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Towards an autonomous maintenance, repair and overhaul process

Exemplary holistic data management approach for the regeneration of aero-engine blades

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Abstract

The maintenance, repair and overhaul (MRO) processes of aircraft engines are dominated by a high proportion of manual work and subjective condition assessment of used parts. This leads to inefficiency due to additional, partially not required workload and high scrap rates. Further, there is a lack of knowledge about the effects of the respective repair measures on the performance of the parts. So far, there are no autonomous repair solutions that allow an optimal and individually tailored regeneration. In order to realize such a process, it is necessary to bring together the manufacturing, function-simulating and logistics-oriented disciplines in an integrated system. For this, data management along the process chain is an important success factor. In particular, the provision and linking of the data and data formats required for simulation and the production environment is of fundamental importance. This paper presents a data architecture that can serve as a framework for data integration within a representative process chain for regeneration.

Keywords: MRO; High-pressure turbine blade; Virtual workpiece twin

1. Introduction

According to the forecast by Oliver Wyman, the global fleet of aircraft will rise by around 10,000 aircraft to nearly 40,000 aircraft in service until 2029 [COO19]. In addition to sales revenues, an increase in expenditures for MRO activities is foreseeable and expected in the long term. Besides fuel and personnel expenses, maintenance, repair and overhaul (MRO) costs account for around 10% of an aircraft's operating costs. Around 40% of these MRO costs are attributable to engine regeneration [COO18]. High share of costs is mainly related to the costly repair of engine blades, especially high-pressure turbine blades. These are the most heavily loaded components in an aircraft engine [ASC14]. To withstand the high thermal and mechanical loads, they are costly manufactured as technical single crystals. Due to the operational loads, the blades are subject to wear as the service life progresses. In particular, material is removed from the tip of the blade as well as from their leading edge. In conjunction with additional damage, e.g. induced by foreign objects, this reduces the performance and efficiency of the entire engine.

The monocrystalline microstructure of the high-pressure turbine blades poses a major challenge for the repair processes to be used. So far, a patch repair is not possible and deposition welding leads to a polycrystalline material. In addition, the MRO process for the regeneration of high-pressure turbine blades is dominated by manual work [BÖß17]. After an inspection, the damages are polished out using a rotary tool or belt grinder. If the required material thickness or geometric shape is not maintained locally, material is applied by manual

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welding. Therefore, the entire repair process is extremely time- and cost-intensive. The success of the regeneration work depends strongly on the training and experience of the individual employee. To reduce costs and repair lead times and further improve the quality of regeneration results, approaches to automate blade repairs have been researched. However, up to now these have focused exclusively on compressor or turbine blades that do not consist of a technical single crystal [BRE06, ERN18, GAO08, JON12, TAO15, YIL10]. In these different approaches, a new target geometry of the blade is generated by means of different processes. Based on these, individually adapted repair measures are derived. The target geometry does not always correspond to the new part geometry since the blades are partially deformed or bent during operation, so that the new part geometry cannot always be restored economically. Instead, the target geometry is adapted to the real blade geometry. This is done by reverse engineering the real blades geometry. However, only geometric deviations are taken into account in the repair measures. Information about the performance gains, efficiency increases and service life extensions to be achieved by the repair are not taken into account so far [ASC14]. To be able to include these aspects in the design of MRO measures, this information must be available before the start of the repair measures. This is the only way that MRO measures can identify not only safety-relevant damage, but also damage that limits the performance and efficiency of the blade to be repaired. Such an autonomous or even an automated process chain for the condition-based regeneration of high-pressure turbine blade is currently not available.

The design of the planed process chain presented in this paper serves as a proof of concept for such an automated regeneration process. On the one hand, the processes involved in the process chain are examined for their interactions with each other. On the other hand, a condition-based regeneration is being developed. To record the individual condition of the blades, the scanned actual geometry is subjected to aerodynamic and structural simulations to determine the current performance and the expected remaining service life. For the selection of the repair strategy to be applied, the achievable performance and service life increase as well as individual customer requirements are taken into account. Moreover, alternatively applicable repair methods, such as combined brazing and alitising, open up additional repair paths [NIC15,KAI17]. In addition to pursuing logistical cost and performance goals, a large number of additional influencing variables and boundary conditions have to be considered simultaneously when selecting a repair strategy. These include, for example, individual customer requirements, capacity restrictions, legal requirements and general conditions, the individual damage pattern as well as the expected component performance after applying repair measures [KEL16]. The customer requirements include the respective flight profiles and operating points of the engines, the performance increase and service life extension to be achieved as well as the regeneration throughput time.

