

Lecture Notes in Mechanical Engineering

Károly Jármai
Betti Bolló *Editors*

Vehicle and Automotive Engineering 2

Proceedings of the 2nd VAE2018,
Miskolc, Hungary

 Springer

Lecture Notes in Mechanical Engineering

VAE 2018

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. 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 Jármái · Betti Bolló
Editors

Vehicle and Automotive Engineering 2

Proceedings of the 2nd VAE2018,
Miskolc, Hungary

 Springer

Editors

Károly Jármai
University of Miskolc
Miskolc
Hungary

Betti Bolló
University of Miskolc
Miskolc
Hungary

ISSN 2195-4356 ISSN 2195-4364 (electronic)
Lecture Notes in Mechanical Engineering
ISBN 978-3-319-75676-9 ISBN 978-3-319-75677-6 (eBook)
<https://doi.org/10.1007/978-3-319-75677-6>

Library of Congress Control Number: 2017930169

© Springer International Publishing AG, part of Springer Nature 2018

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 the registered company Springer International Publishing AG
part of Springer Nature
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland



Significance of the Residual Stress Monitoring in the Automotive Industry

Mate Sepsi^(✉), Maria Salata, David Cseh, Valeria Mertinger,
and Marton Benke

University of Miskolc, Miskolc-Egyetemvaros H3515, Hungary
femsepsi@uni-miskolc.hu

Abstract. Determination of the residual stress is highly important because it has a strong effect on the lifetime of the component and it can cause deformation or failure during the manufacturing. Nowadays, the residual stress characterization became an everyday requirement in the automotive industry. 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 components. If the effect of these processes are known, it is possible to reach such a stress state in the component 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. With this paper, our purpose is to introduce the non-destructive residual stress measuring by XRD, and show quantitative characterization and stress monitoring from the automotive and machine industry.

Keywords: Residual stress · Non-destructive measurement · XRD
Stress monitoring

1 Introduction

Residual stress can be defined as the stress that remains within a material or rigid body after manufacturing and material processing in the absence of external forces or thermal gradients. Residual stress originates from several sources and is generated during most manufacturing processes involving plastic deformation, heat treatment, machining or processing operations that modify the shape or change the density of the material [1]. Residual stress is superimposed on the stress conditions occurring during the service of the component, so its volumetric extent, magnitude and nature have a strong influence on the lifetime of the component. In some cases, the presence of residual stress - its magnitude and its nature (compressive or tensile) at defined locations of the component - are the same requirements that has to be fulfilled for the suppliers, as strength, hardness or elongation. Typical surface compressive or heat treatment methods (burnishing, rolling, shot peening, carburizing etc.) are used to induce compressive stress near the surface region to improve the lifetime against to fatigue [2]. Using those methods, the final stress state can be controlled very well. There is an another very important character of residual stress. The nature and the distribution of the residual

stress formed during the manufacturing process can be various. Residual stresses are not caused by loads (forces or moments), therefore they have to be globally balanced. After its formation, balance is achieved inside the component, but if any subsequent technological steps disrupt this balance, the relaxation of the stresses may cause macroscopic deformations. For example, the stress condition may be changed by another heat effect e.g. welding, or by machining, which is the last technological step where the added value of the component is the highest. This type of distortion is irreversible and remains till the end of the technological process and increases the ratio of waste product. Thus, the control of residual stress not only at the end of the process line but during the whole technological procedure becomes more and more important. Large number of investigations have been carried out to study the residual stress phenomenon and its effect on the mechanical characteristics of the components, but the number of monitoring report about whole process line is rather low [3, 4].

This paper provides an overview about the stress monitoring during the process line of a typical component from the automotive industry.

