Engine blade regeneration: a literature review on common technologies in terms of machining

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Abstract Repairing technologies enable a huge economical potential, especially in high-technology sectors like the aerospace industry with complex capital goods. Companies in these industries retain their knowledge concerning repair technologies, in order to maintain the advantage over their competitors. Thus, the quantity of publications dealing with technological challenges and scientific basics for repairing are limited. The main purpose of this literature review is to collect published information on common technologies regarding the regeneration of turbine blades to extract scientific basics and to present challenges that are currently unattended. The attention of this paper is focused particularly on the machining process. Due to the variety of damages on engine blades, the general process chain has to be adapted partly or in whole for each component. In the second part of this paper, a general process chain for regeneration is presented, including a classification of repair methods. The main interest of the third part addresses the recontouring, which is the final shape cutting of repaired engine blades. At this point, the previous research and occurring challenges are pointed out in two stages related to the machining process—before and during machining. In the last part, the achievable workpiece quality after machining is discussed.

Keywords Aerospace · Regeneration · Process · Machining

1 Introduction

In today’s economic climate, cost pressure is a pervasive problem. One way to reduce costs is to carry out repair of single components within assemblies. In some applications, the regeneration can save up to 70 % of the costs compared to the replacement with remanufactured components [5]. Due to the high potential in cost saving, most companies try to keep their knowledge in repair processes for themselves. Though Yilmaz [54] provides an overview of scientific approaches in blade repairing methods, there is still little information on single steps of the regeneration process in literature.

Much effort is put into the improvement of processes in the maintenance, repair, and overhaul (MRO) of engines. An engine consists of approximately 30,000 components. Their repair takes a significant volume of the engine business with an increasing trend [21]. Furthermore, Rupp [46] indicates that the material costs add up to 50 % in the maintenance costs of engines.

The repair or regeneration of components such as castings [34, 42, 57], seal fins/labyrinth [27, 35, 57], and notches [35] is mostly carried out manually [5, 30, 53]. Engine components of particular interest regarding the regeneration process are compressors [21, 42, 53], and turbine blades and vanes [20, 29, 30] due to their high value. Most available references regarding the regeneration of these components concern the material deposit. Information on the recontouring is even harder to find. Nevertheless, this final shape cutting of a workpiece is a crucial step regarding the later workpiece quality. Engine blades are an example for workpieces that have high requirements in accuracy and quality combined with a complex shape and difficult material conditions.

The usual procedure for recontouring is characterized by a lot of manual working steps. This includes, e. g., manual grinding in the area of interfering contour. Achieving the final
chapter takes a close look on the recontouring process, which provides the restoration of the blade contour after the material deposit. The focus lies on challenges in machining thin blade-shaped workpieces. Changing shape and material properties require adaptive process strategies. Current researches dealing with this issue are mentioned. Furthermore, approaches regarding the right tool choice are described. In addition, the attainable surface quality and consequential surface zone properties after machining are discussed. In general, the focus lies on the current state of research as well as the applied technologies.

2 Process chain for regeneration

As mentioned before, MRO companies have a big interest in optimizing regeneration strategies and therefore keep their technology expertise for themselves. Figure 2 illustrates a generalized process chain for the regeneration of engine blades [11, 12, 13, 20, 21, 32, 39, 53] and vases [9] as it can be found in literature. Despite the focus of different fields of experiences, all considered process chains have a similar structure. Differences relate to the used materials, the shape of the workpiece, and the scientific focus. The input parameters are type of damage, the base material, the field of application, and the shape. The methodologies that are considered in the literature can be classified into the four basic stages: pretreatment, material deposit, recontouring, and post-treatment. Companies and research institutes have developed plenty of different methods for each regeneration step. Nevertheless, these steps are still characterized through a high level of manual treatment [53]. The three process steps, pretreatment, material deposit, and posttreatment, are described in the following by means of practical application and the state of research. The recontouring step will be discussed in chapter 3 in detail.

Decoating of the engine blade and the preparation of the joint represent the beginning of the regeneration process. The coating consists of a thermal barrier coating against overheating and a bond coat [47]. Methods like grit blasting and chemical stripping are used for the entire or partial removal of the coating [9, 39]. Geffert [24] uses a system
that detects the individual layer height of the coating which allows to only remove the necessary amount and therefore to enable a multiple regeneration.

The following choice of an appropriate deposit methodology depends on the type of damage. According to the amount of material that has to be replaced, the material deposit will include welding, brazing, or patching (see Fig. 3). Additionally, the used deposit method directly influences the choice and the extent of the recontouring process.