2. The regeneration process

An essential basis for the development of an autonomous regeneration process is the knowledge of the structure of the regeneration supply chain, which is independent of the capital goods [LUC19]. The manual diagnosis and subsequent implementation of MRO measures described in the introduction are usually preceded by an initial inspection and the disassembly of the complex capital goods. If the findings show that the respective components cannot be repaired, a replacement is procured. Once all components are ready for installation after repair or procurement, the capital goods are reassembled and quality assurance is completed (see **Fehler! Verweisquelle konnte nicht gefunden werden.**) [EIC11, HER13].

In addition to the elementary, sequential process steps, pool stages can be provided along the regeneration supply chain. If it is not possible, for example due to a lack of capacity in the repair processes, to make all the components to be repaired available in time for reassembly, the components required for further reassembly can be made available from the pool warehouses. After their repair, the originally dismantled parts fill the pool warehouse from which the replacement components were removed previously. Pooling warehouses thus enable flexibility and logistical influence on the

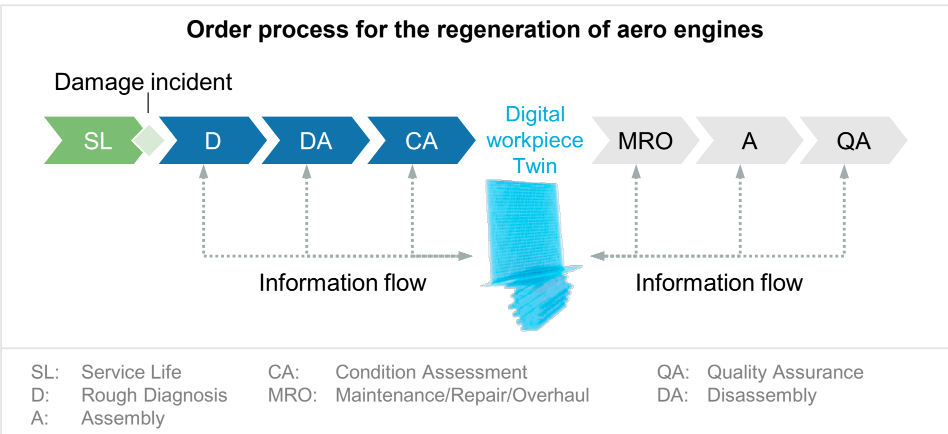

Fig. 1: Exemplary representation of the process chain

Fig. 2: Schematic arrangement of the included process cells within the demonstrator

regeneration process. This results in several possible paths for the provision of components for the reassembly of the capital goods at the production logistics level [HEU19]. To be able to consider influencing factors mentioned above in decision-making within an autonomous regeneration process, comprehensive data management along the process chain is indispensable. The basic conception can be carried out analogously to the systematic approaches to capacity and load planning on the basis of damage libraries [EIC14]. While the investigation of the logistic potentials of pooling measures within the regeneration process is already focused on in other work [HEU19], the work described below focuses on the design of an autonomous MRO process taking into account the interactions of the processes involved.

3. Components of the process chain

The planed process chain consists of individual process cells that are connected via a mobile handling system (MHS). Figure 2 shows an example of the structure of the real regeneration system. The real layer contains all essential repair technologies involved in the MRO measures in an individual cell (e.g. disassembly, diagnosis, laser deposition welding, recontouring). It is controlled from a central control station. The modular design allows easy expandability to integrate newly developed repair technologies in the long term. In addition, several machines of the same type can be provided in the event of bottlenecks due to long processing times.

