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Procedia CIRP 35 (2015) 31 – 37

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MIC2015 – 15th Machining Innovations Conference for Aerospace Industry

Simulation and evaluation of different process strategies in a 5-axis re-contouring process

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Abstract

In the regeneration of turbine or compressor blades each blade damage is varying in location, size and shape, depending on the cause of damage. An important regeneration step is the re-contouring which is applied after the deposit welding to remove excess material. With complex blade shapes this step requires 5-axis machining methods. Due to different cases of damage, the re-contouring has to be adapted to each individual repair case to satisfy the high quality requirements regarding the final workpiece. This paper combines the two topics machining strategy and emerging workpiece quality. In this context the work demonstrates a simulation-based approach for the 5-axis re-contouring process. Hence, different 5-axis tool-paths strategies are applied on an analogy repair case including a modelled weld shape. The re-contouring is performed virtually via a dexel based material removal simulation as well as experimentally by using a 5-axis milling machine. Afterwards an evaluation of the different tool-path strategies is done considering achieved workpiece quality. The results imply that the simulation is applicable to predict certain aspects of the workpiece quality such as surface topography. With the simulation system, a tool-path evaluation is possible before re-contouring real workpieces.

Peer-review under responsibility of the International Scientific Committee of the "New Production Technologies in Aerospace Industry" conference

Keywords: milling; simulation; re-contouring; blade repair

1. Introduction

1.1. Regeneration and re-contouring

The repair of expensive goods like blades and vanes of aircraft engine components is daily practice in Maintenance, Repair and Overhaul (MRO) business. However, the process chain significantly differs from part to part. The repair process consists of pre-inspection, material deposit, re-contouring and a post-inspection, see figure 1 [1].

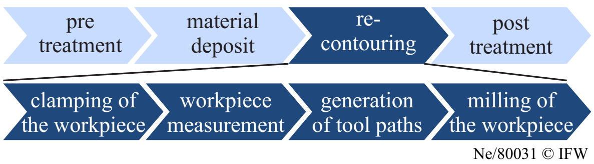

Fig. 1. Process chain of regeneration and re-contouring

The re-contouring, which is the final shape cutting of the blade, has a major influence on the performance of the repaired blade. A high accuracy in surface finish is important for compliance with performance and safety regulations for the aircraft engine. One challenge for the MRO 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 [2–4]. Though the re-contouring process is daily practice in industry, it has not been intensively examined from a scientific base. Nowadays, re-contouring mostly falls back on adjustment of a predefined tool path based on position identification of the workpiece and an adaption of the tool path offset. Scientific based researches use offset-based tool-paths as well, to provide reliability and repeatability in process, as seen in figure 2.

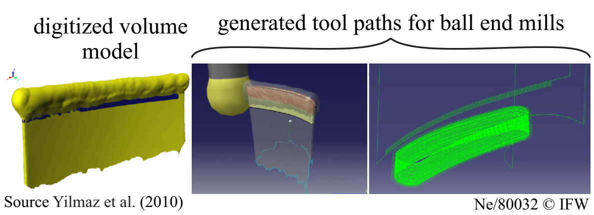

Fig. 2. Tool path strategy for tip repair used by Yilmaz et al. [3]

Peer-review under responsibility of the International Scientific Committee of the "New Production Technologies in Aerospace Industry" conference
doi:10.1016/j.procir.2015.08.059

Companies have established, offering specialized software to adapt tool-paths for the re-contouring of blades and vanes, e.g. TTL or BCT [5,6]. For this purpose a Master CAD model of the blade is fitted to the individual shape of each blade. Nevertheless, tool path adaption in these cases does not consider the deposit material and the changing tool engagement conditions. The process development and run-in processes on the machine tools based on experience. This can lead to form deviation, undetermined part properties and even scrap parts [7,8]. From a scientific point of view, it has been pointed out that the shape of the deposit material respective the weld is of major importance regarding the re-contouring step. This has been shown through experiments and simulations on the titanium alloy Ti-6Al-4V [9]. An active guiding system has been established to compensate tool deflections while re-contouring [10]. Blade digitization is applied by reverse engineering of the blade, which leads to suitable CAD data for further processing [3,4]. To provide a proper clamping of the workpiece, different clamping methods were examined. Pin-type clamping has been found to be a solution for the demands of differing blade roots [11,12]. These works show the potential and the possibilities for adaptive machine functions. However, the tool-path itself has not been explicitly considered. Assuming the shape of the deposit material is known from blade digitization, a material removal simulation can be used to reach a higher adaptability of the tool-path. The simulation therefore serves for examining dimensional accuracy and furthermore for prognosis of forces and residual stresses. Hence, the scientific view on tool-path planning and re-contouring technology cannot be separated from each other.

