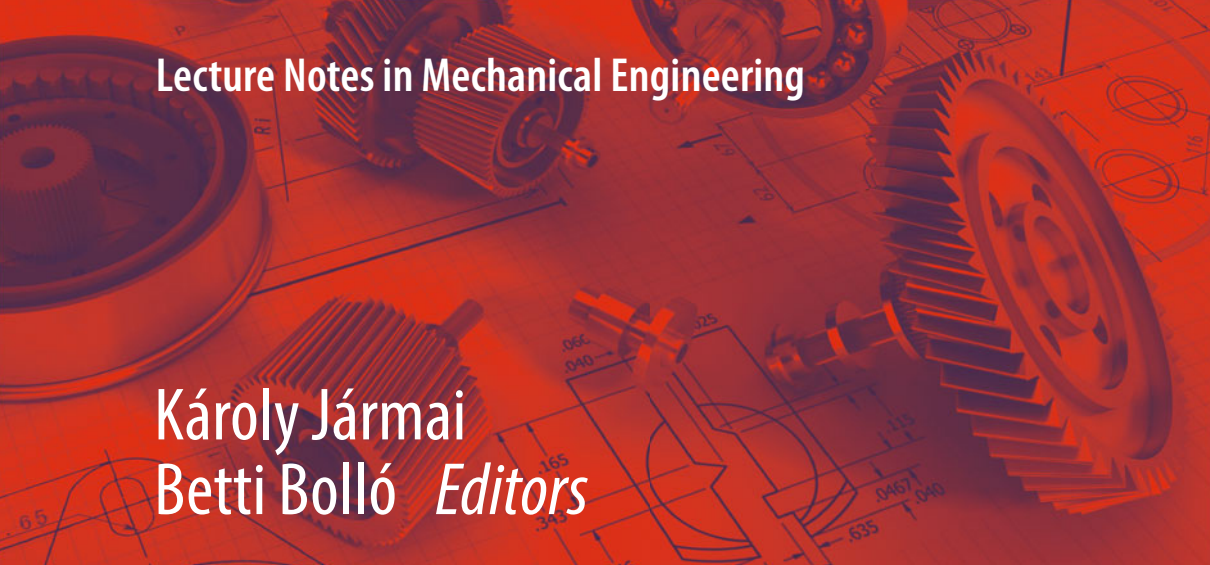




Lecture Notes in Mechanical Engineering

Károly Jármái
Betti Bolló *Editors*

Vehicle and Automotive Engineering

Proceedings of the JK2016,
Miskolc, Hungary

Lecture Notes in Mechanical Engineering

About this Series

Lecture Notes in Mechanical Engineering (LNME) publishes the latest developments in Mechanical Engineering—quickly, informally and with high quality. Original research reported in proceedings and post-proceedings represents the core of LNME. Also considered for publication are monographs, contributed volumes and lecture notes of exceptionally high quality and interest. Volumes published in LNME embrace all aspects, subfields and new challenges of mechanical engineering. Topics in the series include:

- Engineering Design
- Machinery and Machine Elements
- Mechanical Structures and Stress Analysis
- Automotive Engineering
- Engine Technology
- Aerospace Technology and Astronautics
- Nanotechnology and Microengineering
- Control, Robotics, Mechatronics
- MEMS
- Theoretical and Applied Mechanics
- Dynamical Systems, Control
- Fluid Mechanics
- Engineering Thermodynamics, Heat and Mass Transfer
- Manufacturing
- Precision Engineering, Instrumentation, Measurement
- Materials Engineering
- Tribology and Surface Technology

More information about this series at <http://www.springer.com/series/11236>

Károly Jármai · Betti Bolló
Editors

Vehicle and Automotive Engineering

Proceedings of the JK2016, Miskolc, Hungary

Editors

Károly Jármai
Miskolci Egyetem
University of Miskolc
Miskolc, Egyetemvaros
Hungary

Betti Bolló
Miskolci Egyetem
University of Miskolc
Miskolc, Egyetemvaros
Hungary

ISSN 2195-4356

ISSN 2195-4364 (electronic)

Lecture Notes in Mechanical Engineering

ISBN 978-3-319-51188-7

ISBN 978-3-319-51189-4 (eBook)

DOI 10.1007/978-3-319-51189-4

Library of Congress Control Number: 2017930169

© Springer International Publishing AG 2017

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, express or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Printed on acid-free paper

This Springer imprint is published by Springer Nature

The registered company is Springer International Publishing AG

The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Innovation Methods for Residual Stress Determination for the Automotive Industry

Máté Sepsi, Dávid Cseh, Ádám Filep, Márton Benke
and Valéria Mertinger

Abstract Determination of the residual stress state in a loaded automotive component is highly important because of its strong effect on the lifetime of the element. Nowadays, the residual stress characterization of products became an everyday requirement in the automotive industry, and the quality control is impossible to imagine without it. Forasmuch as every producing process (casting, heat treating, different kinds of metal deformation processes and surface compressing methods, etc.) influences the residual stress state, therefore it can be very complex and various within the materials. If we conscious in the effect of these processes it is possible to reach such a state in the material which can enhance its lifetime and quality, and with an optimized process, the costs could be reduced. Several methods exist for measuring the residual stress and each of them has its own advantage and disadvantage. With this paper our purpose is to introduce nowadays' available stress measuring methods such as X-ray diffraction, magnetic Barkhausen noise and the hole drilling methods and a few more alternatives. Some useful results from the practice are also presented.

