Modelling of Mechanical Loads on Multi-Layer Varnishes

Norbert Schwarzer, Saxonian Institute of Surface Mechanics, Lieschow 26, 18569 Ummanz, n.schwarzer@siomec.de; www.siomec.de

Abstract

Within this short note a variety of loading situations on multi-layer varnish structures is investigated in order to find worst case contact situations, study the effect of impact and detect mechanically weak points in the multi-layer structure such a coating system is usually made of. The effect of intrinsic stresses is mentioned and will be taken care of in a second study.

Introduction

There are quite a number of methods to estimate the life time and protective efficiency-development of varnishes, be it for rather monolithic or more multi-layer structures. A very important and too often rather neglected point within almost all of theses models however, is the mechanical loading of the varnished surface during its preparation (here we mainly have intrinsic stress development), transport, installation and service life of the corresponding product or part. There usually is no question about the need of knowing the mechanical load limits of such structures for the purpose of production, transport and installation, where bad treatment can lead to ugly scratches and other surface damage. Rather often however, people ask why this topic is also interesting after the installation when, the varnishes part apparently rests safe and peacefully on whatever surface it is brought on. The most thing to worry about, so the often heard opinion, is a hard obstacle the surface could be scratched with. Here it obviously is difficult to make the user understand what disastrous effects rain drops, hailstones or even dust particles can have, if they hit the multi-layer structure with sufficient force. Not to mention flying bigger objects in stormy weather, Insects, bird or simple rain drops or the wrong method of cleaning.

Examples

As an example we pick a relatively simple four layer-varnish film structure from the aircraft industry [1] and subject it to a variety of mechanical loading situations in order to study their effects. Therefore we at first define the multi-layer structure as shown in fig. 1 within the software package FilmDoctor [2 - 8].

The next step is choosing a suitable loading method (fig. 2). For the reason of simplicity we here start with a spherical steel indenter of 10mm radius (fig. 3 red rectangle), because this type of indenter would provide us with “depth information” about the interesting interface regions without the need of too high normal loadings in order to obtain sufficiently big enough contact regions.

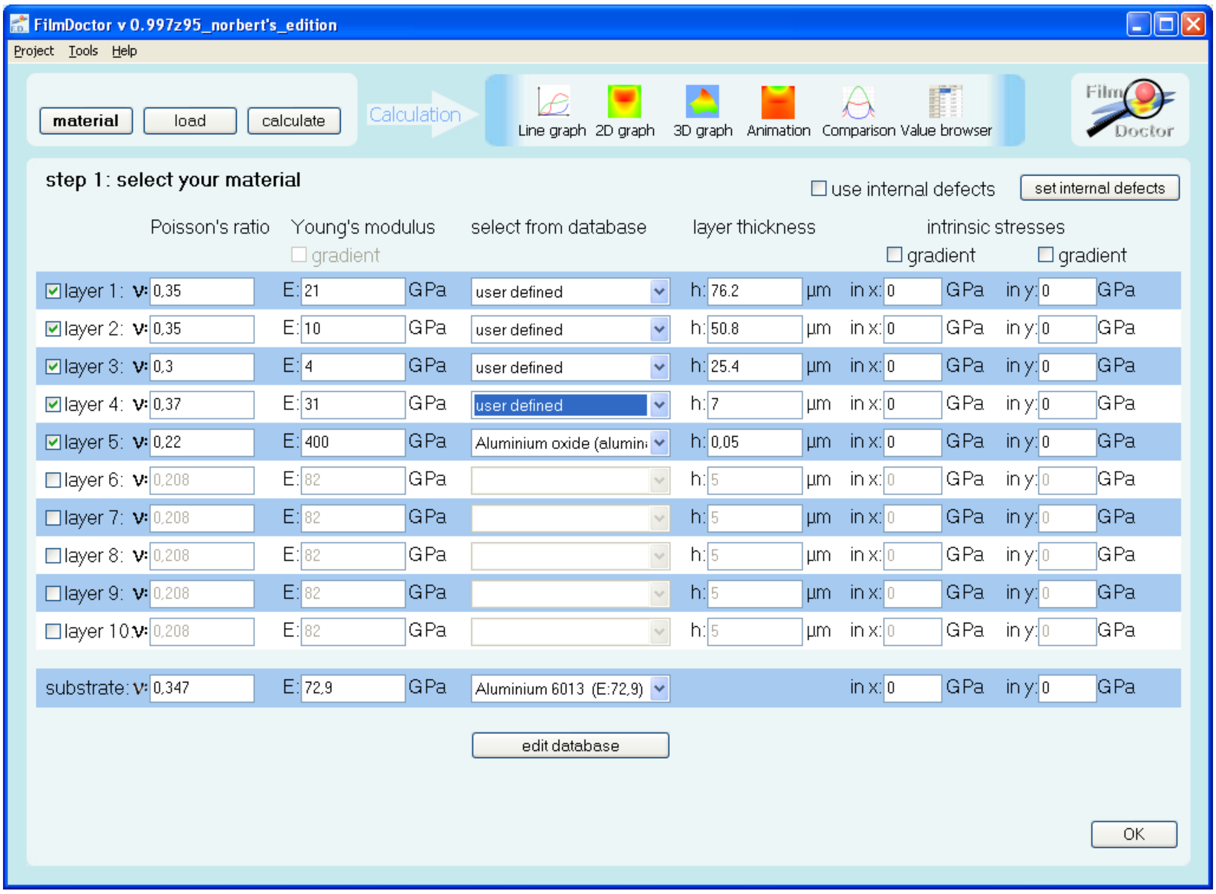


Fig. 1: Material definition page. Material parameters from the SIO data-bank or [1].

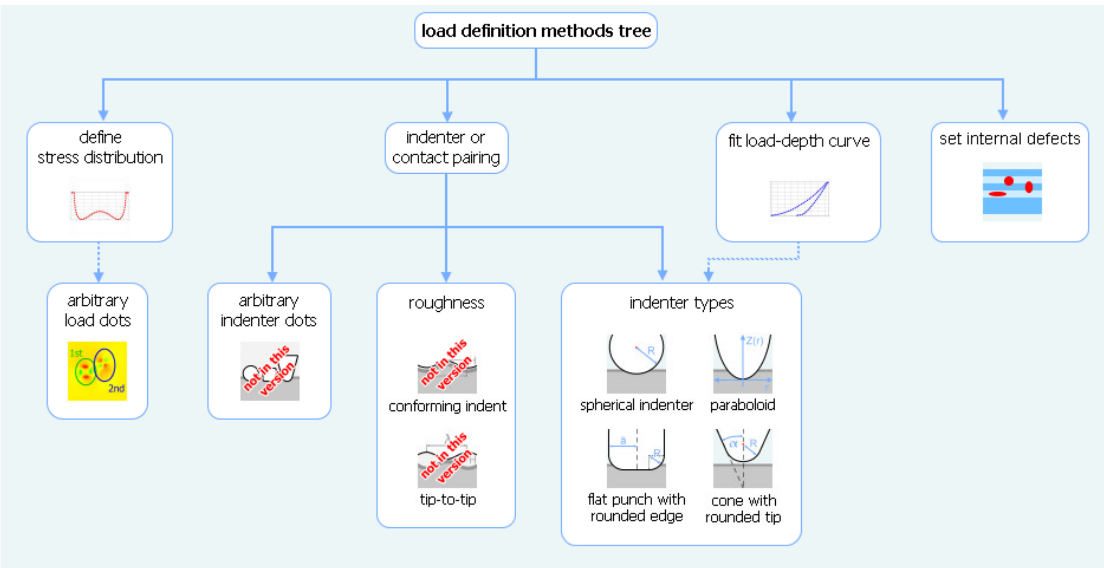


Fig. 2: Choosing "spherical indenter" from the load definition methods tree.

