Technology-Based Recontouring of Blade Integrated Disks After Weld Repair

The widespread adoption of blade integrated disks (blisks) made of titanium demands tailored regeneration processes to increase sustainability and economic efficiency. High standards regarding geometrical accuracy and functional properties as well as the unique characteristics of each type of damage complicate the repair. Thus, flexible and well-designed processes are necessary. Typically, material deposit is followed by a milling or grinding process to restore the original shape. Here, the individual repair processes not only have to be controlled but also their interaction. For example, depending on the resulting microstructure of the welded seam, the recontouring process needs to be adapted to minimize tool wear as well as shape deviations of the complex blade geometries. In this paper, the process chain for a patch repair is examined, consisting of a tungsten inert gas (TIG) welding process followed by five-axis ball nose end milling. Conventional TIG as well as a modified TIG process producing a finer grain structure and enhanced mechanical properties of deposited material was investigated. Grain refinement was achieved by SiC particles added to the weld pool. Based on the characteristics of the fusion material and static stiffness of the component, a methodology is introduced to minimize shape deviation induced by the subsequent milling process. Special attention is given to tool orientation, which has a significant impact on the kinematics and resulting process forces during milling. An electromagnetic guided machine tool is used for compensation of workpiece deflection. [DOI: 10.1115/1.4040738]

Introduction

Due to increasing demands for economic and more sustainable jet engines, the aviation industry uses more blade integrated disks (blisks) within their engines. Because of their integral construction, blisks offer advantages regarding the power-to-weight ratio. They are commonly used in compressor stages and thus made from Titanium, e.g., Ti–6Al–4V. If one single blade of the blisk fails during operation, the maintenance provider has to consider replacing the whole blisk or repairing it if possible. Depending on the type of damage, e.g., crack, bended tip or simple abrasion, there are different methods to restore the blades functionality. Except for a blend repair, the excessive deposit material due to brazing (filling a crack) or welding (patch-repair) has to be removed to rebuild the final shape. This material removal can be done either by grinding or milling. If there is no further post-treatment applied, the material removal process determines the final surface integrity. The corresponding process chain is depicted in Fig. 1.

To fulfill the high standards regarding functional and mechanical properties of the repaired components, the individual repair processes welding and recontouring have to be matched. However, the knowledge regarding repair processes and their interaction, especially recontouring, is limited. Often, the existing knowledge for manufacturing new components is directly transferred and the work is carried out manually. Unsatisfying quality and higher tool wear result [1–3]. Additionally, the variety of occurring damages makes an automation difficult. The complex blade geometries and their low stiffness require adaptive and flexible processes. Thus, it is necessary to consider the different material properties and unique geometries for a successful repair.

To extend the knowledge regarding the repair process, this paper examines the process chain for a typical patch-repair including welding, process planning, and recontouring with a novel machine tool. The results are derived from the research projects B2 “dexterous regeneration cell,” B6 “arc welding processes for repair of high-performance titanium-alloy components” and C1 “simulation based planning of recontouring metal cutting processes.” They are located within the Collaborative Research Center (SFB) 871 “regeneration of complex capital goods,” funded by the German Research Foundation (DFG). First, the state of art is given in this section. Afterward, the influence of the TIG welding process on the properties of the welded joint is examined. A modified TIG process producing a finer grain structure and enhanced mechanical properties of deposited material is introduced. Second, the effects of the different welding processes on subsequent
five-axis ball end milling are shown. Special attention is given to tool orientation to counter shape deviations and limited accessibility during blisk repair. Third, recontouring with a novel machine tool featuring a magnetic guided spindle carriage is described. This tool allows compensating workpiece deflection without modifying the G Code.

**Tungsten Inert Gas Welding of Titanium Alloys.** For the assembly or repair of titanium and titanium alloy components, tungsten inert gas (TIG) welding is a commonly employed method [4]. The resulting mechanical properties depend on the microstructure of the welded seam [5]. The welding process typically causes the growth of coarse, columnar grains within the fusion zone (FZ), and the heat affected zone (HAZ) with a graded grain texture [6]. Due to high cooling rates in the FZ, a martensitic z’ or a Widmanstätten type of microstructure is formed. The fusion material is often characterized by increased tensile strength and decreased ductility [7]. Generally, the mechanical properties of the fusion material can be improved by grain refinement [8,9].