1.1 Classification and Measurement of Residual Stress

Residual stresses in the solid body exert their effect in different magnitudes. They can be classified as: Type I, II, and III. Type I is macro residual stress that develops in the body of a component on a scale larger than the grain size of the material. Type II is called micro residual stress which varies on the scale of an individual grain. Type III is also referred to as micro (sometimes so called submicro) residual stress, but this varies within a grain, essentially because of the presence of dislocations and other lattice defects. Micro and macro stresses may be present in a component at the same time [5]. During the last few decades many different methods for measuring stresses, especially Type I, which has the greatest industrial interest were developed [6, 7]. Techniques to determine Type I residual stresses may be classified as destructive (semi destructive) or nondestructive methods. The destructive (called also mechanical or stress relaxation) methods are based on the measurement of deformations due to the release of residual stresses upon removal material from the component (sectioning, contour hole-drilling deep hole is the principal destructive techniques. The nondestructive methods include X-ray or neutron diffraction, ultrasonic and magnetic methods and these usually measure parameters that are related to the stress [8]. Non-destructive implies that the component may be returned to service after the residual stresses are measured and the stress fields evaluated. Thus, either the measuring instrument must be portable and sufficiently compact to be brought to the component, or the component must be carried to the instrument, intact and without sectioning.

1.2 Measuring Residual Stress by X Ray Diffraction Methods

Diffraction methods exploit the ability of electromagnetic radiation to measure the distance between atomic planes in crystalline or polycrystalline materials [9]. When any external mechanical or thermal load is applied or incompatible strains occur, the material deforms in response. This deformation is linear when the response is in the elastic range. The diffraction methods effectively measure a crystal inter-planar dimension that can be

related to the magnitude and direction of the stress state existing within the material. These measurements are independent of whether that stress is residual or applied. The fundamental equation of X-ray diffraction analysis is Bragg's law, which describes the interrelation between the interplanar distance d , the incident angle θ (angle between the incident beam and the diffracting lattice plane), the wavelength λ of the X-ray used and the order n of the diffraction.

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

If stress is present, this interplanar distance becomes larger (tensile stress) or smaller (compressive stress). Assuming linear elastic distortions, the related normal stresses can be calculated:

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

where d_0 and d_ψ are the interplanar distances of the strained 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.

For stress measurement using X-ray diffraction, a range of θ angle is scanned and the angle peak intensity is defined as the Bragg angle. Small changes in the corresponding d-spacing that tend to broaden the diffracted peak reflect Type II and Type III stresses. So the measured residual stress data supplemented with full width at half maximum (FWHM) data of the diffracted peak can be very informative with the associated broadening. In the XRD method, X-radiation only penetrates up to a few microns. This shallow depth accommodates the assumption that the stress normal to the surface is zero. Thus, the irradiated volume or gauge volume, under investigation is considered to be in a state of plane stress. This condition allows for simplification of the stress-strain equations and avoids the need for precise determination of the unstressed lattice plane dimension. Thus, simplified equations using the difference between specific lattice planes at several angles to the surface plane are used to extrapolate the strain condition to a vector in the plane of the surface.

The present manuscript gives an overview on the measurement possibilities by an innovative equipment of the Institute of Physical Metallurgy, Metalforming and Nanotechnology at the University of Miskolc. The equipment is a Stresstech Xstress 3000 G3R type X-ray diffractometer developed especially for non-destructive residual stress measurements. The presented diffractometer has a remarkable innovation compared to the traditional ones. In the case of traditional diffractometers, the sample is tilted by precision mechanics. The revolutionary construction of the G3R tilts the device instead of the specimen, which allows measurements without sample cutting, so the true stress state of the component is unaffected. Furthermore, there are no sample size and weight limits for the measurements. This method provides residual stress values from 10 μm depth of the surface layer (depending on material type, applied generator power, Bragg-angle) [10].

