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Elementary studies on the inducement and relaxation of residual stress

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Abstract

In order to qualify residual stress relaxation as an indicator of mechanical overloading of machined parts, an individually designed residual stress profile has to be allocated. Even though numerous investigations have been carried out in the past, residual stress profiles cannot be predicted to a satisfactory degree. For this reason, essential studies on the reproducibility of residual stress profiles for several external cylindrical turning parameters are conducted and it is demonstrated that identical residual stress profiles can be induced successfully. Subsequently, specimens with defined residual stress profiles are loaded in bending tests with various numbers of test cycles. The amount of residual stress relaxation in the specimen's surface layer is measured to determine the influence of the applied load on the stress relaxation. By applying single tensile and compressive loads below and above the material's yield and ultimate strength, the stress relaxation can be evaluated in detail.

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Keywords: Residual stress; Surface integrity; Fatigue

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1. Introduction

The Collaborative Research Center SFB 653 "Gentelligent Components in Their Lifecycle – Utilization of Inheritable Component Information in Product Engineering" researches on technologies to enable components to store information on their own production, or to self-monitor their condition [1]. The influence of load and fatigue on subsurface properties, mainly residual stress, will be used to draw conclusions on the load history of a component and thus to predict the remaining life span. Being capable to induce a predefined residual stress profile offers the possibility to utilize the correlation between the effective stress at the workpieces surface and the residual stress relaxation, resulting of the load applied.

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Despite numerous investigations on the subsurface alterations caused by material removal processes in the past, the residual stress profile cannot be predicted to a satisfactory degree [2].

The residual stress profile is an important integrity attribute of a machined workpiece due to its direct effect on fatigue life and fracture behavior. The correlation of residual stress and functional performance needs to be understood in order to improve the performance and reliability of machined components [3]. In 1951 Henriksen investigate the surface integrity characteristics of components through an analysis of residual stress induced in machining processes [4]. The term surface integrity and typical surface characteristics such as plastic deformation, micro cracking and residual stress distribution were acknowledged by Field and Kahles [5]. Subsequently, several surface characteristics and associated classification methods have been extensively studied. These publications contain experimental methods for the assessment of residual stresses and their causes in different machining processes [6]. Recently, an overview of the extensive research on surface integrity in machining was presented by M'Saoubi et al. [3]. Research on the correlation between fatigue life of machined parts and their surface condition show a strong dependency. The reason for this are cracks normally initiating from free surfaces due to fatigue. The highest stress in loaded parts is located at its surface. Besides geometric irregularities, metallurgical alterations of the surface layer were identified to be important aspects of a surface, regarding crack initiation. It could be demonstrated, that compressive residual stress at a components surface increases its fatigue life [7, 8].

One main objective of recent investigations is the control of residual stress inducement during the material removal process. The CIRP Collaborative Working Group on Surface Integrity and Functional Performance of Components has conducted extensive research for the last three years (2008-2011). Recent advances in experimental techniques, state-of-the-art modeling efforts including analytical and numerical studies for predicting surface integrity machining parameters were summarized. Round Robin Studies on surface integrity parameters were conducted. One study exposed the experimental process capability for producing a target compressive residual stress at the workpiece surface, using an arbitrary machining operation. A variety of material removal processes was selected by the participants. The given target was achieved by only few specimens. The results demonstrate that the inducement of a predefined residual stress level is not controlled to a satisfying degree today [2].

2. Inducement and assessment of residual stress profiles

Due to unsatisfying results of analytical and numerical approaches to precisely predict residual stress profiles, essential studies on the reproducibility of residual stress profiles for several external cylindrical turning parameters were carried out to create reliable data. As a result, process parameter sets were determined to produce specimens with three characteristic initial residual stress profiles. Furthermore it is demonstrated that residual stress profiles can be induced and assessed reproducibly. The experiments were conducted on two machine tools to enlarge the validity of the results using identical cutting parameters as listed in table 1. The CNC lathes used are a Gildemeister CTX 520 L and a Gildemeister MD 10 S. Identic cutting tools were used on both machines. The specimen's material is untempered AISI 1060 steel. A one factor at a time process parameter variation was carried out for a wide range of cutting velocity and feed values. The cutting velocity and the feed were varied in three steps, resulting in a total of nine parameter sets. The parameters were chosen to realize high tensile and compressive stresses due to varying passive forces as well as low and high cutting temperatures. Each specimen was machined using a new cutting edge to exclude the influence of wear. Due to a length of cut $l_{c,max}$ = 350 m, the effects of wear are not taken into account. After analyzing the induced residual stress profiles, three parameter sets, leading to a high compressive, a high tensile and a medium tensile residual stress at the specimens surface were picked and repeated nine times. Three additional repetitions were conducted on the lathe Gildemeister MD 10 S.