Here, the interactions between the TIG welding and the five-axis ball end milling process were considered. For this, a comparison of conventionally welded samples and samples with a fine-grained FZ structure was done.

**Recontouring Using Five-Axis Ball End Milling.** When recontouring, five-axis ball end milling is often preferred due to the complex parts. Shape deviations mainly occur due to part and tool deflection during machining. The low Young’s modulus of titanium and wall thicknesses less than 2 mm result in vibration prone parts. Reduced process parameters and special clamping systems are often necessary for a successful repair. Using five-axis processes, selecting an appropriate tool orientation during process planning can also help avoiding vibrations and increase surface quality [10]. There are a few studies dealing with the influence of tool orientation on process dynamics in five-axis milling. For example, Ozturk and Budak developed a model to predict cutting forces and investigated the effect of tool inclination on chatter forces and torque values depending on the inclination angle. All of these studies have their focus on the machining of new parts and do not specifically address the recontouring. Thus, boundary conditions like the limited accessibility as well as different material properties are not considered.

Extensive research has been done to predict the surface topography, which has a significant impact on flow loss [14]. Empirical (fast but limited scope), analytical, and numerical approaches (more general) have been investigated for the production of new parts [15,16]. The slowest but most flexible method because of its general validity is the use of the numerical method “material removal simulation” (MRS). Using an MRS, the workpiece is discretized using, e.g., voxel, dixel, or constructive solid geometry. Nespor et al. investigated the use of a dixel-based MRS to predict the surface after recontouring [17]. They included an actual tool model for simulating real process kinematics including runout and chipping effects. Surface defects due to the tools micro geometry (scuffs) as well as vibrations were not considered. Especially, for a blisk repair with blades prone vibrations, long tools are necessary due to the limited accessibility. Thus, the simulation of dynamic effects can be beneficial for an increased accuracy.

For a successful repair, the effects of different material properties, tool angles, and process parameters as well as workpiece-tool dynamics have to be modeled accurately and in a flexible manner.

**Compensation of Tool and Workpiece Deflections.** Besides additional clamping systems, there are basically two approaches to reduce shape deviations due to process force-induced workpiece and tool deflection. On the one hand, cutting forces can be reduced by adapting process parameters and on the other hand, deflections of tool and workpiece can be compensated by adapting the toolpath. Both approaches can be followed either offline within process design or online within a control framework.

The adaptation of the toolpath has the advantage that productivity is not reduced and surface quality is not influenced. Beyond that, online compensation offers the possibility to react flexibly to unpredictable variances in workpiece geometry or material [18]. This is of great interest especially in recontouring, due to the individual machining tasks.

Existing implementations of online toolpath adaptations manipulate either the NC-axes of the machine [19] or use special devices that provide additional degrees-of-freedom [19,20]. Typically, cutting forces measured with a dynamometer serve as input to the compensation algorithms.

Magnetic guides are capable of highly dynamic positioning in several DOFs and even force measurement [21]. They thus enable an adaptation of the tool path independent of the NC control and without additional devices.

**Grain Structure of Welded Material**

The properties of the welded material were investigated experimentally executing bead on plate welding on rectangular Ti-6Al-4V alloy substrates (100 mm x 84 mm x 10 mm). For subsequent analysis of the welding process, a milled groove (0.5 mm deep and 5 mm wide) was filled in one pass by TIG welding using additional filler wire (Ti-6Al-4V; 1 mm Ø). To characterize the influence of different grain structures of the fusion material on the process forces during milling, the samples were welded conventionally and in a modified TIG welding process. For the modified welding process, a suspension of SiC particles in acetone was sprayed on the groove’s surface before welding. As the acetone evaporated, a layer of approximately 2.7 mg/mm SiC powder was effectively adhered to the surface. The welding was carried out in a shielding gas chamber with protective argon gas atmosphere (O₂ content < 10 ppm). In Table 1, the used welding parameters are listed.

The microstructure, in particular the grain size, of the welded specimens was analyzed using optical microscopy. For this, the samples were polished and etched with Kroll’s reagent. The hardness of the welded samples was measured using a Ness Q10 A+ Vickers hardness tester with a load of 9.8 N.