2 Stress Monitoring During Process Line of Counter Shafts

2.1 Experimental

The practical and industrial example to monitor the residual stress state in components was carried out on two counter shafts during their main manufacturing steps. The material of the shafts is 20MnCr5, and the examined semi product is a forged shaft. The industrial manufacturing process could be divided to four main section which have effect on the residual stress state: machining in annealed state, heat treatments (carburising), shot peening and the final step, machining in hard state. It is necessary to mention that there is another technological step after the carburising, the straightening, which was not investigated from the aspect of residual stress. Residual stress measurements were carried out after each of the mentioned manufacturing steps on the same shaft, at the same 12 measurement points to monitor the evolution of residual stress field during the manufacturing. Tangential stress was determined on 6 points at the cylindrical surfaces (at the $\varnothing 72$ and $\varnothing 82$ (Fig. 1)), and perpendicular to the face width of the teathed parts (another 6 points at the $\varnothing 108$ and $\varnothing 80$). Figure 1. shows the “starting points” (0°) and the direction of the measurements. Further points were measured at the rotations of 120° and 240° . The result of these points will be discussed as d72/0; d72/120; d72/240, d82/0; d82/120; d82/240, respectively. On the gear part, the rotation is similar, but the numbering refers the sequence of the teeth: d108/1; d108/6; d108/12, and d80/1; d80/5; d80/9. The difference between the two shafts was only in heat treatment. The marks “P” and “C” refer to heat treated in pusher and chamber furnace, respectively. The stress measurement conditions were the same in each case, the details can be found in the Table 1.



Fig. 1. Counter shaft. The points and the direction of the measured stress are indicated.

Table 1. The stress measurements conditions

Parameters	
Radiation	Cr
Acceleration voltage	25 kV
Current	6 mA
Applied collimator size	0,8 mm
The number of applied tilting	4/4
Exposure time	12–45 s according to the standard requirements

After the last process step and residual stress measurement, sectioning was made to investigate the microstructure and the hardness (HV5) distribution. Since the highest load can be observed on the teathed part and the expected failures appear in this area, the cutting was performed at the largest cross section ($\varnothing d108$). The hardness distributions were detected along two radii of the shafts.

2.2 Results and Discussion

As the residual stress results show (Fig. 2), the final stress distributions are very similar in both shafts, only very sufficient compressive stresses can be observed. But during the process line, the residual stress state could change in a very wide range and also can change sign (this range could be more than 1000 MPa). After machining in the soft state, very high tensile stress distribution is observable which may cause deformation if we disrupt this balance with further technological steps. Due to the carburizing drop of the tensile stress can be observed. Heat treatment in the chamber furnace is more effective in this process, even a small value of compressive stress was also formed. The highest compressive stress was reached after shot peening. The improvement was most successful at the teathed area. The final shaping slightly decreased the compressive stress state but is still stable, the highest value remained at the teathed parts with the shorter face width, but and the weakest part of the shaft is also teathed with the longer face with.

Beyond the residual stress results, further information can be obtained about the material, which is very important in the evaluation such as full width at half maximum value (FWHM) of the interference sign, the Bragg angles, and the interference sign intensity distribution in the different tilted positions. The FWHM and Bragg angles give information about the lattice defects (dislocations, dissolved alloying elements). According to Fig. 3 it can be concluded that the micro stresses are also variable during the process line. The hard finishing introduced the highest value of lattice defect into the surface of the both shafts, the FWHM values were even higher than after shot peening. An unexpected difference was found after carburizing in the chamber and pusher furnaces. The shaft heat treated in the chamber furnace exhibited more than double the FWHM values than that of the other one after the carburizing, especially on the teathed area which means more carbon atoms were dissolved. The hardness test confirms this result (Fig. 4). It is true that the shaft heat treated in the chamber furnace shows only slightly larger value in the core and closed to the addendum circle, but close to the middle bore, where the pure carburized surface is present, the difference is considerable. The larger hardness due to the higher carbon concentration might be compensated by the larger retained austenite fraction in the chamber furnace shaft. The thickness of the carburized zones on the teathed parts are similar in case of both shafts.

