International Conference
ENGINEERING MECHANICS 2010
Svratka, Czech Republic, May 10 – 13, 2010

FINITE ELEMENT INVESTIGATION OF THE ELASTIC-PLASTIC RESPONSE UNDERNEATH VARIOUS INDENTORS AND ITS APPLICATION IN NI-BASED ALLOYS INDENTATION PROCESSES

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Summary: *Stress and strain distribution underneath various types of indentors can be provided by the finite element method. In the presented paper, the indentation of isotropic aluminium is introduced as a benchmark problem, in which plasticity and contact algorithms are tested. The knowledge obtained in this way passes on to the real-life indentation processes involving orthotropic materials such as FCC metals (Ni-based alloys) in the context of nonlinear continuum and finite strain elastoplasticity, including homogenization approach on the material microscale.*

1. Introduction

Modern turbofans for the Boeings latest two engine airliner 787 Dreamliner represent with their higher efficiency, less pollution, and more operative system of maintenance relative to the former four engine aircraft the top quality in jet engine industry. Excellent parameters are

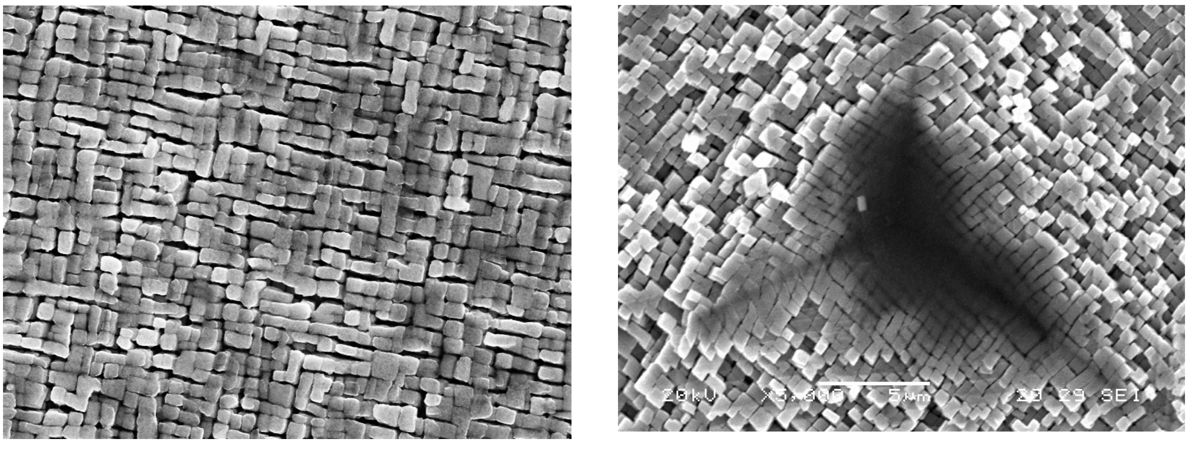

Figure 1 Ni-alloy before and after the process of indentation

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reached, i.a., by increasing the temperature of combustion. This requires the use of materials, which can stand elevated temperatures. Recently, nickel-based superalloys, see Figure 1, are widely used for those purposes representing a broad spectrum of use not only in the above mentioned application.

Different volume fractions of precipitates in a nickel matrix can be produced by controlled crystal growth. This may change mechanical properties significantly. Modern techniques of evaluation of mechanical properties such as micro and nanoindentation are typically employed. Despite relative simple in principle, these methods become complex due to strong demands for correct evaluation of results, taking into account plasticity and contact phenomena. Stress and strain distribution underneath various types of indentors can be determined by the finite element method.