**Table 1 Process parameters of TIG welding**

<table>
<thead>
<tr>
<th>Factor</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current in A</td>
<td>90</td>
</tr>
<tr>
<td>Shielding gas flow in l/min</td>
<td>4</td>
</tr>
<tr>
<td>Standoff distance in mm</td>
<td>3</td>
</tr>
<tr>
<td>Travel speed in mm/min</td>
<td>100</td>
</tr>
<tr>
<td>Wire feed in m/min</td>
<td>0.33</td>
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</table>

**Fig. 2 Macro- (a) and micrograph (b) of weldment in cross-sectional view (without SiC addition)**
Figure 2 shows a cross section of a conventional bead on plate welded specimen. In the FZ, prior β grains with an average size of 380 μm can be observed. The grain size is seen to increase to approximately 1 mm in the middle of the welded seam. Within the β-grains, a martensitic α’ type microstructure is formed. A small amount of the α phase is allocated at the grain boundaries.

Between the HAZ and the FZ, no clear borderline can be seen. In Fig. 3, a cross section of a SiC-enhanced specimen is depicted. In this case, a distinctive borderline between the HAZ and the FZ can easily be identified. Fine β-grains averaging 35 μm were homogeneously distributed in the fusion material.

In Fig. 4, the microhardness of BM, HAZ, and FZ measured at a cross section of a conventionally welded sample is depicted. Compared to the BM (average hardness of 324 HV1), the HAZ and FZ only show a small increase in hardness with a maximum of 369 HV1. This could be attributed to the formation of the martensitic α’ microstructure within the HAZ and FZ, cf. Fig. 2.

The microhardness of the fusion material of a SiC-enhanced specimen (Fig. 5) is clearly increased to values between 375 HV1 and 520 HV1.

Thorough investigations of the SiC-enhanced samples established that silicon carbides were dissociated. Silicon accumulated mostly at the prior β-grain boundaries. In situ formation of dispersed titanium carbides as well as the grain refinement can be given as the main reason for hardness increase.

Recontouring Process Design
As shown in the Grain Structure of Welded Material section, the welding process strongly affects the grain size and microstructure if SiC addition is used. Obviously, this directly influences the recontouring process regarding process forces, which can lead to shape deviations.

In this section, the influence of the welding process on the process forces during five-axis ball end milling is shown at first. Afterward, the effect of tool orientation on the process forces for typical recontouring process parameters is analyzed. For an optimized process planning regarding shape errors, a methodology is introduced, which incorporates the effects of joint properties and tool orientation. It is based on a material removal simulation, cf. [17].

A brief description of five-axis ball end milling with its most important process parameters is given in Fig. 6.

For ball nose end milling, the parameters feed per tooth \( f_z \) and step over \( b_r \) (offset between two cutting paths) define the resulting kinematic surface topography. Typical for recontouring are finishing operations with small feed rates and step overs to guarantee a high surface quality. Also, small depths of cut \( a_p \) are common to lower the process forces. A detailed description about surface topography after recontouring and recommended parameters can be found in Ref. [17].

In literature, there are several definitions to characterize the tool orientation. In this paper, projected angles are used. If the cutting tool is sloped in feed direction, the lead angle \( \lambda \) is positive, referred to as draw-cutting. The cut is referred to as drill-cut, if the lead angle is negative.

Normally, the drill-cut is avoided, because the tool tip may be in contact with the workpiece. This results in additional ploughing, surface blemishes, and increased tool wear. The tool tip contact also depends on the tilt angle \( \tau \) and depth of cut \( a_p \) [10]. If the cutting tool is sloped toward the uncut surface, the tilt angle is positive. Because of the ball end, the cutting speed \( v_c \) varies along the cutting edge. To obtain a constant thermo-mechanical load, Denkena et al. proposed the use of the mean cutting speed \( v_{c,m} \) [22]. The usage of \( v_{c,m} \) can be beneficial when investigating residual stress formation. However, a constant \( v_c \) is preferable for analysis of part vibrations in order to have a constant excitation frequency. Thus, \( v_c \) remains unchanged regardless of inclination angles used in this paper.

Effect of Tungsten Inert Gas Welding on Process Forces.
For a precise process planning, the influence of the weld material

![Fig. 3 Macro- (a) and micrograph (b) of weldment in cross-sectional view (with SiC addition, 3.4 wt % Si)](image)

![Fig. 4 Microhardness of a TIG welded specimen](image)

![Fig. 5 Microhardness of a TIG welded specimen with SiC addition (3.4 wt % Si)](image)

![Fig. 6 Five-axis ball end milling parameters](image)
on the process forces has to be investigated. Therefore, the welded specimens of the Grain Structure of Welded Material section have been recontoured. First, the probes were face milled by a shallow cut of \( a_p = 0.05 \) mm to avoid influences from the weld seam geometry. Hence, the tool cuts pure weld material when entering the weld seam. The experiments have been run on the machine tool prototype “NeXimo.” A 10 mm ball end mill type Seco JH970100 has been used. Process forces have been measured with a Kistler 9257B dynamometer. The used process parameters are typical for finishing operations and mentioned in Fig. 7.

