New measurement approach for determination of residual stress and cold work at surface treated aero engine materials

Bernd Köhler[1], Johannes Kissing[2], Sergey Gartsev[1], Martin Barth[1], Marek Rjelka[1],
Joachim Bamberg[2], Roland Hessert[2]
[1]Fraunhofer IKTS, Germany, Bernd.koehler@ikts.fraunhofer.de
[2]MTU Aero Engines AG, Munich, Germany, Joachim.bamberg@mtu.de

Abstract

The non-destructive characterisation of the effects of surface treatment with respect to cold work, residual stress and surface roughness is a long discussed task. Enough sensitivity for the effect but even more selectivity for separating the contributions is a real challenge. The method must be robust for industrial application. After a short review of the past work with focus on ultrasonic methods, a new approach is proposed. It builds up on Rayleigh wave propagation through a straight interface between surface treated and non-treated areas. Even a slight change of sound velocity between both regions leads to significant refraction effects for the wave paths with near grazing incidence. The wave propagation is visualized for such cases by laser vibrometer measurements. To demonstrate the measurement idea, an immersion set up with two transducers acting at Rayleigh angle is rotated relative to the sample. At rotation positions where near grazing incidence of the Rayleigh wave to the interface line occurs, a significant transmission drop is observed. This comprises a very solid measurement effect. Possible arrangements for future practical applications are discussed.

1. Introduction

Many Aero Engine materials are exposed to high temperatures and high stresses in operation. To increase the fatigue strength, their surface is treated by shot peening, laser peening or deep rolling. These processes introduce compressive residual stress and structure modifications (cold work) in a near surface layer. There are several attempts to determine these advantageous surface property gradients non-destructively. Among the methods discussed, there are X-ray diffraction, neutron diffraction, magnetic methods, thermoelectric methods [1]. Intensely discussed are ultrasonic methods based on the acoustoelastic effect and eddy current methods which are based on the piezo-resistive effect. X-ray diffraction is applied routinely but unfortunately the penetration depth is only a few µm, which is far too less for determining stress profiles without layer by layer material removal. Neutron diffraction does not have this penetration limitation but the experimental effort is much too high for practical application. Magnetic methods such as Barkhausen noise and magnetostriction do work only for ferromagnetic materials, which the typical aero-engine materials are not. A good overview on these methods is given in [2]. Recently, the Hall effect was proposed [3, 4] as a new option.

The eddy current technique showed very promising results for the Nickel base superalloys [5]. Even the depth profiling of the residual stress by the apparent EC conductivity was demonstrated for the given samples [6]. But independent investigations at other samples showed very different results [7]. It turned out that in the unhardened and fully hardened samples of IN718, the effect of shot peening was reversed. Also, for the hardened samples – which are relevant for the application – tempering for stress release increased the measurement effect. This is a hint that the influence of the stress in the EC signal is opposite to that of cold work. Later a detailed study confirmed the influence of hardening [8]. We mention that eddy current story here to stress the fact, that in rating NDE methods, the conclusions drawn for one microstructure state cannot be transferred to another state. Even more, the conclusions from one material cannot be transferred to another material, which, unfortunately, is done very often.

As the eddy current method, the ultrasonic methods for evaluation of residual stress faces the problem to separate the influence of stress from other factors as surface roughness and could work. Early work was done at metals, which are not relevant for the high temperature parts of aero engine turbines. Ruiz and Nagy study Rayleigh wave (RW) dispersion on surface treated aluminium alloys [9, 10] by laser vibrometer RW detection. They observed a decrease of the velocity due to the peening and a reduction of this effect by annealing. From the values of the bulk wave acoustoelastic constants (AEC) they expected an increase of velocity due to the compressive surface stress. They concluded, that cold work dominates the change in velocity over the residual stress at least for that material. A similar conclusion was drawn earlier for aluminium from measurements with the V(z) method. This work was cited later [1] with the statement, that the surface roughness dominates all the other effects like cold work and residual stress.

