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Determination of Residual Stresses in Milled Titanium Parts

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ABSTRACT: *This paper investigates the machining induced residual stresses for milling of a workpiece material with increasing usage in industry, -titanium. Residual stresses can cause part distortion especially in the case of large components such as structural parts in aerospace industry. Afterwards two typical machining processes, face milling and peripheral milling are investigated regarding residual stress. For stress determination a practical modification of an indirect measuring method, the layer removal method, is applied, as it can offer advantages compared to X-ray-measurements. It is robust against material properties such as grain size or texture which can complicate the X-ray-method. Increasing cutting speed leads to increased penetration depth in case of face milling and did not exhibit strong influence on the end milled subsurface. A correlation between process forces and value and depth of the induced stresses is identified by a variation of feed per tooth and the tool geometry by means of usage of a worn tool.*
Keywords: *Titanium; Residual stress; Surface Integrity; Milling*

I. INTRODUCTION

The need for weight reduction in modern aircrafts is faced by an increased utilization of carbon fibre reinforced plastics (CFRP). The high potential difference between aluminum and CFRP bears the risk of contact corrosion in direct junctions of these materials. This challenge is currently faced by increased substitution of aluminum by titanium. Besides the weight reduction potential of the material, titanium enables higher comfort through enhanced air moisture in the passenger cabin

[1]. One of the major challenges in the manufacturing of large structural parts out of titanium besides tool wear is part distortion [1-2]. Structural parts which are often manufactured with a high buy-to-fly ratio are sensitive to residual stresses induced during milling and resulting in part distortion.

Milling of titanium alloys is an important issue for the machining industry. Especially the prediction of the subsurface area characteristic and its adjustability as well as the resulting part distortion are main challenges for researchers [3-4]. Breidenstein describes the correlation of residual stresses within the subsurface area and the workpiece characteristics of polycristaline materials [5]. It is a well-known fact, that the machining parameters influence the subsurface area by mechanical and thermal loads in the tool-workpiece contact area. Extensive research on the effects of cutting parameters (i.e. cutting speed or feed), tool geometry or cooling strategy has been made. Tönshoff describes the effects of planing, turning, milling and grinding of AISI1045 on residual stresses [6]. Tönshoff and Gey [7-8] as well as Sridhar et al. [9] focus on residual stresses in milling titanium alloys, whereas Denkena et al. [10] and de Leon

[2] investigate residual stresses in milling aluminum. Summarizing the previous investigations, general effects of cutting speed, feed (per tooth) and depth of cut can be identified. By increasing the cutting speed the residual stresses are changing from compressive to tensile stresses and the influenced depth decreases [6, 10-12]. Enhancing the feed rate in turning operations, the tensile surface stresses increase, whereas the maximum compressive stress value rises as well as the penetration depth [6, 11]. In milling, the feed rate influences the surface- and subsurface residual stresses the opposite way by leading to decreasing compressive stresses [6-7, 10]. The thickness of the influenced subsurface area decreases [6-7, 10-11]. The depth of cut has minor

effects on residual stress development in the subsurface area [7, 10, 12].

De Leon identified a correlation between the incremental cutting force $F_z' = F_z/a_p$ and characteristic values of the residual stress distribution. This approach however, neglects thermal influences which is shown to be valid for aluminum alloys [2].

II. EXPERIMENTAL SETUP

The cutting experiments are conducted on a 3 axis CNC milling machine tool Heller PFV1 with a rotational speed range from $n = 25\ min^{-1}$ to $n = 5000\ min^{-1}$ and a maximum torque of M = 950 Nm. Its positioning repeatability of the axis is given as 0.015 mm.

For the tests two different cutting tools are investigated, covering typical tool concepts from aerospace manufacturing of structural titanium components. One solid carbide tool and an inserted face milling cutter are used. For rough milling a solid carbide tool from Klenk with a diameter of d = 25 mm is used. For face milling operations a Walter F4033.B40.125.Z08.09 cutter (d = 130 mm) with 16 inserts of the type SNGX1606ANN-F67 WSP45 is investigated. This cutter is used with a single tooth.

