of Non-ferrous Metals, Refining and Recycling, Ostrava - Poruba, Czech Republic
[2)] VŠB – Technical university of Ostrava, CPIT - Centre for Advanced Innovation Technology, Ostrava - Poruba, Czech Republic

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[*]Corresponding author: e-mail: stamborska.michaela@gmail.com Tel.: +420 597 329 421, Department of Non-ferrous Metals, Refining and Recycling, Faculty of Metallurgy and Materials Engineering, VŠB-Technical University of Ostrava, Czech Republic

Abstract
The stress analysis using digital image correlation was carried out on cylindrical tensile specimens made from low carbon 34CrMo4 steel. The results obtained by conventional tensile test were compared with the results obtained by digital image correlation. The true stresses were evaluated from the compiled true stress-strain diagrams and compared with the engineering stresses. The average values of the yield stress and tensile strength reached of 945±15 MPa and 1039±5 MPa, respectively. Thus, parameters obtained from tensile test were plotted in the engineering diagrams that represent often starting diagrams for engineering practice. Based on results of digital image correlation the possibility of construction of the true stress-strain diagrams is discussed with regard to more exact values of stress for use in practice. The evaluation and compilation of the true stress-strain diagrams were carried out by means of image correlation software Vic 2D.

Keywords: Microstructure, tension test, digital image correlation, 34CrMo4 steel, true stress

1 Introduction
The 34CrMo4 steel grade is a low-carbon steel with medium through-hardening for medium-duty machine parts. The use of the 34CrMo4 steel grade lies primarily in the production of blanks – forgings, seamless tubes, steel for refining and in cold drawn steel for refining. It is also used in hot-rolled billets, rolled bars, wire and universal mill plates, steel plates and hot-rolled strips, for free and drope stampings. Machine parts with high toughness in the automotive and aerospace industry, for example axis, pinion shafts, bandages [1-5].
Increasing content of molybdenum in the Cr-Mo steel type, increases not only the through-hardening, but it also prevents significant drop in hardness during tempering. Molybdenum further increases the steel resistance against tempering brittleness. The interaction of molybdenum and chromium to reduce energy on grain boundaries is also not negligible [6-10].
In experimental analysis of plastic deformation on the surface of components, it is advantageous to use contactless sensing methods, allowing to obtain strain fields in pre-selected areas. Digital image correlation (DIC) is one of the non-interferometric contactless methods for determining the deformations on the surface of objects. DIC constitutes one of the most advanced optical

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methods of displacement sensing and subsequent determination of strains on the surface of examined subjects [11-13].
Unlike the interferometric methods (holographic interferometry, speckle interferometry, moire interferometry), the DIC method does not require the use of a coherent light source. Deformation of the surface is determined by comparing the dependence (correlation) of changes in the intensity of grey color in the monitored area of the object surface, before and after the deformation. In principle, the DIC optical measuring method is based on digital image processing and its numerical analysis. For the analysis of plastic deformation in uniaxial loading, it is possible to use specimens of different shapes and sizes.
The article is focused on the stress analysis of tensile tested cylindrical specimens made from 34CrMo4 steel using digital image correlation. Experimental results discussed in this work are focused on the last stage, when the rod forms a local constriction (contraction), mainly in the width, and the rod deforms further only in this one place until it breaks.

2 Experiment Methodology

For the study, specimens of low carbon chromium – molybdenum stainless steel for heat treatment were used. Specimens were taken in the longitudinal forming direction. The structural differences between longitudinal and transversal sections of the specimens were not investigated, so the anisotropy of the structure was not taken account. Heat treatment of the steel consisted from austenitization at 850 °C, water cooling and tempering at 520 °C. Heat-treated steel is characterized by mean values of toughness, yield strength and ductility. This material is not susceptible to tempering brittleness, difficult to weld and prone to chilling cracks after hot forming, initiated mainly by indentations and surface defects [14-18]. The chemical composition of the steel is shown in **Table 1**.

Table 1 Chemical composition according to standards: 34CrMo4 steel ČSN EN 10083-1/DIN 17200/

C	Mn	Si	P	S	Cr	Mo
0.30 -0.37	0.60-0.90	max 0.40	max 0.035	max 0.035	0.90 - 1.20	0.15 - 0.30

The microstructure was evaluated by standard metallographic procedures: grinding and subsequent polishing on the Struers DiaPro Nap-B 1 μm emulsion. The polished specimens were etched by 3% nital solution [19-23].
Tensile test was carried out on cylindrical specimens, whose geometry is shown in **Fig. 1**. In order to demonstrate the suitability of using the method of digital image correlation for obtained parameters, four specimens of the same shape and material were used in this experiment, with the possibility of results comparison.