2. Indentation of isotropic materials

The commercial ABAQUS FE-code was used in simulations. This code's plasticity algorithm in case of nonlinear elastic-plastic continuum relies on additive decomposition of the symmetric part of the velocity gradient and the Jaumann stress rate for continuum elements. Stress-strain curves were extrapolated beyond the measured range to be accessible by the FE-code in

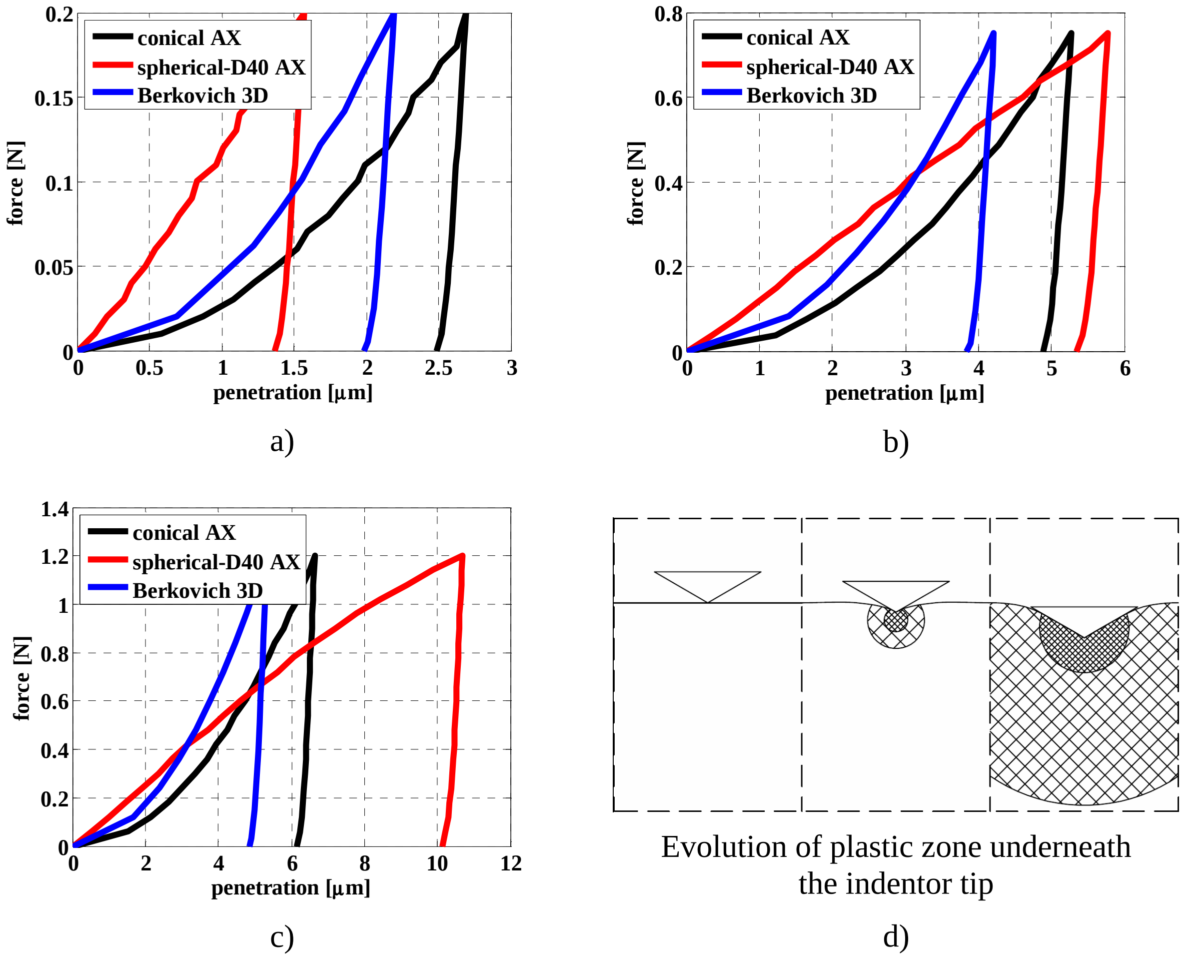


Figure 2 Results of indentation simulation of an isotropic material – various levels of force

case of need. The metal plasticity models in ABAQUS use the von Mises stress potential for isotropic behaviour and the Hill stress potentials for anisotropic behaviour. Both of these potentials depend only on the deviatoric stress, so the plastic part of the response is incompressible.

The conical indentor appears to be the most penetrating for small levels of load. However, increasing the load causes paramount plastic flows at the tip of spherical indentor. This is the reason why spherical indentor is penetrating material the most for high levels of load. Situation is plotted in Figure 2 a), b), c)[4]. The plastic zone underneath indentor spreads with increasing load, however, relative to the total loaded volume, less rapidly as depicted in Figure 2 d). Further plastic strains can be sometime observed during unloading.