M. Sepsi (✉) · D. Cseh · Á. Filep · M. Benke · V. Mertinger
Institute of Physical Metallurgy, Metalforming and Nanotechnology,
University of Miskolc, Miskolc, Hungary
e-mail: mate.sepsi@gmail.com

D. Cseh
e-mail: cseh88david@gmail.com

Á. Filep
e-mail: adam9032@gmail.com

M. Benke
e-mail: fembenke@uni-miskolc.hu

V. Mertinger
e-mail: femvali@uni-miskolc.hu

1 Introduction

Residual stress is introduced into solid state materials during almost all shape modifying processing types including casting, plastic deformation, machining, welding, etc. For most cases, the presence of residual stress is not designed, but is a consequence of the required manufacturing step [1, 2]. In the automotive industry, however, residual stress is introduced within a machine component intentionally to enhance the component's properties, such as resistance against fatigue [3, 4]. The most common techniques to induce compressive stresses are shot peening and ball burnishing. In such cases, the stress state (type and magnitude) of the component is a requirement and regulated similarly to mechanical properties or geometry. Because of that, providing accurate data about residual stress is of great interest. There are many methods that can qualitatively describe the residual stress state of a component [5, 6]. One of them is the Magnetic Barkhausen Noise measurement, which could be the quickest and the easiest measurement from the side of the operator. It is based on a ferromagnetic phenomenon which induced by a changing magnetic field in a ferromagnetic material. Forasmuch the characteristic of the Barkhausen noise is influenced by the microstructure, the hardness and the stress state of the magnetized material, therefor it is suitable to use it in the industry for quality control, where the measurement time is very important [7]. Nevertheless, the description of the residual stress state quantitatively is not easy with this method [1]. Another one is the Hole-drilling method, where the definition of the residual stress based on the macroscopic deformation of a solid material upon changing the stress balance through material removal. The largest advantage of this kind of measurement is that not just the ferromagnetic and the polycrystalline materials are analysable with it. But, as it is mentioned, material should be removed to get result, so stress state on the surface is not definable. However, diffraction based methods are the only ones that provide accurate quantitative information about the stress state from the surface to the deep. While neutron diffraction requires a neutron source, X-ray diffraction based residual stress measurement can be performed in laboratory conditions, or, even as on-site measurements. Using non-destructive X-ray diffraction, no sample has to be cut from the component for the examination. Using this technique, not only remains the component usable after the examination, but the true stress state is not distorted with sample cutting. Thus, the true stress state is provided after such examination. The residual stress measurement by X-ray, as all of the other diffraction measurements is based on Bragg's law [8]:

$$n\lambda = 2d \sin \theta \quad (1)$$

This equation gives the diffraction angle (θ) where the diffracted X-ray photons with a given wavelength (λ) meet in the same phase after scattered on the lattice with a given plane distance (d), (n is an integer.) An intensity peak appears as a function of the diffraction angle in the recorded interference function where Bragg's law is fulfilled. The diffraction angle of a stressed material is shifted relative to the

relaxed value. The lattice parameter change is the source of this phenomenon which is generated by the residual stress. Assuming linear elastic distortions, the related normal stresses can be calculated by Eq. (2) which is called $\sin^2\psi$ method [8]:

$$\sigma = \frac{d_\psi - d_0}{d_0} * \frac{E}{(1 + \nu) \sin^2 \psi} \quad (2)$$

where d_0 and d_ψ are the lattice plane distances of the strained (stressed) material in the normal and in the tilted position defined by the angle ψ , respectively. E (Young modulus) and ν (Poisson number) are the elastic parameters of the material. In practice, several tilting positions ($\pm$) in one measuring point are usually applied and after the interferential functions are recorded, d , normal stress and its scatter, shear stress and its scatter, the average 2 (values and the average full with half maximum (FWHM) can be calculated. Figure 1 provides the process of an XRD residual stress data in one measuring point. In this case 5 tilt positions (3/3) were applied and the interferential functions were recorded at each ($\Psi = -45^\circ, -30^\circ, 0^\circ, +30^\circ, +45^\circ$) tilt positions. The sloop of the parabola axis on the plot of calculating d as the function of $\sin^2\Psi$ gives the value of normal stress data. The direction of the measured stress is given by the direction of the applied tilting was used during the measurement. The FWHM and the Bragg angle are calculated as an average value

