Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 37 (2015) 236 – 241

www.elsevier.com/locate/procedia

CIRPe 2015 - Understanding the life cycle implications of manufacturing

Estimation of load history by residual stress relaxation

B. Breidenstein, B. Denkena, T. Mörke, R. Hockauf*

Institute of Production Engineering and Machine Tools, Leibniz Universität Hannover, 30823 Garbsen, Germany

* Corresponding author. Tel.: +49-511-762-4788 ; fax: +49-511-762-5115. *E-mail address:* hockauf@ifw.uni-hannover.de

Abstract

Focusing on the impact of machining on structural integrity and fatigue life of components the surface and subsurface properties are of major importance. It is well known that machining induced residual stresses have a significant influence on the fatigue life of a component. Due to thermal and mechanical loads during a product's life cycle these stresses relax, which is undesired in most cases.

The presented approach utilizes relaxations due to mechanical load to estimate the load history of a component. It is intended to qualify residual stress relaxation as a load sensor and to determine the limits of this approach. Therefore, it is demonstrated, how the residual stress state induced by turning of AISI 1060 determines the critical load causing relaxation. Subsequently, the influence of load stress and the number of load cycles is used to build up a model. The presented approach accesses load information from mass production components. Until now, this information is typically limited to prototypical developments or high price parts equipped with external sensors. One application of life cycle data is condition-based maintenance. This technology allows to extend service intervals and prevent a premature replacement of undamaged components. Thus, cost and resource efficiency are augmented. It is demonstrated that based on the changes of residual stress, possible mechanical loads and number of load cycle combinations can be identified. The changes are used to estimate the experienced loads.

Peer-review under responsibility of the organizing committee of CIRPe 2015 - Understanding the life cycle implications of manufacturing

Keywords: Residual stress; Fatigue; Surface integrity

1. Introduction

The vision of the Collaborative Research Centre SFB 653 “Gentelligent Components in Their Lifecycle” includes technologies which enable components to store information about their own production and to self-monitor their condition [1, 2]. A special interest is directed towards sensing components that communicate their load history. Enabling future mass production components to give feedback based on real life application offers great potential for life cycle monitoring and maintenance planning as well as for design evolution regarding tailored adaptation to load. One key aspect is the possibility to determine whether and how a component has been loaded during the last maintenance interval and to estimate its failure possibility. The presented approach utilizes the changes of subsurface properties such as residual stress relaxation and change of dislocation density during the component's lifecycle to estimate its load history.

The surface and subsurface properties are of significant importance since they affect directly a component's fatigue life and fracture behavior. The term surface integrity, acknowledged by Field and Kahles, summarizes typical surface characteristics such as plastic deformation, micro cracking and residual stress distribution [3]. A variety of results has been published on the effects of surface integrity on a component's behavior. Regarding residual stresses, it has been demonstrated that near surface compressive residual stress increases its fatigue life whereas tensile residual stress has a negative impact [4].

Starting in 1951 Henriksen investigated the surface integrity characteristics of components through an analysis of residual stress induced in machining processes [5]. One of the most common approaches is the measurement of residual stresses in

Peer-review under responsibility of the organizing committee of CIRPe 2015 - Understanding the life cycle implications of manufacturing
doi:10.1016/j.procir.2015.09.006

the near surface area by X-ray diffraction (XRD) and the $\sin^2\psi$-method [6]. As a result, residual stresses of the 1st order can be measured quantitatively, whereas 2nd order residual stresses are represented by the peak full width at half maximum (FWHM) and have to be regarded as a qualitative indicator.

The machining process, which is mostly the last step in the manufacturing chain has a significant influence on surface integrity of a work piece. In terms of cutting the mechanical deformation of material by the cutting edge leads to compressive residual stresses in the near surface area. The thermal load during the process in interaction with the rapid cooling after manufacturing causes tensile residual stresses [7]. In addition, finishing processes such as burnishing, deep rolling, shot peening or laser shock peening are available to specifically influence surface integrity.

