Didactically optimized training tools for mechanical thin film design

P. Heuer-Schwarzer, ESAE, Am Lauchberg 2, 04838 Eilenburg, Germany, p.heuer@esae.de
N. Schwarzer, J. Schwarzer, Saxonian Institute of Surface Mechanics, Am Lauchberg 2, 04838 Eilenburg, Germany, n.schwarzer@siomec.de

Abstract

In the paper a variety of examples are treated demonstrating the need and the usefulness of training tools in the field of thin film optimization and contact mechanics. From the didactical point of view these training tools are sought to be optimized with respect to imagination (by the means of scale variation), association (arousing interest by finding relations to familiar things) and good visualization.

Preface

When the mechanical properties of a layered material shall be improved, the following three steps must be taken: First of all, the material needs to be characterized carefully with a suitable measurement instrument and an appropriate analysis software. It is a well known fact that the characterization of the mechanical parameters constitute the basis for a successful optimization. Nevertheless, many people do not pay enough attention to this matter and are often content with rather poor results. The very advanced measurement techniques and instruments that exist on the market need to be supported by didactically edited material such as training videos or audiovisual presentations to ensure that the user can apply the techniques efficiently.

In the second step, the exact use of the material must be analyzed. Is its surface exposed to small, sharp contacts or rather to large and blunt contact counterparts. The question about the mechanical loads needs to be answered as well as the kind of contact and damage that occurs. Those concrete contact conditions lay the foundations for a simplified model-contact-system that will, like an idealized experiment, illustrate possible solutions.

Finally, the optimization of the actual mechanical layer can be approached: The characteristics of the layer and surface can be designed in a way that the material is protected optimally against the mechanical stresses and contact loads that do occur during normal use.

The full understanding of these three steps contributes crucially to a successful mechanical thin film design. Thus, this paper will present a specialized didactic strategy for training tools for thin film design models, which include associations, motivate the user and is optimized with respect to the later application.

1 Introduction

If a product wants to be competitive on the much sought-after marked in modern society, it must fulfill, or even better, exceed the standard of similar products. Thus, the optimization of mechanical properties of a product becomes more and more important. But to optimize these parameters correctly, a lot of important facts need to be considered - one of these important things being the mechanical reliability and stability of surfaces.

Effective thin film mechanical design requires a great deal of initial consideration concerning the improvable material itself, its application, typical weaknesses in surface stabilities or failures and the resulting necessary optimization of the layers' mechanical characteristics.

In the present study the authors try to compile three examples of different cases and want to show a way of how to combine the analysis as well as the investigation process itself with didactic fundamentals. The reason for this study is that many manufacturers do not have a sufficient mechanical understanding and thus, often do not see the possibilities of potential product

improvement. Didactically edited material[1], that concentrates on the user-adapted features based upon associations [1], opens the door also for non-scientists and provide access to mechanical optimization tools like specialized software packages as described here.
The authors of this paper selected the following rather diversified examples to illustrate the procedure in a more general manner and elaborated these didactic tools:
Impact on laminate structures - didactic aid: scale variation for better imagination
Mechanical contact loads in dentistry - didactic aid: arousing interest by finding relations to familiar things
Contact modeling of rough surfaces - didactic aid: good visualization

2 Practical Examples

2.1 Impact on laminate structures

Impact loads are one of the main reasons for failure. Very often these problems are quite difficult to describe and initial breaks within a layer-substrate combination frequently happen in a scale of nanometers or even smaller. What can be done to illustrate the main idea and thus, to explain this problem to non-specialists is the following: We build an association to something bigger and already well known where we can find a similar or even the same problem in a bigger scale. Preferably, the chosen topic should be something generally known or of broad public interest. In the example of laminate structures, this link could be an apparatus where the same technical problem occurs - a windsurfing board for example. With this, the interest of the reader can be called.
As already the average windsurfer performs more and more radical moves, a windsurfing board has to withstand high impact loads while being light, maneuverable, stable and reliable at the same time [2]. The basic structure of a hard shell over a relatively pliant foam core suggests that we here can find similar conditions like for hard coatings.
In the following, two typical failure mechanisms are presented:

A failure after a hard contact with the windsurfer's body or the mast on the front part of the board (nose) due to a catapult plunge/crash

B failure after an impact load on the back part of the board (foot pad area) due to flat landings after high jumps.