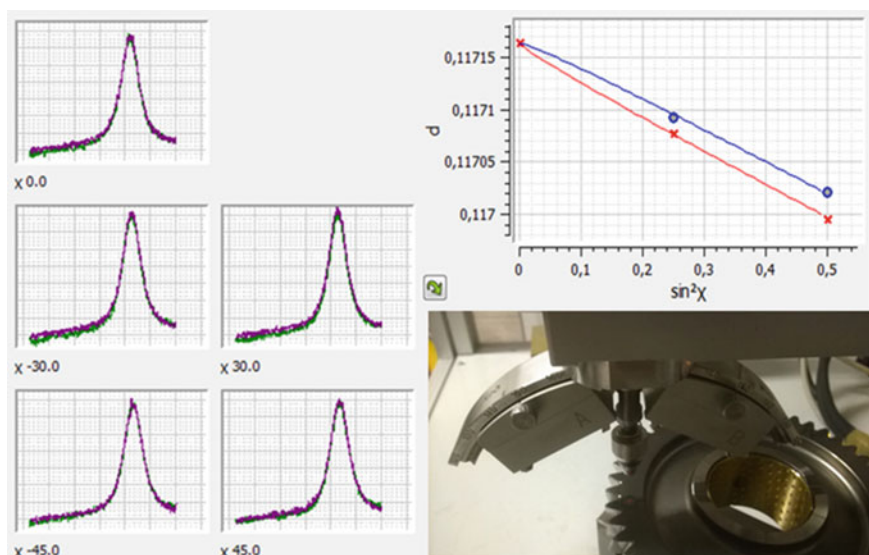


Fig. 1 The process of an XRD residual stress data. The recorded interferential functions at different ($\Psi = -45^\circ, -30^\circ, 0^\circ, +30^\circ, +45^\circ$) tilt positions. The plot of calculating d as the function of $\sin^2\Psi$. The gears under the measuring process at the A location. The calculated results are: $\sigma: -448.7 \pm 9.6$ MPa, $\tau: -16.0 \pm 2.1$ MPa, FWHM: $4.57^\circ \pm 0.07^\circ$, $2\theta: 155.77^\circ$

of the data of interferential functions which were recorded at different tilting positions.

The X-ray diffraction technique is a reliable method for stress measurements. However, the residual stress state of a component can be measured accurately only if the true stress state is not affected by sample cuts. This requirement demands a special equipment and measurement method [2, 8]. Non-destructive X-ray diffraction is generally accepted as the ultimate tool for residual stress measurements and the method meets the requirements of the regarding Machinery and Low Voltage directives and applies the following standards: SFS-EN ISO 12100-1, 12100-2, 13857, 60204-1. Even the method is standardized, the effect of measurement parameters on the obtained result is still debated. The objective of the present manuscript is to examine the effect of measurement parameters, namely tilting range, number of tilting positions and spot size of the measured stress values of a shot-peened gear wheel. Our results also give evidence about the reproducibility and sensitivity of the diffraction method.

2 Experimental

The residual stress was measured non-destructively by a Stresstech Xstress 3000 G3R type centerless X-ray diffractometer, owned by the Institute of Physical Metallurgy, Metalforming and Nanotechnology at the University of Miskolc. This method provides residual stress values from $\sim 10\text{ }\mu\text{m}$ depth of the surface layer (depending on material type, applied generator power, Bragg-angle). A Cr radiation was used to measure the $\{211\}$ reflections of the samples. For stress calculations, the following material constants were used: Poisson's ratio $\nu = 0.3$, Young's modulus $E = 211000\text{ MPa}$. A carburized and shoot peened gear wheel was chosen as test component. All of the measurements were performed at the same two locations (D and A location) and the same direction of the gear wheel. The measured parameters (the investigated variables) such as maximum tilting angle, the number of tilting and spot size (the diameter of the beam on the examined surface) were systematically changed during the test. The exposure time was chosen based on the requirement of proper signal/background ratio, so it was changing, but it is not the investigated variable in this paper. The spot size was 1, 3, 5, mm in diameter. The maximum tilting angles were $\pm 20^\circ$ or $\pm 40^\circ$. The 3/3, 5/5, 7/7 and 11/11 number of tilts were chosen which refers that one stress data were calculated based on 3, or 5, or 7, or 11 tiltings in both plus and minus directions. Three parallel measurements were performed in each case of the measuring conditions. Thus, reproducibility was also tested.

3 Results and Discussion

Figure 1 provides one of the measured data at location A as an example and Table 1 summarizes all of the calculated data, such as normal stress (σ), shear stress (τ), FWHM and Bragg angle (2θ). The normal and shear stresses refer to the stress state in the measured point and direction, which was perpendicular to the axis. The FWHM value is larger if the micro stress caused by dislocations or interstitials is also larger. The Bragg angle is associated with the difference of chemical composition, especially the carbon solution of the carburized gear surface zone.