Table 1. Process parameters and tool geometry

process parameter		tool geometry: SNMA-120408-S02020-MW			
depth of cut	$a_p = 0{,}2$ mm	tool cutting edge angle	$\kappa_r = 75°$	tool orthogonal clearance angle	$\alpha_O = 5°$
cutting speed	$v_c = 30, 120, 300$ m/min	tool cutting edge inclination	$\lambda_S = -5°$	tool orthogonal rake angle	$\gamma_O = -5°$
feed rate	$f = 0.01, 0.1, 0.5$ mm	rounded cutting edge radius	$r_\beta = 50$ µm	corner radius	$r_\varepsilon = 0{,}8$ mm

X-ray diffraction (XRD) was employed to assess the residual stress state of the specimens. The $\sin^2\psi$–method, was conducted [10]. Fig. 1 illustrates depth information of the residual stress profiles in feed direction $\sigma_\perp$, gained by step-by-step electrolytic removal of thin material layers and measurement in each layer. The results demonstrate a high reproducibility of the residual stress profile, whereas the highest deviation is found at the surface. This is due to the measuring principle using the mean information of a point collimator with a diameter of 2 mm, and the fact that the applied CrKα radiation penetrations a depth of about 5 µm in steel [11]. The results are therefore integral measures of the residual stresses. The surface roughness and therefore its influence on the results decrease due to the surface polishing effect of the electrolytic material removal.

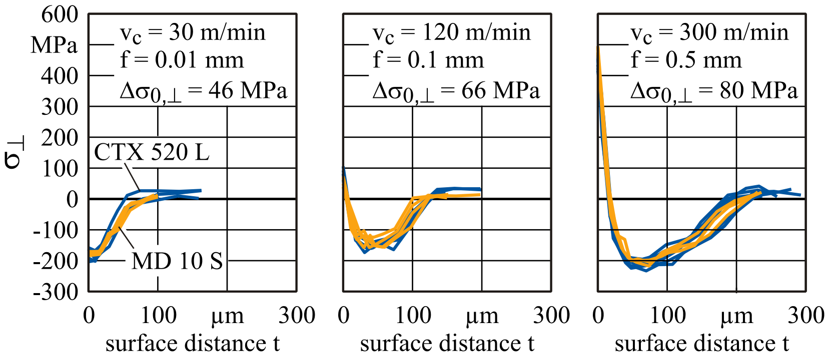

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Fig. 1. Reproducibility of residual stress profiles for three selected combinations of process parameters

It can be demonstrated, that there is no obvious influence of the machine tool on the residual stress profiles. The maximum deviation at the surface amounts to $\Delta\sigma_{0,\perp}$ = 80 MPa. The highest deviation between individual profiles is $\Delta\sigma_\perp$ = 85 MPa. This information represents a key requirement to design residual stress profiles and use them as an offline load sensor. Keeping in mind, that the accuracy of the XRD method of about 25 MPa is given, each of the specimens used in the following load relaxation experiments is measured at the same position before and after the particular experiment is conducted. Hence, the relaxation of the residual stress is based on the initial stress level of the identical specimen.

3. Effective stress level and residual stress relaxation

Subsequently, specimens with three residual stress profiles are loaded in bending tests with various numbers of cycles. High compressive residual stresses ($\sigma_{0,\perp} = -800$ MPa) can be induced by machining specimens with a cutting speed $v_c = 30$ m/min and a feed rate of $f = 0.01$ mm by adapting the contact conditions. Due to the main direction of the stress resulting from the bending loads, the following analyzes consider the residual stress normal to the direction of the cut $\sigma_{0,\perp}$. The residual stress relaxation at the specimen's surface is measured as described above, to determine the influence of the applied load on stress relaxation. To evaluate the fatigue strength, the material properties were analyzed. Based on the determined yield and ultimate strength of the material ($R_{eH} = 440$ MPa, $R_m = 830$ MPa), load magnitudes were defined, to result in effective compressive and tensile stress magnitudes at the specimens surface above and below the yield and ultimate strength of the material. The experiments were conducted at the Institute of Plant Engineering and Fatigue Analysis of the Clausthal University of Technology, Germany. In addition to pulsating loads, experiments with fully reversed loads were carried out and analyzed.

