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# NUMERICAL AND EXPERIMENTAL ANALYSIS OF RESIDUAL STRESSES INDUCED BY CONTACT LOADING

# NUMERICKÁ A EXPERIMENTÁLNÍ ANALÝZA ZBYTKOVÝCH NAPĚTÍ INDUKOVANÝCH KONTAKTNÍM NAMÁHÁNÍM

**Abstract**

The paper deals with numerical and experimental solution of residual stresses, which occures due to a contact loading. The first solved case corresponds to frictionless contact in an indent test accepted from literature. In this case, results obtained by two experimental methods are available, namely by the Neutron diffraction method and by the Contour method, which is not well known in the Czech Republic. Hence, this paper includes also a brief description of the new destructive method. Both methods can lead to prediction of full field residual stresses distribution. Numerical results conducted by the Ansys FE program shows good correlation with those obtained by the experimental methods.

**Abstrakt**

Článek se zabývá numerickým i experimentálním stanovením zbytkových napětí, která vznikají v důsledku kontaktního namáhání. První řešený případ odpovídá kontaktní úloze bez tření převzaté z literatury, kdy byl průběh zbytkových napětí získán dvěma metodami, a to metodou neutronové difrakce a destruktivní metodou kontur. Druhá jmenovaná metoda je kombinací experimentálního a numerického přístupu a není příliš známá, proto jsou její základní principy v příspěvku stručně popsány. Obě metody mohou být použity pro stanovení průběhu zbytkových napětí ve zvoleném řezu zkoumaného vzorku. Numerické řešení realizované v konečnoprvkovém programu Ansys vykazuje dobrou shodu s experimenty.

## 1 INTRODUCTION

As it well known, residual stresses are stress fields, which exist in a material without any external loads [1]. Residual stresses play an important role in the strength and fatigue life of components in engineering applications. A lot of machine components are subjected to repeated contact loading, which leads to changes of residual stresses distribution in surface and subsurface layer. Numerical modeling of the proccess is often difficult, because actual residual stresses are already affected by manufacturing processes. This study show some difficulties in numerical solution of residual stresses induced by contact loading, for the explored materials, as steels are sometimes clasified.

## 2 NUMERICAL SOLUTION

Recently, various numerical methods are used for residual stress analysis. The most applied methods in contact mechanics are the finite element method [2] and the boundary element method [3]. Material model incorporated in such analysis has the main influence on acuraccy of a numerical analysis in case of residual stresses induced by contact loading. However, classical plasticity models

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with a nonlinear hardening rule for metals included now in commercial computational softwares are not able to describe the nonproportional hardening effect that appears for a lot of metalic materials.

A simulation of an indent test will be described to show the problem better. In the solved case, residual stresses due to plastic deformation of indented specimen from 316L steel are known through experimental works of Pagliaro et al [4]. In the paper, particulars of experimental setup are presented in detail. A 60-mm diameter and 10-mm thick disk of 316L stainless steel was plastically compressed through the thickness with a 15 mm diameter flat indenter in the center of the disk. A schema of the contact task is clear from Fig.1.