For each tool, standard cutting parameters are defined based on industrial practice as given in Table 1. In a first step the influence of these process parameters on residual stress is identified. In a second step, the variation of residual stresses due to increasing cutting speed and feed per tooth is focus of the research. Therefore, the cutting speed for rough milling is increased to v_c = 80 m/min, in a following test the feed per tooth is increased to f_z = 0.15 mm. Additionally, the effect of a worn tool with standard cutting parameters is examined. The increased cutting speed for the face milling cutter is chosen to v_c = 45 m/min. The feed per tooth is increased to f_z = 0.3 mm within this operation. All tests are conducted with a cooling of 8% Wisura WM 2282. The cutting forces are measured with a dynamometer Kistler 9255B.

Table 1. Standard experimental cutting conditions

Cutting tool	v_c [m/min]	f_z [mm]	a_p [mm]	a_e [mm]
Roughing tool	63	0.1	50	8
Face milling cutter	31	0.13	40	30

For residual stress measurements a X-ray diffractometer Seiffert XRD 3003 TT with a CuKα radiation is used applying the $\sin^2\psi$-method by mean of feed and feed normal direction. A voltage of 40 kV and an amperage of 30 A is adjusted. Within the measurement the grid plane 213 in a deflection angle of $2\theta_0$ = 139.317° is analyzed by a scan interval from 134°-146° in nine steps. The maximum penetration depth of the radiation is 5.1 µm.

III. EXPERIMENTAL RESULTS

Figure 1 presents the results of force and residual stress determination. The residual stresses are shown parallel to the feed direction, denominated by $\square_{\|}$. The process forces in feed and feed normal direction reach maximum values of F_f = 1450 N and F_{fN} = 1400 N respectively for standard parameters (v_c = 30 m/min and f_z = 0,25 mm). The feed per tooth increase to f_z = 0,3 mm exhibits a slightly higher mechanical load in feed normal direction of F_{fN} = 1500 N. The stress value of $\square_{\|}$ = -780 MPa located at the workpiece surface is not affected by this.

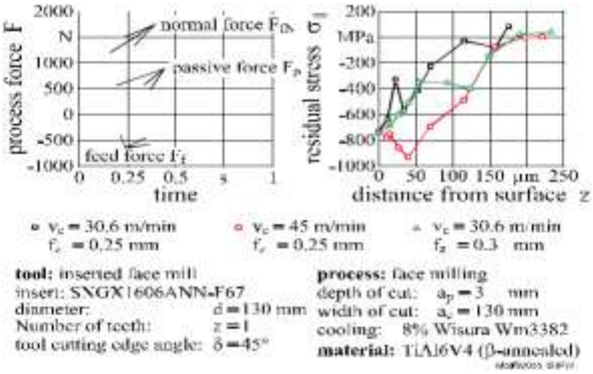

Fig. 1. Mechanical load and residual stresses for face milling

However, it becomes obvious that more energy is stored in the subsurface when applying higher loads as the penetration depth is increased from z_{max} = 120 µm to z_{max} = 180 µm and the stress values are generally higher in the compressive range. The increase of thermal load due to higher cutting velocity is enhanced by a small reduction of cutting forces in all three Cartesian coordinates. The maximum value is increased from $\square_{\parallel}$ = -800 MPa to $\square_{\parallel}$ = -950 MPa and shifted to a depth of z = 45 µm. To provide a significant estimation for mechanical and thermal influences, the temperature values need to be determined.