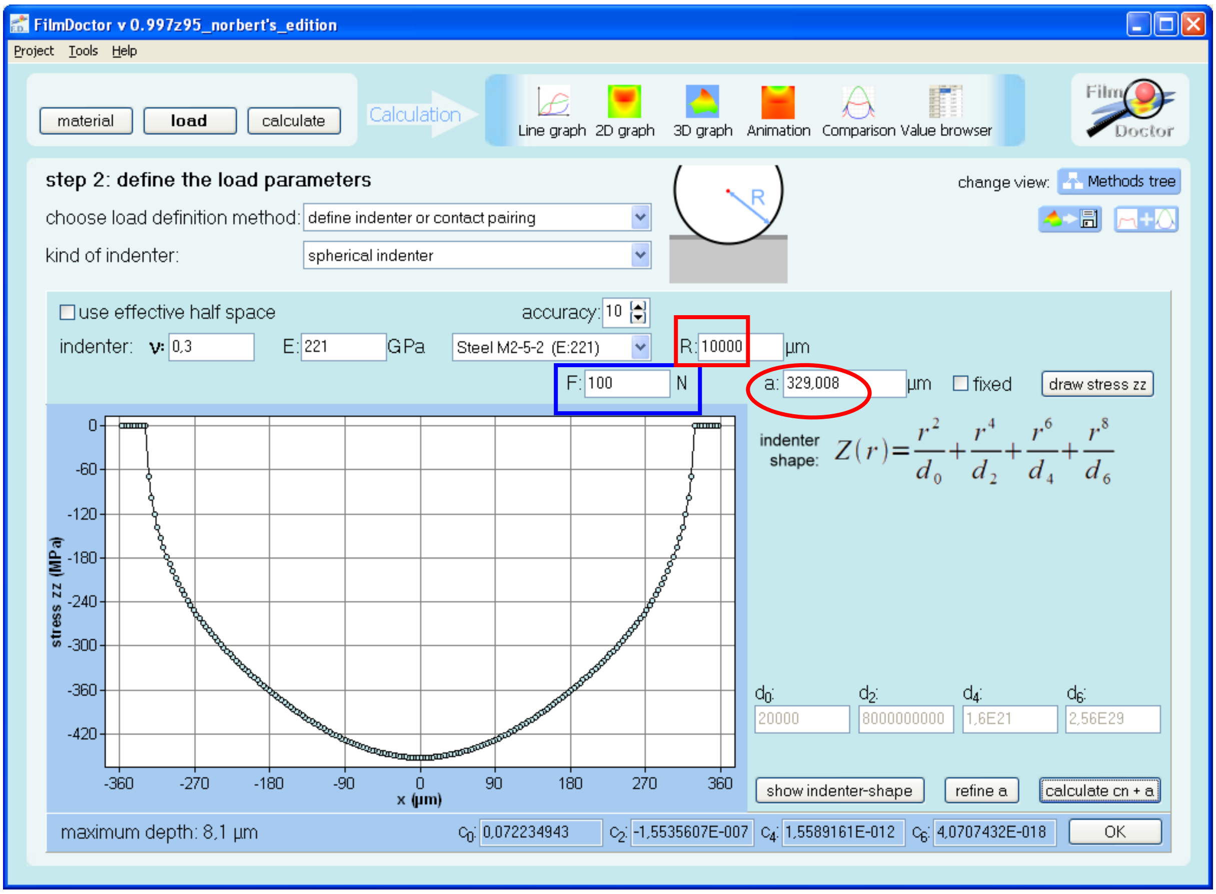


Fig. 3a: Evaluation of the contact load (radius and normal stress distribution) of a spherical 10mm steel indenter.

We apply a rather moderate load of 100N (blue rectangle) and find the resulting contact radius of a=329µm (red ellipse) and a relatively non-Hertzian surface stress distribution shown in the diagram in fig. 3a. Taking into account that usually the substrate (here aluminium sheets) is of limited thickness, too, does not change the stress situation on the surface significantly.

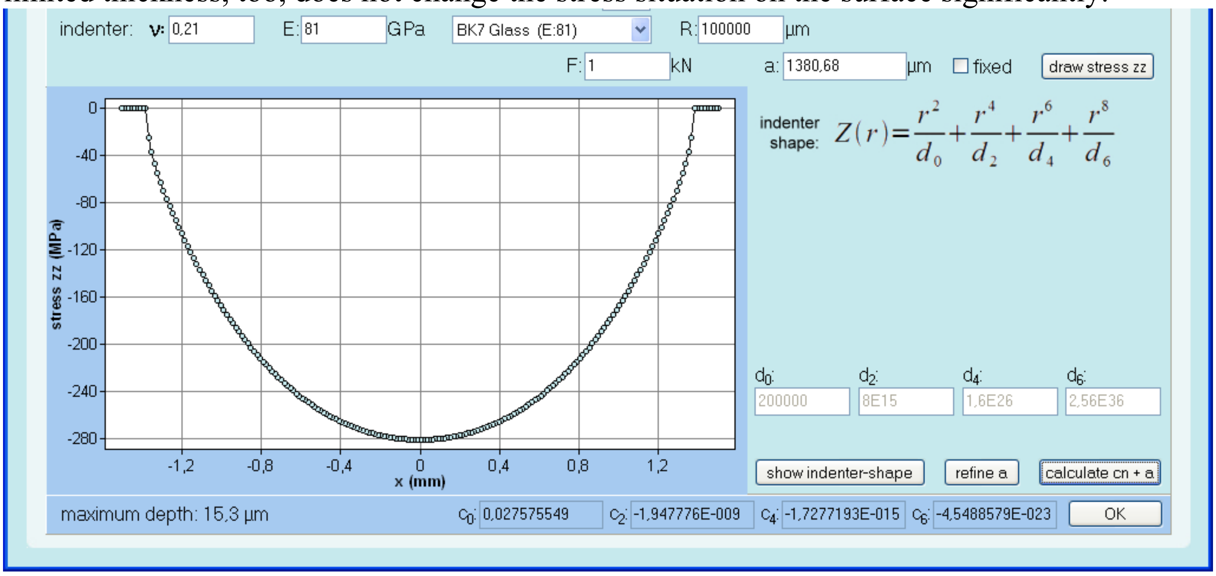


Fig. 3b: Evaluation of the contact load (radius and normal stress distribution) of a spherical 100mm glass indenter.

It should be pointed out here, that slightly different loading conditions, like e.g. a bigger indenter (even though still spherical) or a more flat one can cause much more peculiar (non-Hertzian) normal stress distribution due to the layered character of the structure (fig. 3b and

3c). This clearly shows, that pure Hertzian contact modelling usually does not suffice in the field of simulation of mechanical loads on varnish-structures.