Whereas in case A the main failure is initialized by cracks within the surface (Hertzian cone cracks: tensile stress at contact rim), the failure in case B occurs mostly due to laminate cracks which start in the interior right below the "indenter" but, compared to case A, at much higher loads (star cracks: tensile stress at the bottom of the laminate shell)[2].
This difference in the failure mechanisms is caused by the buffer effect of the rubber foot pads which protect the back part of the windsurfing board where the load is applied in case B [3]. Thus, as these failure mechanisms are also typical for all kinds of hard layers on soft substrates, the difficult to understand stress fields and their effects can be explained in a quite plain way. Thus, two failures that often occur in tiny systems are shown at an understandable example in a scale that people still can visualize and comprehend. In addition, as in the world of thin films the rubber foot pad would be

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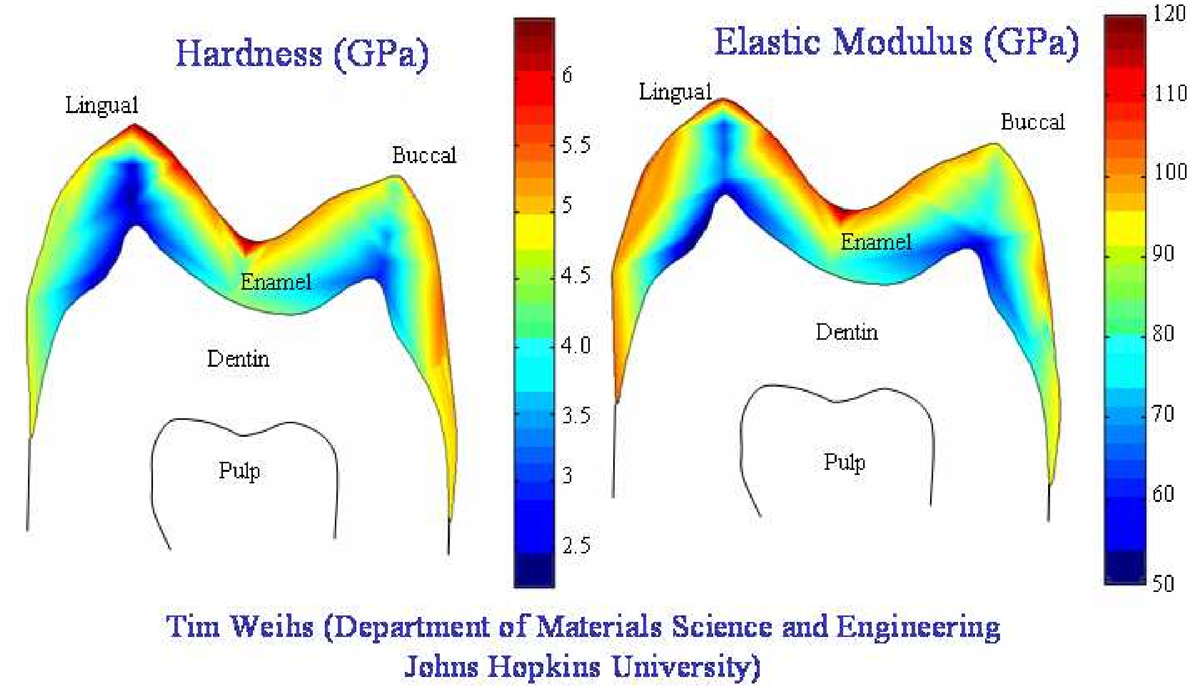
[1] such as documentations, help files or audio-visual training videos. Unfortunately, the authors do not have the possibility to present multi-media training tools within this printed paper. That is why the present study can only concentrate on showing ways of which didactic possibilities can be used additionally.

[2] For the description and visualization of the problem, good, vivid even animated, coloured graphics or pictures are necessary as didactic tools. As this conference publication is restricted in size and number of pictures, the didactic editing is complicated and not optimal so that the authors decided to put the informative pictures into online publications [2, 3] for the interested reader.

nothing else but an additional top layer the chosen example easily explains the influence of coating stack structures on the subsequent stability.

