INDUSTRIAL/COMMERCIAL USE OF NEUTRON DIFFRACTION FOR RESIDUAL STRESS ANALYSIS

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1. GENERAL REMARKS

The determination of residual stress within the volume of an industrial component is of special interest during the optimization phase of production processes and sample design to validate materials, components and process models. Similar questions often occur during failure analyses to prove hypotheses about the origin of damage.

The diffractometric residual stress determination is the only quantitative method to evaluate the averaged 3-dimensional strain tensor within the sampling volume defined by the instrumental setup. Assuming the validity of experimentally found diffraction elastic constants together with the ideal elastic behaviour (Hooke’s law) of the material, a quantitative determination of the 3-axial residual stress tensor is feasible. Thus diffractometric methods can be looked upon as the reference techniques for the entity of residual stress determination tools and structure-mechanical simulations.

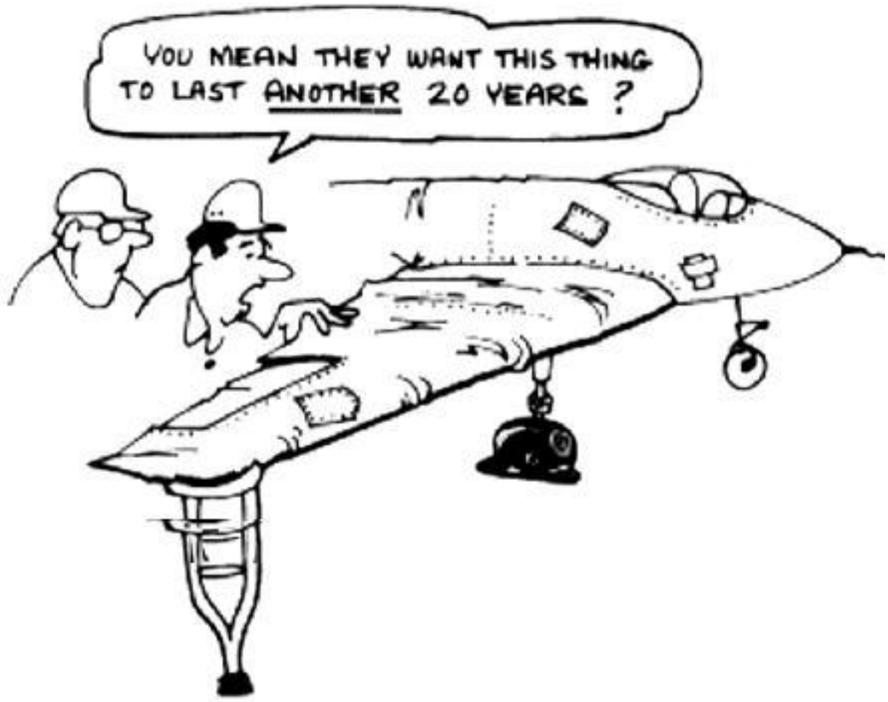
Fig. 1. The dedicated residual stress instrument StressSpec at the research reactor FRM II in Garching, Germany, with a huge impeller on the sample table.

Due to the limited neutron intensity available at research reactors, the maximum spatial resolution accessible, given by the gauge volume size and the neutron beam divergence is limited. Thus the spatial resolution needed to determine steep stress gradients within the near surface region, extending to the first millimeter, due to surface treatments like shot-peening, grinding, etc., can usually not be provided. Here it makes no sense trying to compete with the synchrotron diffraction method that is especially able to provide high resolution stress gradients within the first millimeter below the sample's surface.

But stress gradients that range down to several millimeters below the surface caused by induction hardening, deep-rolling, thermal processes, etc., are generally only achievable by neutron scattering. Neutrons, together with synchrotron radiation and laboratory X rays, can serve as the non-destructive tool to determine stress gradients from the surface to the volume of highly loaded industrial parts.

