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ECM roughing of profiled grooves in nickel-based alloys for turbomachinery applications

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Abstract

The connection of turbine blades and discs in turbomachinery is realized via profiled grooves. To manufacture these slots in turbine discs, made of hard to machine nickel-based alloys, broaching with high speed steel is state of the art. With improving materials, this process becomes less productive. Alternative manufacturing processes like electrochemical machining (ECM) have to be investigated with regard to their technical capability to fulfil the high requirements by the aerospace industry. Hence, in this paper the principle of ECM machining of profiled grooves in a nickel-based alloy with frontal gap flushing is outlined. A machining setup for a first experimental approach is designed, built and profiled grooves are machined. The grooves are measured with regard to the geometrical accuracy. The completion of the investigations is a comparison with other manufacturing processes in order to define an appropriate finishing process.

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Keywords: Type your keywords here, separated by semicolons ;

1. Introduction

Nowadays mobility is one of the major requests of society. This leads to an annual passenger growth rate in aviation of 4-5% [1]. In addition, airlines must meet the increasing demands for environmental protection and resource efficiency [2]. Because of this, manufacturing companies of aircraft engines have to improve the efficiency of their engines. This leads to an increase of the burning temperature and requires a continuous development of the used materials [3, 4]. To sustain increased thermal stresses, high temperature resistant nickel-based super alloys are used [5, 6]. For the manufacturing of profiled grooves in turbine disks, which are used to establish the disk-blade connection, broaching with high speed steel is still the state of the art [7–9]. Within the last decade, different approaches like milling with profiled tools and broaching with cemented carbide tools were pursued to expand the cutting technologies [10, 11]. Though, with an increasing hardness and strength of the used workpiece materials, the tool wear increases in applied cutting processes and the manufacturing process becomes more expensive. Recent investigations have also shown that non-traditional machining processes like wire electro discharge machining (WEDM) or wire electrochemical machining (WECM) are capable to machine profiled grooves in nickel-based alloys [12–15]. ECM is already state of the art for several other turbomachinery components [16]. According to literature, traditional ECM has not yet been investigated to machine profiled grooves in nickel-based alloys or there are no reliable results published. Hence, in this work the capability of ECM is investigated to machine profiled grooves in a nickel-based alloy. Due to its physical working principle, ECM can be a promising alternative. Past investigations have already shown

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that ECM can be used to machine modern alloys for aero engine components [17, 18]. Due to the fact that ECM machining virtually has no tool wear it is very attractive for manufacturing companies. Nevertheless, the process and tool development are very lengthy and hence expensive. In addition, it is difficult to meet tight geometrical tolerances. The following paper will investigate the technical capability of ECM to rough machine a recently relevant profile groove geometry. The results will be analyzed with regard to the geometrical tolerances and the suitability of the machined geometry for the ongoing finishing process.

2. Process design and material characterization

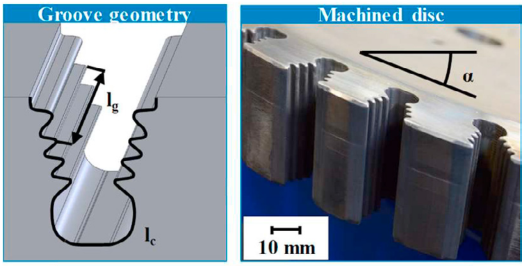
Usually machining of workpieces is divided into roughing and finishing steps. Especially when it comes to machining of parts for aircraft engines a high surface integrity is of urgent importance to guarantee safe air traffic. Although, when designing the roughing process, the focus lies on a high economy under given geometric boundary conditions. In the following investigations, a reference profile groove is machined via ECM. The investigations are divided in fundamental investigations for the design of the tool cathode and the main investigation to machine the profiled groove with use of the cathode. Within the fundamental investigations, lateral gap widths are measured to calculate the tool cathode offset under given feed rates and the frontal gap width and the feed rate as a function of the current density is analyzed.

2.1. Workpiece material

As explained above nickel-based superalloys are used in turbine parts of aircraft-engines. They are characterized by a high temperature strength, toughness and resistance to degradation in corrosive or oxidizing environment [19]. For the following investigations, a powder-based nickel super alloy was used, whose description is subject to secrecy. The chemical composition is comparable to those of other established alloys like Udimet 720LI and Inconel 718 (In 718). Since the electrochemical dissolution is dependent on grain sizes and crystallographic orientation of the grains [20], powder based materials are very beneficial for electrochemical machining because the dissolution is more homogenous and higher specific removal rates can be achieved compared to cast alloys [17]. Because of the comparable alloying components of In 718, parts of the fundamental investigations are carried out with In 718.

2.2. Workpiece Geometry

Profiled grooves in turbine disks are used to connect blades with the main disk. Hence, the resulting radial forces have to be precisely divided to the load-bearing flanks of the profiled groove. This means that they have to be tolerated very tightly. Figure 1 shows the investigated groove geometry as well as the positioning in the workpiece.



Contour length l_c:	70 mm
Contour surface area a:	252.17 mm²
Inclination angle α:	12 °
Length of groove l_g:	40.89 mm

Figure 1: Investigated groove geometry

The geometry of the profiled groove differs in dependence of the turbine and blade size. In addition, every OEM has different approaches when it comes to the design of the groove. For the following investigation, a generic profile groove is being investigated. Nevertheless, the crucial geometrical components of the groove like radii and number of flanks are based on real geometries. The present workpiece has the following dimensions: diameter d = 330 mm and thickness of t = 40 mm.