The fact that friction has significant effect on solution only in case of spherical indentation was proved (Hrubý et al. 2009) as depicted in Figure 3. Results of indentation with so-called flat punch are also introduced with no dependence on value of friction coefficient.

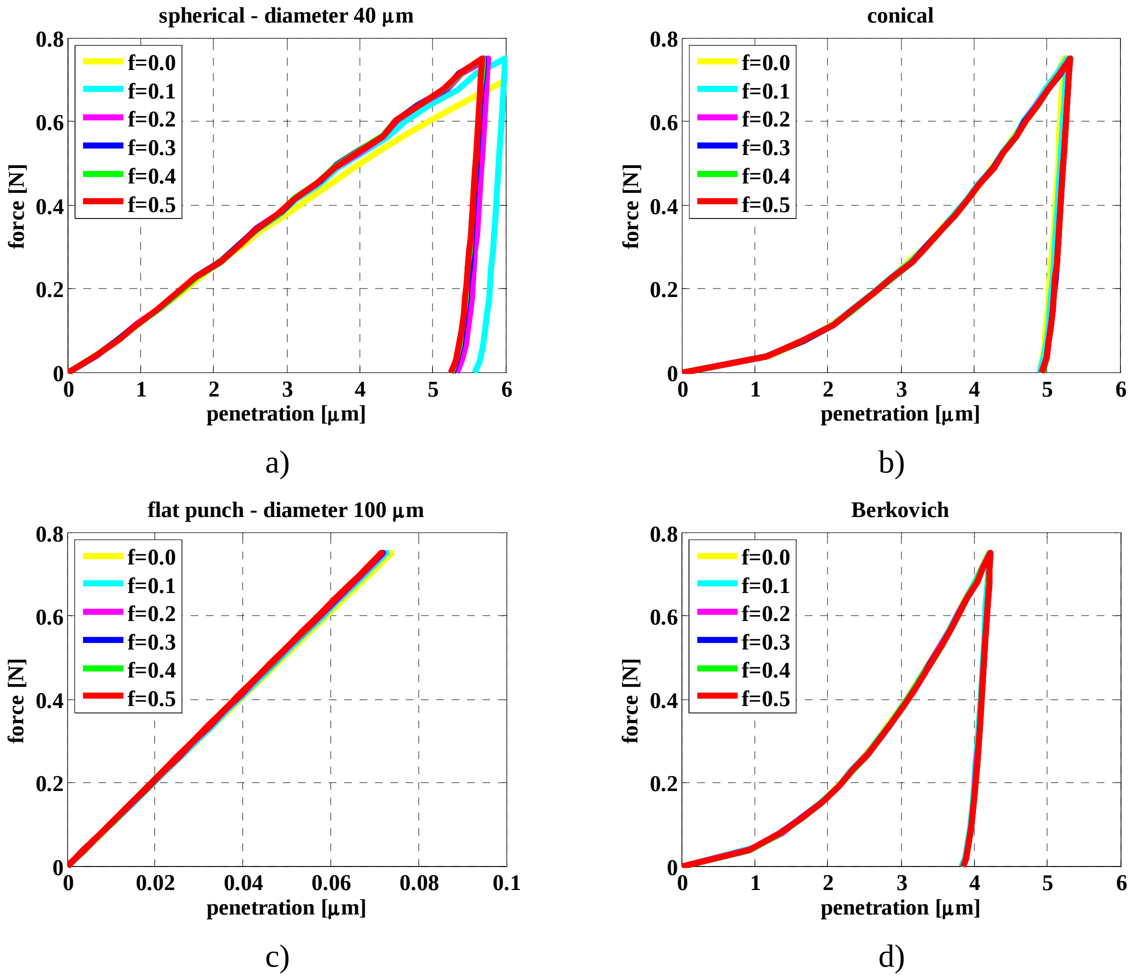


Figure 3 Effect of friction on solution

[4] AX denotes axisymmetric modelling, 3D three dimensional model

3. Indentation of anisotropic monocrystals

With Ni-alloys, the material behaviour is orthotropic. Three independent elastic constants E, υ, G exist. However, elastic properties of Ni-alloys are often acquired in terms of elastic moduli in different directions $E_{<100>}$, $E_{<110>}$, $E_{<111>}$. The calibration of elastic parameters E, υ, G requires further effort due to nonuniqueness of transformation relations.