We learned from the eddy current lesson, that conclusions cannot be transferred from one hardening state to another for one and the same material, not to mention from one material to another material. Thus, RW dispersion measurements have been performed with the materials used in the critical parts of aero engines as IN718 [11]. As earlier for aluminium, shot peened Inconel showed decrease of the surface velocity with increasing peening intensity in the surface near region. The dispersion reflects the depths distribution of the peening effects. Other than Lavrentyev results on aluminium, for IN718 the RW velocity increases with uniaxial tensile stress [12]. This corresponds to a positive Acousto Elastic Constant (AEC) meaning that compressive stress leads to a decrease in the velocity, fitting in the image. Since the surface stress on peened material can be assumed to be isotropic, also the influence of external stress perpendicular to the propagation direction has to be considered. The measurements turned out to be difficult but a trend seems to be there [13]. For IN718, both acoustoelastic constants have opposite sign but do not cancel out with a positive total acoustoelastic constant. For Ti6246 both contributions are positive, giving a positive sum, too.

The acoustoelastic effect is an expression of the materials nonlinearity, which can be described by the Third Order Elastic Constants (TOEC). Thus, a more complementary and more general approach would be the determination the Rayleigh wave AEC out of the materials elastic constants. For the material in question the TOEC are not known from literature, but they can be determined from three independent bulk wave AEC measurements. This has been done IN718 [14] and independently for IN718 and Ti6246 [15]. The latter also calculates the TOEC but still not the AEC for Rayleigh waves. The RW-AEC calculated in this way will be presented in another paper in the present volume [16].

Laser vibrometer measurements need expensive equipment and are time consuming. Thus, they are not very practical if we think about determination of the surface treatment effects in an industrial environment. Therefore, an ultrasonic goniometer approach was developed together with a corresponding device called HUGO (High Resolution

Ultrasound Goniometer). The approach is based on the drop in the direct reflection amplitude at Rayleigh angle in immersion technique [17]. This effect was also studied numerically [18] and is connected to the well-known Schoch displacement [19]. The results for the velocity dispersion obtained with HUGO [17], [20] agree with the former results based on the laser vibrometer.

In the present paper we do not intend to separate stress from microstructure influence, but we propose an approach for further of simplifying the measurements. The idea is to get a stable and significant measurement effect with limited experimental effort and a chance to push it to practical application.

In the next section we will introduce the idea of the proposed approach, and describe the samples used. Section 3 will give a direct experimental visualization of the RW refraction at surface inhomogeneities, which is to the best of our knowledge for the first time. This visualisation will help to better understand the idea of the proposed approach. In section 4 we describe the measurement set up and the carried out measurements, while in section 5 we summarize the results and discuss further possible work.

2. The idea of the measurement and the proposed approach

The evaluation of the effects of surface treatment as cold work and residual stress is via its influence to the RW velocity. This effect is very small, so strong efforts have been made to get reliable measurements of the velocity and its dispersion. Both, laser vibrometer measurement [12] and a goniometer approach are suited for that and have been used [17]. The implicit assumption made in these measurements is, that the surface properties are constant over the length scale involved. While in most practical applications a constant peening is applied, not all surface parts of a component need this peening. It is conceivable, that some surface areas are not peened at all. So, a new approach seems to be possible. Instead of measuring the sound velocity directly, the refraction of the RW while propagating through an interface from unpeened to a peened area could provide information through the change in the wave propagation velocity. With vertical incidence, there is no refraction at all while for grazing incidence the refraction effect should be noticeable.

For practical purposes, nothing is gained if we replace a precise velocity measurement by an equal complex refraction angle measurement. Therefore, we aim for a set-up, which is relying on exact alignment of ultrasonic probes and on very straight propagation of the waves. It is well known, that in trough transmission experiments, maximum amplitude is reached for perfect alignment only and tilting of one transducer by a small angle $\Delta\gamma$ can reduce the received amplitude considerably. The same happens, if the alignment is perfect but the sound field is refracted by the same angle. Motivated by the visible refraction of the RW field at the peened/non-peened interface we tried to get a setup able to show the effect of peening as a drop in the amplitude in a pitch catch RW measurement due to refraction.

In the first part of the paper, we will visualise the wave propagation through the interface line between an unpeened and a peened area by scanning laser vibrometry. This gives a direct impression about the effect introduced by this line. Based on that we give a possible measurement arrangement, where the RW crosses the interface in different angles and the transmitted amplitude is recorded with respect to that angle. We demonstrate, that a significant measurement effect can be obtained. The paper aims only for giving a first "prove of concept". Further ways to improve the effect will be discussed in the conclusions.