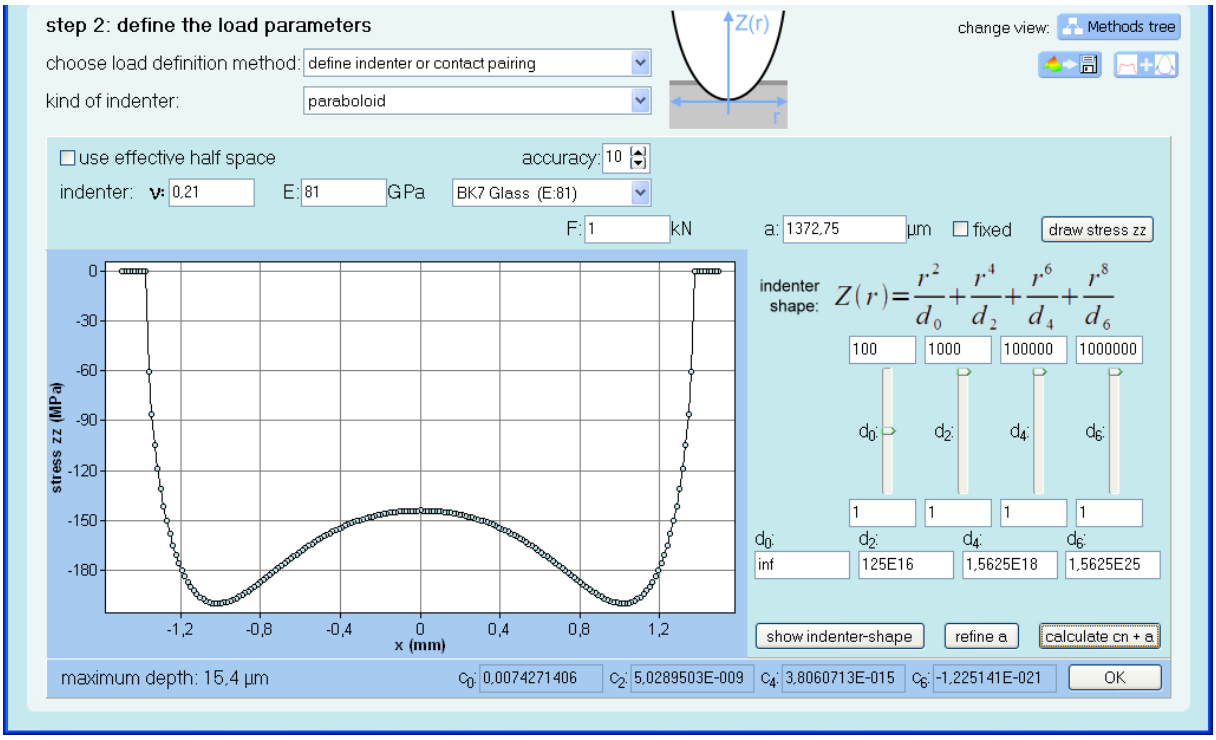


Fig. 3c: Evaluation of the contact load (radius and normal stress distribution) of a relatively flat indenter.

By pressing the OK-button we directly come to the calculation page and define the area for which we intend to evaluate the stress field.

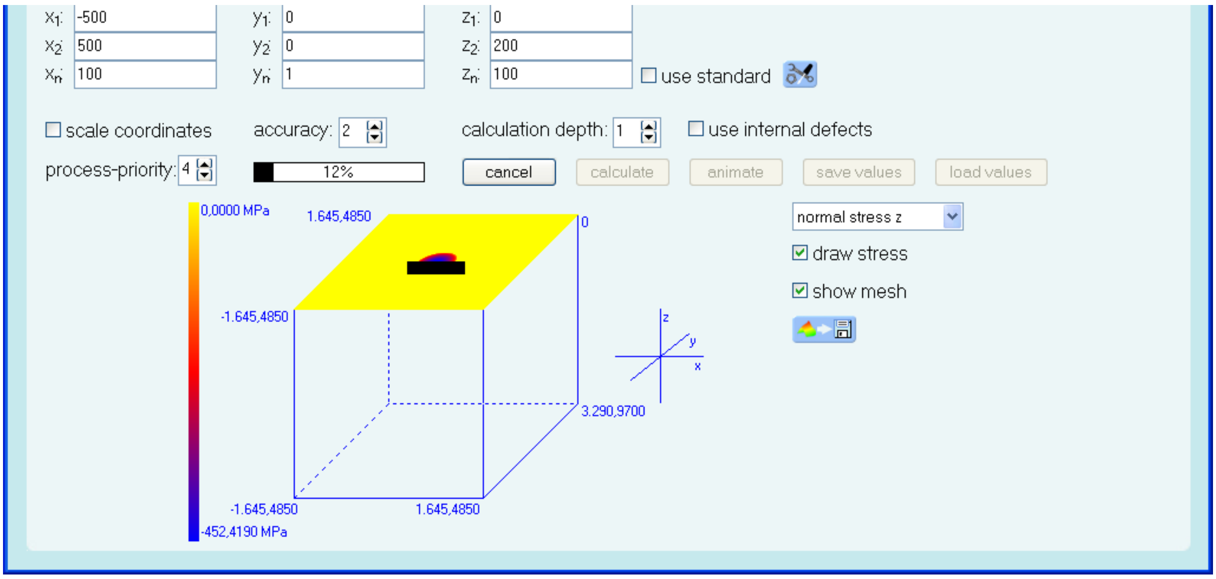


Fig. 4: Calculation-page: Setting the range of calculation of the complete elastic field (for the contact situation as given in fig. 3a).

Then the evaluation can be started by pressing "calculate"(fig. 4) and after only a few seconds the complete contact field with 280000 components is evaluated and ready to be investigated by the means of line-diagrams, 2D contour-plots and 3D-graphs.

Here we restrict ourselves to explore the field with the 2D-graph feature. From the view selector we select the important von Mises stress giving us hints where plastic flow might occur (fig. 5).