Figures 2, 3, 4, 5, 6, 7, 8, 9 and 10 show the results of Location A and D which were the equivalent parts of the gear. The error bars of each data are also presented. The significant different data of the two locations are originated from the treatment of the gear which can also be important information. The sufficient number of tilts has been always a question for the users. Too high number increases the measuring time while the too low causes wide error bars. Figures 2 and 3 show that it is a false theory. The stress results of 11 tilts number shows only smaller error bar, but the difference is much smaller than the difference of the result from the equivalent parts (location A and D) of the gear. The FWHM data show no difference.

The optimal spot size is also a regular question for the operators. The larger collimator (larger spot size) gives higher reflected intensity so the measuring time is decreased which is convenient situation. Also, a feeling of the users that using larger collimator gives better statistic for the material results that the commonly used spot size 3–4 mm in diameter. As we see from Figs. 4 and 5 the stress data deviation is within the error bars, even if 6 times larger spot size was used, so the thumb rule works, but the FWHM data are strongly increased as the spot size is increasing. Which does not originate from the microstructure, but is an artificial effect. So the FWHM data can be compared in the case of same spot size measurements only.

The result in Figs. 6, 7, 8 and 9 has a serious message. The $\pm 45^\circ$ maximum tilting angle is usually used, but in some cases the special geometry limit does not yield such a big tilting. Measuring in the bottom land of a gear is a typical example. In that case the operators cut the gears or apply different measuring mode (psi or omega) or decrease the maximum tilting angle. As we have already mentioned in the introduction, the sample cutting can modify the stress state so the measured data do not represent the real initial situation. The question is always the effect which generated the stress state and the volume fraction of the sample where this state is in equilibrium. Applying the omega mode can be a good solution, but some of the available equipment are not able to fulfil this. Figure 6 shows that applying $\pm 20^\circ$ tilting angle instead $\pm 45^\circ$ results an extremely large increase in the error bars of the measured points and also the large scatter of the parallel measurements and the spot size variation does not help at all (Fig. 7). In front of this, it is obvious that the FWHM data unaffected by the tilting angles (Fig. 8) only the spot size effect is detectable (Fig. 9).

Table 1 Calculated data

Location	Var.	No.	Tilt max, "	No. of tilt	Spot size, mm	σ , Mpa	($\pm$)	τ , MPa	($\pm$)	FWHM, °	($\pm$)	2 θ , °
Location D	a	1	45	3	3	-444.20	11.60	-10.30	2.60	4.52	0.09	155.76
	a	2	45	3	3	-448.70	9.60	-16.00	2.10	4.57	0.07	155.77
	a	3	45	3	3	-435.90	14.50	-11.60	3.20	4.53	0.10	155.80
	b	4	45	5	3	-437.90	7.90	-7.10	1.60	4.53	0.06	155.79
	b	5	45	5	3	-443.90	4.80	-7.30	1.00	4.53	0.07	155.76
	b	6	45	5	3	-447.40	8.40	-8.50	1.70	4.51	0.06	155.76
	c	7	45	7	3	-443.60	5.90	-7.30	1.10	4.50	0.06	155.80
	c	8	45	7	3	-432.50	5.20	-7.60	1.00	4.50	0.07	155.76
	c	9	45	7	3	-452.10	7.50	-7.30	1.40	4.52	0.07	155.77
	d	10	45	11	3	-450.10	6.00	-9.40	1.10	4.51	0.06	155.77
	d	11	45	11	3	-448.50	4.70	-8.20	0.90	4.50	0.06	155.77
	d	12	45	11	3	-441.70	5.70	-9.40	1.10	4.51	0.08	155.77
	e	13	20	5	5	-459.50	30.50	-1.70	2.40	4.43	0.04	155.76
	e	14	20	5	5	-445.60	28.80	-5.90	2.30	4.46	0.04	155.76
	f	15	45	5	3	-437.90	7.90	-7.10	1.60	4.53	0.06	155.79
	f	16	45	5	3	-443.90	4.80	-7.30	1.00	4.53	0.07	155.76
	f	17	45	5	3	-447.40	8.40	-8.50	1.70	4.51	0.06	155.76
	g	18	20	5	3	-459.50	30.50	-1.70	2.40	4.43	0.04	155.76
	g	19	20	5	3	-445.60	28.80	-5.90	2.30	4.46	0.04	155.76
	h	20	45	5	3	-438.4	11.30	-9.10	2.20	4.53	0.08	155.77
	h	21	20	5	3	-438.3	35.80	-7.70	2.80	4.44	0.03	155.76
	h	22	20	5	3	-445.3	27.70	-5.40	2.20	4.48	0.03	155.76
	i	23	20	5	1	-429.4	26.90	5.30	2.10	4.36	0.03	155.83
	i	24	20	5	1	-408	27.60	2.70	2.20	4.35	0.03	155.84
	i	25	20	5	1	-464.5	28.90	3.40	2.30	4.36	0.04	155.81

(continued)

Table 1 (continued)