When recontouring conventional welds, the process forces remain almost unchanged when entering the joint as depicted in Fig. 7. The process forces occurring while machining the HAZ and FZ are similar to the base material. The process forces are increased considerably, when machining the modified TIG weld with SiC added to the weld pool.

This can be related to the higher mechanical strength, caused by grain refinement and allocation of titanium carbides within the FZ. Thus, the different material properties have to be considered during process planning. Therefore, force coefficients have been determined for the base and weld material using the method proposed by Altintas [23]. They are needed for a precise process force prediction within the MRS. A dexel-based MRS has been used to obtain the cross section of undeformed chip as a function of time. With the measured process force data for different feed rates, the force coefficients are calculated solving the system of linear equations. They are shown in Fig. 8 with process parameters similar to Fig. 7. Especially, the radial and tangential coefficients are affected by the SiC addition, leading to higher cutting forces. This underlines the need to consider the weld properties during process planning.

Effect of Tool Orientation. As mentioned in the introduction, the tool orientation can have a significant influence on the process forces as well. Thus, it is necessary to investigate the effect with recontouring specific process parameters. Therefore, slot milling of AMS 4911 Ti–6Al–4V specimen has been carried out on a Deckel Maho DMU 125p duoBlock five-axis machine tool. A 10 mm ball end mill type Seco JH970100 has been used with factor combinations listed in Table 2. Process forces have been measured with a Kistler 9257B dynamometer.

In Fig. 9, the maximum process forces for different lead angles \( \lambda \) and feed rates \( f_z \) are shown in the workpiece coordinate system (WCS). The tilt angle \( \tau \) has been kept constant at \( \tau = 0 \) deg. For lead angle \( \lambda = 0 \) deg the passive, feed and feed normal forces have their maximum as expected due to the tool tip contact. Hence, tool angles with tool tip contact should be avoided as stated in the introduction. Using a depth of cut \( a_p = 0.5 \) mm, the tool tip contact is avoided for all other considered tool angles in this paper.

Differences between the lead angles occur regarding the max. passive force \( F_p \) as well as the max. feed force \( F_f \). Especially, \( F_p \) can lead to high part deflection when milling flexible parts assuming that the direction of highest compliance is normal to the surface. As depicted in Fig. 9, the max. passive force \( F_{p,\text{max}} \) can be lowered by approximately 20% comparing \( \lambda = 55 \) deg and \( \lambda = 30 \) deg. In contrast, the feed force \( F_{f,\text{max}} \) decreases with a higher lead angle. Furthermore, the curves gradient and their initial value vary. Thus, force coefficients according to Refs. [23] and [24] have to be determined separately for each tool angle if precise cutting simulations are needed. The feed normal force \( F_{n,\text{max}} \) remains almost unchanged if the lead angle \( \lambda \) is varied. The differences can be explained by the changed kinematic of the process. Because of the ball nose end, the cutting direction changes when using tool angles. If lead angles are used, the cutting edge orientation to feed direction changes, which affects the composition of resulting process force.

![Fig. 7 Process forces for milling of TIG and TIG + SiC welds](image)

![Fig. 8 Force coefficients for TIG and TIG + SiC welds](image)

![Fig. 9 Process forces for different \( \lambda \)i](image)

Table 2 Process parameters of five-axis ball end milling

<table>
<thead>
<tr>
<th>Factor</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutting speed ( v_c ) in m/min</td>
<td>40</td>
</tr>
<tr>
<td>Feed per tooth ( f_z ) in mm</td>
<td>0.06, 0.09, 0.12, 0.18, 0.21, 0.24</td>
</tr>
<tr>
<td>Depth of cut ( a_p ) in mm</td>
<td>0.5</td>
</tr>
<tr>
<td>Step over ( b_t ) in mm</td>
<td>n.a.</td>
</tr>
<tr>
<td>Lead angle ( \lambda ) in deg</td>
<td>0, 15, 30, 45, 55</td>
</tr>
<tr>
<td>Tilt angle ( \tau ) in deg</td>
<td>0, 15, 30, 45, 55</td>
</tr>
</tbody>
</table>