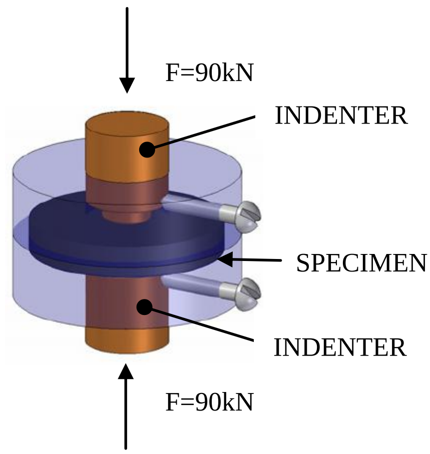


**Fig. 1** Scheme of the experiment from [4]

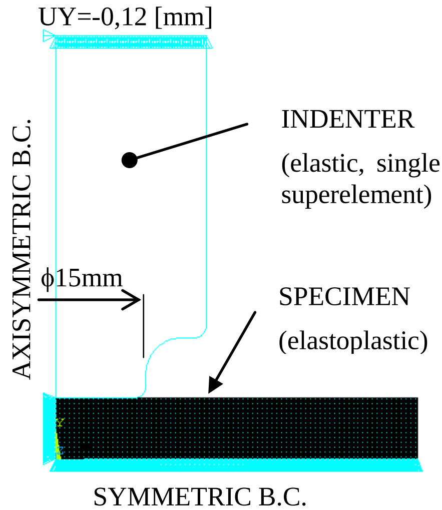


**Fig. 2** Applied boundary conditions (B.C.)

Initially, for own simulation, the axisymmetric FE model of the indenter and the specimen were build with 8132 PLANE42 elements defined by 8408 nodes and 15000 PLANE42 elements defined by 15351 nodes respectively. Appropriate symmetric and antisymmetric boundary conditions and a displacement of -0,12 mm were applied at the top of the indenter, see Fig.2. Then, the augmented Lagrangian frictionless surface-to-surface contact algorithm was utilized to treat contact conditions. The indenter was modeled by one single superelement, because of linear elastic material assumption (A2 tool steel, yield stress about 1300MPa, Young's modulus E=204000MPa and Poisson's ratio $\mu$=0,3). Multilinear kinematic hardening, multilinear isotropic hardening and nonlinear combined hardening options were assumed for stress-strain behavior characterisation of the specimen model.

From the both analysis, with and without superelement, results were almost the same. In some detail, it was already reported in [5]. At the end of unloading process, the residual stresses remained in the specimen. The comparison of numerical and experimental results of the hoop residual stresses on symmetry plane (see appropriate symmetric boundary conditions at the Fig.2) and the cross-section of the specimen are shown at the graph printed as the Fig.3. Differences between numerical and experimental results of the residual stress distribution (Fig.3) can be explained by the remark, that only simple plasticity options were used in the computations. It was recognized by various authors, that multilinear kinematic hardening model of Besseling and other models included in Ansys 11 can not describe stress-strain response of 316L steel correctly [6]. User programmable features (UPFs) approach should be used to implement more robust plasticity model into the FE code, see for example paper [7].

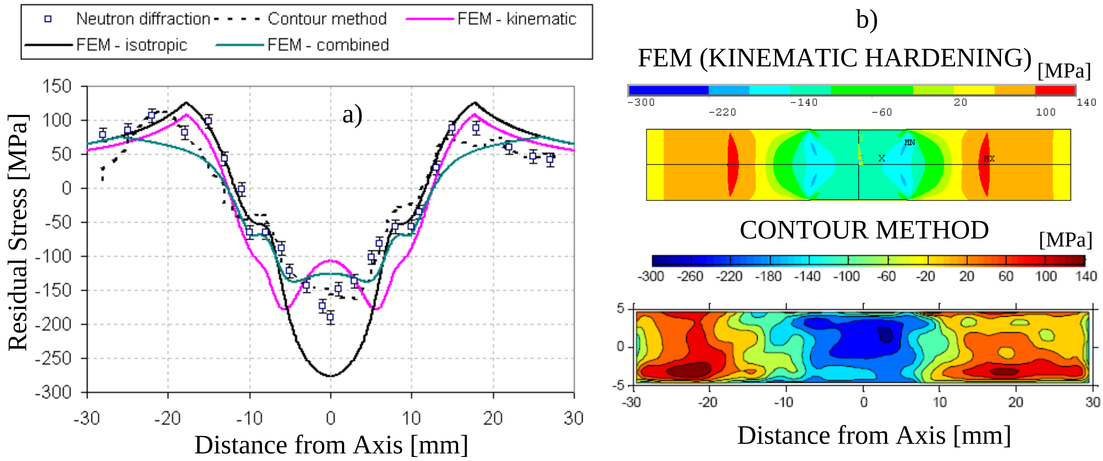


**Fig. 3** Hoop residual stress from numerical and experimental solution: a) on symmetry plane, b) at the cross-section (all experimental data from [4])

## 2 EXPERIMENTAL SOLUTION

Mechanical methods, mainly the hole-drilling method and the slitting method [1], or non-destructive methods, especially the neutron diffraction method and the X-ray diffraction method, are commonly used recently for near surface residual stress measurement [6]. During two last decades, hybrid methods have been developed in the experimental mechanics area mostly combining the best of an experimental and a numerical approach. The new such method was developed by Michal B. Prime in 2001 [7].

### 2.1 Contour method

This destructive method is suitable for measuring a cross-sectional map of residual stresses. Basic idea of so called contour method is quite simple, see Fig.4. The situation A shows the body with original residual stress distribution. After cutting in half along a flat plane a relaxation of residual stresses caused the body to deform (B). Therefore, deviation of the cut plane is measured. Next step involves forcing back the body to its original configuration along the new free boundary (C). Assuming that the relaxation process was elastic, the body has been return to its original stress state (A=B+C). Described principle corresponds to a classical superposition principle.

