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Assessment of mechanical loads based on surface integrity analysis of machined components

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ABSTRACT

Today, the capability of machined components to provide information on mechanical loads during their usage phase is not being assessed. However, it is well known that especially residual stresses change due to mechanical load. An approach is presented, how this effect can be utilized to determine the mechanical loads a component has been exposed to. To enable the identification, more than one property has to be used to identify the combination of load stress amplitude and number of load cycles. The presented paper focuses on the analysis of precision and reliability of the determined solutions.

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1. Introduction

What if mass produced components had sensory properties? Which opportunities would arise if millions of wheel carriers or drive shafts of passenger cars and trucks were able to give detailed information on mechanical loads during their life cycle? Which impact would have safety-relevant components such as engine mounts that report on the maximum load stress they experienced since the last inspection?

The vision of the Collaborative Research Centre 653 strives for technologies enabling cognitive components, which gather and store information on their own production and self-monitor their condition [1]. Future mass production components giving feedback during their application represent an invaluable benefit for design evolution regarding tailored adaptation to load. Detailed information on loads a component experienced during its life cycle is considered as a key aspect to enable condition-based maintenance. The subsurface of machined components can be exploited to realize the vision of 'feeling' components. The approach is based on modeling the changes of a components subsurface properties and the mechanical loads it has been exposed to. Based on this model, monitoring the subsurface properties during the life cycle of a similar component offers the possibility to determine its loading.

It is well known that machining processes change surface and subsurface properties of machined components. This can be utilized to induce a residual stress state with regards to monitoring it throughout a components life cycle. Even though numerous scientific publications on the effect of cutting processes on surface integrity properties exist, residual stress formation has not yet been fully understood [2]. So far, no model is capable to determine a set of process parameters that will cause a specific residual stress state [3]. A summary of fundamental results and an overview on recent developments is given in [2,4].

Various publications demonstrate that residual stress can show a strong influence on its fatigue life [5]. In order to improve performance and reliability of machined components, extensive research was done to gain a deeper understanding of this correlation [4]. It was identified, that the materials ultimate strength determines whether or not the residual stresses relax due to mechanical load. Hence, if relaxation appears, the influence of residual stress on the fatigue life decreases [6]. The general influence of the load stress amplitude and number of cycles on fatigue life of a component has been investigated extensively for different materials and heat treatment conditions [7].

One of the most common approaches for the measurement of residual stresses in the near surface area by X-ray diffraction (XRD) is the $\sin^2\psi$-method [8]. As a result, macro-residual-stresses can be measured quantitatively, whereas micro-residual-stresses are represented by the peak width at half maximum (FWHM) and have to be regarded as a qualitative indicator.

In summary basic information about residual stress measurement, process dependent stress induction and load dependent relaxation are available in literature. However, today they are not used for load determination during the usage phase of a component. The presented work introduces an approach based on surface integrity analysis to assess the load stress amplitude as well as the number of load cycles a machined component experienced. It does not focus on the fatigue life of a component since the effect of residual stresses on the fatigue life decreases due to relaxation. The first section of this paper covers the reproducibility of residual stresses induced by turning. Following, the modeling of residual stress relaxation is described based on experimental results. Concluding, the procedure for reconstruction of mechanical loads is presented and its precision and reliability are discussed.

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2. Repeatability of residual stress inducement by turning

If a change of residual stresses is to be used to determine the load, causing it, the initial residual stress state has to be determined as precisely as possible. So far, the potential scatter within a series of components, machined under the same conditions, has not yet been analyzed. If parts within a large batch are not to be evaluated individually, the standard deviation of residual stresses has to be identified. Therefore, a large number of rotary bending test specimens is machined on a Gildemeister CTX 520 L CNC lathe following DIN standard 50113 (smallest diameter 7 mm). To ensure comparability of results with former publication of the author (see [9,10]), identical cutting and tool parameters summarized in Table 1 were applied. 50 specimens of each process parameter set are machined. The specimens' material is AISI 1060 high carbon steel.

Table 1
Process parameters and tool geometry.

Process parameters			
Cutting speed	v_c = 30, 120, 300 m/min	Depth of cut	a_p = 0.1 mm
Feed rate	f = 0.01, 0.1, 0.5 mm		
Tool geometry: SNMA-120408-S02020-MW			
Cutting edge radius	r_β = 50 µm	Corner radius	r_ε = 0.8 mm
Cutting edge angle	κ_r = 75°	Clearance angle	α = 5°
Cutting edge incl.	λ_S = −5°	Rake angle	γ = −5°

Each specimen is machined using a new cutting edge to exclude the influence of wear. The parameters are chosen to realize three residual stress states. High tensile or high compressive stresses result due to varying passive forces as well as low and high cutting temperatures. The residual stresses were evaluated by the $\sin^2\psi$−method regarding normal stresses as well as peak width (FWHM). A point collimator with a diameter of 2 mm and Cr Kα radiation were employed causing a maximum penetration depth of about 5 µm in steel [11]. Measurement results have to be regarded as an integral of this depth.

