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Technological and Economical Assessment of Alternative Process Chains for Blisk Manufacture

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Abstract

Due to the increase of blisk (blade integrated disk) demands instead of the conventional fir-tree design in current aero-engine concepts there is a high resource-driven need for a comprehensive evaluation of different process chain alternatives for blisk manufacture. Therefore, in this paper different manufacturing chains consisting of roughing, pre-finishing and finishing/polishing are compared to each other by the example of a HPC-blisk out of Inconel 718. Beside conventional milling and electrochemical machining also alternative manufacturing technologies like wire-based laser cladding, water jet cutting and automated polishing are taken into account. Based on a technological analysis an adaptable methodology is introduced, which allows an independent economical assessment of different process chains regarding e.g. company-specific boundary conditions or different production quantities.

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Keywords: Blisk; Assessment; Process Chain

1. Introduction

In recent years the blisk (blade integrated disk) design has been established as an option in civil aero engine concepts replacing the conventional fir-tree design. The integrated design allows improved aerodynamics leading to higher efficiency and thus less fuel consumption. However, in production the blisk design results in evidently higher amounts of material to be removed. Taking into account the common use of hard to machine alloys such as Ti-6Al-4V and Inconel 718 the conventional milling process can reach its economic and technological limit. The main drawbacks of this technology are high tool wear for roughing and long machining times for finishing processes. From a technological point of view it has been demonstrated that electrochemical machining (ECM) [1, 2] as well as wire-based laser cladding and water jet cutting are promising alternatives to manufacture blisks.

However, most manufacturers of turbine engine components lack knowledge and experience with these alternative technologies making it difficult to decide on a technology to establish for the production of blisks. Especially the economic assessment is crucial for a profound decision.

When evaluating alternative technologies from an economic point of view the whole manufacturing chain consisting of roughing, pre-finishing and finishing/polishing has to be considered. Therefore, each technology must not be assessed separately. Instead a combination of different technologies has to be found that utilizes the advantages and compensates the drawbacks of each technology applied. Furthermore, company-specific boundary conditions as well as different production quantities distinctly influence economic assessment.

This paper suggests seven different process chains applying a combination of milling, ECM, laser cladding, water jet machining and automated polishing. Based on a technological analysis an adaptable methodology is introduced, which

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allows the selection of the most suitable process chain as a function of the present boundary conditions.

2. Technological analysis

For the assessed technologies reachable material removal rates and cutting rates are presented in this section. The data are either based on literature reviews or results of own machining experiments. Subsequently, seven promising process chains are derived.

2.1. Blisk for the case study

The generic nickel-based high pressure compressor (HPC) blisk geometry regarded in the case study was provided by EMAG ECM GmbH. The 72 blade blisk is manufactured from Inconel 718. As shown in Figure 1 the cross section is tolerated with 50 µm and the required surface roughness is Ra 0.4 µm.

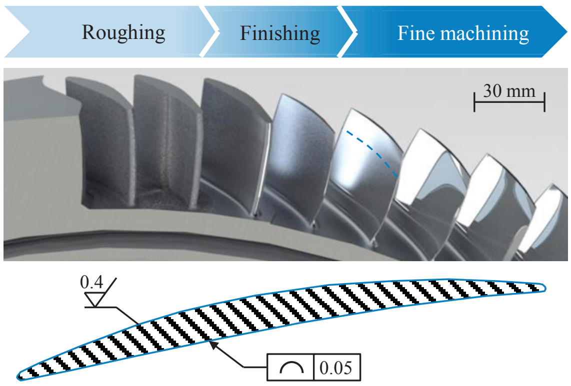

Fig. 1. Generic HPC Blisk for the case study [EMAG]

2.2. Milling from solid

Today, milling from solid of forged discs is the most common technology for the manufacture of blisks. The main reasons are a high flexibility, the availability of many affordable standard tools and the existence of a great knowledge base with most manufactures. Drawbacks of the technology lie in a high tool wear during roughing, long machining times during finishing and the dynamic excitation of the workpiece. The selection of a suitable milling strategy is essential for the economy of the process step. In the present case study peripheral milling was chosen for roughing and ball end milling for finishing steps.