To sum up: it is a difficult task to explain nanometer scale impact problems to non-specialists. But as failure mechanisms of bigger laminate structures are quite similar to those occurring in all kinds of applications of hard-coating-pliant-substrate-compounds, it can be done easily by finding a subject to which people can establish a link and an association that changes the scale to a size that the human mind still can grasp.



Tim Weihs (Department of Materials Science and Engineering Johns Hopkins University)

Fig. 1: Mechanical parameters of a natural tooth [4]

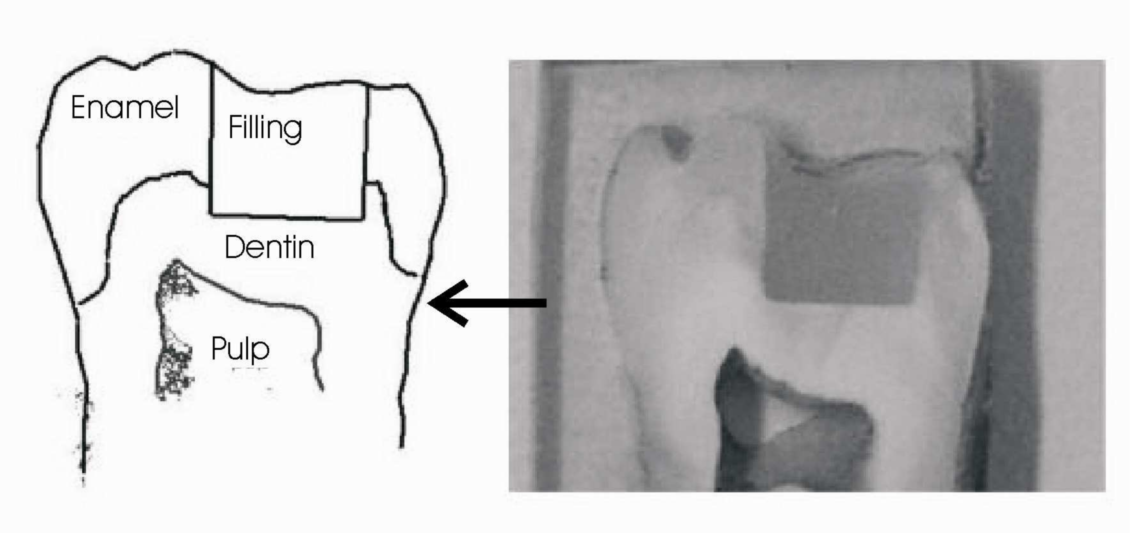


Fig. 2: Cut through a natural tooth with composite filling adjacent to dentin and enamel

2.2 Quasi-static mechanical contact loads in dentistry

Quasi-static contact loads are a second important reason for failure mechanisms and again, many things that break are very small so that initial damages (cracks, plastic flow) appear in tiny scales. The

intention shall be now to demonstrate the effect of two important mechanical parameters of a composite material, namely
hardness[3] and
Young's modulus
intrinsic stresses.

While the first parameter can be understood even by non specialists rather easily as a measure of how the material withstands external mechanical loads without suffering damage due to plastic deformation, the second and the third ones need some good elaboration and "didactic modeling" before they can be presented in a comprehensible manner. This time, the didactic aid is not the adaptation of scales to visualize the problematic nature, but another idea: we are searching for a subject that is not necessarily much bigger in size, but which arouse interest and appeals to the public. Like contact loads that occur everyday in every human body and which most of us can connect to painful experiences like, for example, visiting the dentist. Especially nowadays, in times of growing self-responsibility for ones health, many people care more and more about their body and thus, inform themselves about most effective ways to maintain their health as long as possible. That is why “dentistry” seems to be suitable for discussing some difficult questions coming from the field of contact mechanics.

Fig. 3: Yield strength of a variety of filling materials [5]

The enamel of the teeth is the hardest substance in the human body and needs to withstand very high mechanical contact loads in the course of a man's lifetime. Biting and chewing food, as well as gritting the teeth are the main loads that a natural, inhomogeneously structured tooth must withstand. It is since the end of the saurian age that nature invented lateral masticatory movement - a technique that simplifies the crushing of our food, but leads to very complex mixed loading conditions and high shearing stresses that demand a very high surface stability of our teeth.