A frequently applied repair procedure is filling material at the blade tip, e.g., the tip repair. The material that gets lost through abrasion processes is commonly replaced by cladding. Whole breakages are replaced by a patch that is joined through welding techniques. An advantage of the patching method is the minimum difference in material properties, as the patch corresponds to the material of the original engine blade [21]. The crack repair includes welding or brazing methods.

Challenges regarding the material deposit occur from two different aspects (see Fig. 3). One aspect is the application of a single or polycrystalline material of turbine blades that necessitates appropriate deposit welding techniques [5, 25, 51]. Nickel-base alloys, e.g., lead to increase crack formation after welding. Hence, brazing is a common method for these materials [9, 45]. Second is the repair of blade-integrated disks (blisks) that requires different deposit strategies because of the poor accessibility of the blades [34, 45]. The objective is to get a near-net shape to reduce the use of material as well as the further expense in the recontouring process. Furthermore, base material should be affected by the deposit process as less as possible. Regarding this, the laser welding has advantages because of its very low range of influence of up to 10 μm [44]. Geffert [24] and Eberlein [21] propose plasma arc welding for the repair of blisks. Oxygen-free conditions increase the chance of a proper weld shape [21, 24]. A method for the repair of small cracks is diffusion brazing, which allows material deposit without common welding defects like cracks or distortion [6, 26]. Generally, the industrial approach is to fill deep cracks through brazing methods, taking advantage of the capillarity, whereas damages in the near surface zone are repaired through welding. Both methods have a negative influence on the mechanical properties of the blade and therefore reduce the fatigue limit [45].

A downstream heat treatment is often provided to reduce the residual stresses that occur due to the welding and the milling process. Eberlein [21] shows that a local heat treatment of patch-repaired turbine blades can reduce stresses in the weld zone. Miglietti and Summerside [39] apply a rejuvenation heat treatment on a welded Inconel (IN738) turbine blade, which provides increased stress rupture properties of the laser-welded zone. Kim [37] investigates the hot isostatic pressing (HIP) uses as a posttreatment of welded nickel-based material, which results in a higher tensile strength and yield strength of the material.

3 Recontouring

The main interest of this chapter concerns the recontouring, which represents the final shape cutting of repaired components. MRO companies use different methods to regain the original contour of the repaired turbine blades. The steps regarding the identification of damage, the choice of the recontouring method, and the recontouring itself are carried out individually for each workpiece. Industrial recontouring of compressor blades is commonly performed through belt grinding as rigid G-code data is not applicable regarding the variety of damages [11, 12].

To ensure a consistent workpiece quality, it is useful to gradually increase the automation in the recontouring process. Nevertheless, this is difficult because of the variety in damages as described above. Hence, this chapter deals with the issues that arise due to the aim of an automated process. Therefore, a crucial focus lies on individual shapes and damages.

Workpiece digitization therefore is a present topic in current developments. Correct CAD data is essential for an adaptive recontouring process. Walton [52] points out the importance of a correct tool path based on the digitized workpiece shape and a two-way communication between machine tool and the attached CAD/CAM system. A correct shape reconstruction is essential for the tool path planning and the following machining process as each surface exhibits very small individual variations affecting the result. MRO companies put much effort into an overall solution for digitization, surface reconstruction, and tool-path planning.

Workpiece digitization comes with the challenge to provide an individual clamping position for the workpiece and the computer-aided restoration of the actual geometry for further
process planning. Researches focus on the development of new strategies for localization of damages, shape recovery as well as the path planning for the recontouring process [3, 22, 43]. In addition, a correct tool choice, the attainable surface quality, and the consideration of machining parameters are discussed in current researches [8, 39].

3.1 Before machining

Different requirements regarding the recontouring, resulting from the material deposit, need to be fulfilled to obtain an adequate result of the final shape, and sufficient surface-zone properties. Figure 4 exemplarily shows the main recontouring issues on an engine blade, repaired through a patch at the upper corner and a tip weld. The main problem results from the individual regeneration process that is needed for each repaired workpiece. Each engine blade features individual deformation compared to the original contour. During the manufacturing process as well as during use in the engine, the actual blade deforms, e.g., because of creep that occurs due to high temperatures and high centrifugal forces. Consequently, the machining surface differs between applications so that each tool path needs to be adapted to the actual shape. Material characteristics in the weld seam, the base material, and the heat-affected zone differ between workpieces as well. Hence, it is important that the geometric information about the surface and the weld are measured and considered in the planning process.