2.3. Electrochemical machining (ECM)

The major advantages of Electrochemical Machining are its process specific characteristics of high material removal rate in combination with almost no tool wear and no thermally or mechanically damaged workpiece rim zones. Because of a cost intensive tool pre-developing processes and rather high investment costs for the machine tools, however, ECM is specifically used in large batch size production [3].

For the machining of turbine components by ECM two different process modes have to be distinguished. The classical DC-ECM applies a DC-Voltage of 5 V to 40 V and reaches feed rates up to 10 mm/min. Precise Electro Chemical Machining (PECM) combines a pulsed voltage with an oscillating cathode to allow significantly smaller working gaps and, thus, resulting in a higher contour accuracy. Drawbacks of PECM are the higher investment cost for more complex generator technology and machining axis as well as feed rates below 0.5 mm/min [4]. Consequently DC-ECM is commonly used for roughing (Ra 0.8 µm) and PECM for finishing operations (Ra 0.3 µm).

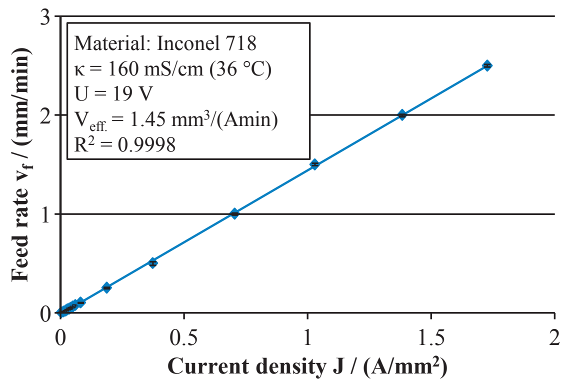

Fig. 2. Feed rates as a function of current density for ECM

In order to derive the process time for ECM and PECM the v_f - J interrelationship for Inconel 718 was determined. Under certain limitation and provided that direct current generator can supply enough power to realize the required current density, Figure 2 allows to calculate material removal rates for any specific surface cross-section.

2.4. Laser cladding

In contrast to the conventional abrasive technologies presented before, the wire-based laser cladding is an additive technology. It can not only be used for manufacturing of new parts but also for repair and geometrical modification of existing parts.

An integrated CAx-based process planning for automated laser cladding on 5-axis machining systems in industrial applications was developed. By building the parts layer-by-layer, the integration of functions can be considered, e.g. close contoured cooling channels [5]. The localized deposition of material allows modifications of the workpiece´s geometry which leads to a reduced effort in changes.

Within the manufacturing of blisks laser cladding can replace the conventional roughing steps. Thereby the amount of material needed as well as the effort for subsequent process steps is reduced to a minimum. Two different strategies are possible, either the whole blisk is build up by laser deposition or only the functional surfaces and blades are deposited on a cost-effective base material [6].

The wire material (Inconel 718) is available in two different forms and qualities (cored-wire or solid-wire). In case the process properties are adapted accordingly both yield the same results. For the case study, a cored wire was used due to its higher cost efficiency.

2.5. Water jet machining

Water jet cutting offers another technology to substitute the rough milling process in blisk manufacturing. It allows saving costs and resources while reducing chip removal volume and the amount of cooling liquid employed [7]. The development of five axis kinematics extends the area of operation to 3D-geometries near to a net shape surfaces for finishing processes. Using a system pressure up to 600 MPa makes it possible, to increase cutting feed rate by up to 40 % compared to conventional cutting with 400 MPa, with a surface quality in a range of 10 – 50 µm Ra. Innovative CAx-modules and strategies for tool path planning of the water jet cutting process are developed while taking the specific technological conditions into account.

2.6. Fine machining

Conventional processes for the fine machining step are slide grinding and manual polishing. In the case study, however, a machine integrated process was chosen. In contrast to conventional processes the integrated approach is realized on standard milling machines, thus, allowing the whole process chain to be realized with the same clamping device, machine tool and CAM software.