But what if the natural hard and protecting enamel and the dentine are damaged as for example due to "caries"?

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[3] from the theoretical point of view it would be better to use yield strength instead of hardness because the latter very often is a mixture of several physical parameters, while yield strength can be clearly defined

The dentist can repair the damage with fillings. So called "composite materials" with nano-particles have been introduced lately for this purpose. The reasons are simple and convincing:

a) the materials are easy to handle
b) they are non-toxic
c) they are chemically and mechanically stable
d) they can be fitted according to the color of the human tooth in a rather perfect way (cosmetics).

Unfortunately, this artificial substitute does not fulfill completely the same physical and mechanical parameters as the natural material: whereas the natural tooth is built up in an inhomogeneous way so that there is a perfect transition from the inner soft pulp (living and tender material) to the hardest part of the tooth, the enamel (see fig. 1) [4], none of the existing filling materials do provide such a transition. Instead, they are put into the cavity within the damaged tooth as one uniform, macroscopically (mostly) homogeneous block (see fig. 2). If such a structure would be now exposed to mechanical loads all interfaces where we find high differences between the Young's moduli of tooth material and composite would produce interface shear stresses. This automatically leads to a stress amplification with subsequent interface failure due to fracture followed by the growth of gaps and finally a higher probability of secondary caries. In addition, the filling shrinks during the process of hardening (polymerisation) which produces tensile stresses and weakens the mechanical stability with respect to contact loading.

Here, the engineer could learn how nature has solved the problem of adapting material properties to the external loading conditions by "inventing" gradient structures (figure 1). As a recent study showed [5], the stability and reliability of the filling and thus, also the tooth prepared with it, depends dramatically on the filling material used by the dentist. Nanoindentation experiments brought to light, that even the age of the composite material and the way of filling a tooth have an effect on the final result and durability (fig. 3). For example, if the ideal dentist chooses to follow nature and prepares a bigger filling in a layered fashion he can, to some extend, improve the mechanical reliability of the resulting filling because he reduces the intrinsic filling stresses caused by the shrinking during the polymerisation procedure.

However, compared to other mechanical parameters of a human tooth (Yield strength Y and Young's modulus E), all investigated filling materials end up far below the desired values of enamel (Y_{enamel}=2.66GPa, E_{enamel} up to 120GPa, while “Grandio” the best filling very recently investigated [5] could provide only $Y_{Grandio}$=0.893GPa, $E_{Grandio}$=19.23GPa) (for other fillings also see fig. 3 and [6]). We see, the problem of interface failure due to mechanical loads combined with high differences of the Young's moduli of the joining materials can be illustrated at an example that is anybody's business. So, not being able to reduce the complexity of the principle physical problem of intrinsic and interface stresses we rouse the interest and understanding for this complex field by associations that everybody can imagine and probably has experienced first-hand. Due to the restriction in pages we can not comprehensively discuss and visualize the stress field effects within this paper, but as intended we demonstrated that we find similar problems to thin film structures in completely different applications being more “down to earth” and thus easier to comprehend for a non-specialist.

2.3 Contact modeling of rough surfaces

There are examples, however, where a change of scale is problematic and where finding a practical association depends dramatically on the group of customers or persons that should be addressed. An example is rough surfaces where mechanical contact happens only within very small scales. An appropriate didactical aid here could be a good visualization of the problem so that one can understand and literally "see" what processes take place during such a contact.

As mentioned above, it is important to adapt the example to the target group for which the problematic nature of this subject should be explained. As demonstrated in section 2.2, a good example from the engineer's store of experiences must be found and finally fitted. In a general case we could imagine the example of joints within a human body (rough contact surfaces of the gristly surfacing of our knees, shoulders, hips or ankles). But as this association would go beyond the scope of this paper, we will only concentrate on the didactic aid of a good and memorable visualization. By applying simple mathematical tools, rough surfaces can be visualized easily (see fig. 4). Concerning the mechanical consequences, however, it is important to explain clearly, which concrete geometrical pairing might occur. Considering only normal loads in the case of rough contact conditions, we can define a worst case scenario and a best case scenario [7]. Whereas during the worst case situation, the peaks of both contact bodies touch directly (see fig. 5) and thus, result in higher stresses, the best case situation, visualized in fig. 6, shows a perfect "interlocking" of the counterparts.