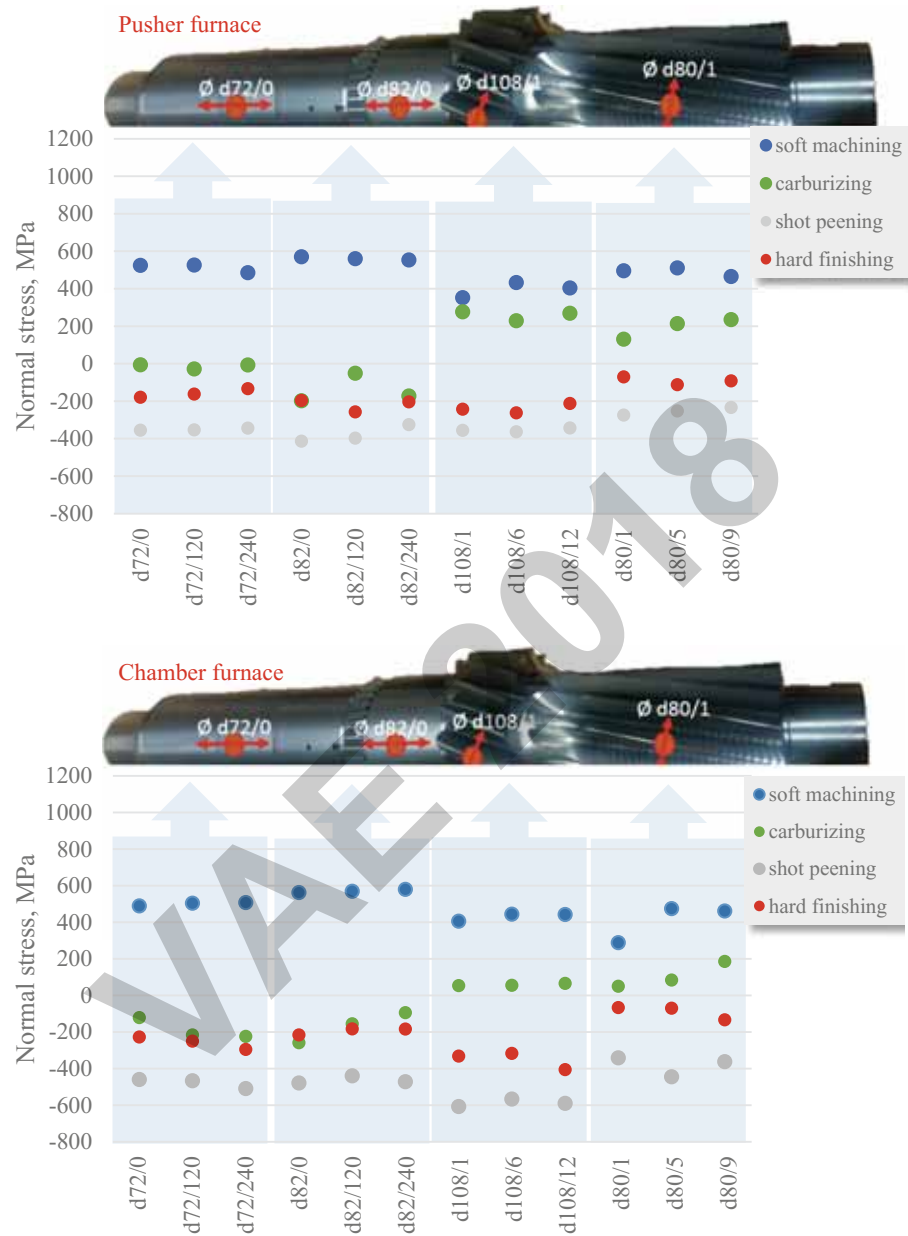


Fig. 2. Normal residual stress distribution of the shafts

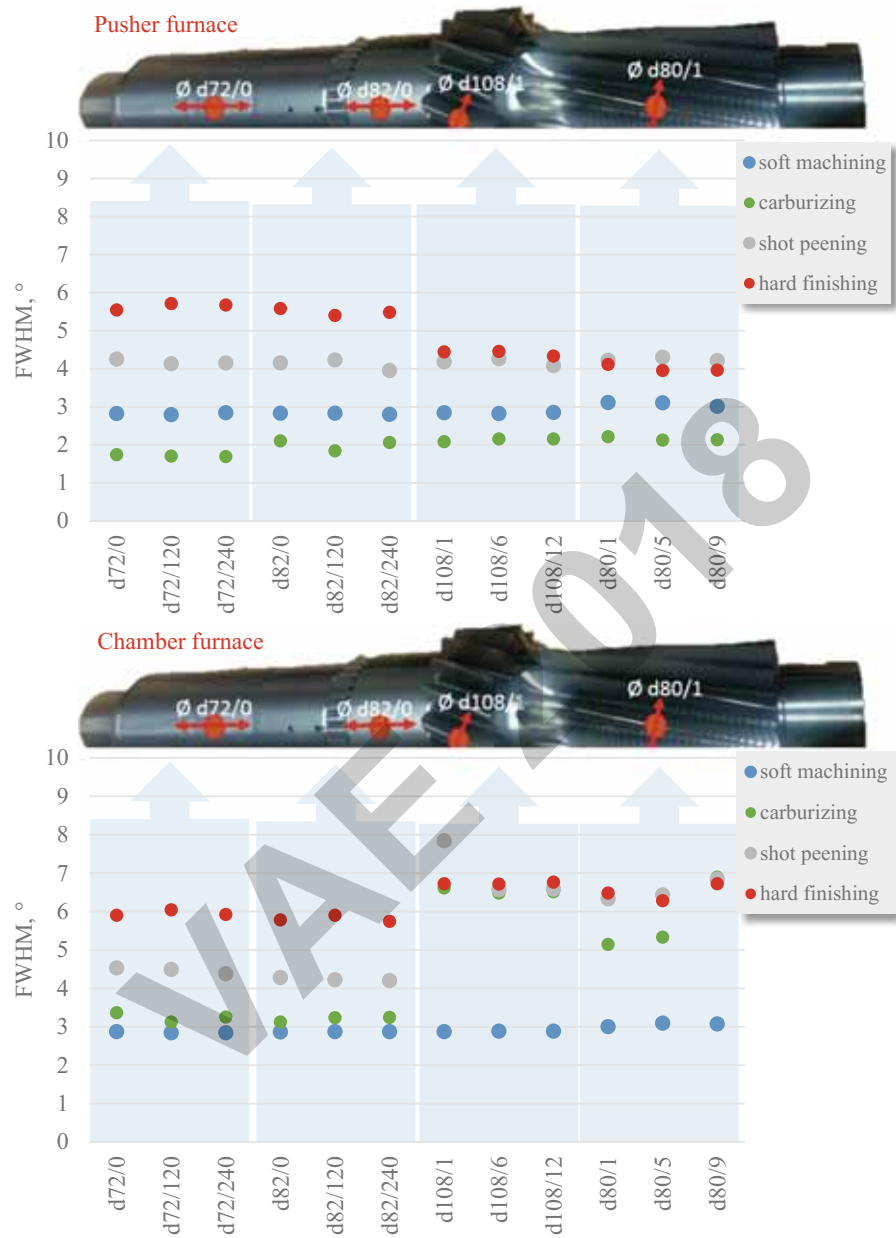


Fig. 3. FWHM distribution of the shafts

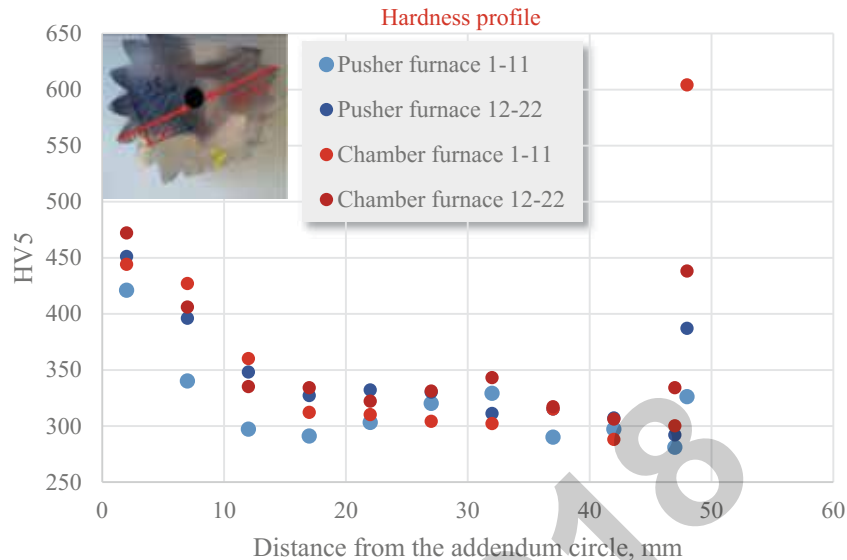


Fig. 4. HV distribution on the cross section of the shafts at Ø108

3 Summary

The residual stress distribution was monitored on the surface of the same two counter shafts during the whole industrial process line such as soft machining, carburizing, shot peening and hard finishing. For carburizing, a pusher furnace and a chamber furnace were used for the two shafts. The results of the two alternative methods were compared. The stress distribution was measured at 12 points, 6 in the cylindrical parts and other 6 in the teethed parts of the shafts in each cases. The residual stress state was determined by nondestructive X ray diffraction method. Not only the residual stress Type I, but the micro stress Type II and III were also recorded associated with the broadening of diffracted peaks. It was experimentally and numerically showed that the residual stress varied dramatically during the production line. Compressive stress was measured at the end of the process in case of both shafts, but harmful