The machine integrated process utilizes elastically bonded grinding tools which consist of abrasives like silicon carbide or corundum and rubber or polyurethane bonding. The elastic bonding provides remarkably different properties compared to solid bounded grinding tools. For instance surface roughness values of below 0.2 µm Ra can be achieved on steel surfaces [8, 9]. In contrast to grinding tools with resin, vitrified or metallic bonding, elastic bonded tools adapt to the workpiece macro geometry to some extend [10]. Hence, the grinded free form surface is not significantly effected by the interpenetration of the tool geometry (e.g. ball end or toric) and the workpiece material. Therefore, elastic bonded tools can be operated with larger cutting width.

Further improvement can be achieved by compliant tool holders which use a sensitive suspension to produce a constant, adjustable tool contact force. Thereby referencing errors are compensated and air cuts or excessive material removal are avoided. The design of the compliant tool holders used in the presented study was based on the experience gathered in research projects in the field of robot based polishing [11]. The contact force can be adjusted either via air pressure or using selected pressure spring systems.

2.7. Process chains

Figure 3 shows the seven different process chains assessed in this paper. The conventional combination of milling and fine machining was chosen as reference. Process chains 2, 4, 5 and 7 allow the comparison of four different roughing technologies all combined with PECM for finishing/polishing. Process chains 3 and 6 apply milling and fine machining instead of PECM and therefore provide an evaluation of the finishing/polishing steps.

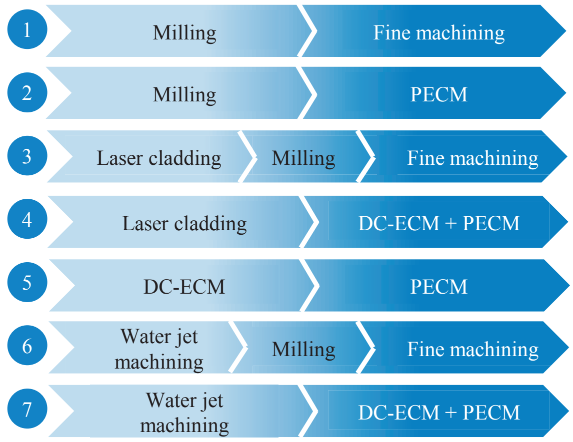

Fig. 3. Assessed process chains

3. Economic Assessment

Transparency of the feasible way to manufacture parts is crucial to companies for their investment in new machines as well as for “make or buy” decisions. To ensure a well-founded basis for decision-making, assessment of alternative process chains must always be adapted to the analyzed part and its geometry. Moreover, company specific boundary conditions have to be taken into account.

For that purpose, a flexible, software-based methodology was developed that contains a two level approach based on the life cycle assessment according to ISO 14040. In the end of this process chain analysis companies have a holistic overview in form of e.g. estimated values of their production costs and processing times depending on the production volume for each process chain. Additionally, the possibility of more detailed, for example resource-based results exists.

As mentioned, the goal of the case study is defined by revealing the most efficient process chain for manufacturing the given blisk. Setting the framework of the assessment, it is defined that the output of all the seven analyzed process chains is a functional equivalent. This means that the manufactured blisk properties are identical and all calculations are made for this reference value. Therefore, the use- and end-of-life phase can be neglected and the case study concentrates on the production phase.

The applied parameters and assumptions used in the case study are listed below:

- Comparable maturity level of each production technology
- Three shift production with a capacity of 4800 h/a
- Green field approach: multi-machine operation without personnel takeover, machine utilization without alternative manufacturing orders
- No consideration of overhead costs
- Wage costs: 50 €/h skilled worker; 80 €/h engineer
- Inclusion of setting-up and production planning times
- Tool costs not comprised in machine hour rate

Process analysis, life cycle-inventory and impact assessment are the core elements of the suggested concept. Consequently these are extended in a standardized, software based five-step-approach visualized in Figure 4. In the first three steps the process chains are analyzed independently to reduce the complexity. Firstly, all process information e.g. regarding resources, times, prices and process parameters are collected in a process entry sheet for each process step, which is filled out by process experts. Secondly, the information is aggregated to costs and output emissions. These output emissions are the basis for further modelling in the life cycle assessment software GABI that converts the emissions to CO_2 equivalent respectively primary energy demand. In this way the ecological aspect of the holistic assessment is covered.