The residual stress distributions in flank milling exhibit tensile stress values at the workpiece surface with a value of up to $\square_{\parallel}$ = 190 MPa for the increased feed per tooth of f_z = 0,15 mm (see Fig. 2). The increase of mechanical load due to feed per tooth increase shifts the maximum stress value to a depth of z = 70 µm. The greatest influence, however, is due to usage of a worn cutter with a flank wear land of VB = 200 µm. The tool wear changes the contact behavior between cutting edge and workpiece and though results in an almost threefold force increase from F_{fN} = 6000 N to F_{fN} = 17500 N. The consequent maximum residual stress value equals

$V_{\parallel}$ = -450 MPa in a depth of z = 70 µm instead of

$V_{\parallel}$ = -180 MPa in a depth of z = 25 µm for a sharp tool.

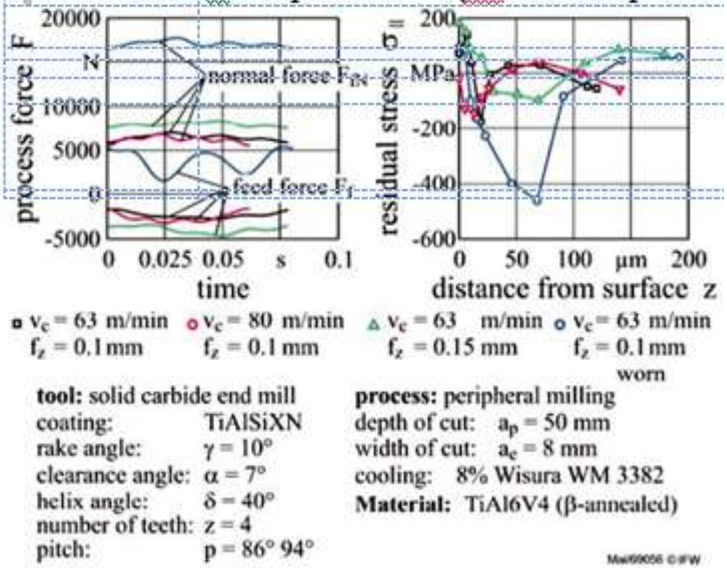

Fig. 2. Mechanical load and residual stresses in periph-eral milling

IV. LAYER REMOVAL METHOD FOR RESIDUAL STRESS DETERMINATION

Residual stress is defined as the stress within material in thermal and mechanical equilibrium. The most established residual stress measurement method is the sin²-\ X-ray method as applied in the previously presented investigation. The procedure was introduced by Macherauch and Müller [13]. It emerges with high measurement accuracy. But due to comparatively long measurement periods and high security restrictions, this method is unpractical for industrial use. Therefore within this study the layer removal method, an indirect measurement method, is presented as an alternative.

This method utilizes the distortion of a part caused by the removal of stressed material with respect to the part in equilibrium. Comparing the initial and deformed workpiece geometry after material removal, the residual stresses can be determined. Stäblein described this method by removing layers with a thickness of several millimeters in planing operations [14]. This is not applicable for residual stresses induced by common cutting operations, due to a thickness of the influenced material smaller than d_0 < 500 µm. Furthermore, the layer removal method using Stäblein's approach is not applicable for residual stress measurement at the surface, because in this case the equation is not defined.

Within this study the layers are removed using a milling tool (ph Horn 380.0063.05) in a 3 axis CNC milling machine. The deformation of a titanium workpiece, with a thickness of d = 8 mm, is measured with a strain gauge HBM 3/350 LK11K on the opposite workpiece side.