This poses major challenges on the used technologies within the process chain of recontouring. Flexible clamping of the workpiece has to be provided in order to cope with shape deviations and different areas of material deposit. Every workpiece has to be digitized and reverse engineered for tool path planning. For accurate machining results, the process has to compensate variation of material characteristics and cutting volume.

General decisions have to be taken on the reference situation while clamping the workpiece. Clamping-based reference, workpiece-based reference, or a carrier system can be deployed. Clamping-based reference, where the workpiece always has the same position in the clamping system, allows a fast and frequent replacement of the workpiece with a coincident maintaining of the reference. However, this clamping system has to be designed for one workpiece type only [33]. Workpiece-based referencing allows the usage of more flexible clamping systems but needs referencing runs with every change in the clamping situation. Usage of low-temperature melting alloys as well as pinpoint clamping systems can be used for this approach [41]. Carrier systems are often used in industrial applications. The workpiece is brought into a reference position onto the carrier, and the carrier is zero-point referenced in the different steps of recontouring.

Referencing itself can be done by tactile or optical measurements. Easy integration and good accuracy make the tactile testing the favorite choice in machine tools. However, point density is clearly limited when using measuring tactile probes. Higher point densities can be achieved by optical measurement techniques. Bichmann [4] investigates integration of laser triangulation sensors.

An additional challenge results from workpiece deviation. Hence, a reference on the workpiece does not necessarily coincide with knowledge of the total shape. Most often, assumptions are made for the shape of the workpiece. CAD techniques exist to rebuild the actual shape of the engine blade from a given amount of measurement points (point cloud).

Different approaches are described in literature. Most authors describe a reverse engineering process, which is a step-by-step reconstruction of the original engine blade from the digitized workpiece data. The reconstruction is performed either through triangulation for three-dimensional measurement data [23, 32] or through extension of a two-dimensional profile [3, 30]. The single steps for the blade recovery are mostly carried out within a CAD environment, which requires several individual operations. The subsequent tool path generation is carried out either based on the reconstructed shape or directly from the point data. One main issue in regeneration path planning is the adaption of the tool path onto the actual blade shape.

On the one hand, the blade shape differs between each individual workpiece. Therefore, a general tool path needs to be brought on an individual-scanned engine blade [7] applies the free-form-deformation method to automatically adapt a nominal tool path onto a modified surface, which results in less workpiece deviations. Chui [16] develops a tool path generation based on the measurement points from the digitization. Through a series of filtering methods, a three-dimensional triangular mesh is obtained for a complex free-form surface. The surface normals serve as input data for the tool path generation. The accuracy of the variable tool axis
positions is strongly depending on the applied filtering method for the digitized points. Issues may arise at sharp edges or vertical surfaces that are possibly omitted by the algorithm. On the other hand, unknown material conditions and local shape variations in the weld zone affect the machining result. Therefore, these effects have to be considered in the process planning [56]. A general example for this technological orientated NC-planning is found in the application of Lopez de Lacalle [38]. He introduces a system that generates a tool path with a minimum tool deflection. For defined calculation points along the machining surface, the process forces are evaluated in different directions based on the pre-calculated chip volume. The inferring tool path produces a minimum deflection and therefore a minimum shape error.

As a general approach, Yilmaz [53] identifies the machining tolerance and the number of tool path control points as important parameters to receive an exact shape after milling of blade-shaped workpieces. A critical area is the leading and trailing edge of the engine blade, as the edge radius is much smaller than the tool radius. Hence, a larger number of control points is recommended in this area to avoid gouging effects. Furthermore, Yilmaz [53] mathematically determines the path interval by regarding tool radius, local curvature radius, and scallop height.

Hence, you can see that the design of the recontouring process increasingly necessitates reverse engineering technology. The primary aim is to get a virtual copy of the original blade shape providing an individual process for each workpiece. Adaptive strategies using single clamping position for both—digitalization and recontouring—are important for an efficient automated process to minimize losses of accuracy. Specialized companies like TTL and BCT provide necessary software and machine tools for an adaptive recontouring considering workpiece deviation [11, 12, 52]. Yet, current tool path planning is an individual matter, which rarely considers actual weld geometries or properties. Technological aspects like residual stresses or distortion are barely considered in the path planning of recontouring processes.

3.2 Machining process

Different challenges occur during the machining process such as tool or workpiece vibrations, changing engagement conditions, or step forming. In addition, the induced residual stresses are important due to the high load of the workpieces.