The material used in this study is the nickel-base superalloy IN718 as used for aeroplane turbine discs. A part of the sample surface is shot peened with an intensity of 0.25 mmA and the remaining part is untreated (Figure 1, left). By application of the rule that 0.1 mmA corresponds to 4 A and that the connection is linear [21], the peening intensity corresponds to an Almen intensity of 10 A.

3. Wave propagation visualisation by laser vibrometry

3.1. Experimental background and set up

Scanning Laser vibrometry has proved as a viable tool for mapping of elastodynamic waves at the surface of solids (e.g. [22]). For high frequencies normally a good surface quality, perpendicular laser beam incidence, and heavy averaging is necessary to ensure an acceptable signal to noise ratio. For keeping the normal incidence a mechanical scanning [23] instead of laser beam scanning was performed. A special pulsing scheme [24, 25] allows high pulse rates and averaging over a large number of signals in reasonable time. The improved signal to noise ratio also enables the extraction of small "hidden" effects out of the wave traces, as shown in the grazing incidence ultrasound microscopy [26]. We use this special averaging technique to visualise the RW propagation at the non-penned to peened interface.

The surface wave was excited by a commercial wedge probe with frequency of 10 MHz mounted carefully on the peened area with the sound beam directed towards the interface line with a given small angle α. The probe was excited by a Panametrics PR5900 pulser receiver. The out-of-plane displacement was picked up by Polytec OFV 353 vibrometer head. The laser beam was carefully adjusted normally to the surface and scanned over the surface with a scan resolution of 0.1 x. 0.06 mm^2.

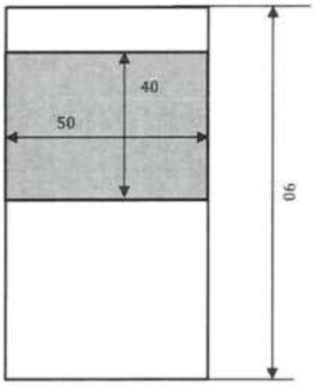

Figure 1: Drawing of test sample with indication of the peened area by grey shading.

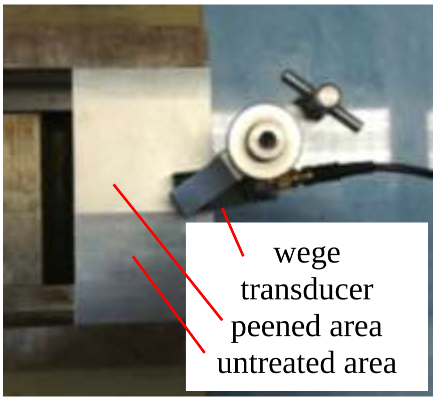

Figure 2: Photo of the sample with mounted transducer slightly tilted with respect to the peened non-peened interface.

3.2. Measurement results

Figure 3 shows a snapshot of the wave in the untreated area, when the transducer is orientated parallel to the scan axis, while Figure 4 gives the situation with the transducer located in the peened area and directed under $\alpha = 6°$ towards the interface. Expectedly, the wave propagating totally in the unpeened area shows no peculiarities. Instead, the snapshot of the Figure 4 is very interesting. The wavefront in the peened area is inclined by $\alpha = 6°$ as intended by the rotation of the transducer (see dotted line). However, at the borderline, the wavefront has a kink and continuing in the adjacent untreated area with about 0° (red arrow). That is just the expected effect due to refraction of the RW from the area of lower velocity in the peened region to the slight higher velocity in the untreated region.

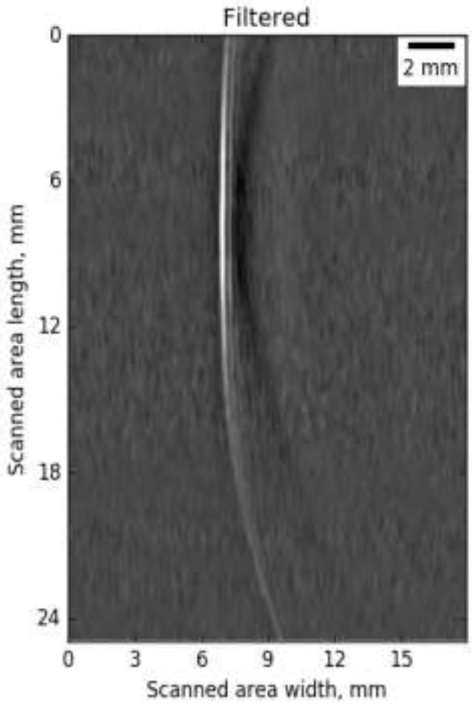

Figure 3: Snapshot of the Rayleigh wave in an unpeened area. The orientation of the transducer is $\alpha = 0°$.