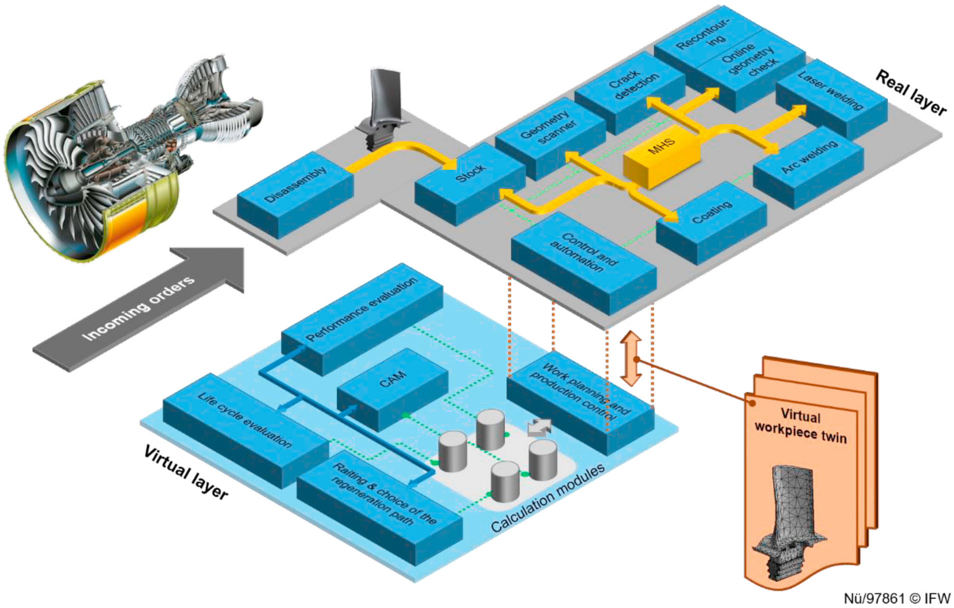

Fig. 3: Schematic representation of the structure and networking in the process chain

To enable automatic communication and control between the various process cells as well as coordination with underlying online simulations, the central control station must communicate with the individual process cells. On the other hand, the models used in the various simulation programs have to be prepared in a way which allows them to be cross-linked automatically. This results in a total set of data sources and sinks that can be assigned to either a real or a virtual layer. In the virtual layer, the structural-dynamic lifetime prediction, the performance assessment as well as the planning and control are implemented. The purpose of the virtual layer is to quantify the functional benefit of the repair measures and results and based on the results to select a customer-specific optimal repair path for each individual component. The entire communication of the virtual and real components of the process chain takes place via the central control station. There, a virtual workpiece twin is compiled out of the individual data sources.

4. The regeneration process

Figure 3 shows the systematic structure of all process cells and calculation modules on the real and virtual layer. The decision on the individual component regeneration is made in a process between the calculation modules of the performance and service life evaluation, the process design and the evaluation and selection of the regeneration path.

The central data management converges on a single server called: “control and automation”. All process cells communicate exclusively via interfaces with this central server. It is also the platform for the entire virtual layer. On the virtual layer, the data is filtered and merged into a virtual workpiece twin of the high-pressure turbine blade to be repaired, as shown above. It thus contains all information that is generated before and during the repair. This includes master data such as customer data or the repair history of the work piece as well as transaction data such as feedback parameters from the sub-processes that have already passed through. The central component of the virtual workpiece twin is geometric data, which is recorded in the real layer as a point cloud by different optical measurement systems. These are mounted on an industrial robot and the data is merged together into one model. In connection with an inductive crack test, a comparison with legal requirements as well as manufacturer specifications from the engine manual can be accomplished. Geometric deviations, e.g. in the form of depth measurements of dents as well as the position of existing cracks on the component, are compared with legal and manufacturer's specified parameter ranges. The comparison enables a classification of the identified defects. Defects which cannot be repaired lead to scrapping of the blade. Permissible repairs are also checked for cost-effectiveness and compared with customer preferences stored in the virtual workpiece twin. In this way, individual customer preferences between remaining service life, performance and regeneration costs can be met. The performance and service life data generated from the simulations are used to choose the regeneration path to be individually selected in addition to customer requirements and information on machine availability. Due to the long processing time, these simulations are done in advance. If the measured parameters are outside the previously simulated parameter space, a new simulation is triggered. The tool paths to be traversed are then derived for the machine tools used for the repair measures. They are stored in the virtual workpiece twin and made available to the machine tools. Conversely, the process data generated during machining is fed in from the machine tools. In addition to monitoring process compliance and process progress, they are used for process chain control.