2. NON-DESTRUCTIVE TESTING — A TOUGH TASK

Neutron diffraction is a non-destructive testing (NDT) tool that provides quantitative values for three-axial strain tensor averaged over the sampling volume. NDT plays a big role within the industrial production process, especially in monitoring, as well as for component maintenance to prove structural integrity and to ensure reliability and safety. Structural health monitoring systems have to be mentioned in addition.



During the 1970s and 1980s a large variety of NDT tools have been developed, driven by the nuclear power sector. These methods are well developed for the investigation of components made of steels and metals in general. Here ultrasound, eddy current and micromagnetic (Barkhausen noise) testing have been developed successfully. These are standard tools in industry today. But they always have to be re-calibrated when materials or geometry variations change the relationship between the parameter in question, e.g., stress value, and the parameter accessible by the NDT tool, e.g., velocity of sound. Today there is a strong need for the development of NDT tools for polymers and especially composites. The latter, like fibre reinforced polymers, metal matrix composites are microstructured materials that exhibit a much more complex fatigue and degradation behaviour than steels, which can be treated like a continuum. For these types of materials the currently existing models are still not developed far enough to enable reliable lifetime predictions of components even assuming a completely known component structure, stress distribution, pore distribution and so on. Thus to avoid very conservative decisions, the "effects of defects" have to be studied in detail. Based thereupon, a second model has to be developed, an NDT tool calibration model describing the relationship between the defect or local material parameter of interest and the measured parameter by the NDT tool in use.

Therefore reliable non-destructive lifetime predictions are based on two models, one describing material or component behaviour depending on its structural characteristics and the second describing the NDT probe’s interactions with the component structure. Both models require reference methods for quantitative analyses of the component structures to be used for validation and for calibration purposes. These tasks are marked by the fact that the immobility, slowness and costs of a method are of secondary importance. Here the major focus lies on reliability and availability of quantitative results together with adequate spatial resolution. Here neutron and synchrotron methods are playing a key role for the determination of urgently needed reference values. For this purpose it is even acceptable to cut a sample into smaller pieces in order to reduce neutron or photon path lengths within the material as well as the required beam time. However, especially for the determination of stress, it is very important not to influence the local stress tensor within the volume of interest by sample cutting.

To summarize, neutron methods should not try to compete with well-established NDT tools due to their immobility, their high operational costs and the small number of available neutron sources and dedicated instruments. But they can be used to achieve the reference data for validation of material models and for calibration of conventional NDT tools. This results in an enhanced reliability of lifetime predictions, enabling less conservative quality control decisions without reducing the degree of safety. Finally the appropriate use of neutrons as a reference method can be really cost-effective for commercial users.

3. TYPICAL SAMPLES AND RESULTS

Typical samples successfully investigated by neutron diffraction to determine local stress states are crankshafts, pistons, turbine blades and wheels, impellers, shot peened components and welds. Usually the error bars of the stress data are larger than 25 MPa mostly due to a bad conditioned signal-to-background ratio. Aluminium parts usually are marked by large grains, demanding large gauge volumes to fulfil the powder condition. Thus the possible spatial resolution is significantly reduced. Very often no remarkable stress distribution is found. Titanium based alloys don’t reveal deep insights into the sample’s 3D stress distribution due to titanium’s strong incoherent scattering background. Finally, for the determination of the stress-free lattice distance, small rotating cubes and combs nearly filling the gauge volume are the first choice.

3.1. A truck crankshaft — tensile stresses at inner surfaces

To improve a crankshaft’s lifetime induction hardening of the bearing zones is usually applied, leading to a martensite and compressive stress formation within the first millimeters below the bearing surface. But as is commonly known, compressive stresses develops with tensile stresses within the surrounding. Tensile stresses should seriously be avoided at surfaces of the components – outer surfaces as well as inner surfaces – because they support strongly the growth of microcracks.