Plastic behaviour is controlled by the Hill yield condition. Using the Schmid's law, one can obtain yield stresses in different direction according to Figure 4. Coefficients of Hill yield condition were dictated by the minimum error of description of crystal plasticity by the continuum mechanics, Figure 5, for evaluation mechanical properties of each single phase.

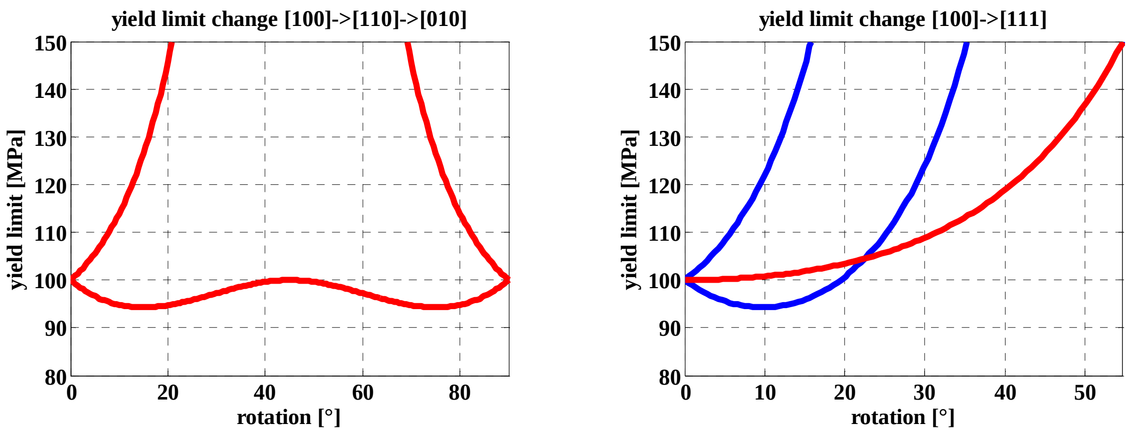


Figure 4 FCC-material yield limits in various directions (initial yield limit 100 MPa) for slip systems of FCC metals