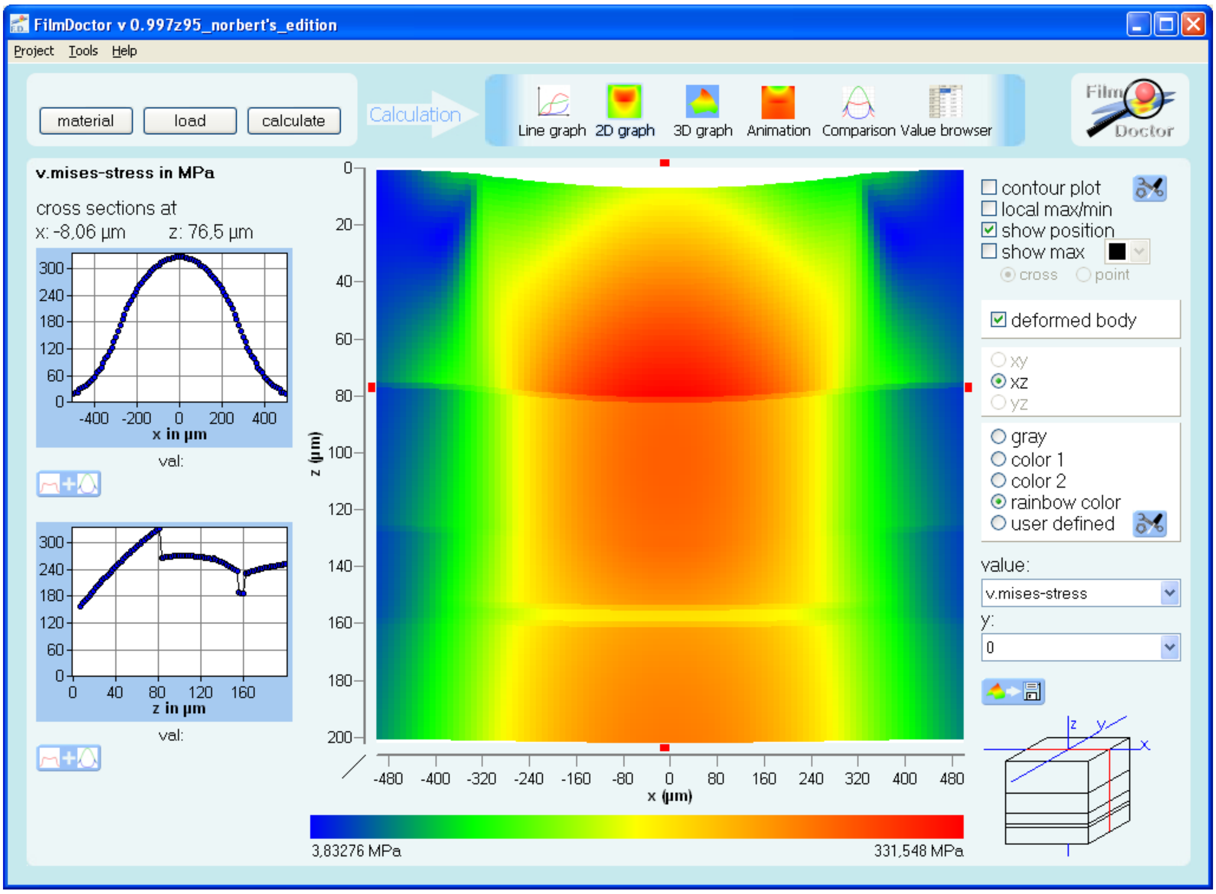
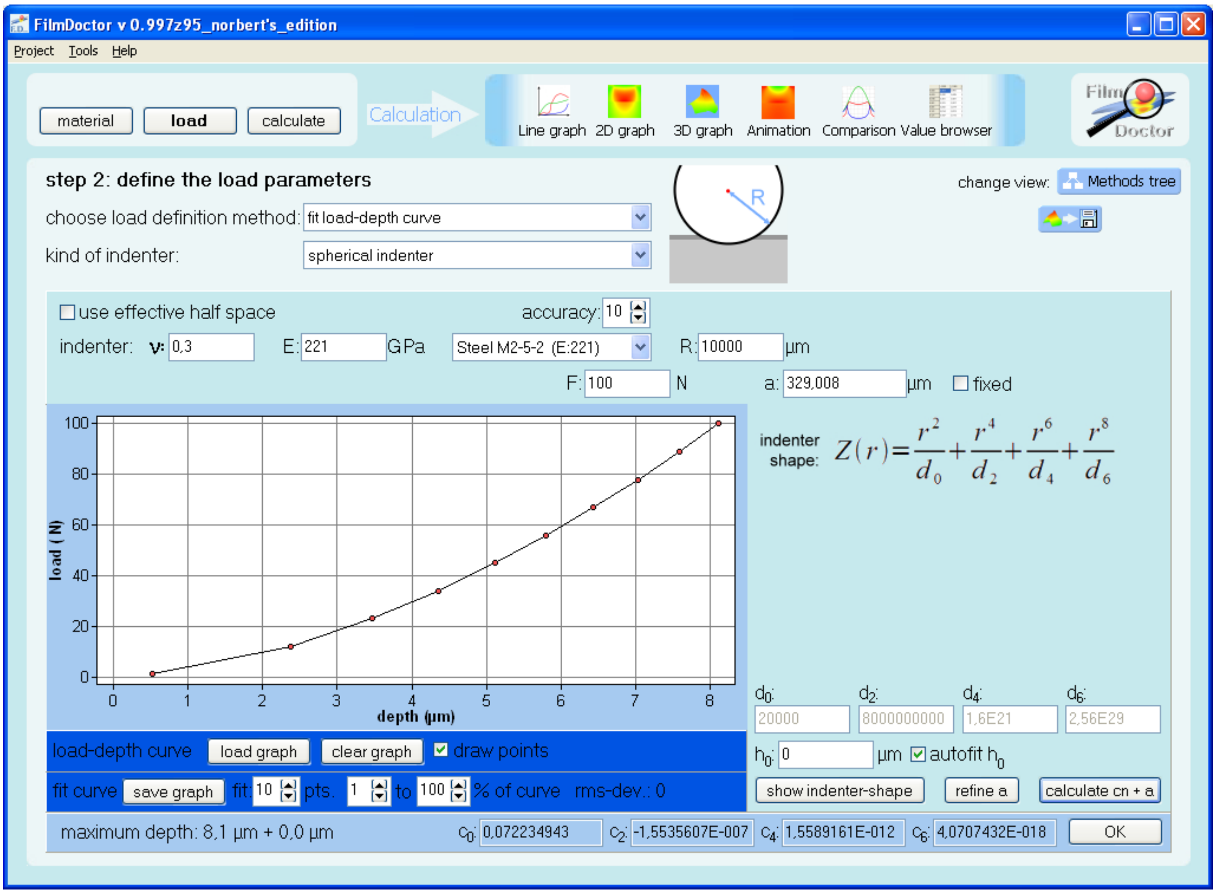


Fig. 5: Resulting von Mises stress distribution around the axis of indentation.

In fact we find one area in danger at the interface between the 1st and the 2nd layer (fig. 5). In order to study the stress development of this loading problem more closely, we go back to the load definition page and now chose "fit-load-depth-curve". There we evaluate a complete penetration-load-curve (fig. 6) for our 10mm indenter and let FilmDoctor evaluate the field development during penetration by simply pressing "animate" instead of "calculate" on the calculation page. We perform this evaluation for 10 frames. As there are now 2.800.000 field values to be evaluated the calculation takes about 5 minutes on a small laptop for this 5-layer system.



$$Z(r)=\frac{r^2}{d_0}+\frac{r^4}{d_2}+\frac{r^6}{d_4}+\frac{r^8}{d_6}$$

Fig. 6: Load depth curve, evaluated for a 10mm spherical steel indenter. Limited Al-sheet thickness was taken into account.

This time we look at the radial stress and show only 4 steps of the penetration process (fig. 7).