2.1. Macro- residual-stresses

The thermomechanical load caused by cutting speed v_c = 30 m/min and feed f = 0.01 mm results in compressive residual stress parallel to the cutting direction $\sigma_{||}$ = −144 MPa and normal to the cutting speed of $\sigma_\perp$ = −198 MPa. Additionally the normal stress in diagonal direction (φ = 45°) σ_{45} = −89 MPa is measured. Fig. 1 depicts the probability density function resulting from 50 specimens turned and measured under identical conditions. The absolute values correspond to generally accepted correlations, such as compressive stresses for low cutting speed and small feed rates. In addition, the evaluation of the standard deviation σ_{Std} is a measure for the repeatability of the stress induction (Fig. 1, top). The applied process parameter set causes 16 MPa $\leq \sigma_{\text{Std}} \leq$ 32 MPa, which represents a value close to the theoretical measurement accuracy of the used X-ray technology of ±5–10 MPa [12] and the common conservative assumption of ±25 MPa reproducibility as a standard practice. As expected from consistent reports in literature, an increase of cutting speed and feed to v_c = 120 m/min and f = 0.1 mm, respectively, results in tensile residual stresses $\sigma_{||}$ = 74 MPa, $\sigma_\perp$ = 64 MPa and σ_{45} = 277 MPa). A further increase to rather aggressive parameters of v_c = 300 m/min and a feed f = 0.5 mm leads to a further increase of the tensile stresses $\sigma_{||}$ = 604 MPa, $\sigma_\perp$ = 459 MPa and σ_{45} = 598 MPa. The behavior is explained by the increasing thermal and mechanical loads the material experiences by the cutting process. Increasing friction leads to a greater amount of heat, which is transferred into the machined surface. As a result, tensile stresses increase. Overall, a wide range of residual stresses was induced into three sets of specimens (Fig. 1). Standard deviation for the three parameter sets and three directions each is between 13 MPa $\leq \sigma_{\text{Std}} \leq$ 34 MPa.

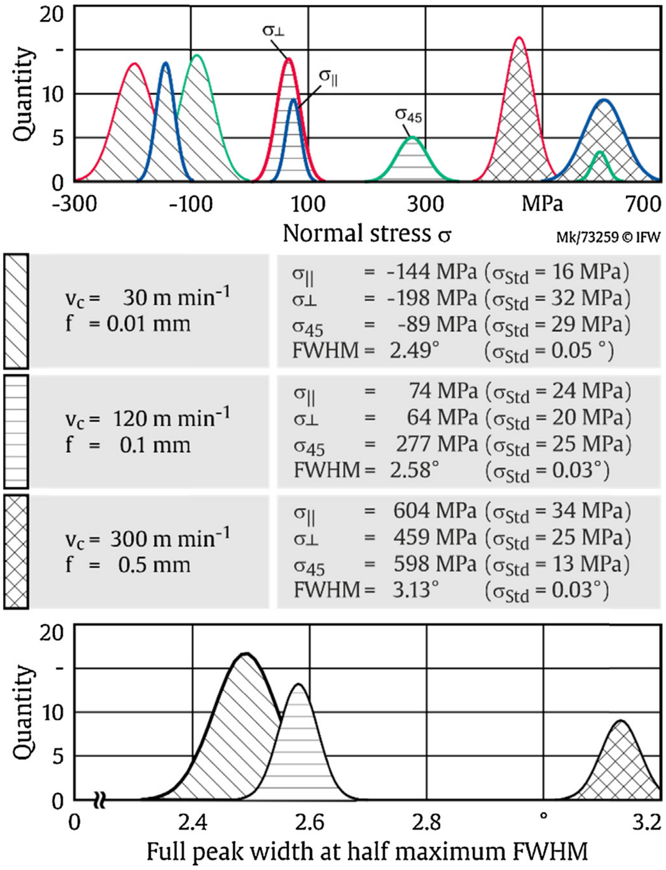

Fig. 1. Probability function of macro-residual-stresses and FWHM.

2.2. Full width at half maximum

In addition to macro-residual-stresses, the full width at half maximum (FWHM) is used as a second property to characterize the subsurface of a component. It qualitatively describes micro-residual-stresses. The determination of the FWHM shows a corresponding behavior to the macro-residual-stresses in this study (Fig. 1, bottom). An increasing load results in a growth of the FWHM due to an increasing dislocation density (micro-residual-stresses). With regard to the assessment of loads based on surface integrity analysis, the investigations focus on the standard deviation rather than on the absolute value. It differs in the second decimal place. Provided that the cutting process is done under identical conditions, it is therefore assumed, that the reproducibility of FWHM as well as of macro-residual-stresses are virtually independent of the process parameters.

It is demonstrated, that the turning process enables the inducement of a wide range of macro-residual-stresses and FWHM by a variation of the process parameters. At the same time a high reproducibility is given. Since the superposition of load and residual stress determines the critical load that leads to a residual stress relaxation, the actual value of the latter is of importance. The standard deviation matters regarding the model based reconstruction of the components' loading, since it has to be considered when evaluating the change of residual stresses.

3. Modeling changes of macro-residual-stresses and FWHM

After cutting a two-dimensional stress state is present within the near-surface area of a component. Following the von Mises yield criterion, it is transformed into a scalar stress value that can be compared to material properties evaluated by standard testing, such as quasi-static or cyclic yield strength. Material characterization indicates quasi-isotropic behavior. Under consideration of a superimposed load, the critical load stress is determined by solving the von Mises yield criterion. Following, rotating bending

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