Figure 5 takes a brief view of the local requirements regarding the weld zone and points out the issues regarding the machining of an inhomogeneous workpiece. In the particular case of recontouring, the available literature is limited to meet these challenges. Five-axis machine tools are used to recontour a complex-shaped workpiece by milling due to the advanced possible kinematics compared to three-axis machine tools. High damping and stiffness as well as the number of clamping positions are essential to achieve high accuracies. Brecher [10] investigates the integration of material deposit and recontouring in a single machine tool, where inaccuracies due to re-clamping of the workpiece could be avoided. Robot-based recontouring is a more flexible alternative to machine tools, but the lack of stiffness causes difficulties in milling. Hence, some researches focus on force-controlled grinding processes [49].

Other challenges are the high demands on dimensional accuracy, surface roughness, and material microstructure for the recontouring process of engine components, as pointed out by Brinkmeier [13]. Milling experiments with Ti-6Al-4V are conducted as a reference process to gain required machining and tool parameters and to ensure a high workpiece quality after recontouring. He highlights the reduced tool wear of carbide tools compared to high-speed steel and suggests overflow-cooling lubricant for recontouring. However, it has to be mentioned that the evaluated cutting data is based on slot milling experiments in down-cut direction without recontouring weld geometries. The study of Yilmaz [53] presents a three-axis tip repair methodology for thin-curved Inconel 718 engine blades to remove the weld, which reduces the total repair time by nearly 30%. Furthermore, roughing, semifinishing, and finishing with different cutting strategies are established due to the material properties and high abrasive tool wear. It is shown that shape deviation and surface topography can be set with applicable clamping, machining, and tool path strategies. A coated carbide ball end mill is used for recontouring the flanks of the blade tip and a flat end mill cutter has been used to remove the deposition from the blade tip.

Boess [8] recontours welded, solid Ti-6Al-4V workpieces with ball end milling tools in order to characterize the influence of inhomogeneity due to different welds. He concludes that the shape of the weld has a higher influence on the process forces than a material inhomogeneity due to welding for machining of Ti-6Al-4V. Both influences are included into a multi-axial simulation for predicting process forces with arbitrary engagement conditions considering different material properties within the weld [8].

Another challenge for recontouring is the step formation because of tool deviation during the removal of the weld. Moosling [40] measures up to 150-µm deviation using ball end milling of cast iron and a transportable hybrid kinematics
machining unit for maintenance of large metal forming tools. He attributes this to the higher hardness of the weld and the heat-affected zone compared to the surrounding material. Yiilmaz [54] also emphasizes the challenges of blade and cutter deflection and highlights the need for advanced tool path planning to eliminate these interferences.

Based on the literature, it can be concluded that ball end mills are often used for recontouring because of their easy usage and their spherical shape for adaptive CAD/CAM strategies. The disadvantage of ball end mills is their poor productivity. Tool vibrations are not mentioned as a problem, even if high length to diameter ratios used for recontouring may result in chatter. This is especially the case for future regeneration of blisks because the tool path strategies are limited compared to single blades. The engagement conditions during recontouring are only considered for scientific purposes but not for current industrial adaptive processes.

3.3 Workpiece quality after machining

The achievable surface quality, e.g., depends on the material, the used milling tool as well as tool deflections. Besides the achievement of the final blade shape, another aim is to get appropriate stress conditions in the surface zone of the material (see Fig. 6). The fact that the material provides an inhomogeneous structure, due to the deposit process, is important for the final material conditions. The investigation of the quantitative influence of each the welding process and the recontouring on the residual stresses is an important issue.

The restoration of a sufficient geometrical shape, surface quality, and suitable workpiece properties is the most important aim for recontouring [1, 54]. For instance, Butler [14] describes the importance of the surface topography after refurbishment using grit blasting and polishing and their impact on engine efficiency. The value of desired surface roughness depends on the workpiece and operational environment. Blades and vanes for the turbine stages are often coated, and therefore, the demand for surface quality is less important than for the compressive stages [15]. Huang [31] and Huang [30] quantify the surface roughness to Ra=2.3 µm for high-pressure turbine blades (cobalt-chromium-nickel) after grinding and Ra=1.5 µm after polishing. By using a robot-based system with tool wear compensation, the total cycle time was reduced by 42% in comparison with the manual operation. A comparable quality is also achieved by milling as shown by Yiilmaz [53]. He increases the number of tool path steps in the recontouring, which results in a roughness of Ra=2.5 µm for thin high-pressure compressor blades (Inconel 718). Using a small radial depth of cut and feed results in small scallop heights and respectively high surface quality, which are sufficient for airfoil dimensions and surface roughness.