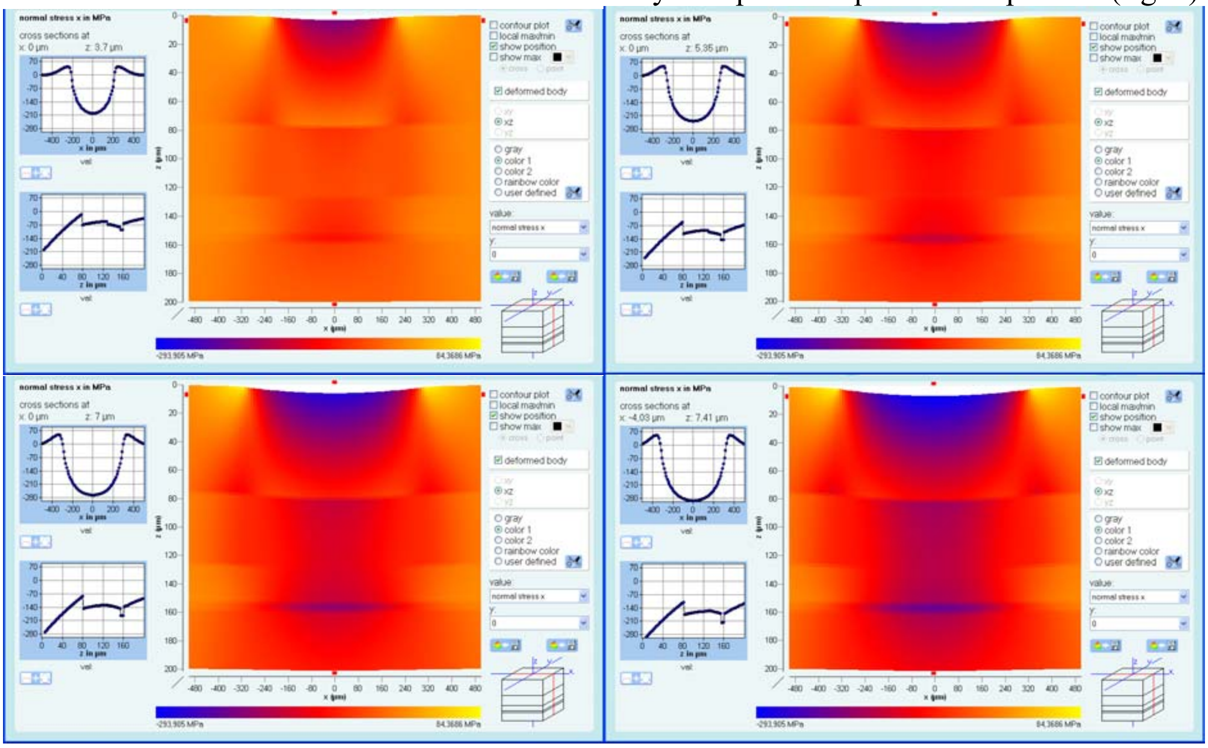


Fig. 7: 2D view of the radial stress development within the plane of intenter axis.

The next example shall show us the effect of an average hailstone with relatively high kinetic energy as they can occur during thunder storms, which will in future increase in number due to the climatic change. With the help of the impact-module in FilmDoctor, we find that a 5mm hailstone with 120km/h would indeed carry a rather threatening kinetic Energy (fig. 8).

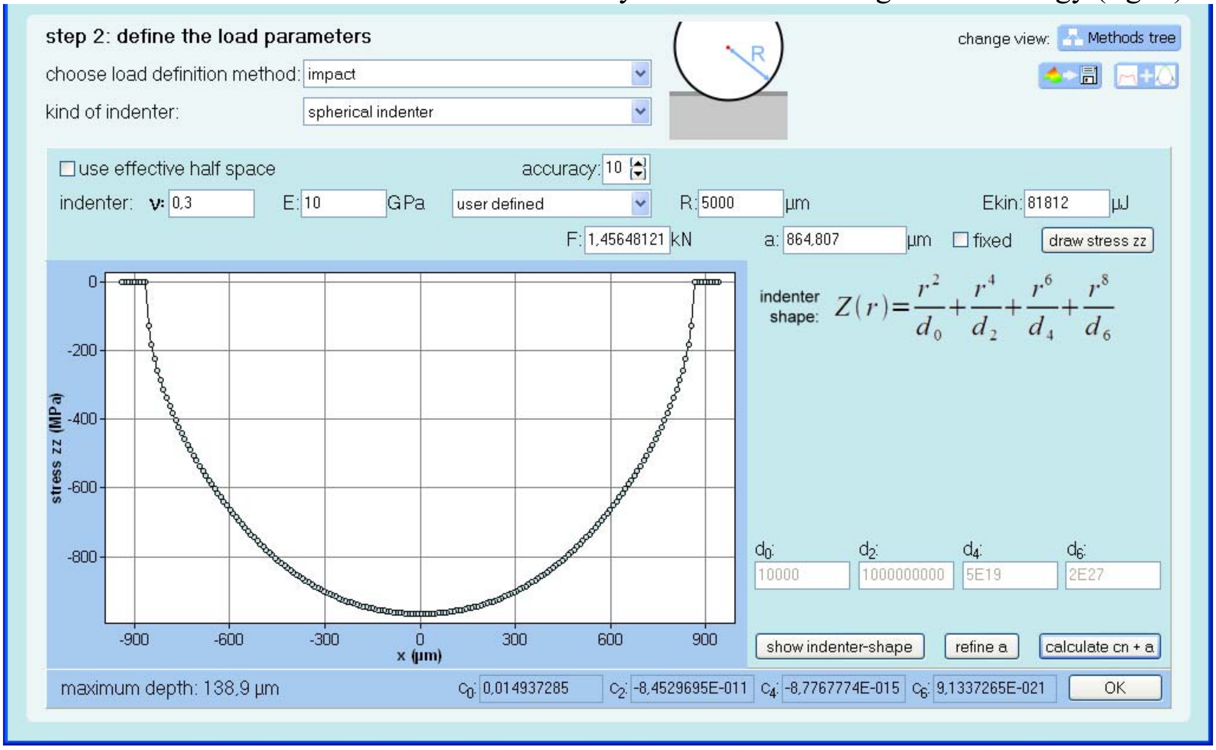


Fig. 8: Resulting normal surface stress for non-inclined impact of a hail stone with 120km/h.

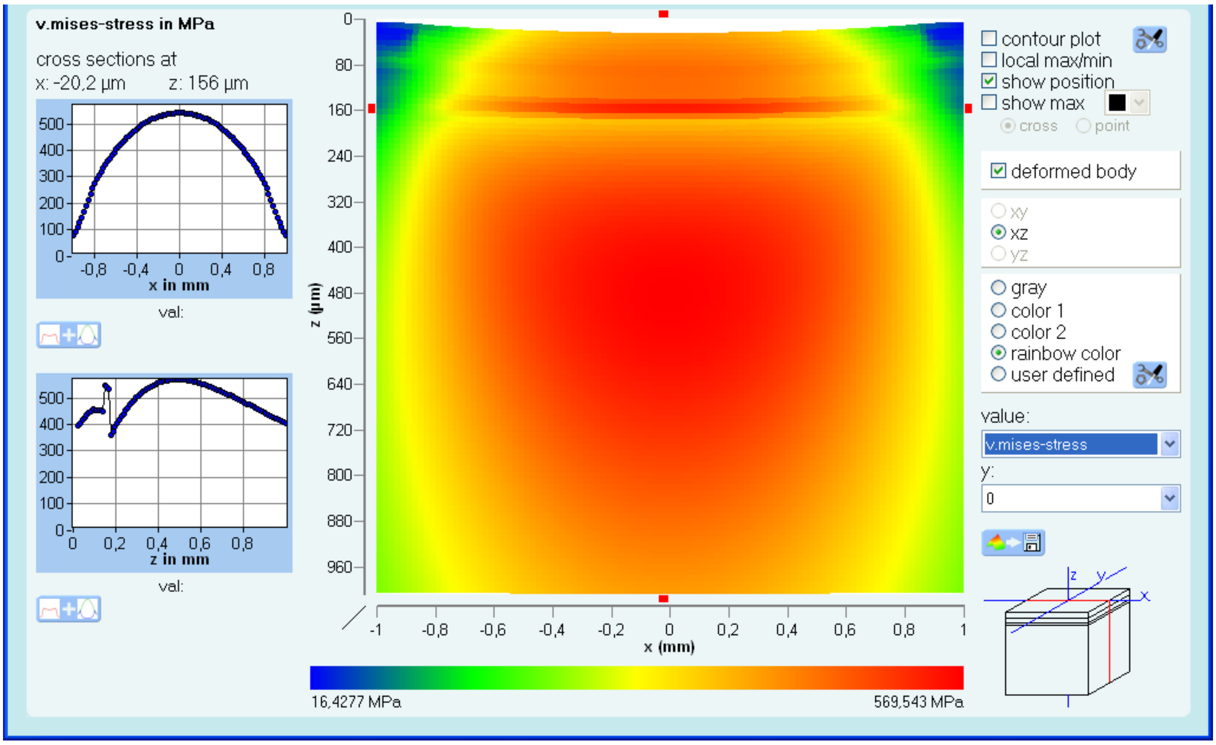


Fig. 9: Resulting von Mises stress shown in the scale of the impacting hailstone.