Location	Var.	No.	Tilt max, "	No. of tilt	Spot size, mm	σ , Mpa	($\pm$)	τ , MPa	($\pm$)	FWHM, °	($\pm$)	2 θ , °
Location A		1	20	5	5	-498.4	16.80	11.50	1.30	5.06	0.03	155.71
		2	20	5	5	-448.6	11.10	-10.10	0.90	5.07	0.02	155.71
		3	20	5	5	-504.7	15.60	-10.00	1.20	5.08	0.03	155.72
		4	20	5	4	-481.9	28.30	-8.40	2.20	4.91	0.05	155.71
		5	20	5	4	-446.9	22.60	-10.60	1.80	4.91	0.03	155.71
		6	20	5	4	-503.1	16.20	-8.40	1.30	4.91	0.02	155.72
		7	20	5	3	-467.6	16.00	-6.80	1.30	4.73	0.03	155.73
		8	20	5	3	-492.6	28.20	-7.60	2.20	4.73	0.03	155.73
		9	20	5	3	-463	20.80	-6.60	1.60	4.73	0.04	155.73
		10	20	5	1	-485.2	20.70	-7.80	1.60	4.65	0.06	155.75
		11	20	5	1	-498.1	41.00	-6.70	3.20	4.65	0.06	155.75
		12	20	5	1	-462.4	24.20	-8.60	1.90	4.68	0.05	155.75
		13	20	5	1	-498.8	24.40	-5.60	1.90	4.58	0.04	155.74
		14	20	5	1	-461.9	20.50	-5.70	1.60	4.58	0.05	155.74
		15	20	5	1	-493.1	13.00	-6.00	1.00	4.60	0.06	155.75
		16	45	5	5	-497.6	8.20	-10.90	1.90	5.15	0.10	155.71
		17	45	5	5	-501.7	9.90	-12.50	2.00	5.14	0.09	155.70
		18	45	5	5	-500.3	6.60	-11.40	1.30	5.13	0.09	155.71
		19	45	5	4	-491.5	8.30	-9.70	1.60	4.95	0.09	155.69
		20	45	5	4	-498	9.00	-12.70	1.80	4.94	0.07	155.73
		21	45	5	4	-488.9	7.80	-10.90	1.50	4.95	0.08	155.70
		22	45	5	3	-490.8	5.70	-8.50	1.10	4.74	0.05	155.73
		23	45	5	3	-488	5.40	-9.10	1.10	4.74	0.05	155.73
		24	45	5	3	-479.2	6.20	-7.80	1.20	4.74	0.06	155.72

(continued)

Table 1 (continued)

Location	Var.	No.	Tilt max, "	No. of tilt	Spot size, mm	σ , Mpa	($\pm$)	τ , MPa	($\pm$)	FWHM, °	($\pm$)	2 θ , °
		25	45	5	1	-469.9	11.70	-5.10	2.30	4.63	0.05	155.74
		26	45	5	1	-474.6	11.70	-4.50	2.30	4.62	0.05	155.75
		27	45	5	1	-470.3	11.30	-3.50	2.20	4.60	0.05	155.75
		28	45	5	1	-494.8	8.30	-5.30	1.60	4.54	0.06	155.74
		29	45	5	1	-485.7	7.20	-4.30	1.40	4.56	0.07	155.72
		30	45	5	1	-485	6.00	-6.10	1.20	4.54	0.05	155.74