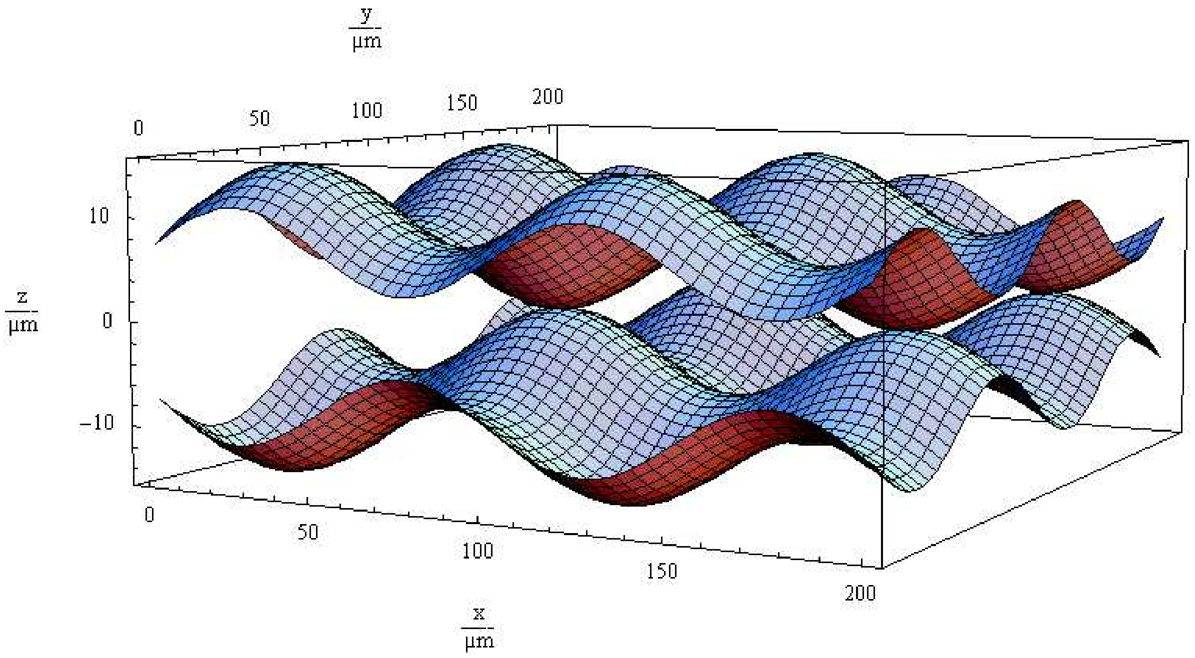

Fig. 4: Simple example for two rough surfaces in contact (equal roughness)