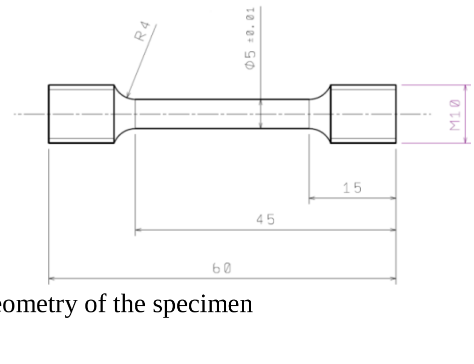

Fig.1 The shape and geometry of the specimen

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Stress – strain diagrams were obtained for all four specimens by the tensile test on the Zwick / Roel Z150 device. Evaluation and compilation of the true stress –strain diagrams were carried out using image correlation software Vic 2D and scanning was performed using Canon 5D MARK II.

3 Results and Discussion

3.1 Microstructure and Material Specimens' Parameters

From metallographic observation it was found that the microstructure was formed of ferrite and perlite with ferrite / pearlite ratio of 56 / 44 determined using digital image analysis. The original grain size was estimated in accordance with the standard ČSN EN ISO 643 and reached of G = 12. The final fine-grained microstructure resulting from the heat treatment was formed of mixture of lamellar pearlite with a ferrite network at grain boundaries (**Fig. 2**).

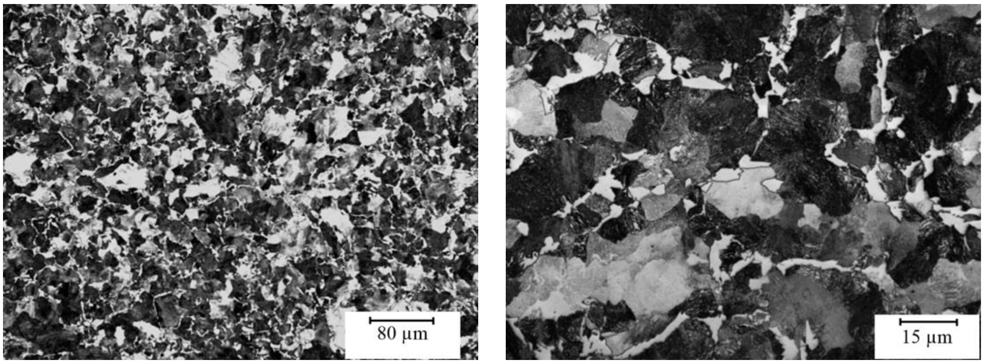

Fig.2 Material Microstructure – confocal microscope

Material parameters that are listed in **Table 2** were obtained by conventional tensile test (**Fig. 3**). The measured values confirmed high strength characteristics typical for the chrome-molybdenum steel.

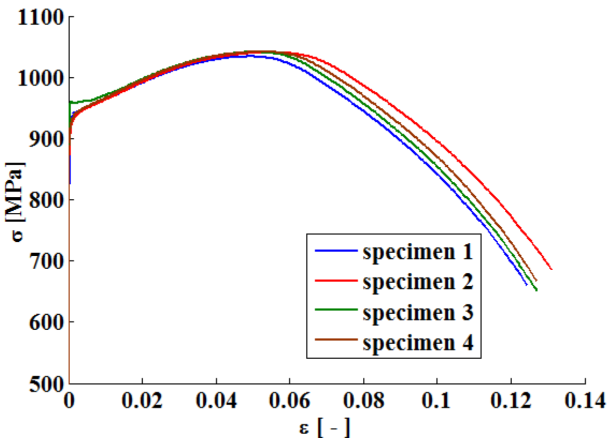

Fig.3 The stress-strain diagram for all four specimens

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Table 2 Material Parameters of specimens

No.	E [GPa]	$R_{p0.2}$ [MPa]	R_m [MPa]	F_m [kN]	d_0 [mm]	S_0 [mm^2]	L_0 [mm]	L_u [mm]	A5 [%]	d_u [mm]	Z %
1	208	943	1034	20.47	5.021	19.80	33.39	37.56	13	3.03	63
2	208	937	1040	20.44	5.001	19.64	32.19	36.41	13	3.02	63
3	209	958	1041	20.53	5.011	19.72	31.48	35.48	13	3.06	63
4	207	941	1041	20.50	5.006	19.68	32.70	36.85	13	3.02	63

3.2 The Results Obtained by DIC

The principle of the method is based on scanning of stochastic black and white spotted pattern created on the surface of the examined object, for example, by spraying black paint on white background. The observed area is divided by virtual grid into smaller subareas called facets, so that each of them would contain a characteristic part, with a sufficient contrast, of the pattern.