Thus, we already find critical stress distributions if we investigate the impacted area of our varnished Al-Sheet structure in the scale of the impacting hailstone, meaning around 1mm in radial directions and depth (fig. 9). By looking closer at the surfaces however, we also find tensile stresses near the contact rim with much too high values. The varnish-Al-structure would surely not survive such an impact (fig. 10).

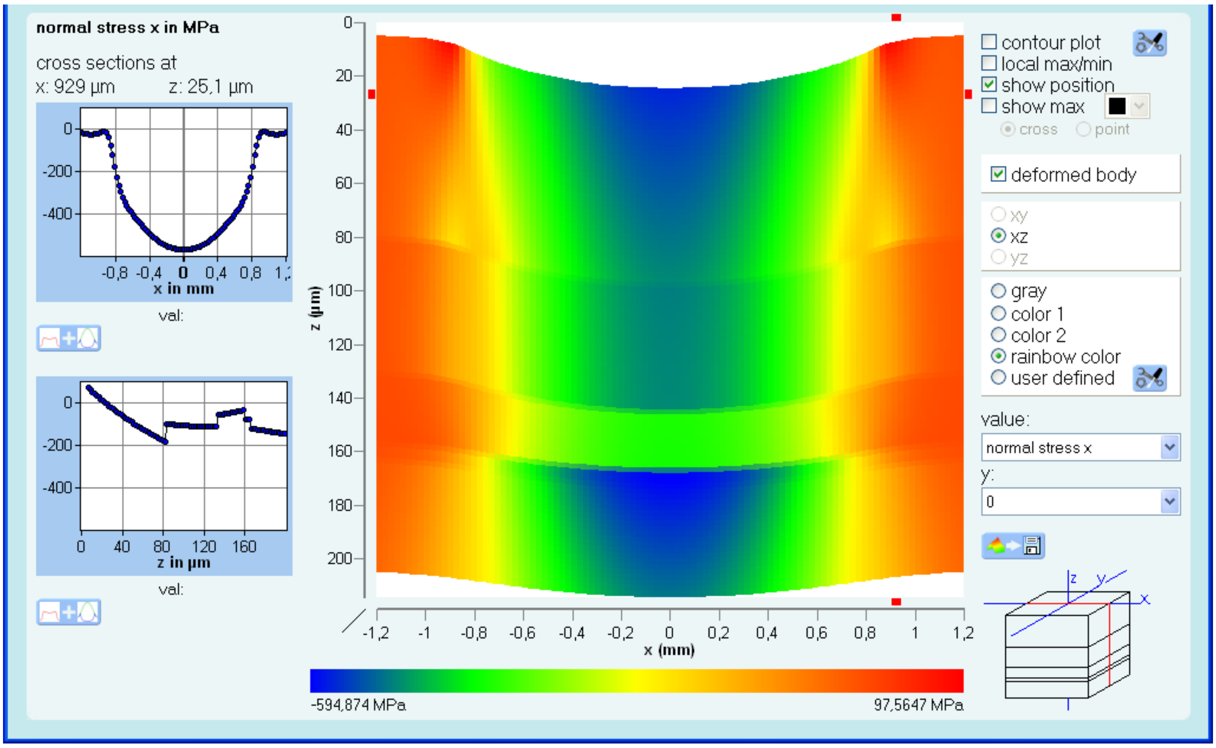


Fig. 10: Resulting radial stress shown in the varnish-contact scale.

The situation even worsens in the case of inclined impact, especially if a dusty or slightly roughened surface leads to some effective lateral and tilting forces in connection with the impact angel. In this case unbearably high tensile stresses can occur and either destroy the layer structure straight away or lead to initial damage causing failure later (fig. 11 and 12). We should point out here, that we have neglected some aspects of hailstone or droplet impact leading to additional tensile and high shearing stress components (caused by the hailstone or droplet burst often combined with cavitation), but as already the most simple impact calculation demonstrates us how critical such an impact can be, we have decided to consider such additional effects elsewhere [9].

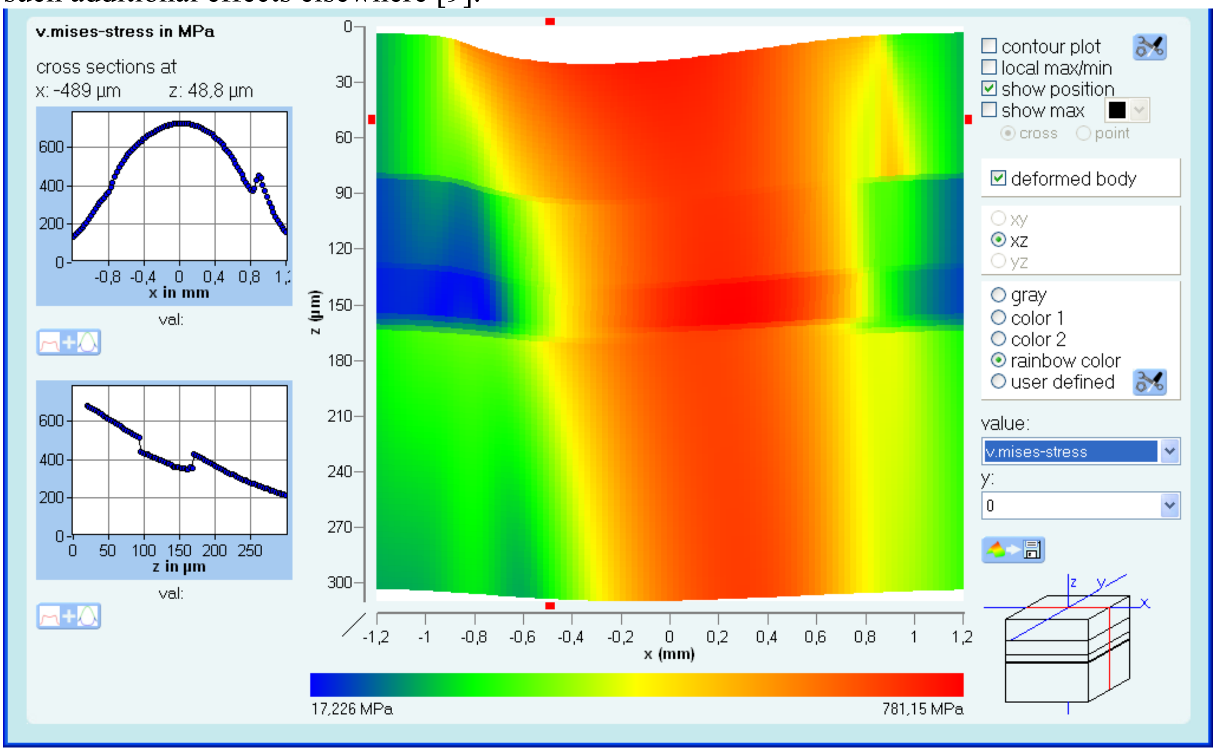


Fig. 11: Resulting von Mises stress shown in the contact-scale area for the case of an inclined impact situation.