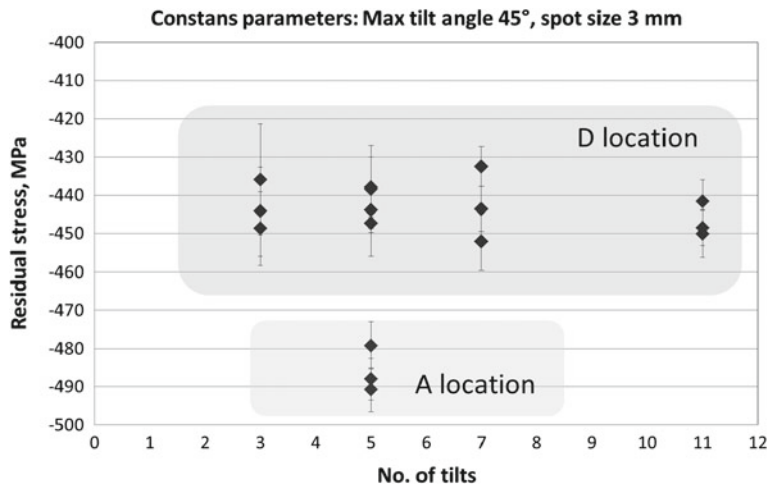


Fig. 2 Residual stress data in function of number of tilts

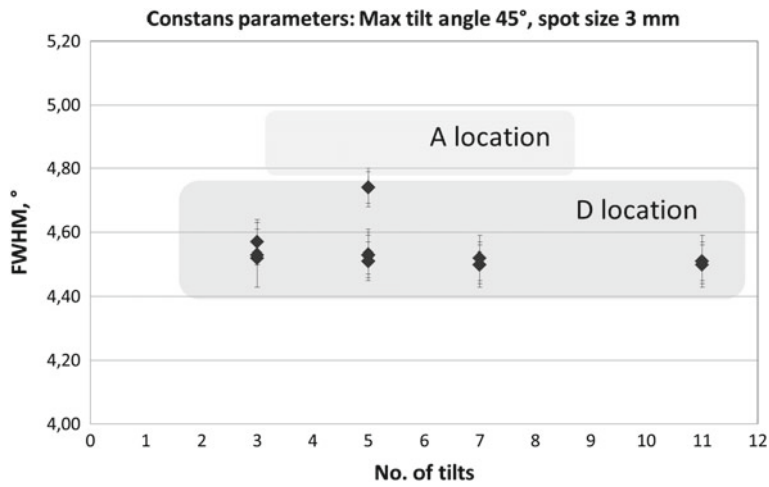


Fig. 3 FWHM data in function of number of tilts

The difference of the two locations (A and D location) can be explained based on the results of Fig. 10. All the residual stress and FWHM data at A and D locations are plotted. The spot size, the max tilting angle and the number of tilt are variables. Three parallel measurements were performed with a given set of variables. The Bragg angles have a small scatter in both locations due to the measuring parameters, but the data of the two locations are markedly different. The A location represents smaller Bragg angles and larger FWHM values. It can happen, if the soluted carbon concentration is higher at the A location. The intensity difference of shot peening

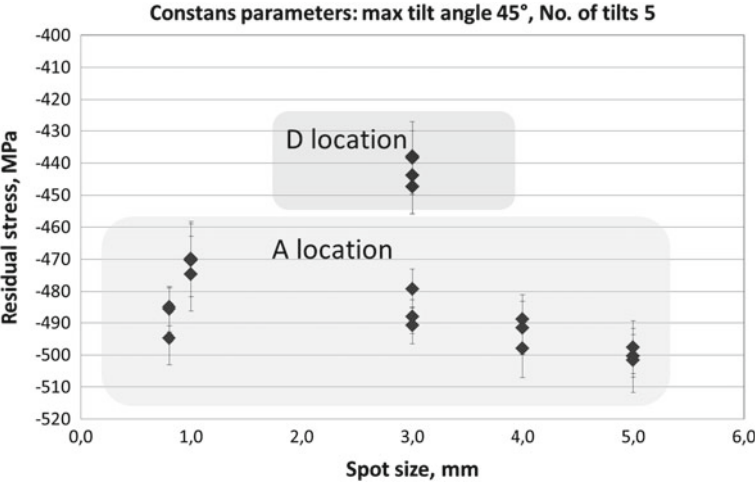


Fig. 4 Residual stress data in function of spot size

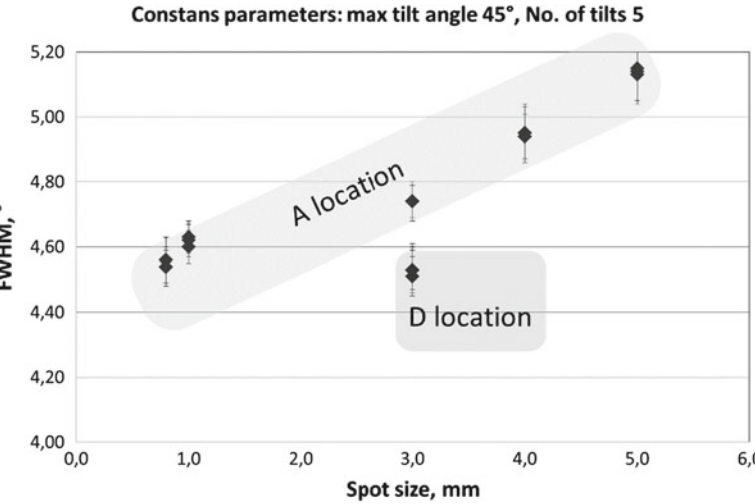


Fig. 5 FWHM data in function of spot size

can cause a shift of FWHM value, but in that case the Bragg angle is unaffected. Because reporting stress results together the other parameters (FWHM, θ) gives a full description with much additional information is always highly recommended in case of any component investigation.