The virtual workpiece twin is based on an adapted version of the "IFW CutS" simulation software for machining manufacturing processes developed by the Institute of Production Engineering and Machine Tools (IFW) [DEN09]. This software has a modular structure and can be used with

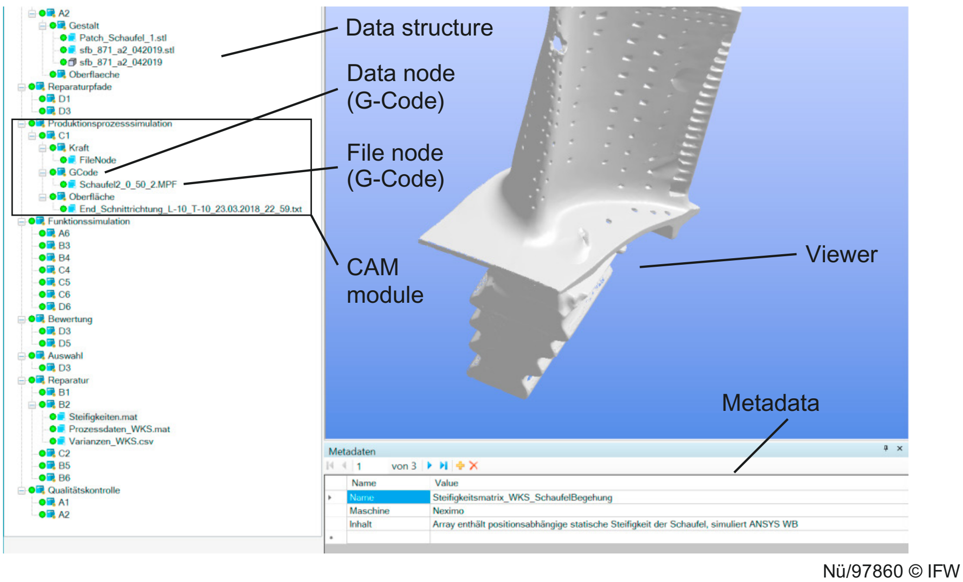

Fig. 4: Basic structure of the virtual workpiece twin in "IFW CutS”