1.2. Simulation approaches for manufacturing of parts

In the last decades enormous effort has been put into prediction of certain aspects of the machining process, e. g. cutting forces, surface quality or residual stresses. These three aspects are described in the following because of their high importance for re-contouring high value parts. The prediction of cutting forces is one subject of research for almost 100 years. All methods can be classified into analytical, empirical and numerical models or combined, so called hybrid approaches [13–17]. One of the most established methods are the mechanistic models, which use empirical, material-specific cutting force coefficients, combining them with process specific undeformed chip dimensions such as uncut chip thickness. This type of cutting forces models can also be enhanced with additional terms in order to consider e.g. the indentation effect due to low cutting speeds at the tool tip for ball end milling processes [17]. It is shown, that mechanistic models are also applicable for re-contouring due to the low influence of the weld inhomogeneity [9].

The surface topography is often predicted by modelling the cutting edge kinematics by numerical or analytical methods [18–20]. The universal, numerical approach is the usage of a material removal simulation using e.g. dexel, voxel or constructive solid geometries (CSG) for workpiece definition [21]. Besides surface topography prediction, the material removal simulations are also used for cutting force prediction [9,22]. It has to be mentioned that the influence of tool micro-geometry is less investigated than the influences of specific process kinematics for surface topography simulations.

The cause-effect relationships of residual stress formation after machining is still not fully understood as shown by Jawahir et al. [23]. One possible reason is the high interaction between the most influencing factors to residual stresses, which are the choice of the material, the machining process and the tool micro-geometry. Most residual stress predictions are based on FE-Simulations [24] or hybrid methods [25]. The prediction methods in literature aim to virtualize the machining process to reduce or eliminate physical trails to ensure the workpiece quality or improving performance [26]. This is also important for the re-contouring process but these methods are not applied for 5-axis machining yet. Virtual machining processes use tool-workpiece-engagement algorithms. For the work described in this paper, a multi dexel model was used in order to verify different re-contouring strategies. The first part describes an analog workpiece providing a realistic interference contour, which is re-contoured on a 5-axis machine tool. Three derived tool-path strategies are applied afterwards for the re-contouring of the workpiece. Further on, the tool path strategies are considered in simulation and experiments. The measured factors of workpiece quality, namely surface topography and residual stresses are compared to the simulation results. Also it is shown in simulation, how process forces vary between each process strategy.

2. Manufacturing of the analog workpieces

Due to the individual material deposit each workpiece differs in re-contouring applications. Different workpieces would change the initial situation for comparing different tool path strategies and to verify the methods for prediction. Therefore an analog workpiece is milled from a whole piece which emulates a repaired blade. This method is valid, because the influence of the inhomogeneity of the weld is negligible [9]. The thickness of the analog workpieces is increased in order to reduce the influence of workpiece vibrations during re-contouring and to ensure the transferability of previous findings. Another advantage of the analog workpieces is that the re-contouring can be applied in the same clamping as the manufacturing. This eliminates the inaccuracies of the workpiece measurements, which is an issue in practice. Two different repair methods are included at the analog workpiece. The first is the patch repair, where the damaged part of the blade is removed and replaced by a spare part, called patch [27]. The second is the established tip-repair, which is used to decrease the gap between the blade and the case. Figure 3 shows the CAD-model and the corresponding workpiece after 5-axis machining, which are virtually re-contoured by three different strategies. Due to its more complex shape, only the weld is considered for further progression in re-contouring.

3. Simulation methods for re-contouring

The virtualization of the re-contouring process is utilized with the material removal simulation CutS [28], which uses a dexel model for workpiece discretization. The simulation environment considers the real tool geometry and the tool kinematic instead of a body of rotation, which is a sphere in the case of ball end mills. The advantage of the consideration of the cutting edge movement by angular steps is more realistic surface