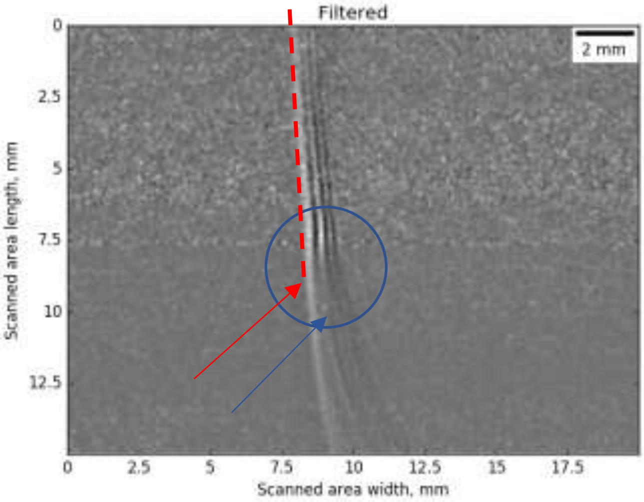

Figure 4: Snapshot of the Rayleigh wave emitted by a transducer in the peened area (upper part of the image) and orientated by $\alpha = 6°$ towards the interface.

We observe another interesting effect. In the peened area, the RW snapshot is led by a half-wave followed by some wave cycles with lower wavelength. This can be explained by dispersion because wave packet contributions with higher frequency (lower wavelength) travel with lower velocity. Following these wave traces into the untreated area, they nearly disappear. We explain this by the stronger change in the sound velocity for higher frequencies, which leads to stronger phase shift and destructive interference. With another equivalent explanation, we can say that for the higher frequencies the incidence angle is larger than the critical angle, so no high frequency waves are transferred to the untreated region. The fact, that we see this high frequency wave traces further away from the borderline has the simple explanation, that the probe was positioned a bit on the untreated region, so these wave parts travelled from the beginning in the untreated region.

4. Rayleigh wave amplitude drop measurements

4.1. Experimental, the ultrasound goniometer HUGO

According to the discussion in section 3, we need to generate a RW in the sample surface and manage to rotate the travel path with respect to the borderline between peened and unpeened parts of the surface. For the coupling of the RW into the sample we used the **H**igh **R**esolution **U**ltrasound **Go**niometer (HUGO), a device developed for RW dispersion measurements [17]. Figure 5 shows the scheme of the measurement together with a photo of the device in operation. In the RW dispersion measurements, the sending and receiving transducer point at the same spot. This setup can be called “reflection set up” in which the incidence angles of both transducers are identical and are varied simultaneously. The excitation of the RW is connected with a drop of the reflected amplitude due to the ultrasonic energy carried away by the RW, which gives a drop of the reflected amplitude at the RW angle. Here we use the additional option of HUGO to move one axis away from the reflection point by a defined distance Δx. The ultrasonic wave has an additional sound path as RW along the surface, so the signal is delayed by an additional travel time by $\Delta t = \Delta x / v_R$. In the experiments we present here, the length of the RW path was set to $\Delta x = 20\ mm$.

To realize the controlled change in the RW orientation with respect to the borderline, the water bath containing the sample was mounted onto a precise rotation table allowing a full 360° rotation. HUGO remained fixed independently and was adjusted such that the middle of the RW sound path lies on the rotational axis of the table (as good as possible) and the border line goes just through the same point.

The excitation of the transmitting transducer was by a burst of 50 cycles with frequency of f = 10 MHz. At each rotation angle γ the maximum amplitude of the received signal was determined and 10 successive measurements were averaged. These mean values were plotted over the rotation angle, where the 0° position was chosen as the one where the sound path crosses the interface line perpendicular.