Fig. 7 Process forces for milling of TIG and TIG + SiC welds

Fig. 8 Force coefficients for TIG and TIG + SiC welds

Fig. 9 Process forces for different \( \lambda \)i
The location of immersion along the ball end shifts toward the cylindrical part of the tool. With increasing tilt angles $\tau$ while keeping $\lambda = 0$ deg, the feed normal force $F_{fn,max}$ decreases. The cutting edge trajectory is shifted in the direction of feed motion. In Fig. 10, the maximum passive force $F_{p,max}$ and the maximum resultant force $F_{r fn,max}$ of $F_{f fn,max}$ and $F_{f p,max}$ are shown for all considered inclination angles. Depending on the direction of maximum workpiece compliance, small lead and tilt angle should be chosen to reduce deflection. This is in line with the findings of Ref. [13]. Nonetheless, small angles are not always applicable for recontouring of damaged blisks due to the limited accessibility. This additional boundary condition has to be incorporated for process planning of recontouring tasks.

For a precise force prediction, cutting force and edge force coefficients for different $\lambda$ and $\tau = 0$ deg are shown in Fig. 11. The force coefficients for $\lambda = \tau = 0$ deg are listed as well. However, in the following discussion, they will be neglected because of the tool tip contact. The tool tip contact has to be avoided and is not considered inclination angles. With an increasing lead angle $\lambda$, the tangential cutting force coefficient $K_{tc}$ decreases, whereas the radial cutting force coefficient $K_{tc}$ and the axial cutting force coefficient $K_{te}$ increase. When comparing the cutting force coefficients for $\lambda = 15$ deg and $\lambda = 55$ deg, $K_{tc}$ decreases by 12%, $K_{te}$ and $K_{ac}$ are raised by 33% and 310%, respectively. To explain the decrease of the tangential cutting coefficient $K_{tc}$, the changed effective rake angle $\gamma_{eff}$ has to be considered. It is known from literature that an increased rake angle $\gamma$ causes a lower cutting force $F_c$. Using higher lead angles raises the effective rake $\gamma_{eff}$. Thus, the cutting force $F_c$ is lowered. Additionally, the helix angle $\varepsilon$ is raised with increasing lead angles $\lambda$, which results in higher axial forces. Hence, $K_{ac}$ is raised with increasing lead angles $\lambda$. Furthermore, the cross section of undeformed chip changes depending on the tool orientation. For a sharp tool, the effect of the lead angle $\lambda$ on the tangential, radial, and axial edge force coefficients $K_{te}, K_{re},$ and $K_{ac}$ is comparably small. The radial edge force coefficient $K_{re}$ is highest for all lead angles $\lambda$ followed by the tangential edge force coefficient $K_{tc}$. The axial edge force coefficient $K_{ac}$ can be neglected. In this direction, the workpiece material is only slightly deformed. For recontouring it follows, that tool deflection is minimal, when using small lead angles, because the maximum compliance of a tool is perpendicular to its axis.

**Methodology for Choosing Process Parameters.** As shown in the previous part, designing a process for recontouring differs from the machining of new parts. Thus, the additional boundary conditions like altered material properties and limited accessibility have to be incorporated during planning. Denkena et al. demonstrated a simulation-based approach, which considers these boundary conditions [25]. This paper uses this approach and extends it by considering static part deflection when recontouring. The corresponding methodology is shown in Fig. 12.

The basis is a static MRS as shown in Refs. [17] and [25]. It allows the prediction of process forces and resulting surface topography. First, boundary conditions like geometric tolerances, surface topography requirements, and accessibility define initial process parameters. Afterward, the process forces are calculated running the MRS using the experimentally determined force coefficients for the model of [23] as well as the real tool geometry. Finite element method (FEM) computes the position and time-dependent static stiffness $k$ of the part in each direction of the Cartesian workpiece coordinate system. The tool stiffness has been neglected because of the high workpiece flexibility. With the calculated forces and the computed stiffness $k$, the static part deflection $\delta$ is predicted. If the deflection exceeds the given geometric tolerances, the process parameters are modified and the MRS is run again. The result is a set of process parameters including the predicted surface topography. This process planning does not consider any dynamic effects so far. In future works, the time domain MRS will be extended by the use of simulated frequency response functions to describe part and tool dynamics. Harmonic oscillators derived from the frequency response functions will be used to model the dynamic behavior. For more information on the general simulation-based approach, the reader can refer to Ref. [25].
Reactive Machining

The methodology introduced in the Methodology for Choosing Process Parameters section allows considering shape deviations within process planning. The effects of material properties and process kinematics were taken into account. However, local variances of the workpiece (e.g., material or geometry irregularities) can induce unpredictable process force fluctuations. The resulting tool and workpiece deflections in turn affect the workpiece geometry.