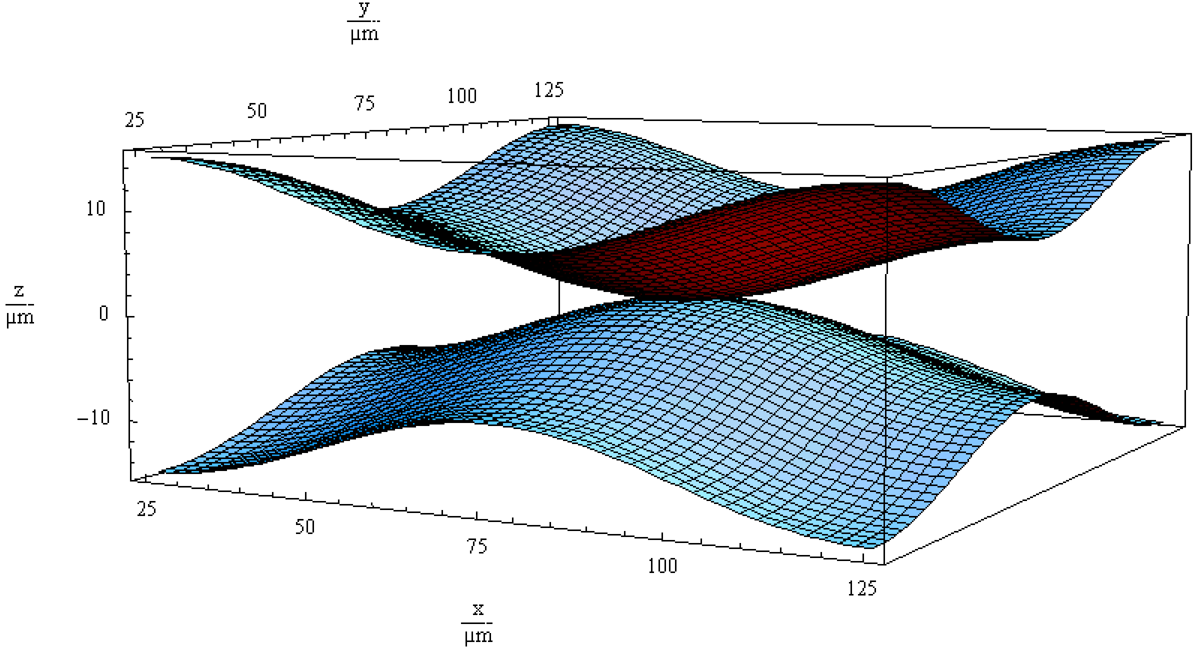

Fig. 5: Single contact - worst case situation. Total load F=9.5N.

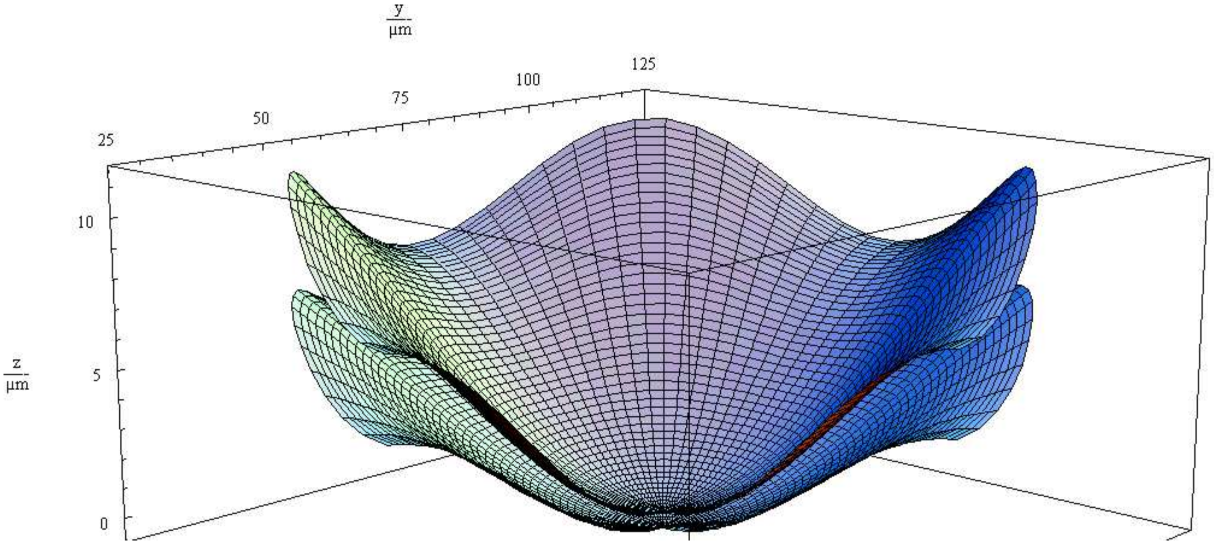

Fig. 6: Single contact with conforming contact conditions. Total load F=9.5N.