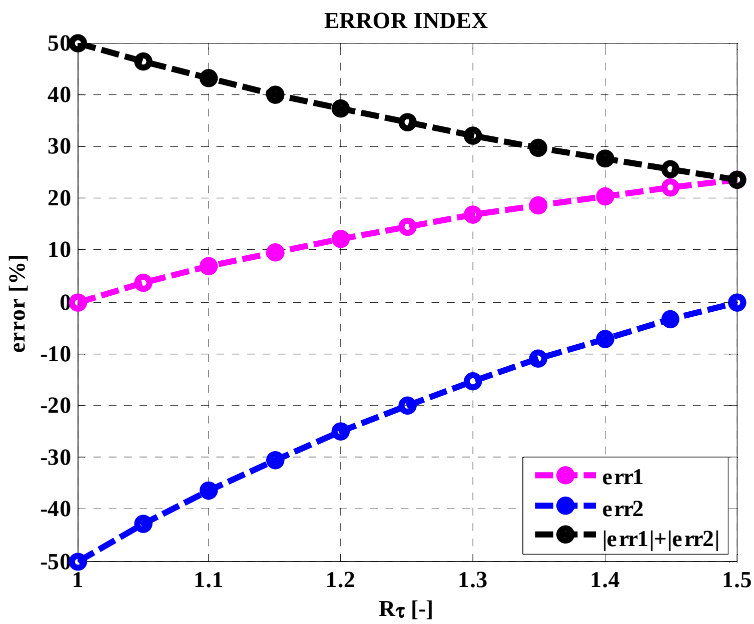


Figure 5 Yield limit – coefficient R_τ of Hill yield condition – error index

4. Indentation of composite structure Ni-base alloys

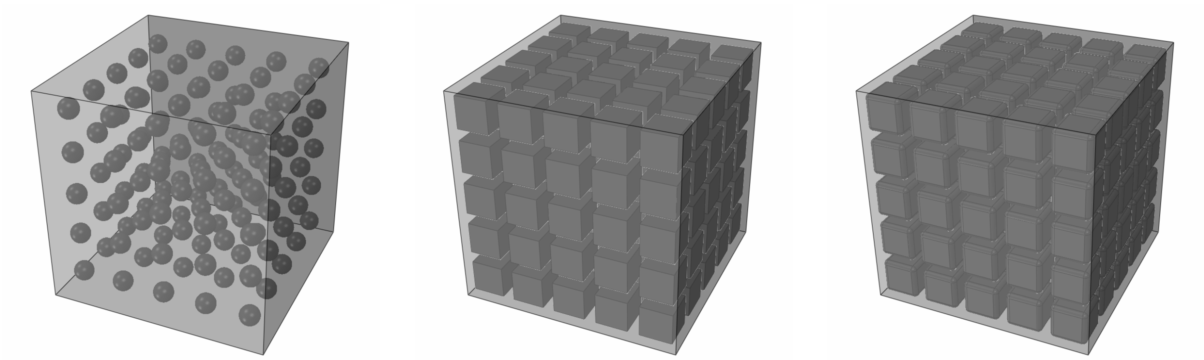
Precipitates are much smaller than indentors and/or the total material volume affected by the indentation process. Homogenized mechanical properties for different compositions of precipitates in the matrix were studied. For this reason, a family of idealized samples was generated with volume fractions of precipitates ranging from 1 % to 70 % according to Table 1. Various shapes of precipitates were studied according to Figure 6.

Compression and pure shear tests were performed to obtain the homogenized orthotropic mechanical properties on the macroscale. Results of homogenization procedures are plotted in Figure 7, Figure 8 and Figure 9. Results in terms of indentation curves are than easy to obtain according to (Hrubý et al., 2009).

Table 1 Volume fractions of precipitates

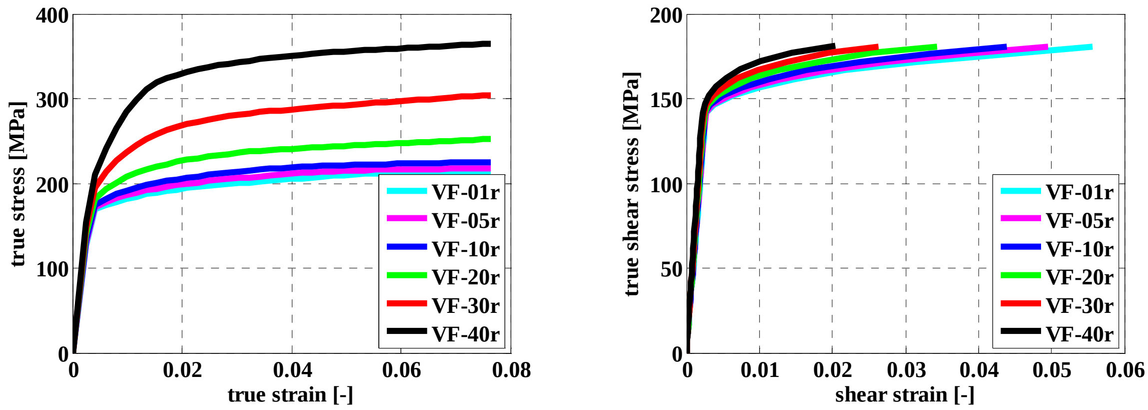
denotation	volume fraction	dimension
[–]	[%]	[nm]
	spherical shape	
VF-01r	1	45.5
VF-05r	5	78.0
VF-10r	10	98.0
VF-20r	20	123.0
VF-30r	30	141.0
VF-40r	40	155.0
	cubic shape	
VF-30a	30	228.0
VF-40a	40	250.0
VF-50a	50	270.0
VF-60a	60	287.0
VF-70a	70	302.0
	rounded cubic shape	
VF-30sa	30	192|28[5]
VF-40sa	40	212|31
VF-50sa	50	228|33
VF-60sa	60	242|35
VF-70sa	70	256|37[4]