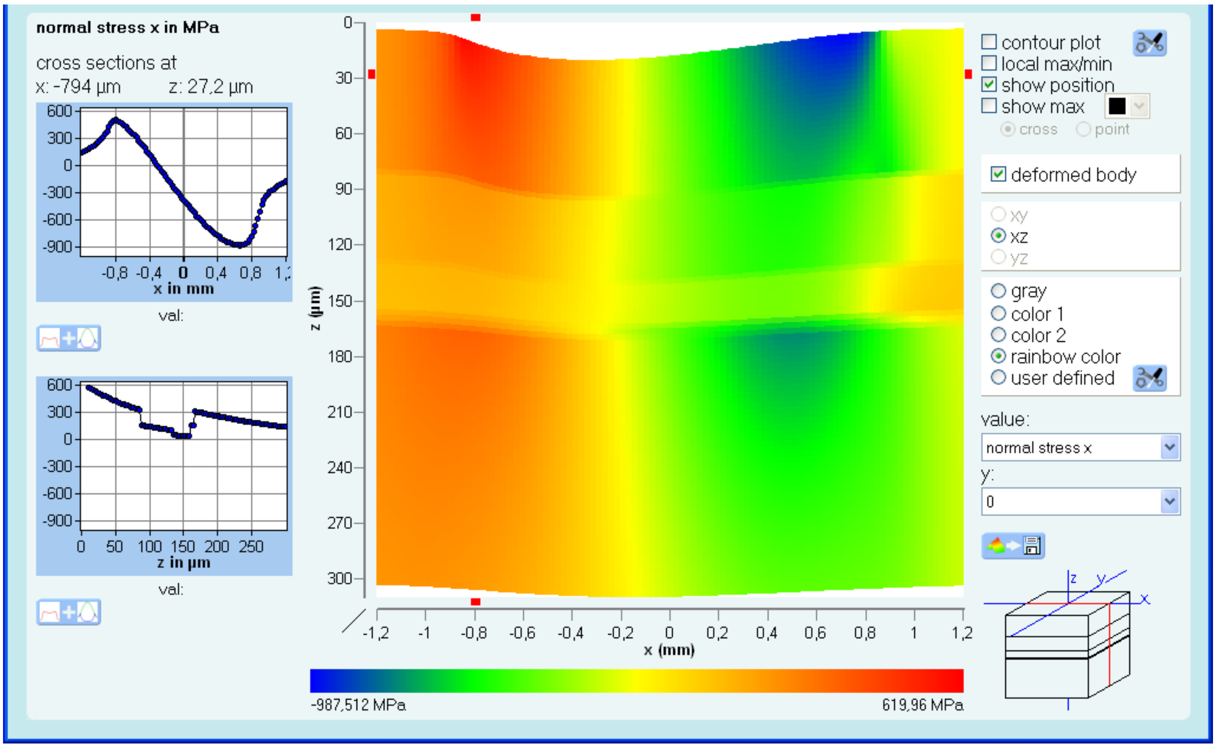


Fig. 12: Resulting radial stress shown in the coating area for the case of an inclined impact situation.

In the next example we will consider an apparently much less dangerous water droplet impact at a velocity of 600km/h. The resulting normal stress distribution for such an impact with a droplet of about 1mm (fig. 13) will not result in any critical stress situations due to its well distributed character. However, this is only the first stage of an impact. Within the second phase, where the droplet bursts, strong tensile and shearing forces can appear.

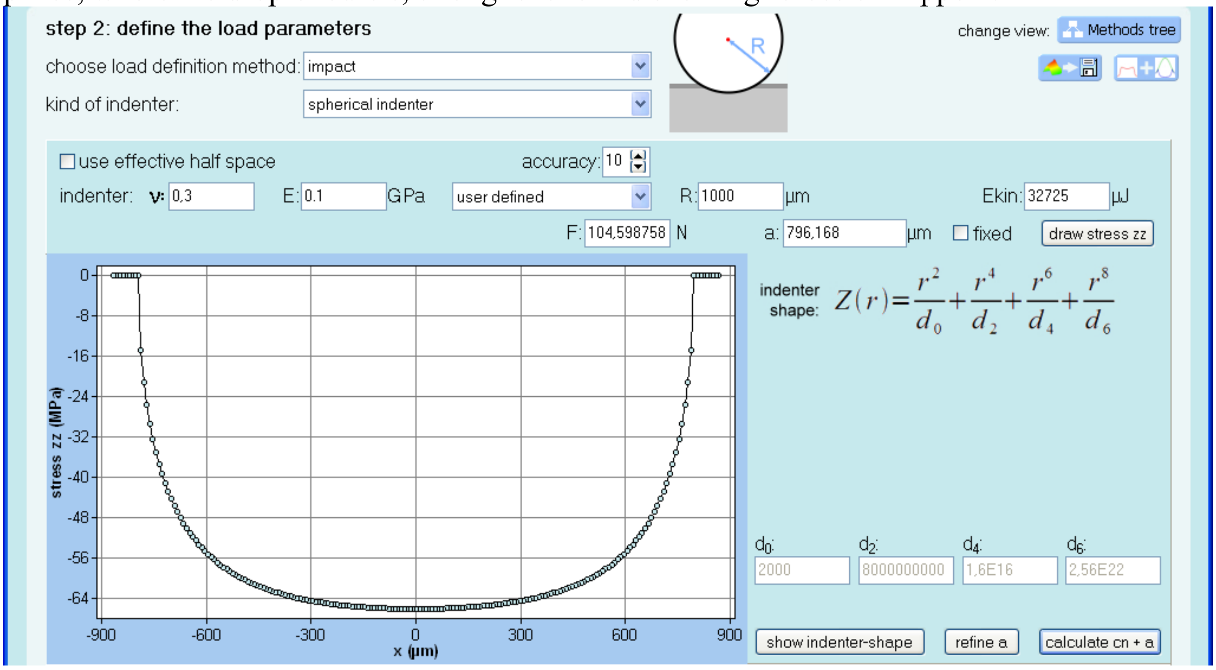


Fig. 13: Resulting normal surface stress for non-inclined impact of a water droplet with 600km/h.

Some physical evaluations would result in a mixed shear tensile loading, where the latter results from “snapping-off” forces during the cavitation-like droplet burst.

Within this burst phase both the radial stress (fig. 14) and the von Mises stress (fig. 15) would easily reach critical values leading to surface damage. In the figures 14 and 15 we also see, that the endangered region is directly on the surface, which also explains, why in droplet erosion one usually does not find Hertzian-like damage in depth, but material fatigue and wear straight on the surface.