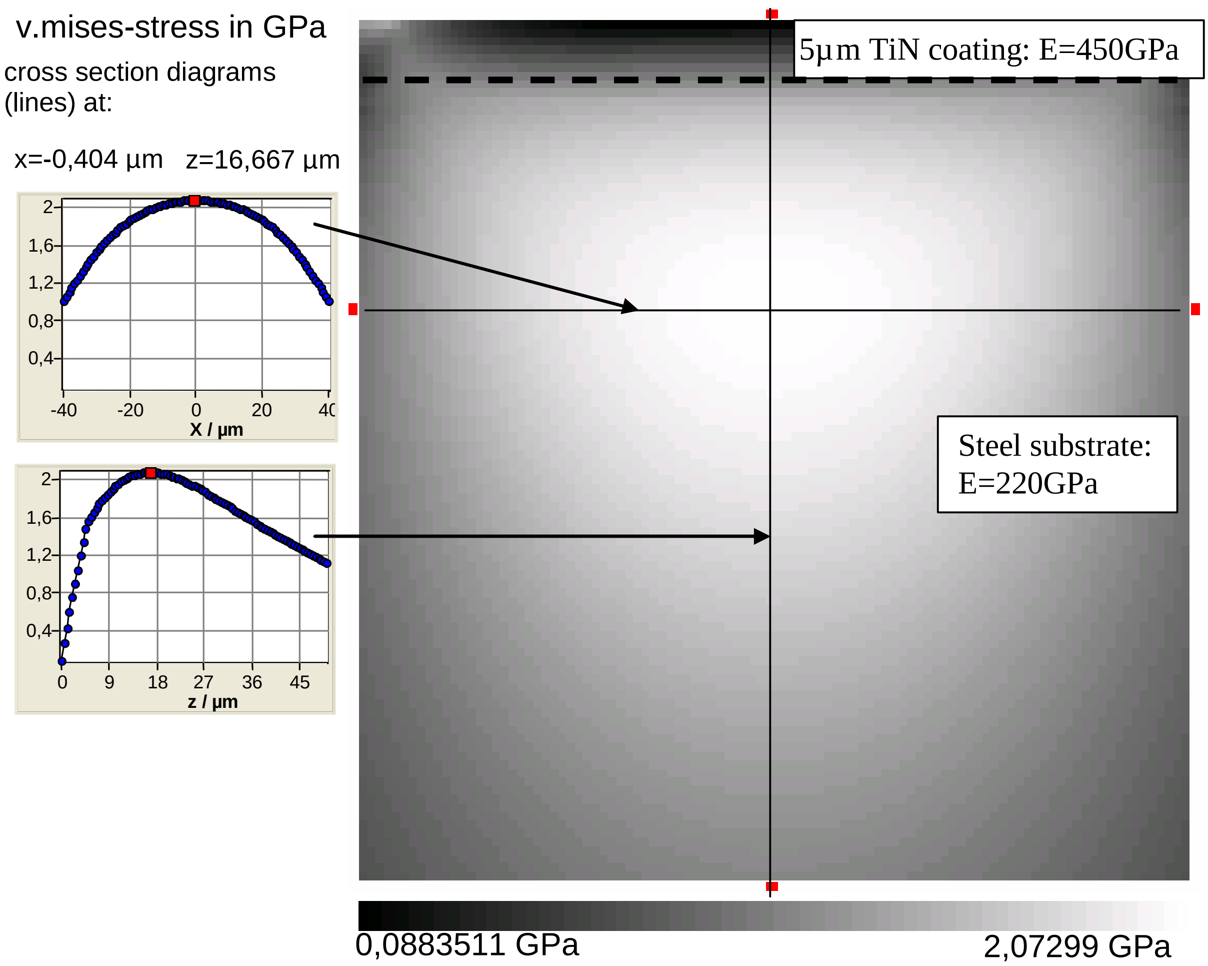

Fig. 7: Resulting von Mises stress distribution for a single contact with conforming contact conditions according to fig. 5. The evaluation has been performed using a prototype of the Software package "FilmDoctor"[8]