[5] edge length | radius



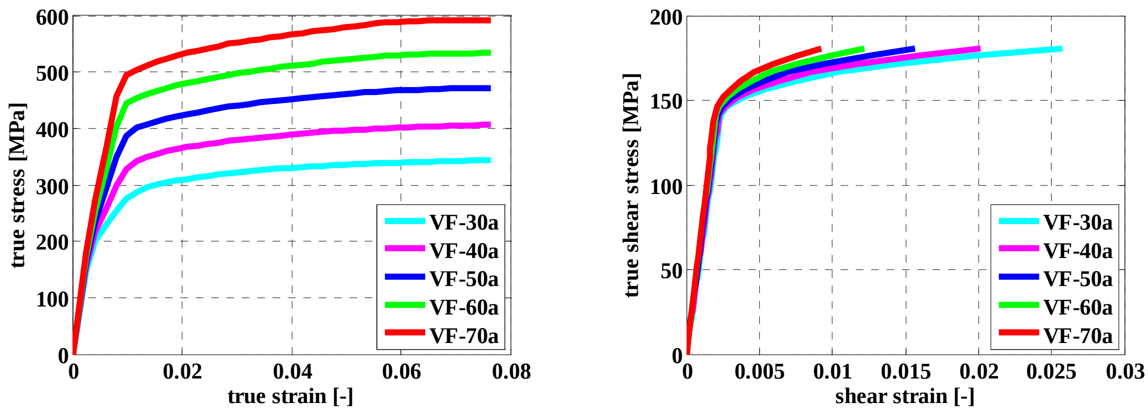
a) spherical shape “r” b) cubic shape “a” c) rounded cubic shape “sa”

Figure 6 Shapes of precipitates



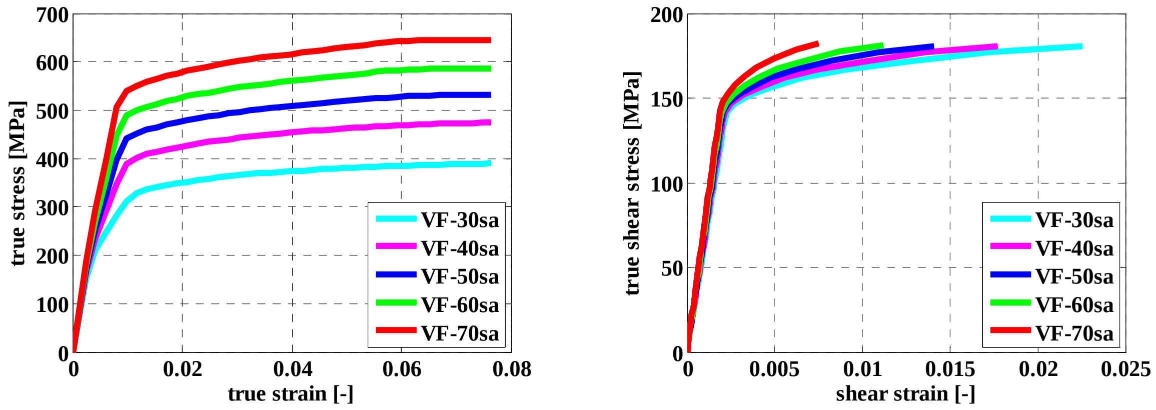
a) compression test b) shear test

Figure 7 Results of homogenization for spherical precipitates



a) compression test b) shear test

Figure 8 Results of homogenization for cubic precipitates



a) compression test b) shear test

Figure 9 Results of homogenization for rounded cubic precipitates

5. Conclusion

The fact that friction has significant affect on solutions in case of spherical indentation was proved. Numerical examples of indentation of an isotropic material were presented.

The plastic zone underneath the indentor spreads with increasing load, however, relative to the total loaded volume, less rapidly. Additional plastic straining can occur during unloading in certain cases.

Homogenization approach for the evaluation of apparent mechanical properties on the macroscale was performed. An attempt at modelling the indentation of Ni-based alloys was successfully made. The cause of the 'squaring-the-circle' phenomenon (Eidel & Gruttmann, 2007) of FCC metals was confirmed.

Indentation itself should be used for acquiring compression elastic-plastic stress-strain curves. Usage of indentation to determine tensile stress-strain curves is questionable in principle.

6. Acknowledgement

The paper was supported by the grant project of the Czech Science Foundation GA ČR 101/09/1630, GA ČR 101/08/H068 and GA ČR 101/07/1471.

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