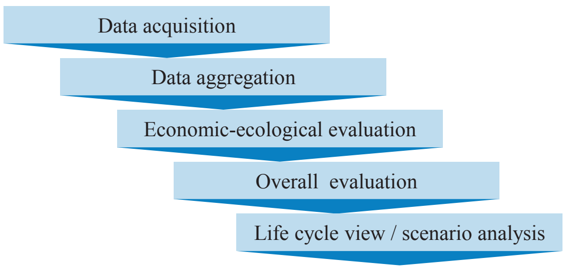

Fig. 4. Assessment methodology

Economically the process step specific calculation ensures a high level of detail. As shown in Figure 5, the overall production costs for one blisk can be separated into the specific process steps and from this to several resource dimensions, which again can be aggregated to the overall resource based view for the process chain. This allows a well-grounded perspective of the assets and drawbacks of competing process chains, especially because technology-specific ramifications of different part-characteristics (allowance, roughness etc.) only occur in downstream process steps.

Apart from costs, processing times can be calculated. Consequently the methodology provides the following assessment dimensions:

- PED (primary energy demand)
- GWP (global warming potential)
- Production costs:
    - Machine costs
    - Tool costs
    - Energy costs
    - Operating material costs
    - Personnel costs
    - Material costs
- Processing times

The calculated results of each process chain are compressed in an "*overall evaluation*". In this key performance indicator cockpit certain boundary conditions which apply for the assessment of all process chains like production quantities, working time model or fundamental prices are fixed in form of master cells. This allows a wide range of easily conducted scenario analysis with respect to sensitivity. Especially for investment decisions, differences between expected and realized production quantities have a great impact on the actual commercial viability. Characteristic for this are curves with saw tooth tread design, which are part of the overall assessment.

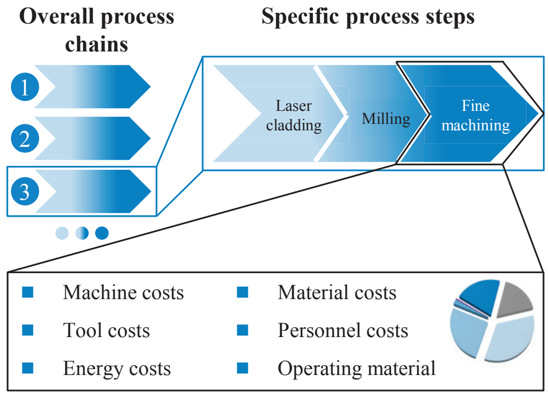

Fig. 5. Possible detail level

4. Results and Conclusions

The main assessment results of the case study are presented in Figure 6. It shows the production costs ration of each process chain evaluated for two different scenarios. Scenario 1 represents the production of 70 blisks per year and scenario 2 of 800 blisks respectively. The costs for scenario 1 and the conventional process chain consisting of milling and fine machining were set to 100 %. Generally, the costs range from 83 % to 123 % in scenario 1 and respectively 34 % up to 104 % in scenario 2. Process chains 1 and 6 have a lower sensitivity to batch size than for example the ECM process in process chain 5. This means that companies on the one hand have to anticipate their market share properly and on the other hand can drive themselves out of the market in case of misleading technology selection. High decrease of production costs of ECM related process steps with increasing batch size is mainly founded in a better machine utilization. Just like PECM at higher production quantities in comparison to fine machining, in this case water jet machining is a possible substitute to conventional roughing with the advantage of much lower tool costs and economic working conditions independently of batch sizes.

Although manufacturing blisks by laser cladding is not as feasible as other process chains, the technology is interesting due to its significant savings in raw material and its possible application as a repair strategy. Moreover, the actual maturity level of these process chains is expected to improve regarding processing times and resource consumption in the future and, thus, decreasing production costs.