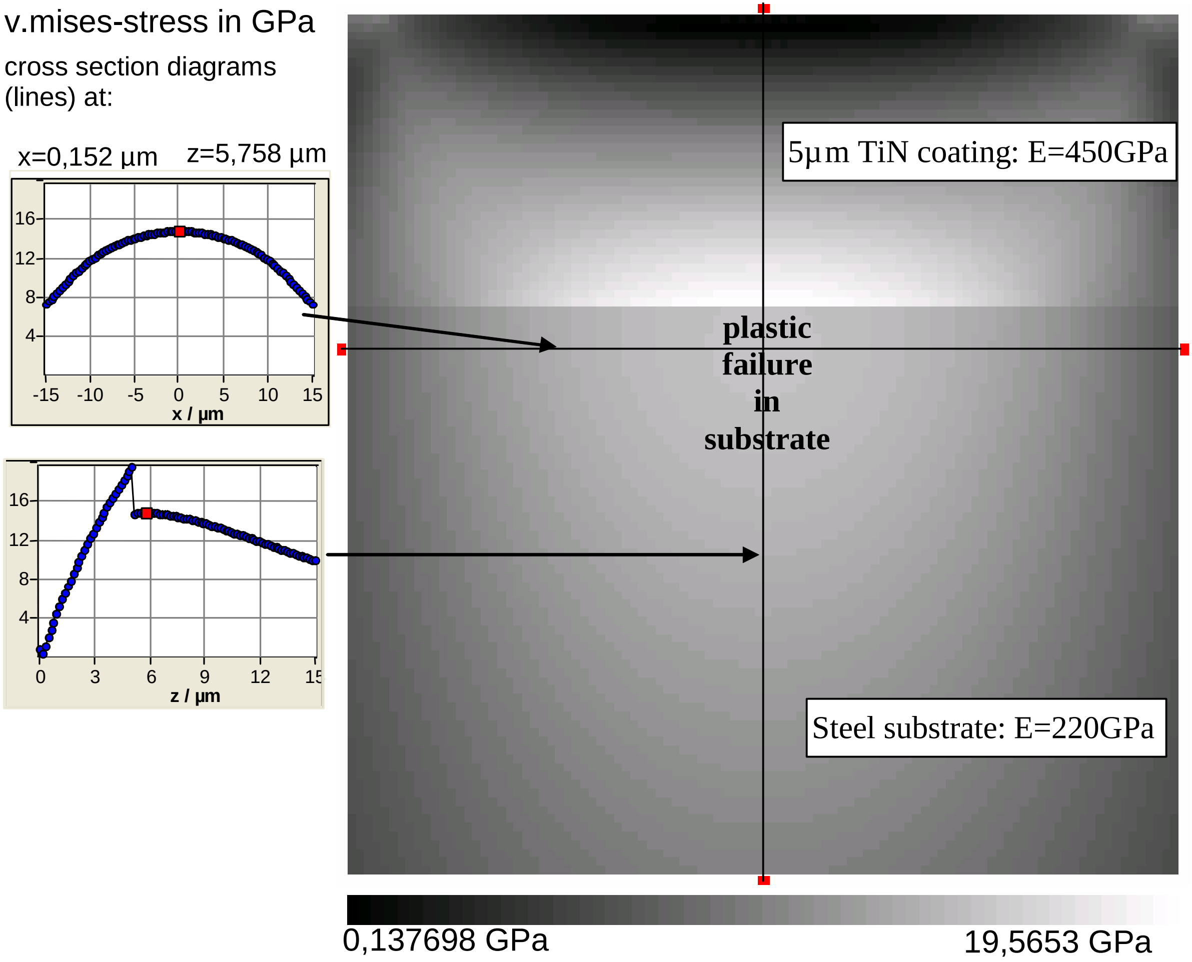

Fig. 8: Resulting von Mises stress distribution for a single contact with ideal asperity tip contact conditions according to fig. 4. The evaluation has been performed using a prototype of the Software package "FilmDoctor" [8]

An evaluation graphically presented with the help of specialist software can show how big the differences in the von Mises-Stress of both extreme contact conditions are (see fig. 7 and 8).
We can see that even complicated and complex mechanisms can be presented in a way that non-specialists can understand or at least re-enact them in their mind.

3. Conclusion

As we have seen within this study, many subjects in the field of mechanical thin film modelling - as difficult as they might be - can be presented in a clear and understandable way if it is only combined with didactic tools and aids. An additional task that needs to be considered is the one of the final form of the problem's presentation: It is always advisable to select a medium that does not only concentrate on one stimulus but combines more of them - like for example acoustic and visual senses. The medium of the choice therefore are audio-visual presentations. With them, the non-specialist can see animated pictures, hear explanations and read instructions in an entertaining and easy to remember way. The three didactical aids explained within the present study, however, serve as basis for a good preparation for such videos or training documentations. Concerning contact mechanical problems involving thin films, one should always bear in mind that:

A) choosing an appropriate and imaginable scale
B) finding a suitable association
and C) selecting the best way possible to visualize the subject

are most important for making topics accessible to somebody who knows little about it so far.

4. Acknowledgement

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