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Prediction of the Principal Stress Direction for 5-axis Ball End Milling

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Abstract

While regenerating damaged components, e.g. compressor blades, the removal of excess weld material called re-contouring often determines the surface integrity including the residual stress state. A load-specific residual stress state is beneficial for lifetime. This leads to the necessity to predict the resulting residual stress state after machining. The paper describes two models, which predict the principal stress direction as a residual stress characteristic for 5-axis ball nose end milling of Ti-6Al-4V. One model uses process force components, the other is based on the microtopography of the workpiece, which is influenced by the kinematics of the process.

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1. Introduction

In the sector of aviation, an important source of revenue are aftermarket services, where repair represents 67 % of the total revenue in the field of maintenance, repair and overhaul (MRO) [1]. As an example, economical repair processes for compressor or turbine blades are crucial to reduce life cycle costs [2]. The increasing usage of Blade Integrated Disks (BLISKs), where blades and disk are made out of one single workpiece, offer advantages e.g. in weight reduction, although raising the repairing process degree of complexity and need for cost effectiveness. Therefore, it is necessary to investigate such processes in terms of economy and effects on the refurbished product.

The process chain of blade repair consists of four phases: pre-treatment, material deposit, re-contouring and post-treatment [3]. The pre-treatment incorporates de-coating, cleaning, inspection and measurement, whereas the material deposit can be accomplished by built-up or patch welding and filling cracks through brazing [2]. The re-contouring is done either manually or automatically via cutting. If no further post-treatment is applied, it determines the final surface integrity, including the residual stress state after machining, which has a major impact on fatigue life [4], [5]. In this paper, due to the

sustained growth of BLISK usage, which have a complex shape, the process of ball end milling will be examined. They are commonly made of titanium, wherefore Ti-6Al-4V will be considered.

There is only limited knowledge concerning machining induced residual stresses of repaired parts. To expand the research field of re-contouring dealing with residual stress formation, Denkena et al. investigated the residual stresses after ball end milling of welded Ti-6Al-4V (abbr. Ti64) parts [3]. They identified the most significant parameters on the amount of residual stresses, namely the cutting edge radius r_{β} , cutting strategy (up/down cut) and feed per tooth f_z . It is also shown that thermal induced residual stresses can be neglected in the investigated parameter field. The temperatures during re-contouring seldom exceed $T_{crit, Ti64} = 480^{\circ}\text{C}$, at which the comparative stress equals the yield strength and tensile residual stress may occur according to [3]. Furthermore, they introduce the term “surface generating forces”, which considers the cross section generating the final surface during cutting. The surface generating forces are used to explain the mechanical effects of residual stresses for re-contouring and will be applied in this paper. A detailed explanation of the surface generating forces is given in [3].

Besides the amount of residual stress, compressive or tensile, the principal stress direction is needed to fully characterize the residual stress state and it has an effect e.g. on crack propagation. This leads to the necessity to predict the principal stress direction, which is the aim of this paper.

While the principal stress direction correlates with the direction of primary motion during planing [6] and face grinding [7], this can be different for processes with more complex kinematics. For orthogonal turning, Jacobus et al. showed that the tool cutting edge inclination δ correlates with the principal stress direction while the cutting speed v_c does not during an oblique cutting operation. This is represented through the coordinate system X', Y', Z' in Fig. 1, which is in line with σ_1 and σ_2 . The principal stress direction of σ_1 is more aligned with the direction of the resulting force vector from F_{cN} and F_c . These findings are expanded upon the prediction of the principal stress direction during ball nose end milling.

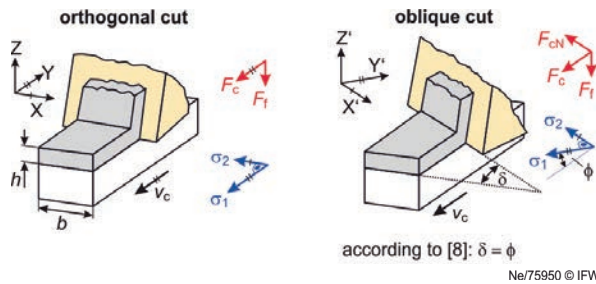


Fig. 1. Correlation between principal stress direction and forces according [8]