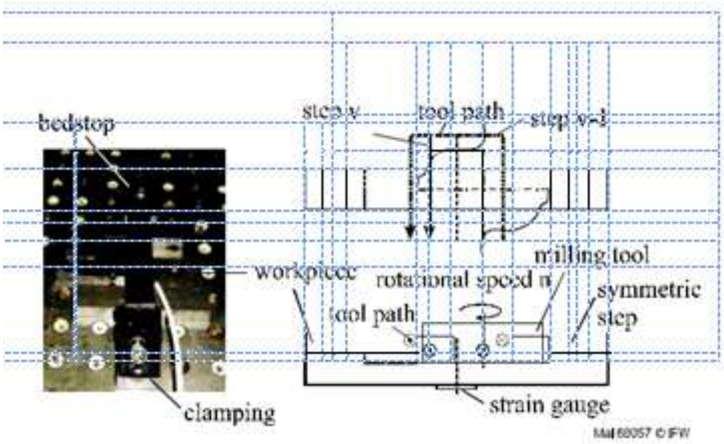

Fig. 3. Experimental setup for layer removal method

Low cutting speed and feed rate are applied to reduce mechanical and thermal load on the workpiece (Table 2). The tool geometry is defined in a way that subsurface influences are minimized based on the findings of [2]. Therefore the material removal process is assumed to not introduce any residual stress into the workpiece. The depth of cut represents the thickness of the removed layers. During the experiment 12 layers were removed with a thickness between a_p = 5 µm and a_p = 50 µm. The maximum measurement depth amounts to z_{max} = 250 µm. The procedure is shown in Fig. 3.

Table 2. Cutting conditions for layer removal method

Cutting Parameter	Unit	Value
Cutting Speed	m/min	22.6
Feed per tooth	mm	0.05
Width of cut	mm	48…60
Depth of cut	mm	0.005 – 0.05

To preclude machine tool inaccuracies, symmetric steps are machined on the surface at both ends of the slender workpiece. The height of the steps is measured with a surface metrology system at 5 different measurement points. After each machining step the workpiece has to be unclamped in order to achieve novel equilibrium and to measure the strain of deformation due to the last material removal step. The strain gauge.
It detects strain values between ε_{min} = -400 µm/m and ε_{max} = 120 µm/m. To calculate the residual stresses from the strain values the equation from Stäblein [11] is used.
E is the elastic modulus, a the measurement length (here length of strain gauge a = 3.2 mm), h_0 the thickness of the bar before the first cut and h_v the thickness of the bar after step v.
The deflection s of the bar is identified from geometrical relationships and the strain values by

$$s \quad a \quad \sqrt{\square^{2} \quad 2\square}$$

The accuracy of this method is determined by a comparison with a sin²-\ X-ray measurement. The residual stress values for each measurement method correlate well. For the layer removal method the results are about 20% higher for the compressive stresses. For a distance from the surface of z = 15 µm a difference of about 40% is given, as it is illustrated in Fig. 4.

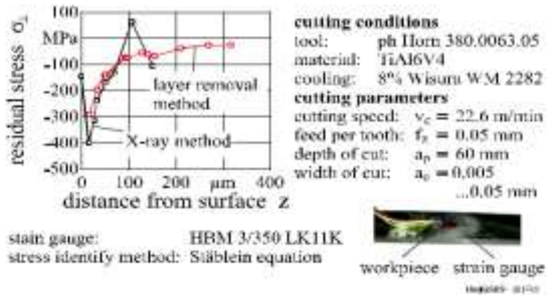

Fig. 4. Residual stresses identified by using layer removal- and X-ray method.

The results show the general adaptability of the layer removal method. Less measurement time is necessary, as in the common X-ray method. However, it is not possible to measure the residual stresses at the surface. Furthermore, the reproducability of clamping the workpiece to the machine tool has to be ascertained.

V. SUMMARY

Machining induced residual stresses can cause part distortion especially in the case of large structural components in aerospace industry. The usage of high performance workpiece materials, such as titanium increases within this field. However, only little knowledge about the influence of machining processes on the residual stress state is available.

The investigations exhibit a correlation between residual stress value as well as the depth of maximal values in the subsurface with the process forces. The influence of increased cutting speed values differs for the investigated milling tools. Increased compressive stresses are induced by face milling. Minor influences are detected in the case of end milling. Therefore additional investigations concerning the temperature of the workpiece subsurface are necessary and will be carried out. Furthermore, an alternative measuring method has been investigated. In terms of measurement time and -complexity, the layer removal method offers advantages compared to X-ray methods. Moreover negative effects due to the large grain structure as well as possible textures are avoided.

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