Fig. 2 illustrates the results of the conducted experiments. The top diagrams a to c demonstrate initial stress of each specimen, the effective stress while the load is applied and the final stress state after the load has been removed. Each diagram compares the influence of 100 pulsating tensile and compressive as well as 100 fully reversed loads. This procedure allows a separate examination of the influence of the individual stress state and a comparison of the effects of 100 load cycles for different initial stress levels for fully reversed and pulsating loads. The bottom diagrams summarize the residual stress relaxations.

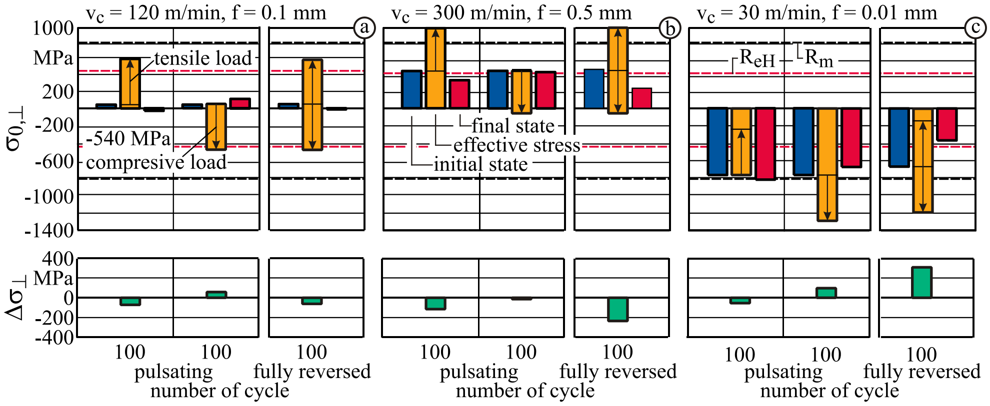

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Fig. 2. Effects of fully reversed and pulsating loads on residual stress relaxation for different initial stress magnitudes

Fig. 2 (a) illustrates the relaxation of an initial tensile residual stress level of $\sigma_{0,\perp} = 50$ MPa due to the application of 100 tensile pulsating loads of $\sigma_{load,\perp} = 540$ MPa. The effective stress magnitude $\sigma_{0,\perp,max} = 590$ MPa equals the sum of the residual stress axial to the cutting direction $\sigma_{0,\perp}$ and the stress induced by the bending load $\sigma_{load,\perp}$. It exceeds the yield strength R_{eH} of the material and leads to a relaxation of the residual stress. The application of 100 compressive pulsating loads $\sigma_{load,\perp} = -540$ MPa, exceeding the yield strength of the material under compression. As a result, tensile residual stress build up. 100 fully reversed loads represent a combination of both previous presented loads. Both stress magnitudes exceed the yield strength of the material and lead to similar results.

Loading the specimen with an initial residual stress of $\sigma_{0,\perp} = 450$ MPa with a tensile stress of $\sigma_{load,\perp} = 540$ MPa for 100 cycles leads to a reduction of the residual stress of $\Delta\sigma_{0,\perp} = 116$ MPa (fig. 2 (b)). The effective load reaches a maximum of $\sigma_{0,\perp,max} = 990$ MPa. Regarding the stress-strain-curve the yield strength R_{eH} as well as the ultimate strength R_m of the material is reached. Thus the material starts to creep. This leads to a reduction of the residual stress at the workpiece's surface, when the specimen is unloaded. The application of a compressive load of $\sigma_{load,\perp} = -540$ MPa results in an effective stress below the yield strength of the material and does not affect the residual stress level at the workpieces surface. Therefore, a stress above the materials yield strength $\sigma_{load,\perp} = 540$ MPa $> R_{eH} = 440$ MPa does not necessarily lead to a residual stress relaxation. Fully reversed loading leads to analog results to pulsated loading. During the tensile phase of the loading the material's yield and ultimate strength are exceeded, the material creeps and residual stress is reduced by a similar degree compared to the pulsing load.