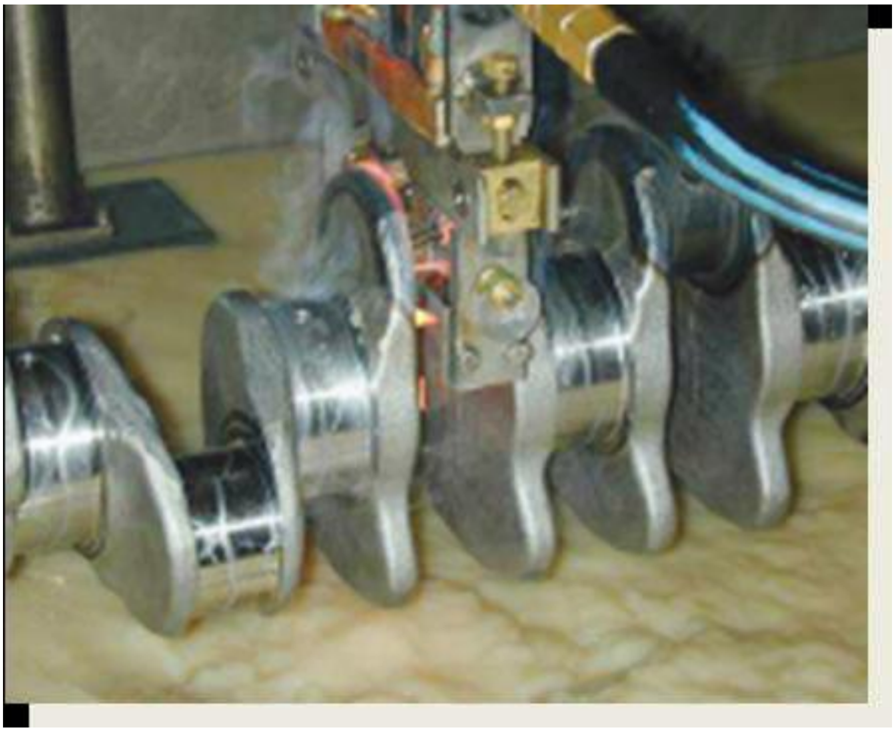


Fig. 2. Induction hardening of a con-rod bearing of a truck crankshaft.

For crankshafts there are inner surfaces providing for oil channels. In the presented case a special type of truck crankshaft has been suffering from rare but remarkable failure events from time to time. Product liability is an impressive driver for product optimization focused on reliability. X rays applied after cutting equivalent samples at the region of interest did not show any evidence for residual stresses caused by the induction hardening process. Afterwards the company thought about neutron diffraction to determine the stress component released by the cutting process. The measurement was carried out at the research reactor BER II and revealed a huge difference in the X ray results. The absolute values of the “real” stress states found in the region of the oil channel surface was approximately three times higher than the results determined by the in-house X ray experiments. This study has shown dramatically the importance of non-destructive neutron investigation. The problem has been solved by further neutron experiments in combination with finite element simulation while varying the induction hardening parameters and additionally the crankshaft’s material. The final design of the crankshaft has been marked by negligible stresses at the oil channel’s surface and didn’t suffer from the reported type of damage events.

This case is a wonderful but exceptional example marked by the fact that the problem could be solved by neutron experiments only.

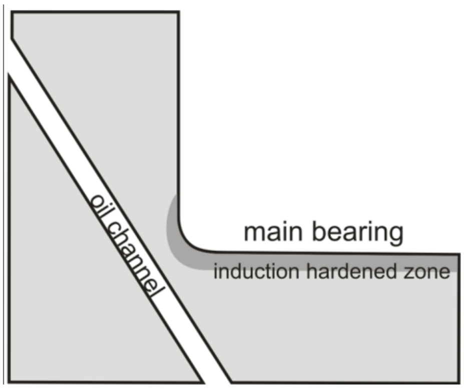


Fig. 3. Sketch of the main bearing of a crankshaft displaying the induction hardening zone close to the inner surfaces given by the oil channel.