Based on the correlation of corresponding facets before and after deformation, displacements and strain fields of individual points are determined. In case of plane image correlations, the object deformations are determined by an observation through one camera directed perpendicularly to the surface of the object. This procedure allows to determine the deformation of the object in the level parallel to the image level of the camera. **Fig. 4** shows the results of strain field ε_x [-] obtained by the VIC 2D software for all four specimens.

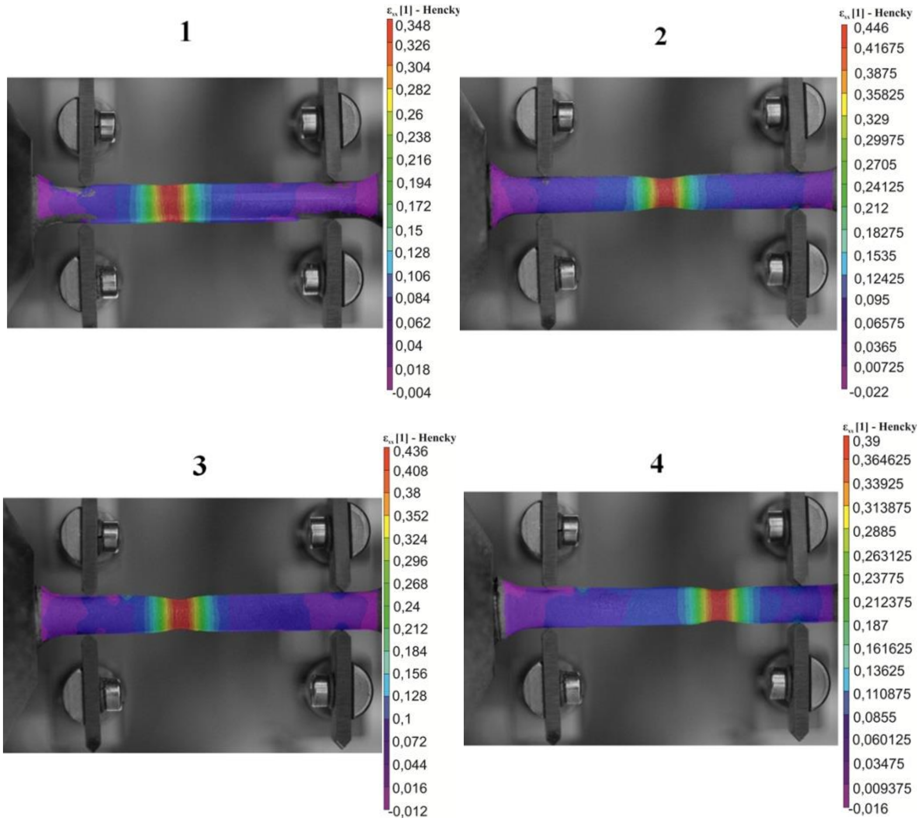

Fig.4 The strain fields obtained by Vic 2D for specimen 1,2,3,4

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On plastic deformation, above the yield strength, the rod is extended with increasing force evenly throughout its length. Tough the permanent deformation displays considerably non-uniform development in terms of the microstructure, at the macro level, we can consider the deformation as uniformed along the entire length of the test bar. Therefore, this stage is called the region of uniformed (homogeneous) deformation and is terminated at the moment of first appearance of the local bar narrowing, which begins to form so-called neck. Measured results (Fig. 4) are focused on the last stage, when the rod forms a local contraction of the width and deforms further only in this one place until it breaks. In places away from the neck, the tested rod does not extend. From the results displayed in fig. 4, we can see that the values of strains, shown in red in the narrowed area of the specimens, reach maximum values from 35-45%. The results were shown for the last image, in which the added extensometer from tensile machine can still be seen.

3.3 Diagrams of True and Engineering Stress

When using digital image correlation, we can see not only the distribution of strains, but also the evaluation of the specimen's narrowing and the concentration place before cracking of the specimen. One other possibility is plotting of a true stress –strain diagram, which becomes to be more and more desired by engineering practice. **Fig. 5** shows the diagrams of the true and engineering stresses with marked points corresponding to the strain fields (Fig. 4) for all four specimens, obtained from the measured values by using digital image correlation and standard tensile test.