Vice versa, alike results are gained for identical experiments with specimens, that have an initial high compressive residual stress level of $\sigma_{0,\perp} = -770$ MPa (fig. 2 (c)). Yield and ultimate strength of the material are exceeded applying a compressive load of $\sigma_{load,\perp} = -540$ MPa. Hence the material creeps and the residual stress magnitude reduces. A tensile load of the same magnitude results in an effective stress magnitude below the yield strength and has only minor influence on the specimens residual stress level. The stress relaxation of $\Delta\sigma_{0,\perp} = 50$ MPa results from the fact, that the applied load leads to an effective stress magnitude below the yield strength of the material. The residual stress level exceeds the yield strength, as the load is removed. Consequently the material creeps and the residual stress level decreases.

Analyzing the influence of a varying number of pulsating loads on the specimen shows that the amount of residual stress relaxation does not increase with the number of loads. The data shown in fig. 3 (a) is gained from specimens with initial tensile stress. It demonstrates that the residual stress relaxation resulting from a single pulsating load relaxes an equal amount of residual stress, than 100 pulsating loads. As explained earlier, the application of an additional tensile load leads to the relaxation of the residual stress, due to the exceeding of the yield and ultimate strength of the material. Minor relaxation is determined for compressive stress due to a low effective stress (fig. 3 (b)). The results obtained for an initially high compressive stress are analog to these results and therefore not presented in detail.

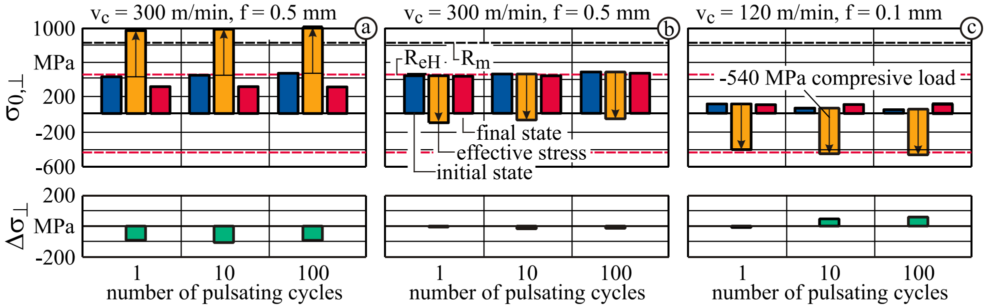

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Fig. 3. (a, b) Equal residual stress relaxation for varying load cycles; (c) strong influence of minor yield strength exceeding

A detailed analysis of the results for pulsating loads using specimens with initial low tensile residual stresses shows, that the observed effects can be used to determine the applied loads precisely. Due to a small initial stress level deviation at the specimens' surfaces, the effective stress magnitudes are slightly below and above the yield strength of the material, as illustrated in fig. 3 (c). The specimen single-loaded with a compressive load of $\sigma_{load,\perp} = -540$ MPa does not results in a recognizable stress relaxation. The effective stress magnitude is about 10 MPa below the yield strength of the material. Due to a deviation of the initial stress the specimen loaded with ten compressive load cycles, it exceeds the yield strength of the material by about 40 MPa. As a result the tensile residual stress relaxes by $\Delta\sigma_{0,\perp} = 50$ MPa. Analog to the observed behavior, the specimen loaded 100 with compressive cycles, exceeds the yield strength by 60 MPa and builds up by about $\Delta\sigma_{0,\perp} = 60$ MPa.

4. Conclusion

In course of this paper, it can be demonstrated that the residual stress profile can be induced and assessed with a high reproducibility. Based on that, specimens with three initial residual stress profiles are used to analyze the effect of single tensile and compressive loads. Experiments were conducted to differentiate between cyclic and pulsating loads. It is demonstrated, that the effective stress at the specimen's surface is of preeminent importance, regarding the stress relaxation. Exceeding the yield strength of the material leads to a change of the residual stress magnitude. So far, the quantity of load cycles cannot be determined by the amount of relaxation. An overloading itself can be considerably determined though. A smart design of surface and subsurface layer and precisely induced initial residual stress levels at the surface can be used for an accurate determination of the load applied to the specimen. A combination of varying residual stress magnitudes at the surface of one specimen can therefore be used to exceed the yield strength of the material at different loads and relax the residual stresses.

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