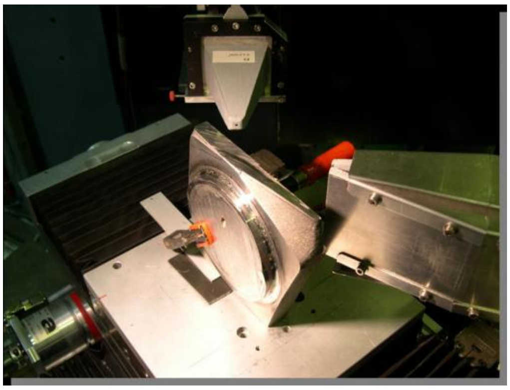


Fig. 4. In order to reduce the neutron path length but to keep the stress gradient of interest alive the sample has been cut. The gauge volume of 2×2×2 mm has been defined by the slit system.

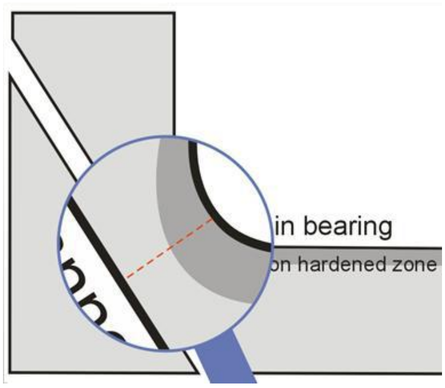


Fig. 5. The stress gradient along the red line from the bearing surface to the oil channel has been determined.

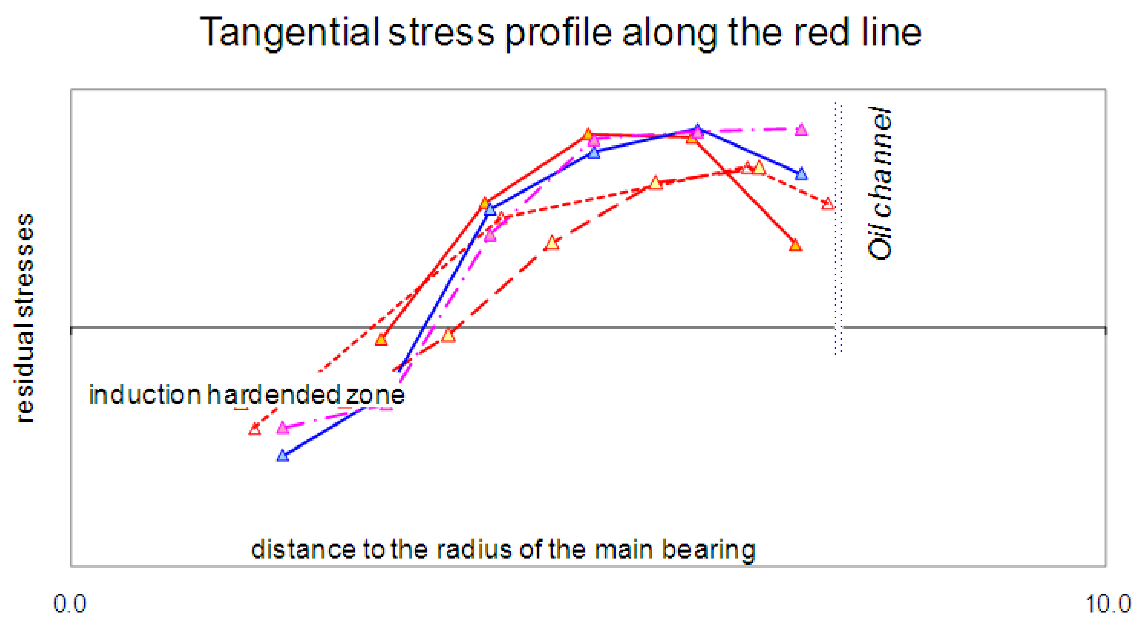


Fig. 6. The tangential residual stress data determined by the neutron diffraction experiment revealed compressive stress states in the region of the induction hardening changing to strong tensile stresses when approaching the oil channel. The maximum of the tensile stresses could be found very close to the oil channel surface.

3.2. Effective commercial use by facility pooling and healthy time-sharing with R&D

Using neutron instruments for commercial purposes results in a remarkable increase of the facility's third-party income, but beam time used for commercial experiments will not result in publications. Therefore this task fits better with permanent staff at the facility, taking into account the publication interest of post-docs. Experiences at FRM II and BER II have revealed a 50:50 commercial-to-non-commercial use of the residual stress instrument to be a healthy compromise in order not to prohibit instrumental developments and research.

