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Approaches for improving cutting processes and machine tools in re-contouring

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Abstract

Re-contouring in the repair process of aircraft engine blades and vanes is a crucial task. Highest demands are made on the geometrical accuracy as well as on the machined surface of the part. Complexity rises even more due to the unique part characteristic originating from the operation and repair history. This requires well-designed processes and machine tool technologies. In this paper, approaches for coping with these challenges and improving the re-contouring process are described and discussed. This includes an advanced process simulation with its capabilities to accurately depict different material areas and predict process forces. Beyond, experimental investigations on workpiece-tool-deflection are presented. Finally, a machine tool prototype with a novel electromagnetic guiding system is introduced and the benefits of this technology in the field of repair are outlined.

Keywords: re-contouring; process simulation; machine tool

1. Introduction

The repair of expensive goods has a huge economical potential compared to manufacturing of new parts. Blades and vanes of aircraft engine components are one example. However, the process chain significantly differs from new part production since operating and repair history makes every part and repair task unique. Generally, the repair process chain for blades and vanes consist of a pre-inspection, material deposit, re-contouring and a post-inspection [1].

Thereby, the shape-giving re-contouring process has a major influence on the performance of the repaired part [2]. Form and surface accuracy have close tolerances in order to comply with performance and safety regulations for the aircraft engine. One major challenge for the production industry arises from the reverse engineering of the repair part with unknown material deposit plus the deviated shape of the part. This has been addressed by various researchers [2, 3, 4]. The machining process itself has not yet intensively been studied for the case of re-contouring. Nowadays, re-contouring mostly falls back on adjustment of a predefined tool path based on position identification of the part. Knowledge-based or run-in processes on conventional machine tools are used. This can lead to form deviation, undetermined part properties and even scrap parts. In order to improve this approach, Uhlmann et al. investigated the life time and process stability with significant improvements in cutting built-up welds [5]. Yilmaz developed a machining strategy including the correct choice of tool and milling method [3]. Instead of using a conventional machine tool, Brecher presented a hybrid machining center, which combines material deposit and re-contouring [6]. Huang proposed the use of robots as more flexible alternative to machine tools [7].

These works show the potential for solutions that reduces costs due to scrap parts and expensive extra work and may also improve quality of the repaired parts. Approaches for improvements are addressed in three following chapters: In the second chapter a process simulation is presented, capable

of accurately predicting process forces and surface topology. Chapter three covers experimental investigations on workpiece-tool-deflection. In chapter four a new machine tool technology and its benefit in re-contouring is presented.

2. Process simulation

The simulation environment CutS [8] – an inhouse development of the IFW – is used for simulating re-contouring processes. Dexels are used to discretize the workpiece in three dimensions. Changing materials, like in material deposit areas, are taken into account through local material information at the dexel. The different sections of the part are identified automatically by comparison of a part before and after material deposit. Original part section, welding material or patches can thus be separated. In Fig. 1 the interface of CUTS with its functionality is presented.

The simulation allows traveling the tool along a given NC-path, what eventually leads to precise information of the cut material volume and the spatial orientation of the tool axis and the tool center point (TCP). With this information and the known material characteristic a process force algorithm has been developed which allows detailed cutting force estimation in re-contouring [9]. The general force model of Altintas is integrated, which only makes the identification of the cutting constants K_{ci} and K_{ei} mandatory.