In this section, a reactive approach for compensating workpiece deflection is proposed. It uses an active electromagnetic guiding system to carry out compensating movements independently of the NC-control and the machine tool axes. After introducing the machine tool and the experimental setup, its operation is explained in detail. Finally, first results of a five-axis milling experiment are presented.

Machine Tool and Experimental Setup. The five-axis vertical milling machine “Neximo” is a prototype, built by the Institute of Production Engineering and Machine Tools. The X and Z-axes are arranged in a cross table setup. The carriage of the Z-axis travels on top of the X-axis. All remaining axes are workpiece-sided, cf. Fig. 13. For highest dynamics all five axes are directly driven.

The active magnetic guiding technology is used in the Z-axis. Eight electromagnets stabilize the slide. They are tilted by 45 deg, resulting in an O-arrangement (Fig. 13). The position of the slide is measured by eight eddy current sensors (Micro-Epsilon eddy NCDT 3700) located next to each magnet. State space control with an additional integrator allows highly dynamic slide positioning in five degrees-of-freedom within the air gap of the magnets. While an industrial Siemens environment (840d sl) is used for NC-control of the machine axes, the control of the magnetic guide is implemented separately on an I-PC. The controller runs at a cycle time of only 50 μs in a BECKHOFF TwinCAT environment. For more information about the “Neximo” and the magnetic guide, one can refer to Ref. [18].

The following investigations are carried out on blade-shaped titanium components that mimic a real-life patch repair scenario. The dimensions of the blade dummy are depicted in Fig. 14(a).

Figure 14(b) shows the clamping of the workpiece on the rotary table. In order to obtain high precision measurements of the cutting forces, the workpiece is placed in a machine vice on a dynamometer (Kistler 9257B). The signals of the dynamometer are processed by a charge amplifier (Kistler 5015a) and captured at a sample rate of 20 kHz using the control hardware of the electromagnetic guide (Beckhoff I PC, EtherCAT bus).

The calculation of compensation movements for the magnetic guide, as described in the Compensation of Workpiece Deflection section, also takes place on the I PC. Information from the NC-control is submitted via PROFIBUS-connection and SIEMENS synchronized actions to the I PC. This allows for example to send the tool center point (TCP) position at interpolation cycle rate.

The experimental cuts were executed with a Seco JH970100 ball end mill (diameter $D = 10$ mm, flutes $z = 2$, cutting edge rounding $r_b \approx 4$ μm). The process parameters have been chosen according to typical finishing operations. They are summarized in Fig. 15.

Compensation of Workpiece Deflection. Figure 16 illustrates the information flow for the deflection compensation. The local workpiece deflection $\Delta_{WCS}$ at the current TCP position is calculated within every control cycle from the local workpiece stiffness and the measured process force. The result given in the workpiece coordinate system is then transformed to the machine coordinate system based on the current orientation of the rotary machine axes (A, C). The projections of the displacement vector $\Delta_{MCS}$ on the X- and Y-axes of the machine coordinate system (Fig. 17) are used as set values for magnetic positioning. This way, the tool follows the workpiece until the deflection is compensated or until travel is limited by the air gap of the electromagnets.

Next, the critical aspects of obtaining the local stiffness of the workpiece and processing the raw force signal shall be discussed in more detail.

Local Workpiece Stiffness. The local workpiece stiffnesses of the test workpiece were determined by FEM. Simulations were...
carried out for 35 positions on the patch area that are uniformly distributed in an orthogonal point grid. A static load was applied in X, Y, and Z directions of the WCS at each point. With this load and the simulated displacements, an equivalent stiffness was calculated for each direction (kX, kY, kZ). The local stiffnesses were then implemented in a look-up table, which interpolates linearly between the simulation points. Input arguments for the table are the Y- and Z-positions of the TCP given in the WCS. The tool stiffness has been neglected due to the high workpiece flexibility.