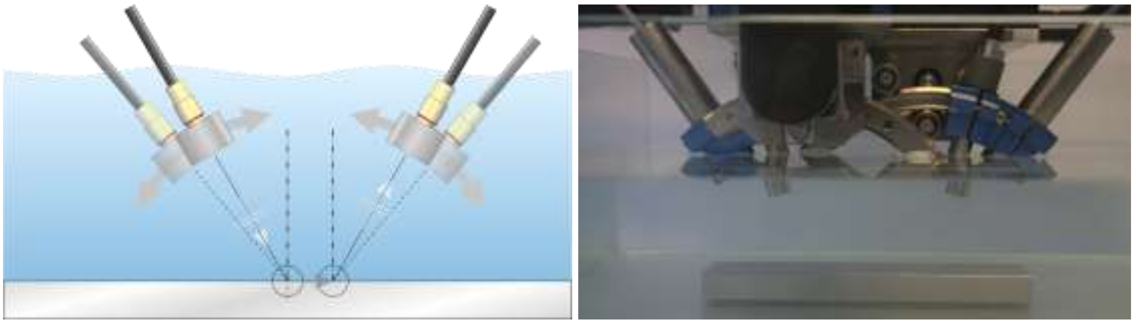

Figure 5: Schema of the goniometer measurement (left) and Goniometer HUGO in action (right).

4.2. Results of the measurements

Figure 6 gives the result of a representative measurement. It is to be noted first, that the sound amplitudes for the two directions with perpendicular crossing of the RW path through the interface, i.e. the 0° and 180° orientation differ. An influence of the orientation of the rotation axis with respect to the goniometer symmetry plane was expected as contribution. With a perfect alignment, the reference amplitude measurement in an unpeened area should give a straight line, which is not the case as can been seen in Figure 7. Therefore, all signal amplitude measurements have been referenced to the measurement in the unpeened area by calculating the ratio. This improves the situation (see Figure 8) but there still must be other sources of the mentioned effect as differences in the 0° and 180° amplitudes remain.

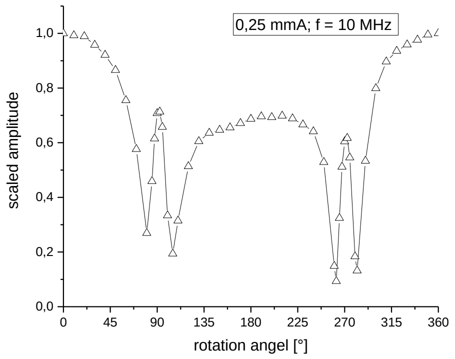

Figure 6: Angle dependent RW pitch catch intensity for borderline crossing.

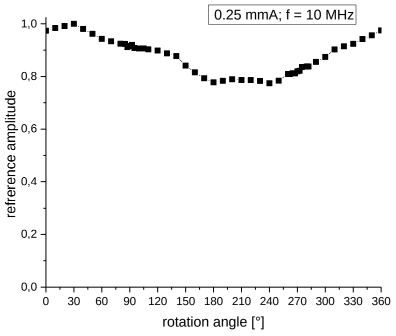

Figure 7: Angle dependent RW pitch catch intensity in untreated area.

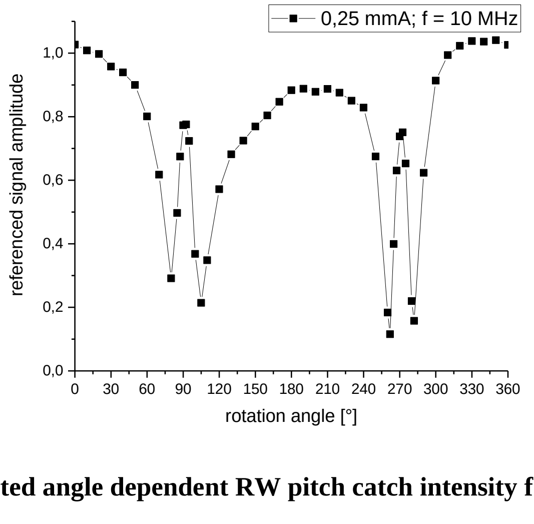

Figure 8: Compensated angle dependent RW pitch catch intensity for borderline crossing.

Very fortunate we see a very pronounced reduction of the transmitted amplitude for angles near 90°, i.e. for grazing incidence. This is the expected effect, but we were surprised that it is so strong. By reciprocity [10], exchanging the transmitter and receiver in a trough transmission experiment of the sound path the amplitude curve should be symmetrical with respect to the +- 90° orientations. This is fulfilled to a good approximation while again small deviations from this symmetry remain.