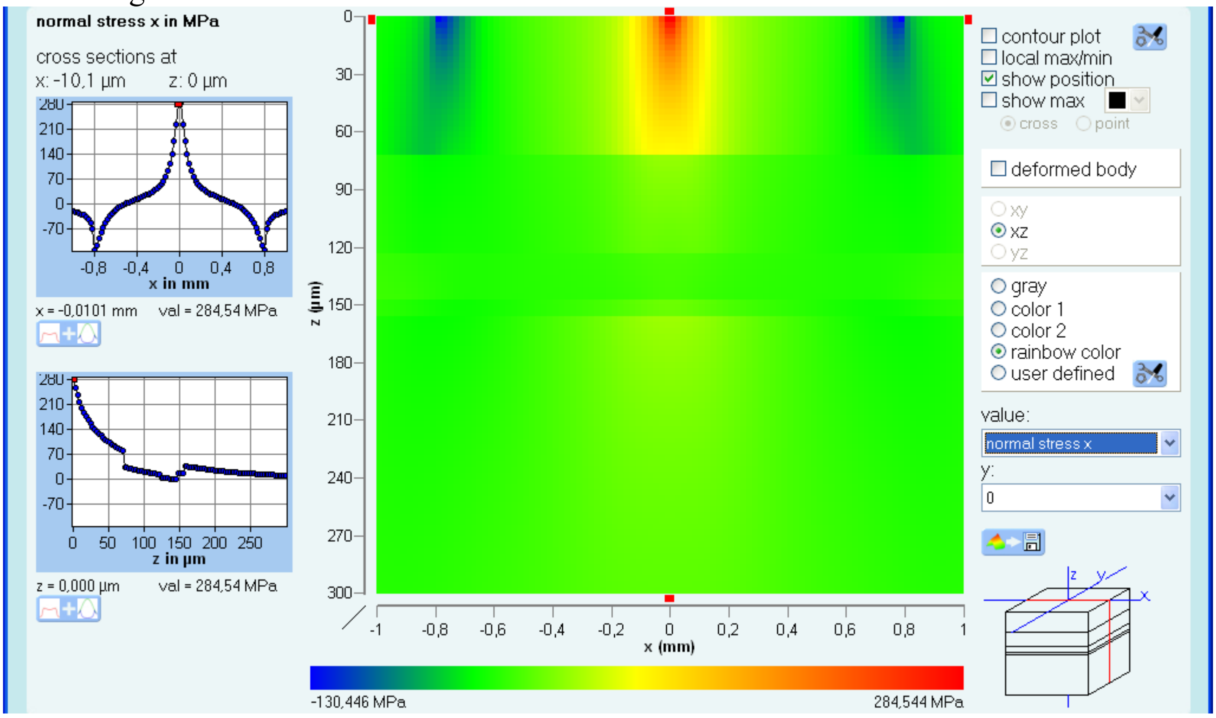


Fig. 14: Resulting radial stress for non-inclined impact of a water droplet with 600km/h during the burst phase of the droplet.

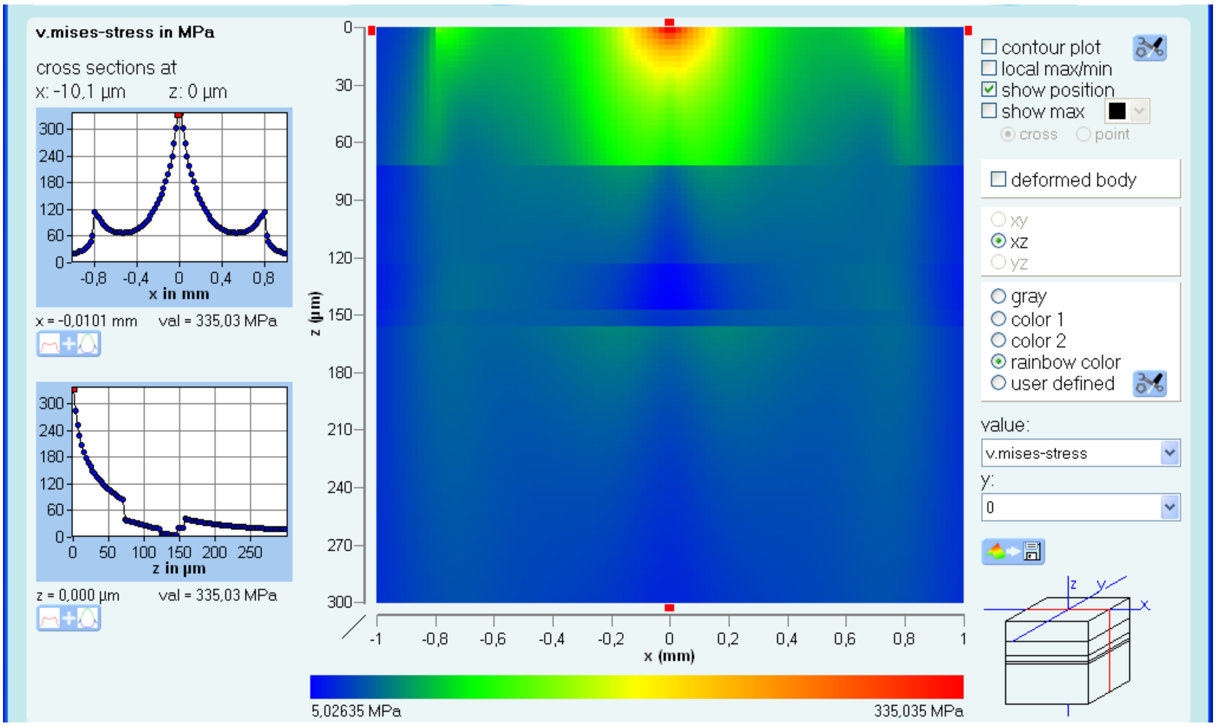


Fig. 15: Resulting vonMises stress for non-inclined impact of a water droplet with 600km/h during the burst phase of the droplet.

Another important but still often neglected aspect is that one of intrinsic stresses. Especially in thin varnishes intrinsic stresses are almost always part of the layered structures (mainly caused by the shrinking during the hardening process) and so they must be taken into account when the external loads possibly occurring during production, transport, installation and service time are simulated. This will investigated within a more comprehensive study [9].

References

[1] Aircraft Coatings: Internet-page of the company DETCO (August 2007)

[2] N. Schwarzer: "Elastic Surface Deformation due to Indenters with Arbitrary symmetry of revolution", J. Phys. D: Appl. Phys., 37 (2004) 2761-2772

[3] N. Schwarzer, G. M. Pharr: „On the evaluation of stresses during nanoindentation with sharp indenters", proceedings of the ICMCTF 2004 in San Diego, California, USA, also in Thin Solid Films, Vol. 469-470C pp. 194-200

[4] N. Schwarzer, T. Chudoba, G. M. Pharr: „On the evaluation of stresses for coated materials during nanoindentation with sharp indenters", Surf. Coat. Technol, Vol. 200/14-15 pp 4220-4226

[5] N. Schwarzer, T. Chudoba, F. Richter: „Investigation of ultra thin coatings using Nanoindentation", Surface and Coatings Technology, Vol 200/18-19 pp 5566-5580

[6] N. Schwarzer: "Analysing Nanoindenation Unloading Curves using Pharr's Concept of the Effective Indenter Shape", proceedings of the ICMCTF 2005 in San Diego, California, USA, also in Thin Solid Films 494 (2006) 168 – 172

[7] N. Schwarzer: "The extended Hertzian theory and its uses in analysing indentation experiments", Phil. Mag. 86(33-35) 21 Nov - 11 Dec 2006 5153 – 5767, Special Issue: "Instrumented Indentation Testing in Materials Research and Development"

[8] FilmDoctor: software for the evaluation of mechanical loading on monolithic and layered structures, www.siomec.de/filmdoctor

[9] N. Schwarzer: About the aspect of intrinsic stresses in connection with mechanically loaded varnish structures, to be published