Signal Processing. Finishing operations with small feed rates and step overs, as they are typical for recontouring, show low cutting forces and extensive delay between cutting tooth contacts depending on the tooth pitch.

Therefore, a three-stage signal-processing is necessary to prepare the raw force signal Fraw,WCS for displacement compensation (Fig. 16).

The mass of the vice and workpiece causes a weight force, which is of the same order of magnitude as the occurring cutting forces. In a first step, the weight force component FG,WCS is removed from the signal, since it does not contribute to the deflection of the blade. The weight force vector can be measured and stored initially. However, the orientation of the dynamometer changes with respect to the earth’s gravitational field during five-axis machining. It is therefore transformed according to the movement of the rotational machine axes (A, C) before it can be subtracted from the raw signal of the dynamometer (Fig. 16).

In the second step, the envelope of the measured cutting force FWCS is determined. An algorithm identifies the peak force at tooth engagement and holds it until the next tooth contact occurs. Figure 15 shows a time sequence of the cutting forces in X direction for one milling pass near the tip of the test workpiece. Single tooth engagements can be seen in the close-up. The resulting envelope is a step function that has to be low-pass filtered in order to avoid high frequent excitation and bad surface quality. This is the final step of signal processing. A first-order Butterworth low-pass filter with a cutoff frequency of 4 Hz proved suitable for this purpose. The resulting signal FX,max,WCS follows the peak forces smoothly. Zero crossing of FX,max,WCS clearly marks the transition from milling on the suction side to milling on the pressure side of the blade.

Results. Figure 18 shows the workpiece deflection ΔWCS along the toolpath that was calculated during the finishing process. The maximum of 29 μm is reached on the pressure side near the edge of the blade. When the edge itself is machined, the blade is deflected mainly in the X direction. This is due to the low stiffness in this direction and the tangential cutting force (down-cut milling). Because of the high local stiffness in the Y-direction, the passive force contributes little to the deflection in this position.

Figure 19(a) shows a recontoured blade. To highlight the difference in the final geometry, compensation was switched on and off during the finishing cut.

Figure 19(b) shows the deviations of the machined geometry compared to the CAD model of the blade. The three-dimensional geometry scan of the real workpiece was produced by a structured-light scanner (GOM ATOS Core) and fitted to the corresponding surface of the CAD model. The fitting algorithm only considers surfaces, which were not machined during recontouring. This comparison shows the effect of the deflection compensation. The offset between the surfaces that were machined with and without compensation is approximately 20 μm in the upper area of the patch. The absolute deviation from the target geometry cannot be quantified in this example, since the machined surface is tilted relatively to the original geometry due to misalignment of the workpiece. This becomes obvious at the left and right boundaries of the patched area in Fig. 19(b).

Conclusion and Outlook

In this paper, a process chain for a weld repair has been examined. A modified TIG welding process with SiC addition to the weld pool has been used. It could be shown that SiC addition can be used to enhance joint properties by grain refinement but also...
leads to increased hardness. The effect of the altered microstructure leads to higher process forces during recontouring and must be considered for process planning. Within an MRS, the different material properties are represented by additional force coefficients to predict process forces during milling. Furthermore, the importance of tool orientation when recontouring has been demonstrated. Depending on the inclination angles, the process forces can significantly be reduced. This leads to a higher machining accuracy while maintaining the same productivity. In combination with a static structural mechanics FEM analysis, the part deflection during machining is predicted. If necessary, the process parameters are adjusted to improve geometric accuracy. The optimized process parameters are then used for G Code generation.

The capabilities of a novel machine tool featuring an electromagnetic guided Z slide were shown. Process monitoring, e.g., chatter identification, and the compensation of workpiece deflection are possible use cases. A reactive machining approach for workpiece quality enhancement in single part production has been presented in detail. Based on the online measured process forces and simulated local compliances, the magnetic guide reduced the geometric error due to workpiece deflection by about 20 µm.

In future work, the time-domain MRS will be extended by tool and workpiece dynamics using harmonic oscillators. Additionally, the effect of tool microgeometry on the surface (scuffs) will be included. Artificial intelligence will be used to model the process forces to counter the variance of repair cases. Regarding the magnetically guided machine tool, online process monitoring will be improved for identifying local variances.

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