Very interesting is the “two dip” behaviour, that is, the amplitude is again relatively high when the sound path is parallel to the interface line. The sound paths on both sides of the interface interfere with each other in the receiving transducer and destructive interference could appear. There are several possible explanations. One is a remaining inaccuracy of the alignment in such a way, that the sound path in the 90° orientation is mostly on one side of the border. This would reduce the interference between the contributions of the rays from both sides of the border leading to a comparably strong signal. Modelling of the wave propagation should help to clarify, whether this mechanism or another explains the behaviour correctly. Such investigation was not possible in the present project and has to be left for further work.

5. Summary and Conclusions

We presented an alternative approach for investigating the influences of shot peening on IN718. This approach relies on the refraction of Rayleigh waves when crossing a treated-untreated borderline at nearly grazing incidence. This diffraction has been visualised here by laser vibrometer sound field measurements. A refraction of the RW for grazing incidence is observed. The field in the unpeened side for grazing near grazing incidence shows indications of an evanescent field.

The measurement of the amplitude drop of a pitch catch RW arrangement was performed with an ultrasonic goniometer. A very pronounced amplitude drop for near grazing incidence was observed. This opens up the possibility to apply that type of measurements for estimation of the surface treatment effects as combined cold work and residual stresses. While applied on a shot peened sample the same effects are to be expected for materials treated by laser peening or deep rolling.

The use of the ultrasound goniometer for the measurements in this study was just for availability reasons. The approach can be transferred easily to a sensor arrangement with RW transducers mechanically fixed to each other in a given distance but free to rotate. That way, stable measurements can be performed with very limited technical effort.

One seeming disadvantage of the method is the need of a borderline of the treated area to an untreated one for the measurement. Very often, practical parts do not need the treatment in all surface areas, so such borderline can be created during production of the parts without additional expenses and other disadvantages.

We presented a first feasibility study of a new approach. A much more detailed investigation is necessary and possible. So, easily the frequency dependence of the observed effect can be studied just by changing the frequency of the excitation burst. It would also be interesting to see the effect of the peening intensity to the measurement. Modelling of the wave propagation would help to understand the involved effects. All these investigations will be subject for further research.

Acknowledgements

The author Sergey Gartsev has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 722134 – NDTonAIR.

References

1. H Carreon, PB Nagy, and M Blodgett, "Thermoelectric nondestructive evaluation of residual stress in shot-peened metals", Journal of Research in Nondestructive Evaluation, Taylor & Francis, 2002, 14, 59-80
2. PB Nagy, "Opportunities and Challenges for Nondestructive Residual Stress Assessment", Proceedings of the Rev. of Progress in QNDE 2005, ed. by D.O. Thompson, D. E. Chimenti, Vol. 25, (2006), 1349
3. PB Nagy, "Hall coefficient measurement for nondestructive materials characterization" AIP Conference Proceedings, 2013, 1511, 1482-148
4. D Velicheti, PB Nagy, W Hassan, "High-frequency Hall coefficient measurement using inductive sensing for nondestructive materials characterization", NDT & E International, Elsevier, 2018
5. MP Blodgett, PB Nagy, "Eddy current assessment of near-surface residual stress in shot-peened nickel-base superalloys" Journal of nondestructive evaluation, Springer, 2004, 23, 107-123
6. F Yu, PB Nagy, "Simple analytical approximations for eddy current profiling of the near-surface residual stress in shot-peened metals", Journal of applied physics, AIP Publishing, 2004, 96, 1257-126
7. S Hillmann, H Heuer, HU Baron, J Bamberg, A Yashan, and N Meyendorf, "Near-surface residual stress-profiling with high Frequency eddy current conductivity measurement", Proceedings of the Review of Progress in QNDE 2008, ed. by D.O. Thompson, D.E. Chimenti, Vol 28, p.1349 ff
8. BA Abu-Nabah, WT Hassan, D Ryan, MP Blodgett, and PB Nagy, "The effect of hardness on eddy current residual stress profiling in shot-peened nickel alloys Journal of Nondestructive Evaluation", Springer, 2010, 29, 143-153
9. A Ruiz, PB Nagy, "SAW dispersion measurements for ultrasonic characterization of surface treated metals", Instr. Meas. Metrol. 3 (2003) 59.
10. A Ruiz, PB Nagy, "Laser-ultrasonic surface wave dispersion measurements on surface-treated metals", Ultrasonics, Elsevier, 2004, 42, 665-669
11. Lavrentyev, A. I., Stucky, P. A., & Veronesi, W. A. (2000, May). Feasibility of ultrasonic and eddy current methods for measurement of residual stress in shot peened metals. In *AIP Conference Proceedings* Vol. 509, No. 1, pp. 1621-1628, AIP.
12. B Koehler, M Barth, F Schubert, J Bamberg, and HU Baron, "Characterization of surface treated aero engine alloys by Rayleigh wave velocity dispersion", Proc. of Rev. of Progress in QNDE, Ed. by D. O. Thompson and D. E. Chimenti, 29, (2009)
13. B Koehler, M Barth, J Bamberg, and H-U Baron, "Rayleigh wave velocity dispersion for characterization of surface treated aero engine alloys", Proceedings of the ECNDT 2010, NDT-NET, 2010
14. S Hubel, M Spies, H Rieder, A Dillhöfer, J Bamberg, R Hessert, C Preikszas, "Basic investigations to establish an ultrasonic stress evaluation technique for aero engine materials", 4th International Symposium on NDT in Aerospace, 2012, 13-15