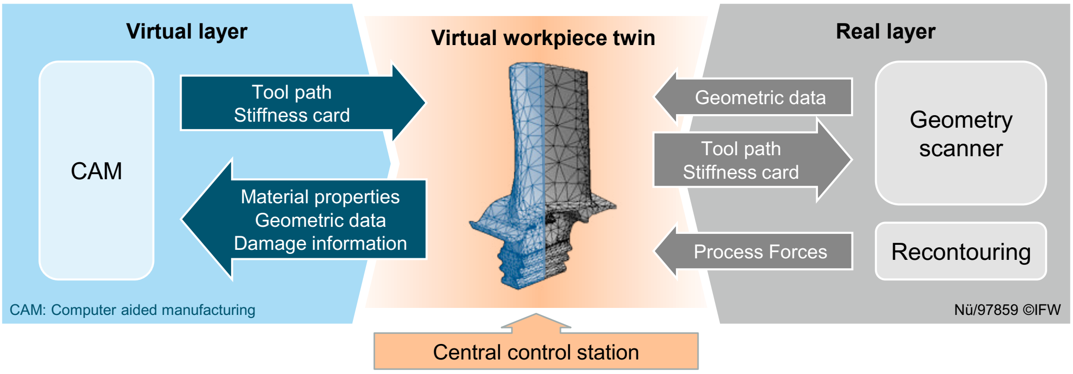

Fig. 5: Exemplary schematic data flow of the recontouring process

plug-ins for different manufacturing processes such as milling, turning and grinding. This software was selected because of its simple extensibility. Due to the high amount of process cells in the real layer and calculation modules in the virtual layer, direct communication would have led to many different interfaces. With the virtual workpiece twin, all process cells and calculation modules only need to have one interface. In the adapted version, “IFW CutS” offers the possibility to save data and files automatically and in a structured way. Data and file nodes are implemented for storing data. Master and transaction data can be stored line by line in data nodes. These are e.g. the blade number or other manufacturer information. The file nodes allow the storage of various files and the linking of data with them. Furthermore, structures can be created with the data nodes by creating further levels with data and file nodes under a data node. This makes it possible to systematically create a structure of all process cells and calculation modules. In addition, the viewer implemented in "IFW CutS" allows the visual representation of the contents of different file types as 3D or 2D objects. This is required for the commissioning of the automation and for fast control in the event of malfunctions in automated operation. In addition to manual use, automated storage of data and files is also possible. The creation of a virtual workpiece twin for each blade enables the data to be archived not only during repair, but also after repair, e.g. during subsequent regeneration as master data. An example of a virtual workpiece twin in "IFW CutS" is shown in Figure 4. The geometry data recorded in the real layer by measuring the blade is stored in the structure of the virtual workpiece twin. It is visualized directly so that a consistency check of the measurement and a macroscopic assessment of the measurement can be carried out if required. The black rectangle shows the structure of the CAM module. The data nodes are used in this module to form a structure. Hierarchically below the data nodes are the file nodes in which, for example, the G-code is stored. The level of detail of the data required and which information is decisive for the success of the regeneration is one of the research questions. The challenge of data management is explained below using an example, which can be seen in Figure 5. In the real layer, the actual geometry of the blade is measured and stored as a point cloud in a file node in the twin. In previous process cells, the material properties were already stored in a data node and the damage information in a file node. The CAM module receives this data from the virtual workpiece twin and automatically generates a tool path for the recontouring and a stiffness map of the blade. Both are stored in file nodes. Thus, data storage, processing and transfer are integrated within a single structure. The transfer of the measurement and calculation results into the real layer takes place automatically via the interfaces of the virtual workpiece twin. The machine tools can access this data and use it to physically recontour the blade.

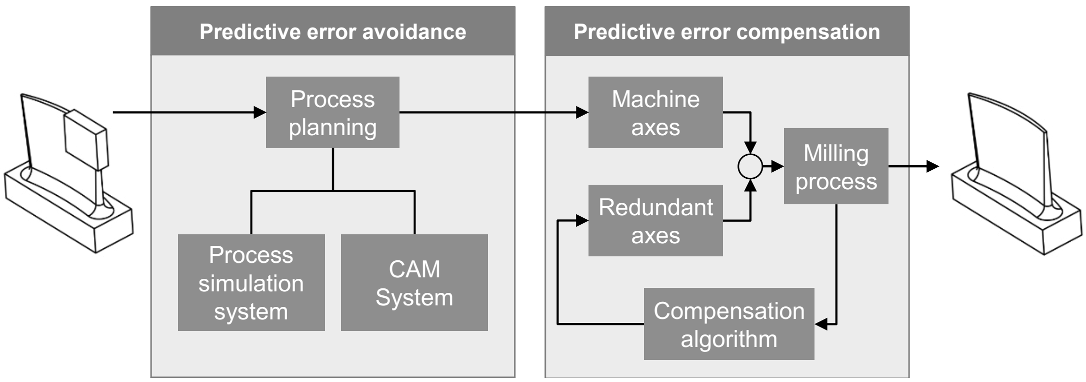

Fig. 6: Error compensation for the recontouring process [7]

For a minimal form deviation, the recontouring process consist out of two stages, as it can be seen in Figure 6. The first stage is executed in the CAM module. An optimal tool path with minimal process forces is generated through knowledge of the machine and previous processes. Therefore, the form deviation is reduced. Due to the remaining process forces, an additional stage is necessary. This second stage uses force measurements, stiffness cards and redundant axes in the machine tool to compensate the form deviation. The process forces are also recorded and stored in the virtual workpiece twin. They can then be used for an optimization of the welding and milling process [DEN19]. This optimization is besides other a research topic when the process chain is running.

5. Conclusion

The presented approach shows the basic concept for a process chain for the regeneration of complex capital goods in the application case of high-pressure turbine blades. The approach serves as a basis for a condition-based regeneration of the blades. For this purpose, the geometry is recorded before the start of the repair measures.

From this, the individual condition of the components to be repaired is recorded and evaluated by means of aerodynamic performance and structural simulations. An individual regeneration is carried out for each turbine blade in accordance with individual customer requirements, technical restrictions and legal requirements. In contrast to the methods used today, the achievable performance and service life before and after successful regeneration can be estimated. The central hub for storing, processing and providing the relevant data for all process elements of a blade is a virtual workpiece twin. This is achieved by the software "IFW CutS". By bundling the data in a central virtual workpiece twin, all data of the process chain is combined and processed. The decisions on the regeneration path to be chosen can be evaluated by the quality assurance carried out after the repair and the automated simulations. Thus, the boundary conditions and prerequisites are created to operate the described process chain autonomously in the future and to establish it as a "proof of concept" for the autonomization of regeneration. The whole process chain is currently under construction. At first, the focus is on the automated tip repair, but it is planned to extend the possible repairs.

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