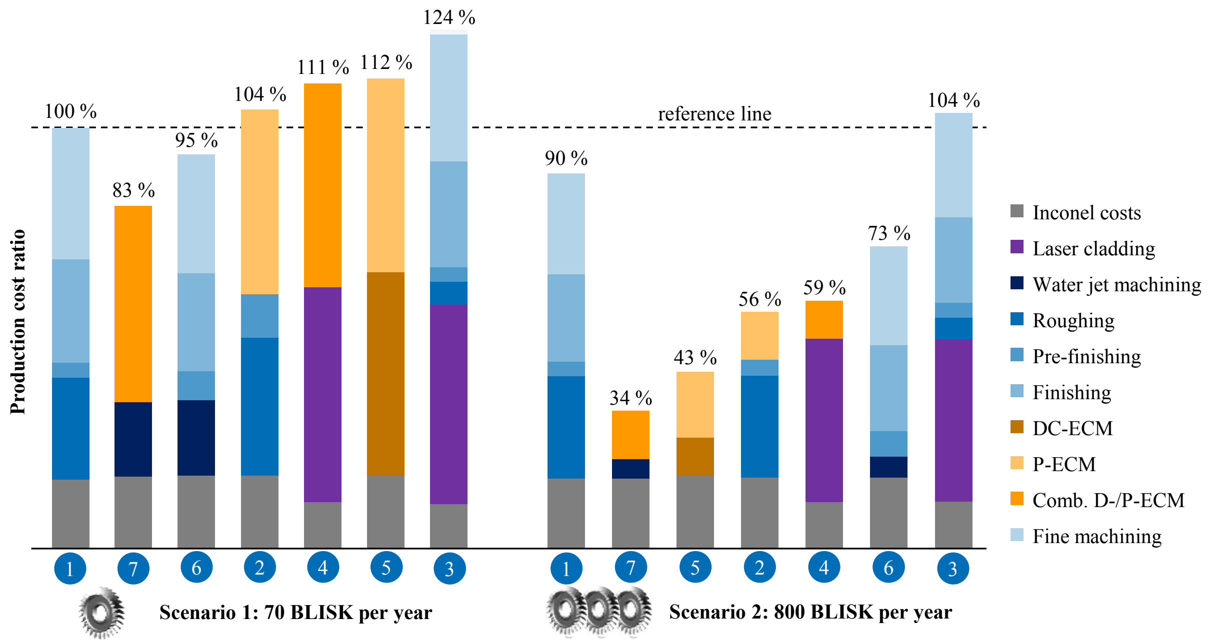

Fig. 6. Overall assessment results

Due to high machining and personnel costs production costs strongly depend on processing times that are presented in Figure 7. Separating the effects of varying machine utilization from this hypothesis consequently cost intensive process chains tend to have longer throughput times as well. With a throughput time of 23 hours process chain 7 has the shortest production time in contrast to process chain 3 with 390 hours. Again the indication that short processes are less flexible for different products manufacturing because of their higher specialization can be noted.

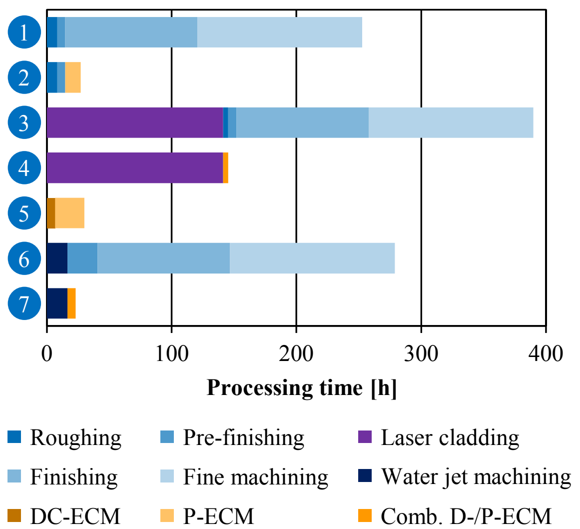

Fig. 7. Overall assessment results

Coming to the resource based analysis results Figure 8 gives a comprehensive overview of the resource based cost share of three process chains based on a yearly production size scenario of 70 blisks. While on the one hand the share of personnel (18-25 %) and material costs (16-21 %) are both significant but similar in each process chain, on the other hand there are distinct differences in machine and tool costs. Tool costs vary from one quarter to just 3 percent of the overall production costs.