Research on the influence of subsurface properties on fatigue life of a component shows that with decreasing ultimate strength of the material the influence of residual stresses on fatigue life decreases [8]. Below $R_m < 1400$ MPa residual stresses in metallic components relax [8]. Relaxation is caused by mechanical and thermal load and depends on material properties such as yield strength, thus it depends on heat treatment. Their effects on lifetime are described independently. A thermal load of about 50 % of the melting temperature causes a significant relaxation of residual stresses. In most cases technical components do not reach those temperatures. At lower temperatures, the decrease is negligible [9, 10, 11]. Therefore, the presented approach focuses on the reconstruction of a component's load history using the residual stress relaxation caused by mechanical loads. A cyclic mechanical load scenario is characterized by the load amplitude and the number of load cycles. Extensive research for different materials and heat treatment conditions has been published. Experiments on AISI 4041 show an increasing residual stress relaxation for increasing load stress amplitude. The strongest relaxation appears during the first load cycles. The material's ultimate strength determines the residual stress sensitivity, which describes the degree of relaxation [8, 11, 12]. The effective stress in a component's surface area equals the superposition of load stress amplitude and residual stresses prior loading. Following the shell/core approach, relaxation is based on local plastic deformation [10]. For steel components the equivalent stress is expressed based on the von Mises criterion [8].

Even though a variety of publications on the change of subsurface properties due to fatigue has been published, there has been no utilization of these changes for an estimation of a component's load history. Based on the description of relaxation, the presented approach combines common approaches to identify load stress amplitudes and number of load cycles that cause a desired change of individual subsurface properties.

2. Experimental setup

AISI 1060 specimens are identically machined by turning to induce defined residual stresses. The residual stresses due to machining are used to set up critical load stresses, causing relaxation. Subsequently fatigue experiments are carried out and the alteration of FWHM and the relaxation of residual stresses are monitored to generate data in order to empirically model the changes individually. The models are combined to identify the most likely combination of load stress and number of loads causing all monitored properties changes.

2.1. Preparation and characterization of the specimens

Machining processes significantly change a component's surface and subsurface properties. Literature results as well as earlier research of the publishing authors show that characteristics such as tensile and compressive residual stresses can be induced by turning with a high reducibility [13, 14]. Specimens for cyclic fatigue tests are machined on a Gildemeister CTX 520 L CNC lathe following DIN standard 50113 (smallest diameter 7 mm). Table 1 summarizes the applied tool geometry. The experiments are carried out applying a feed of $f = 0.01$ mm at a cutting speed of $v_c = 30$ m/min. The depth of cut is set to $a_p = 0.1$ mm. Yield and ultimate strength ($R_m = 830$ MPa, $R_e = 440$ MPa) as well as yield point for compressive load ($\sigma_{d0.2} = 454$ MPa) of AISI 1060 high carbon steel in the as received condition are experimentally determined.

Table 1: Tool geometry

tool geometry: SNMA-120408-S02020-MW			
tool cutting edge angle	$\kappa_r = 75°$	tool orthogonal clearance angle	$\alpha_O = 5°$
tool cutting edge inclination	$\lambda_S = -5°$	tool orthogonal rake angle	$\gamma_O = -5°$
rounded cutting edge radius	$r_\beta = 50$ µm	corner radius	$r_\varepsilon = 0.8$ mm

To characterize the subsurface condition after machining. residual stress measurements are carried out in $\varphi_A = 0$ °, 45 ° and 90 ° to the axial direction of the specimen determining the normal stresses σ_{xx}, σ_{xy} and σ_{yy}. Figure 1 illustrates the orientation of the mentioned stresses.

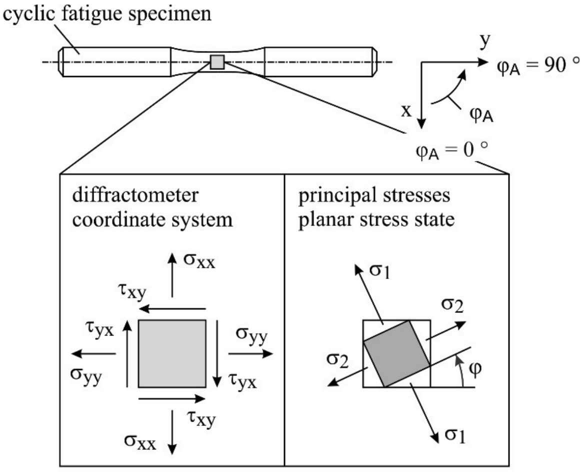

Fig. 1. Location and orientation of normal and shear stresses