Fig. 2 shows a comparison between measured process forces while machining a welded area (TiAl6V4) (upper graph) and the result of the simulation (lower graph). The average discrepancy of the overall milling force F_{xyz} is $\Delta F_{xyz} = 14.6$ %. Beside process forces, also generated surfaces have been predicted [10].
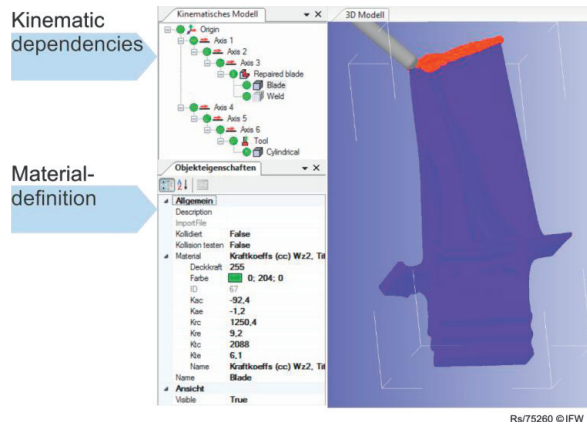

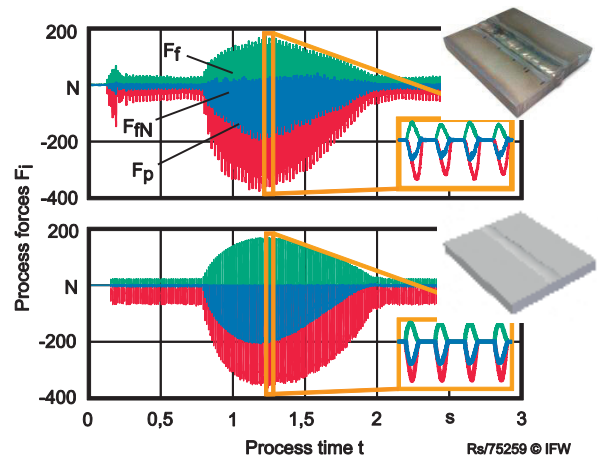
Fig. 1: Interface of CutS

Fig. 2: Measured (top) and simulated (down) process forces

3. Experimental investigations on tool-workpiece-deflection

Tool deflection and vibrations are major sources for unsatisfactory form and surface accuracy. The occurrence is mostly depending on the workpiece and tools, dynamic and static stiffness and the choice of cutting process. During re-contouring of freeform surfaces with inclined tools and compliant workpieces, accurate simulation of deflections and vibrations in the process becomes unlikely. To gain fundamental understanding of the deflection during re-contouring, experiments on form accuracy have been undertaken. Repair cases were imitated by prepared workpieces. Different tools have been used as displayed in Fig. 3.
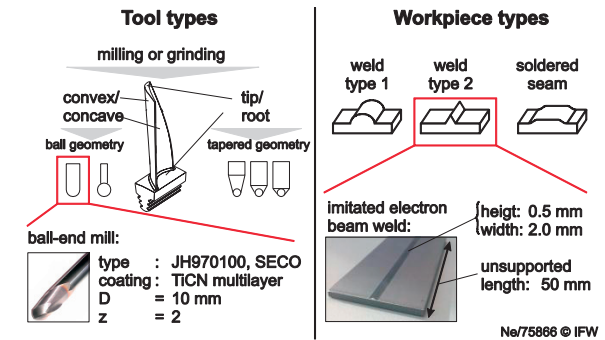

Fig. 3: Tool and workpiece types for re-contouring experiments

Exemplary, the re-contouring of prepared workpieces (Ti-6Al-4V, electron beam weld imitation) with ball-end mills is presented. Different feeds, depth of cut and tool inclinations were set and the resulting form deviations were measured by laser triangulation during the process. Setup and results are shown in Fig. 4.
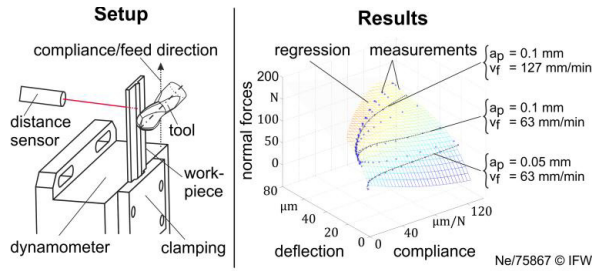
Fig. 4: Test setup and measured data points with extrapolation

Due to the interdependency between tool and workpiece compliance, the resulting deflection exhibits a nonlinear behaviour. While milling highly compliant workpieces, small depth of cuts and low feeds are mandatory. In contrast, at regions with low compliance, high feed rates are possible without violating limits in form accuracy. Small inclination angles give a supporting effect in terms of damping due to the engaged tool tip. Extrapolating the measured data points allows estimating the allowed normal forces for a desired overall deflection and given compliance. This data can thus be used to select suitable tools and parameters for the re-contouring.