Fig. 6 Residual stress data in function of max tilt angle

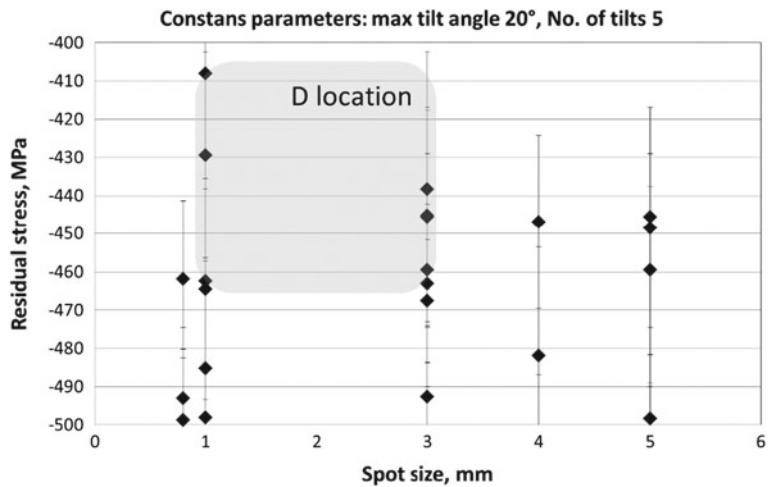


Fig. 7 Residual stress data in function of spot size

The reproducibility of the measurement has been always the question in any case of measurements. Figure 11 shows the reproducibility of stress measurement at the D location in 9 different sets of measurements (a–i). Three parallel measurements were carried out with a given set of variables. Now it is evident that the reproducibility is very good, the scatter of the parallel measured data is smaller than the error bar value.

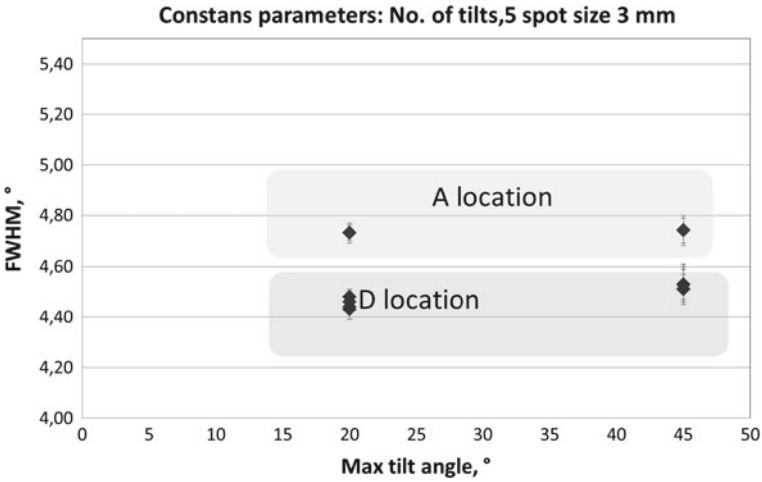


Fig. 8 FWHM data in function of max tilt angle

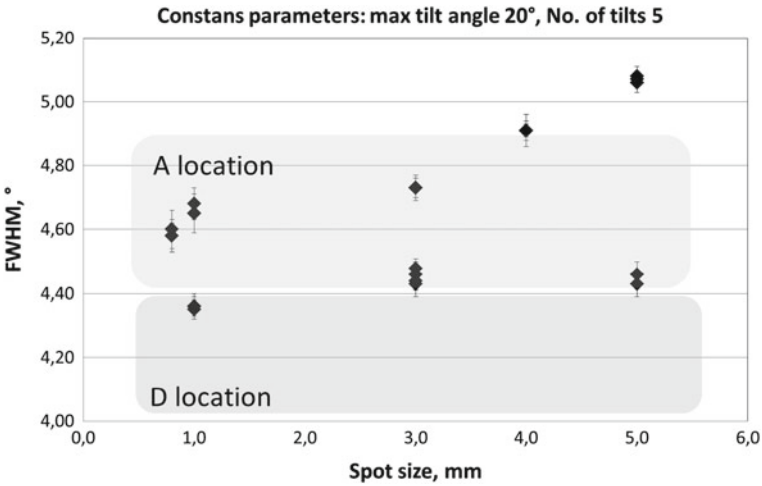


Fig. 9 FWHM data in function of spot size

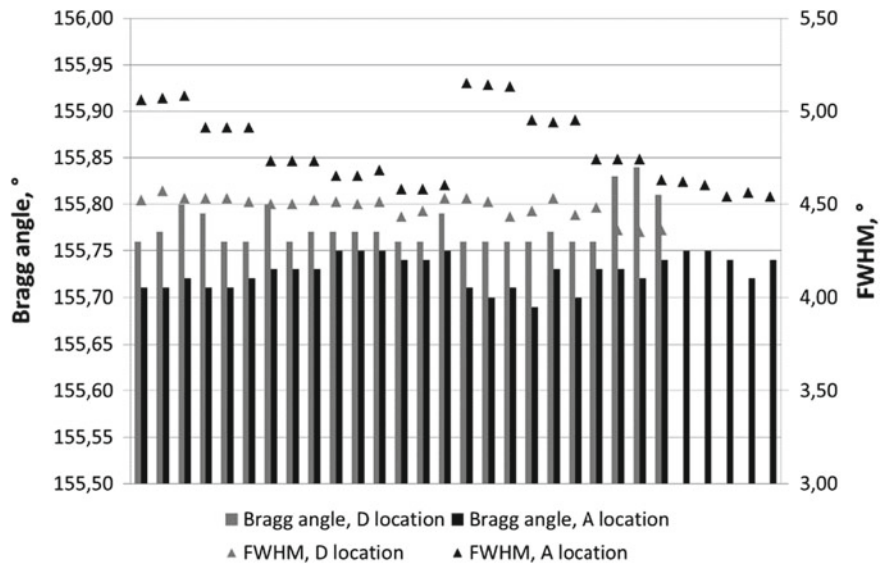


Fig. 10 All the Bragg angle and FWHM data at A and D locations, the spot size, the max tilting angle and the number of tilt are variables. Three parallel measurements were done with a given set of variables