2. Workflow and experimental setup

Ti64 parts were re-contoured on a Deckel Maho DMU 125P using a 10 mm ball end mill type Seco JH970100 to identify the significant factors influencing the principal stress direction. Therefore, residual stress measurements were executed via X-Ray diffraction using a General Electric XRD 3003 TT diffractometer to calculate the principal stresses and their direction ϕ with equation 1, 2 and 3 according to [9]. The corresponding experiments will be detailed in section 3.

$$\sigma_1 = \frac{\sigma_{90^\circ} - \sigma_{0^\circ} \cdot \cot^2 \phi}{1 - \cot^2 \phi} \quad (1)$$

$$\sigma_2 = \frac{\sigma_{90^\circ} - \sigma_{0^\circ} \cdot \tan^2 \phi}{1 - \tan^2 \phi} \quad (2)$$

$$\phi = \frac{1}{2} \arctan \left(\frac{\sigma_{0^\circ} + \sigma_{90^\circ} - 2 \cdot \sigma_{45^\circ}}{\sigma_{0^\circ} - \sigma_{90^\circ}} \right) \quad (3)$$

The principal stress states obtained are used as a reference to judge the capability of the models predicting the principal stress direction. They will be introduced in section 4 and compared in section 5. Finally, a conclusion will be drawn in section 6.

3. Identification of factors influencing the principal stress direction while ball nose end milling of Ti-6Al-4V

Due to the complex kinematic of 5-axis ball end milling, the significant factors determining the principal stress direction

need to be identified experimentally, which is done in this section. Therefore, the main process parameters of 5-axis ball end milling will be described first.

The additional degrees of freedom enable the tool to lean in different directions. This is characterized through lead angle λ and tilt angle τ . The lead angle λ is positive, if the cutting tool is sloped in feed direction, referred to as draw-cutting. For negative λ , the cut is referred to as drill-cut. During drill-cut, the tip of the tool may be in engagement with the workpiece but this is usually avoided because of increased process forces, ploughing, tool wear and surface blemishes. The cutting tool is sloped in the direction of uncut surface for positive tilt angles τ . Due to the ball end, the cutting speed v_c varies along the cutting edge. Therefore the mean cutting speed $v_{c,m}$ is used, based on the cutting edge angle κ , which is valid for the surface generated and described in [3].

A fractional factorial experimental design has been set up to classify the most significant parameters (tool geometry and process parameters) on the principal stress direction. Table 1 lists the factor combinations (screening design), which were chosen to provide stability of the process, prevent tool breakage and to meet the quality requirements for re-contouring high valuable goods in their tolerance field to guarantee the validity of significance.

Table 1. Factor combinations for fractional factorial design.

Factor	-	+
Mean cutting speed $v_{c,m}$ [m/min]	15	60
Feed per tooth f_z [mm]	0.15	0.4
Depth of cut a_p [mm]	0.4	1.0
Step over b_r [mm]	0.2	0.5
Lead angle λ [°]	15	60
Tilt angle τ [°]	0	60
Cutting strategy	Up-cut	Down-cut
Clearance angle α [°]	6	12
Rake angle γ [°]	8	14
Edge radius r_β [μ m]	4	30

Each experiment is repeated once ($n = 2$). The experiments result in 64 variances of 32 combinations for the high (+) and low (-) factors. All effects e of each factor are calculated with

$$e = \frac{1}{32} \sum_{i=1}^{32} \bar{x}_i^{(+)} - \frac{1}{32} \sum_{j=1}^{32} \bar{x}_j^{(-)} \quad (4)$$

where the mean values are $\bar{x}_i^{(+)}$ and $\bar{x}_j^{(-)}$ for all high and low combinations respectively. A student distribution has been used to determine the significance of an effect with a probability of $s = 99.5\%$. Random effects such as scattered values of X-Ray diffraction limit the significance. In Fig. 2, the effects of the fractional factorial design are shown. It can be seen that lead and tilt angle are the most significant factors. For all other factors, the principal stress direction almost corresponds to the machining direction. The high limits of significance are a result of the Gaussian error propagation, because the squared values of the uncertainties of Eq. 1, 2 and 3 add up. Thus, small fluctuations of the three residual stress measurements lead to high variations of the principal stress

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