4. New machine tool technologies

A five-axis machine tool prototype has been developed. Key component is a novel electromagnetic guiding system in the z-axis. The machining center is directly driven in all axes. X- and y-axis are both equipped with roller guides. An industrial Siemens control environment (840d solution line) is used. In Fig. 5 the machine tool and the spindle slide of the z-axis with its electromagnets is shown.

The spindle slide is stabilized in 5 degrees of freedom (dof) by eight electromagnets, whereby each magnet can deliver a maximum force of $F_{max} = 15$ kN. Self-developed 2-quadrant-inverters are chosen for maximum dynamics of the electromagnets. The position of the slide is measured by eight eddy current sensors (Micro-Epsilon eddy NCDT 3700) located next to each magnet. Therewith corrective forces can be calculated by the control system.
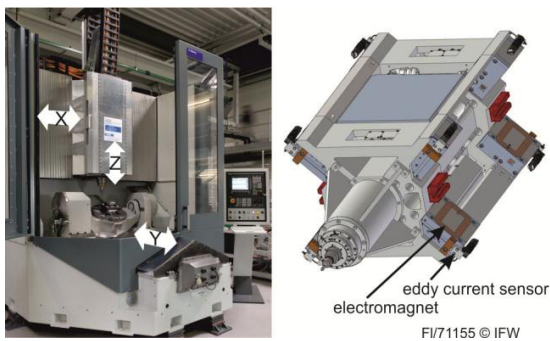

Fig. 5: Machine tool protoype Neximo

A PI-state controller with kalman observer is implemented. The guide's control runs on a separate industrial control environment BECKHOFF TwinCAT with an EtherCAT bus system. A detailed description of the machine tool prototype and its guiding system can be found in [11].

The working principle of the guide allows high damping and thus vibrations, originating from the cutting process, are well attenuated. Considering unknown, heavy-to-cut material deposit areas as a significant source of vibrations, this guiding system can improve the process.

4.1. Fine-Positioning

A benefit of the active system is the possibility to position the slide in its 5 dof within the air gap of the electromagnets (approximately 400 µm). The dynamic and accuracy of this positioning movement considerably exceeds the possibilities of conventional feed drive systems in machine tools. Positioning bandwidth in the 5 dof can be derived from Fig. 6.

In translational direction, a bandwidth of 51 Hz is reached. The rotational movements have a bandwidth of 59 Hz (φ), 46 Hz (ψ) and 72 Hz (θ). All values are given for the -3 dB border.

Positioning accuracy of the magnetic guide in y-direction was measured with a Renishaw ML10 laser interferometer. Due to the friction free operation the random error in positioning is about five times smaller than the conventional feed drive system. The mean position scatter is $P_s = 0.36\ \mu m$ (magnetic guide) and $P_s = 1.81\ \mu m$ (conventional y-axis), respectively.

This functionality offers new possibilities in re-contouring processes, especially the compensation of tool deflection. Estimated or measured deflections can be accurately compensated. Thus, form errors in machining can be minimized.