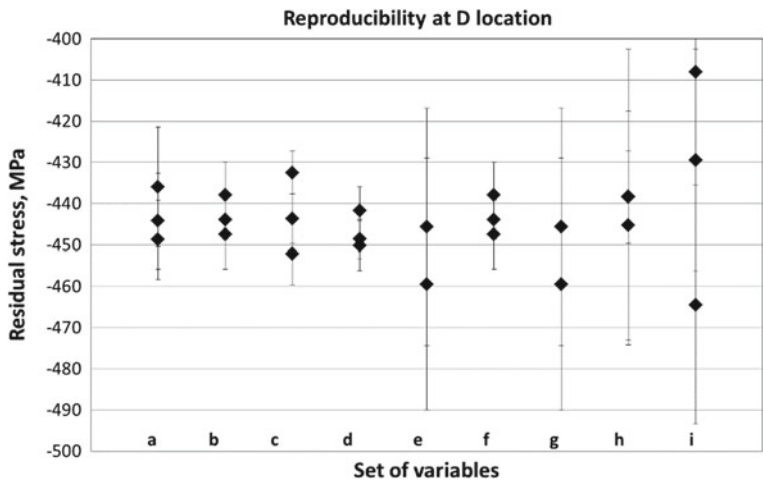


Fig. 11 Reproducibility of stress measurement at the D location in 9 different sets of variables (a–i). Three parallel measurements were done with a given set of variables

4 Summary

The residual stress was measured non-destructively with a Stresstech Xstress 3000 G3R type centerless X-ray diffractometer on a carburized and shoot peened gear wheel using the modified $\sin^2\psi$ method. The data were recorded at two equivalent parts of the gear in the perpendicular direction to the axis. The normal stress (σ), the shear stress (τ), FWHM and Bragg angle (2θ) were calculated at every measuring time. To affect the applied measured parameters such as the spot size, the number of tilting, and the tilting range were showed on based on the highest number of measured data. The result can be summarized as follows:

- The two locations of the gear contain different stress and other results due to the different solute carbon concentration and it is evident on based of simultaneous investigation of normal stress, FWHM, and θ .
- The increase of number of tilting has slightly effect on stress data. The stress results of 11 tilts number shows only smaller error bar, but the difference is much smaller than the difference of the result from the equivalent parts (location A and D) of the gear. The FWHM data are unaffected by the number of tilting.
- The spot size effect on the stress data deviation is within the error bars, if even 6 times larger spot size was used, but the FWHM data are strongly increased as the spot size is increasing. So the FWHM data can be comparable in case of same spot size measurements only.
- The tilting range has the strongest effect on the stress data. In case of $\pm 20^\circ$ tilting range the error bar can be 10 times larger than in case of $\pm 45^\circ$ which is the usually used value. So, the sample cutting may have a smaller modification effect on the original stress state and gives better results than the decrease of the maximum tilting angle.
- The reproducibility was good enough in any case of a set of variables.

Acknowledgements The described article was carried out as part of the EFOP-3.6.1-16-00011 “Younger and Renewing University—Innovative Knowledge City—institutional development of the University of Miskolc aiming at intelligent specialisation” project implemented in the framework of the Szechenyi 2020 program. The realization of this project is supported by the European Union, co-financed by the European Social Fund. The research work of Mate Sepsi was supported through the New National Excellence Program of the Ministry of Human Capacities.

References

1. Handbook of residual stress and deformation of steel. ASM Int 2008, USA pp 347–358
2. Macherauch E, Hauk V (1987) Residual Stress Sci Technol 2:697
3. Soady KA, Mellor BG, Shackleton J, Morris A, Reed PAS (2011) The effect of shot peening on notched low cycle fatigue. Mater Sci Eng, A 528(29):8579–8588
4. Cseh D, Mertinger V, Lukács J (2013) Residual stress evolution during fatigue test of a shoot peened steel sample. Mater Sci Forum 752:95–104

5. Withers PJ, Bhadeshia H (2001) Residual stress Part1—measurement techniques. *Mater Sci Technol* 17:355–365
6. Schajer GS (2013) Practical residual stress measurement methods. Wiley, pp 140–161
7. In: Proceeding of 1st international conference on barkhausen noise and micromagnetic testing, Sept 1–2, 1998, Hannove–Germany, Organized by Stresstech Group and IFW
8. Krawitz AD (2001) Introduction to diffraction in materials science and engineering. Wiley, pp 119–143, 278–318