Finally it must be pointed out that a highly effective commercial use of neutrons can be realized by facility pooling, enabling fast access to the dedicated instruments. Between 2006 and 2009, this has been successfully realized between FRM II, BER II, JRC Petten, the Paul Scherrer Institute (PSI) and NRI Řež, which are the core of "STRAINET". Of additional benefit is the harmonization of the instrumental equipment and a common calibration strategy between the partners in order to enhance the conformance of the experimental results.

4. THE INTERFACE RESEARCH INDUSTRY

In order to promote neutron methods for commercial use, scientists at the facilities usually prepare nice presentations about their own sophisticated, very special methods. In the worst case they present a huge number of mathematical equations to prove their expertise and the beauty of their instrument's optimization over the last years. Especially a presentation of small angle scattering instruments can end up in a horrifying mess of equations and complicated data graphs that are not directly related to the sample characteristics of interest for the industrial engineer. Thus the set of presentations of the scientists as well as their way of thinking can be described by a vector space with methodical eigenvectors that doesn't fit at all to the way of thinking the engineer is used to. He is marked by thinking about materials, design and process parameters to be optimized in order to tune the lifetime of his product. In most cases he doesn't even know which effect plays the key role concerning lifetime reduction of his component.

Usually the scientists offer feasibility tests for free in order to learn about the strength of their tool, the sample characteristics influencing the experiment and to get a reliable estimate for the beam time required to answer a specific question. The advantages of this approach are: 1) increase of experience about "real life" questions for the scientist, 2) learning effects for the involved industrial engineer who will promote this "new" method within his company and 3) the sample is already at the facility and the barrier to a following commercial experiment is drastically lowered due to the feasibility test results. This approach is usually successful for a very small number of samples marked by a clear question that fits to a specific neutron method.

But there is an open question: How to inform the industrial engineer about the availability of neutron and synchrotron methods and their specific characteristics in addition to how to teach him which method to ask for?

5. HOW TO TEACH THE INDUSTRIAL ENGINEER ABOUT THE METHODS AVAILABLE AT LARGE SCALE FACILITIES

Large scale facility methods are usually not part of the curricula of engineering courses at universities. Thus most people in industry think of research reactors as test facilities for nuclear power plants and only of use to fundamental scientists. They don't even know about diffraction methods. But they know NDT methods like ultrasound, eddy current and radiography, as well as finite element simulations, which suffer from their limitations and lack of validation tools, especially in the simulation case. Usually there are committees and consortia discussing, reporting and developing these well established engineering tools. In this case pilot projects for the validation and optimization of the established techniques reported within these consortia can have a high impact. During the previous decades, the international community dealing with the development and the application of NDT tools has grown significantly. Due to the strongly application driven developments of methods in this field, the involved scientists are in close contact to industry and, especially in Germany, have to acquire a significant part of the institute's budget by contract research. Thus these scientists are directly at an interface to industry. Therefore, they know about the current questions to be solved and are trained in the "right language." The industrial engineer, on the other hand, cannot bring all his components to the research reactor. He needs local test equipment to check the components quality — a simple decision about good and bad. But he has to rely on his setup. Its validity can be proven by destructive tests, in most cases the cheapest way, or non-destructively by neutrons, for example. For the residual stress case the final answer only can be given by the diffraction experiment.

To summarize, due to the nature of the neutron scientists' thinking, restricted to their method, and the limited knowledge of the industrial engineers about the methods available at neutron facilities, it makes sense to work closely together with scientists representing the NDT and structure-mechanical simulation field. These are highly significant to industrial users and need the reference methods that are available at large scale facilities in order to validate and to optimize their toolbox. Additionally it can be of strong benefit to invite committees dealing with NDT and quality assurance to the facilities in order to present pilot projects showing the huge benefit of the neutron methods for NDT and structure mechanical simulations.