15. M Rjelka, M Barth, S Reinert, B Koehler, J Bamberg, and HU Baron, “Third order elastic constants and Rayleigh wave dispersion of shot-peened aero-engine materials”, AIP Conference Proceedings, 2012, 1430,
16. S Gartsev, M Rjelka, et al., “Nonlinear elastic behaviour of aero-engine materials for microstructure and stress state characterization”, ECNDT 2018, to be published in the present volume
17. M Barth, M Küttner, B Köhler, J Bamberg, and HU Baron, “Universal ultrasonic goniometer for Rayleigh and surface skimming longitudinal wave dispersion measurements” AIP Conference Proceedings Vol.1430, 2012, 1873-1880
18. M Yuan, T Kang, J Zhang, S-J Song, and H-J Kim, “Numerical simulation of ultrasonic minimum reflection for residual stress evaluation in 2D case”, Journal of Mechanical Science and Technology, Springer, 2013, 27, 3207-3214
19. A Schoch, „Schallreflexion, Schallbrechung und Schallbeugung“ Ergebnisse der exakten Naturwissenschaften, Springer, 1950, 127-234
20. S Hubel, A Dillhöfer, H Rieder, M Spies, J Bamberg, J Götz, R Hessert, and C Preikszas, “Ultrasonic evaluation of residual stresses in aero engine materials using bulk and Rayleigh surface waves”, AIP Conference Proceedings, 2014, 1581, 607-614
21. A Jain, “A database for shot peening parameters and desired residual stress distribution” International Conference on Shot Peening and Blast Cleaning, 2005
22. L Schubert, M Barth, T Klesse, B Köhler, and B Frankenstein, ”Guided elastic waves and their impact interaction in CFRP structures characterized by 3D laser scanning vibrometry”, In *Health monitoring of structural and biological systems 2008* (Vol. 6935, p. 69350G). International Society for Optics and Photonics
23. B Köhler, F Schubert, “Optical detection of elastodynamic fields of ultrasonic transducers”. *Ultrasonics*, *40*(1-8), 741-745
24. M Barth, “Control device for an excitation signal generator”, patent WO 2014037387 A1, 2014
25. B Köhler, “Scannende Erfassung von Ultraschall-Wellenfeldern für die Zerstörungsfreie Prüfung, die Zerstörungsfreie Materialcharakterisierung und die Strukturüberwachung“, Habilitation, Technische Universität Dresden, 2015
26. B Köhler, M Barth, P Krüger, and F Schubert, “Grain structure visualization with surface skimming ultrasonic waves detected by laser vibrometry”. *Applied Physics Letters*, *101*(7), 074101
27. BA Auld, "General electromechanical reciprocity relations applied to the calculation of elastic wave scattering coefficients", Wave Motion **1** (1979) 3-10
28. H Carreon, A Medina, “Nondestructive characterization of the level of plastic deformation by thermoelectric power measurements in cold-rolled Ti--6Al--4V samples” Nondestructive Testing and Evaluation, Taylor & Francis, 2007, 22, 299-311