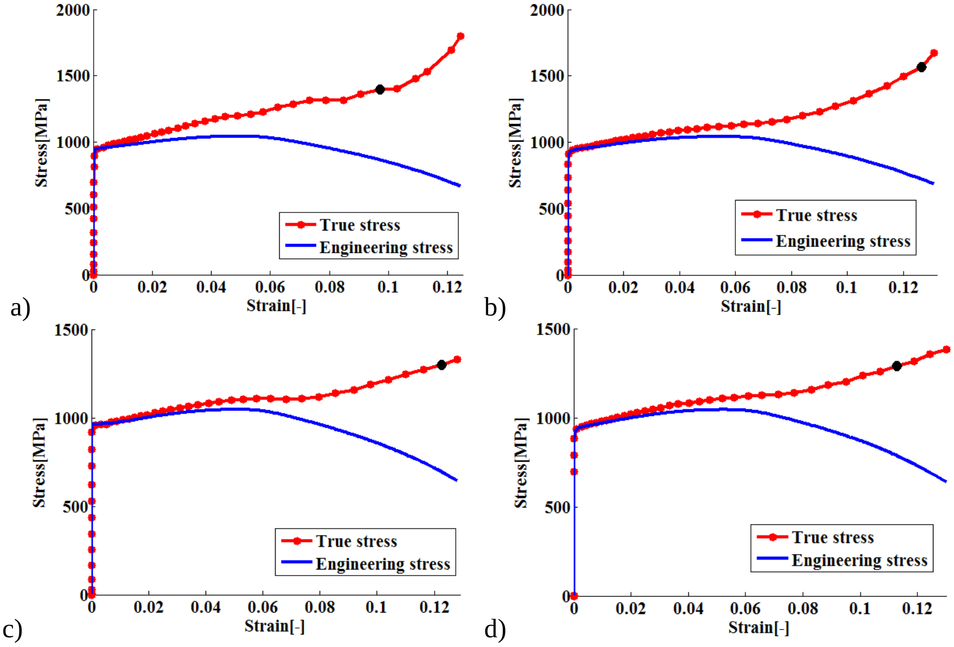

Fig.5 Diagrams of true and engineering stresses for specimens a) 1, b) 2, c) 3 and d) 4

After reaching approx. 9% of strains, it leads to an accumulation of the deformation to a place, where the contraction is subsequently developed. To this point, the stress distribution was

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homogeneous. The diagram shows that from the given place of interest, an increase of stress values occurs, which we would not be able to notice using only the engineering diagram. This is another advantage of using digital image correlation. The maximum values of strains obtained by the digital image correlation were approx. 60% after that, the specimens were broken.
While the engineering stress depends on the force, which leads to break the specimen and begins to decrease after reaching the maximum value, the true stress diagram is based on the measured necking of the specimen recorded during the tensile test. Beyond the elastic region and the average yield stress (945 ±15 MPa) the stress values based on real reduction of the specimen and shown in the true stress diagram (Fig. 5) are increasing. The difference between the maximum measured values in engineering and true stress diagrams followed by rupture of the specimen is about 57%, indicating a further advantage of using DIC methods.

4 Conclusion

The current trend of weight reduction of products, i.e. reducing bearing cross sections, is limited by the requirement for sufficient stiffness of these components. Therefore, not only toughness, but simultaneously yield strength, modulus of elasticity and specific weight are critical demands for the use.
In this work, the stress analysis of tensile tested specimens made from 34CrMo4 steel was performed using digital image correlation.
The advantage of high strength steels is their higher yield strength and strength limit, so it is possible to use higher allowable stress and optimize product design. Proportionally with increasing steel yield strength, the demands on its ductility are increasing as well. This is because higher stresses from the external load, as well as from higher residual stresses, act in the structural detail.
The disadvantage of the engineering stress is fact that it depends on the force, which leads to break of the specimen and begins to decrease after reaching the maximum value. The true stress diagram is based on the measured necking of specimen recorded during the loading to failure, while the neck is still narrowing and stress growing. For this reason, maximum values measured for engineering and true stress, followed by a broke of specimen is about 57% of the difference. The difference of the measured values begins after exceeding of the average yield stress.
Digital image correlation method shows still better use in practice, as its advantages are easy operation, accurate results, and could be used for different types of specimens. The disadvantage may consist in the fact that it requires a precise adjustment of lighting and proper surface preparation of the specimen.
It has been proved that the DIC method is suitable for the determination of the fields of strains on the specimen surface, which enables to determine the strain distribution throughout the loading process. Based on measured fields of strains the true stress-strain diagrams could be plotted that helps to describe the real behavior of materials as well as to obtain sufficient data for potential optimization of components dimensions.

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