4.2. Cutting force estimation

The active guiding system enables the machine tool to estimate process forces without additional instruments. Forces are compensated by the guide's control system and can thus be extracted. This is realized with a disturbance force observer. The algorithm is outlined in [12].
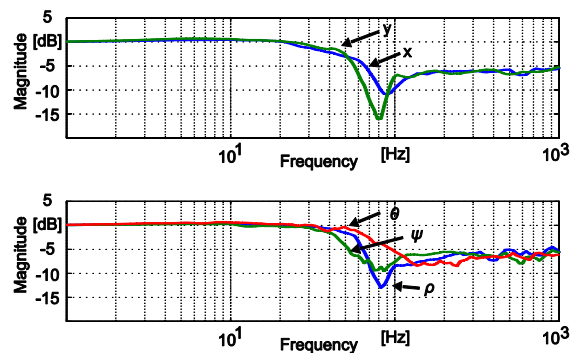

Fig. 6: Bandwidth for fine-positioning in 5 dof

Cutting tests can clearly display the accuracy of force detection. A slotting operation is conducted. The reference force is given by simultaneous measurement with a dynamometer (Kistler 9255b). Calculated and measured feed forces with different observer settings are displayed in Fig. 7.

It can be seen, that a good estimation of a mean value with non-sensitive observer settings is achievable. A more dynamic identification of process forces shows the limitation of this approach. The result is clearly biased by a delay. The deviations in amplitude can be explained by deficits in the identification of the structural dynamics of the spindle slide. A higher noise level is inevitable.

Identifying the compliances of tool and workpiece, with this feature a fully automatic control of tool deflection can be established. Moreover, this function can be used for process monitoring. Feedback about the state of the re-contouring process can be integrated in quality control mechanisms.
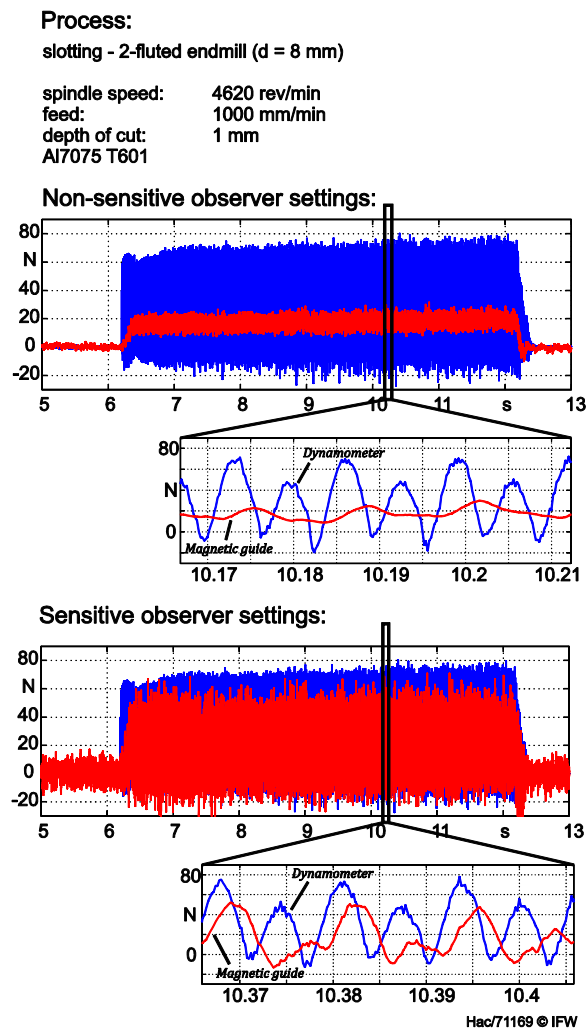
5. Conclusion

The challenges of machining repair parts and the demand for more adaptive machining solutions for re-contouring has been pointed out. Hence, a simulation tool, experimental investigations on the cutting process and a new machine tool technology has been demonstrated as suitable approaches.

Process forces can be accurately determined even when material properties and immersion conditions of complex milling operation continuously changes. This allows a significantly deeper insight in the behavior of the process.

In machine tool technology not only extreme stiff solutions may be suitable. A good damping behavior and additional dof of the machine tool for more adaptive repairing solutions can offer improvements.

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Fig. 7: Cutting force estimation with different observer settings