Besides topography and shape accuracy, the residual stresses are another important factor for the condition of the recontoured workpiece. Tensile residual stresses may be a reason for improved crack initiation and propagation as well as reduced fatigue failure and therefore have to be prevented [50]. Thus, repair or any repair has a significant impact on the endurance limit, as shown by Thomson and Anderton [48]. He investigates the influence of a compressor airfoil trailing edge repair of a gas engine and concludes a reduction of specimen endurance limit of about 41% compared to a non-damaged airfoil. Eberlein [21] also points out the need for a required residual stress level after regeneration, which is important for the validation and certification process for engine regeneration. He identifies welding/brazing and recontouring as two main sources for residual stress induction. The final residual stress stage is important for the regeneration process [21].

However, scientists try to predict stresses due to regeneration, e.g., welding-induced residual stresses and their impact to workpiece distortions [55]. In terms of machining, the residual stresses cannot yet be predicted to a satisfying degree for complex machining processes such as milling [41, 50], which is often used for recontouring. Denkeea et al. [17, 18] name the cutting edge radius as a significant factor in residual stresses formation after recontouring. Furthermore, the so-called surface generating forces, which only consider the final surface in calculating the chip thickness, are suitable for a residual stress prognosis for a rigid workpiece. Altan [1] puts an emphasis on the impact of traditional manufacturing processes, such as electro discharge machining, laser beam material removal and hard machining and their effect on the surface integrity of dies and molds. Therefore, in practice, local heat treatments after recontouring [21] or additional processes such as shot peening [24] are applied to prevent the occurrence of tensile residual stresses. The description of interdependencies of induced residual stresses, due to welding and subsequent machining, is limited in the available literature.

Dattoma [19] numerically investigates the modification and evolution induced in a residual stress field, existing in a welded plate, by milling and cutting processes of Fe 430. As a first step, he neglects the induction of residual stresses due to machining and considers the removed material as a simple stress relief process. However, just by stress relief, the localization of maximum tensile stresses changes significantly in longitudinal direction due to the cutting process. Furthermore, the distribution in material thickness reveals a transition from compressive to tensile stresses and vice versa.
The conclusion for technological machining issues is that the surface quality after recontouring is highly affected by path planning, clamping, and cutting strategy. It therefore has to be defined for the specific repair situation. This means that the choice of the process and the process strategy for recontouring is an individual matter [54]. In terms of residual stresses, a defined, homogenous residual stress field can only be achieved by post-processes such as shot-peening, but not predefined by the recontouring process with a simulation.

4 Conclusion

Regarding an increase of product quality and a reduction of cycle times in regeneration, further progression should lead to an integrated planning of the single processes, e.g., material deposit and recontouring. Many studies aim at a near-net shape application of the filler metal in welding processes. Therefore, an accurate CAD model of the repaired engine blade is necessary for the deposit planning as it differs from the original CAD model.

The recontouring process is often performed on thin-walled parts like compressor blades. As workpiece of a consistent process planning, one central issue is the development of an efficient and reliable clamping, as well as the consideration of possible loss of accuracy in re-clamping. The recontouring itself can be carried out on current machine tools assuming an appropriate process design is given. Anyway, machining-induced residual stresses which are of particular interest are depending on a significant degree on the behavior of the machine tool in process. Vibration of the thin-walled blade structure leads to continuously changing tool engagement conditions. Hence, the machining-induced surface and subsurface properties change. Estimated surface properties as well as surface roughness will not match anymore. As a consequence, the behavior of the machine should be known exactly when dealing with these processes. A pool of deeper examined reference processes helps to find machine tool-specific process variables.

One next step is the transfer of machining parameters and their influence on material conditions to an adaptive machining model. This would as well include machine tool properties. Basic approaches considering a technological path planning are found in the development of new path planning strategies for the minimization of shape errors. On the long term, a simulation-based method is the most promising approach [17, 18]. Engagement conditions can be calculated for a given process. Therefore, geometrical information about the workpiece is necessary, which derives from the material deposit. Integrated calculation models for process forces and considered surface properties allow a prognosis of machining results for an individual process.

Blanks are increasingly used in aircraft engines. Therefore, repair technologies have to be applied on these components as well. Current researches deal with that issue. The intention of Grylls [28] is to gain an as accurate final shape as possible through advanced deposit welding methods [28]. Nevertheless, he mentions further steps to be considered in blisk repair, which includes the final shape cutting of the material. A complex issue is to combine the aerodynamic and structural requirements to achieve within regeneration with laser and machining parameters. Aschenbruck [2] follows the way of an integrated regeneration process. Besides the matters referring to the repair itself, also the blade individual characteristics have to be considered in the integrated process. This is of particular importance when it comes to blisk regeneration [2].

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References


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