tensile stresses were also found after soft machining which exceeded 500 MPa. The advantage of the shot peening was also detected, especially on the teethed part of the shafts. The peak broadening (FWHM) data shows the difference in the carburizing process between the pusher and in the chamber furnaces. Higher soluted carbon concentration was reached in the chamber furnace, but the higher retained austenite concentration compensated the increase in hardness. Therefore, the two different treatments finally resulted similar hardness values.

Acknowledgements. M Seps's research was supported through the new national excellence program of the ministry of human capacities (Hungary). The described article was carried out as part of the EFOP-3.6.1-16-2016-00011 "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.”

References

1. ASM International: Handbook of Residual Stress and Deformation of Steel. USA (2002)
2. Davis, J.: Surface hardening of steels. ASM International, Materials Park, OH USA (2002)
3. Navasa, V.G., Gonzalo, O., Quintana, I., Pirling, T.: Residual stresses and structural changes generated at different steps of the manufacturing of gears: effect of banded structures. *Mater. Sci. Eng., A* **528**, 5146–5157 (2011)
4. Sepsi, M., Angel, D., Cseh, D., Benke, M., Mertinger, V.: Residual stress monitoring for machine industry. In: Bodzás, S., Mankovits, T. (eds.) *Proceedings of the 5th International Scientific Conference on Advances in Mechanical Engineering (ISCAME 2017)*, Debrecen, Hungary (2017). ISBN978-963-473-304-1, old.eng.unideb.hu/gepesz
5. Krawitz, A.D.: Introduction to Diffraction. *Material Science and Engineering*, pp. 119–143, 278–318 (2001)
6. Withers, P.J., Bhadeshia, H.: Residual stress part1- measurement techniques. *Mater. Sci. Technol.* **17**, 355–365 (2001)
7. Rossini, N.S., Dassisti, M., Benyounis, K.Y., Olabi, A.G.: Methods of measuring residual stresses in components. *Mater. Des.* **35**, 572–588 (2012)
8. Schajer, G.S.: *Practical Residual Stress Measurement Methods*, pp. 140–161. Wiley, Chichester (2013)
9. Noyan, I.C., Cohen, J.B.: *Residual Stress, Measurement by Diffraction and Interpretation*. Springer-Verlag, New York (1987). <https://doi.org/10.1007/978-1-4613-9570-6>
10. Sepsi, M., Cseh, D., Filep, A., Benke, M., Mertinger, V.: Innovation methods for residual stress determination for the automotive industry. In: *Lecture Notes in Mechanical Engineering F12*, pp. 483–499 (2017)