Practically, the ideal method for making the cut has been proven to be Wire electric discharge machining (EDM), because the cutting is non-contact and would not cause any plastic deformation. Surface contour measuring can be relised for example by a coordinate measuring machine [7] using touch or laser probe. More precise results of the method are obtained after data smoothing. As the last step, a finite element analysis is suitable for stress calculation. The average surface profile from part I and II is used to apply boundary condition, displacement normal to cut plane, on a FE model.

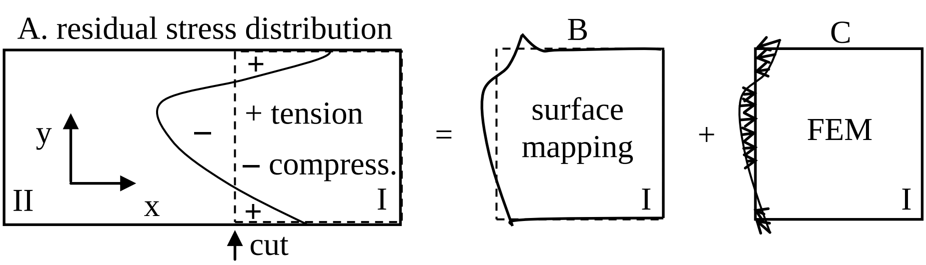


**Fig. 4** Principle of the contour method

## 3 CONCLUSIONS

The main scope of this work was comparison of a numerical solution and an experimental solution of residual stresses induced by a contact loading. In servise, such a loading is often repeated, for example in Wheel/Rail system or bearings. The case solved by author of the paper corresponds to the simple indent test from literature [4]. The results from finite element analysis performed show a neccessity of material model improvement for characterisation of the deemed steel 316L.

The new hybrid destructive method of ressidual stress measurement, so called contour method [7], was briefly described in the previous chapter. First experience of the author with application of the relaxation method to a rolling contact test is reported at the CD ROM version of this contribution. On the other hand, some numerical experiments warn against elasticity assumption in the evaluation process of the residual stress measurement based on relaxation principle [8].

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**REFERENCES**


[1] CHENG, W. & FINNIE, I. *Residual Stress Measurement and the Slitting Method*. 1st ed. New York: Springer, 2007. 209 pp. ISBN 0-387-39030-7.

[2] WRIGGERS, P. *Computational Contact Mechanics*. 2nd ed. Berlin: Springer, 2006. 518 pp. ISBN 3-540-32608-3.

[3] BEER, G. *Programming the Boundary Element Method. An Introduction for Engineers*. 1st ed. New York: JohnWiley & Sons, 2001. 457 pp. ISBN 0-471-86333-5.

[4] PAGLIARO, P. & PRIME, M.B. & ZUCCARELLO, B. & CLAUSEN B. & WATKINS T.R. *Validation Specimen for Contour Method: Extension to Multiple Residual Stress Components.* In *Proc. of the 13th International Conference on Experimental Mechanics, Experimental Analysis of Nano and Engineering Materials and Structures, Alexandroupolis, Greece, July 1-6*, 2007, paper number 246, CD-ROM proceedings.

[5] HALAMA, R. *On Accuracy of FE Contact Stress Analysis with Superelements.* In *Proc. of the 10th International Conference Applied Mechanics, Wisla, Poland, April 7-10*, 2008, in press.

[6] GDOUTOS, E.E. *Experimental Analysis of Nano and Engineering Materials and Structures. Proceedings of the 13th International Conference on Experimental Mechanics, Alexandroupolis, Greece, July 1-6, 2007*. 1st ed. New York: Springer, 2007. 978 pp. ISBN 978-1-4020-6238-4.

[7] PRIME, M. B. Cross-Sectional Mapping of Residual Stresses by Measuring the Surface Contour After a Cut. *Journal of Engineering Materials and Technology*. 2001, CXXIII. Nr. 2, pp. 162-168. ISSN 0094-4289.

[8] FRYDRÝŠEK, K & GANEV, N. Possibilities of FEM for Verification of X-Ray Measurement of Residual Stresses. (printed in this book).

[9] FOJTÍK, F. & FUSEK, M. The Fixation of the Specimen in the Test Machine for High Cycle Fatigue. In *Proc. of the 9th International Conference Applied Mechanics*, Malenovice 16.-19.4.2007. Ed. Frydrýšek K. et al. Ostrava: VŠB-TUO Department of Mechanics of Materials, 2007, pp.233-234. ISBN 978-80-248-1389-9.


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