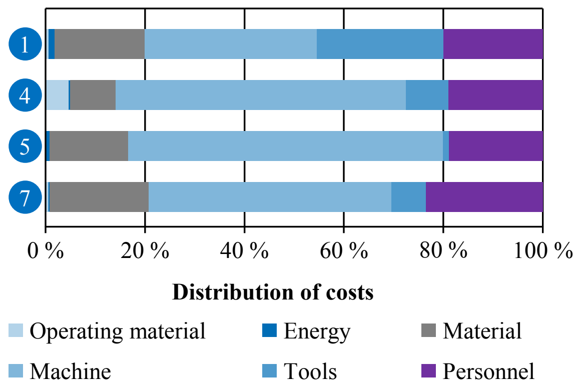

Fig. 8. Resource based assessment

Despite the fact that in case of the ECM manufacturing route higher machine costs compensate low tool costs respectively are at least partially integrated in them. Lower tooling costs of process chain seven dedicate water jet machining as a profound alternative to conventional roughing, although the current calculated tool life of one piece per blade leads to expect further improvement. Regarding the present blisk design, machining costs are the most influential resource within the manufacturing process and, thus, the starting point for further analysis of improvement potentials. Up to 63 % of the overall production costs (ECM) for a blisk are related to machining and therefore fixed cost elements. Apart from high initial investment costs, companies have to deal with extensively, enduring financing costs. Taking into account that especially ECM technology cannot be adapted easily to new products or geometries because of their complex cathodes and processing strategy that is usually integrated within the purchasing process, companies have to be aware of the risk of possible drops in demand.

Surprisingly, energy costs are, even in energy intensive technologies less than expected and can be neglected widely. The same applies to operating material costs like cooling liquid for milling.

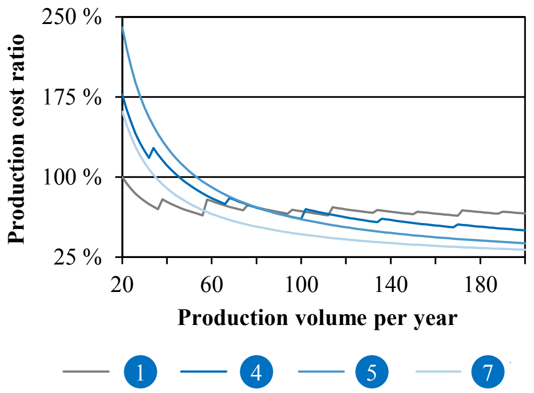

Fig. 9. Overall assessment results

Coming to a central point, production costs per blisk are highly sensitive to the production quantity. Specifying the quantity limits and increment of the analysis, values visualized in Figure 9 are calculated by the tool internally. Process chains 5 and 7 show a hyperbolic decrease whereas milling operations integrated process chains feature the characteristic saw tooth tread design, which occurs if machine utilization reaches its limit and companies have to invest in additional machines. For water jet machining and ECM the limit is reached for much higher production volumes. In these points, production costs reach a local minimum for the specific process chain respectively the production technology and thus should be set as target values of production quantities. With the so evaluated break even points companies can identify their best suitable technology for blisk manufacturing.

5. Summary

For the production of nickel-based blisks seven different process chains were suggested followed by a comprehensive overview of the applied technologies. Subsequently an assessment tool was introduced allowing the selection of the most suitable process chain depending on a company's boundary conditions.

Results show that a precise estimation of the manufactured batch size is crucial for selecting a process chain. Exemplary two different scenarios have been analyzed. In the large batch size scenario all but one process chains exceled the conventional process chain mostly due to the scale effect of ECM. However, in the small batch size scenario only the two process chains applying water jet machining showed lower production costs than the conventional process chain. Consequently, a combination of water jet machining and PECM resulted in the lowest production costs for both evaluated batch sizes.

The resource based analysis demonstrated that the relative costs of personal and material do not differ strongly between different process chains. Machining costs were identified as the most influencing resource within the manufacturing process, therefore, offering the highest potential for improvement.

Overall the assessment results of the specific blisk geometry illustrated that companies searching for their best manufacturing technology are moving in an area of conflict. The great market advantage of low production costs offered by alternative process chains is accompanied by an increasing financial burden and narrowing flexibility with respect to the company's realized production quantity.

Acknowledgements

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