2.3. Preliminary investigations and tool design

For the initial design of the tool cathode, fundamental investigations were conducted to characterize the workpiece material with regard to the frontal and lateral gap evolution, as well as the effective removal rate. Figure 2 shows the machine setup for the fundamental material characterizations.

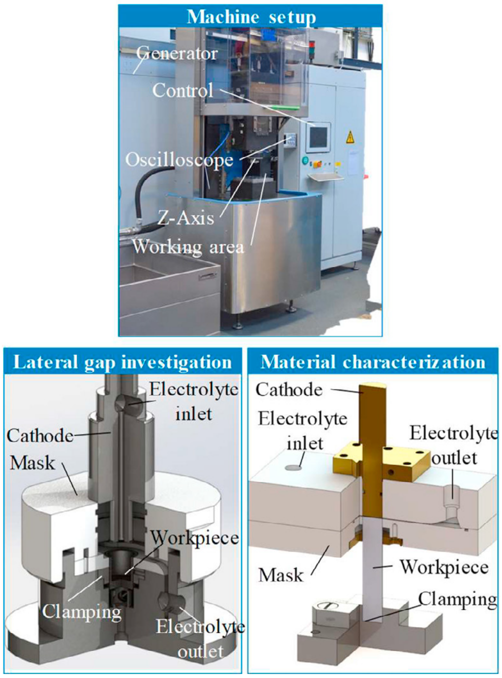
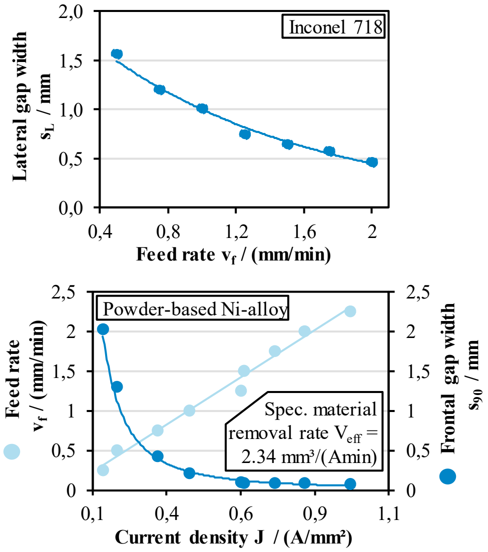


Figure 2: Machine tool and setups for lateral gap investigations and material characterization

The following tests were carried out on an EMAG PTS 1500 machine tool. The fundamental tests with regard to the lateral gap widths were carried out with the chemically comparable nickel based alloy Inconel 718. The resulting tool offset is equal to the identified lateral gap width plus the remaining offset for finish machining. As it can be seen in the diagram, the lateral gap width and respectively the calculated offset to the final contour changes with varying feed rate. Figure 3 shows the lateral gap width as a function of the feed rate and machining characteristics feed rate and frontal gap width as a function of current density.

From the fundamental investigations, the cathode contour offset could be defined according to the calculated feed rate. In addition to the s90-J and vf-J-diagram, the flushing conditions in the working gap were analyzed. Therefore, a simulation of the electrolyte flow in the working gap was conducted using a multiphysics simulation approach. Figure 4 shows the simulated pressure field and the electrolyte velocity in the frontal working gap.



Machine tool:	EMAG PTS 1500	Material:	Varies
Electrolyte:	Aqueous $NaNO_3$	Tool dia. d:	15 mm
El. Cond. κ:	160 mS/cm	Voltage U:	20 V
Feed rate v_f:	Varies	Temperature T:	36 °C

Figure 3: Lateral gap width as a function of on the feed rate and feed rate, frontal gap width as a function of the current density

The turbulent flow behavior was modeled by a k-ε turbulence model while the mesh consisted of 201 000 elements. Analogous to the experimental investigation the pressure at the electrolyte inlet was set to 10 bar. In the process, the main pressure drop takes place in the frontal working gap. This is favorable as no flow energy is lost during the supply of the electrolyte to the working gap. The velocity field in the frontal working gap shows a very inhomogeneous behavior, which is produced by the separate flushing holes that lead to individual jet streams. Due to this behavior, three areas with significantly low electrolyte velocities emerge. It can be expected, that any potential short circuits during the experimental investigations will occur in these areas. In future cathode iterations the electrolyte flow could be improved by rearrangements of the flushing holes, which leads to a more homogenous flow field.

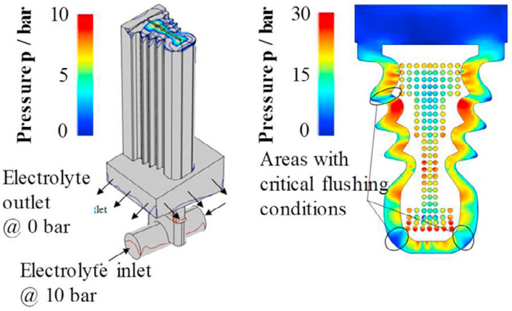


Figure 4: Velocity and pressure simulation of the flushing channel

2.4. Testing setup

As introduced earlier, the profile grooves were machined in a disk workpiece. To realize the inclination angle of 12° on the test machine tool, a dedicated fixture has been designed and built. Figure 5 shows the machining setup for profile grooves and the used tool cathode. As it can be seen in the image, the workpiece is mounted onto the fixture under an inclination angle (12°). Below and above the workpiece two sheet metals, the sacrificial anodes, ensure sharp edges of the profiled groove at the leading and the trailing edge. The flushing chamber is connected to the fixture.

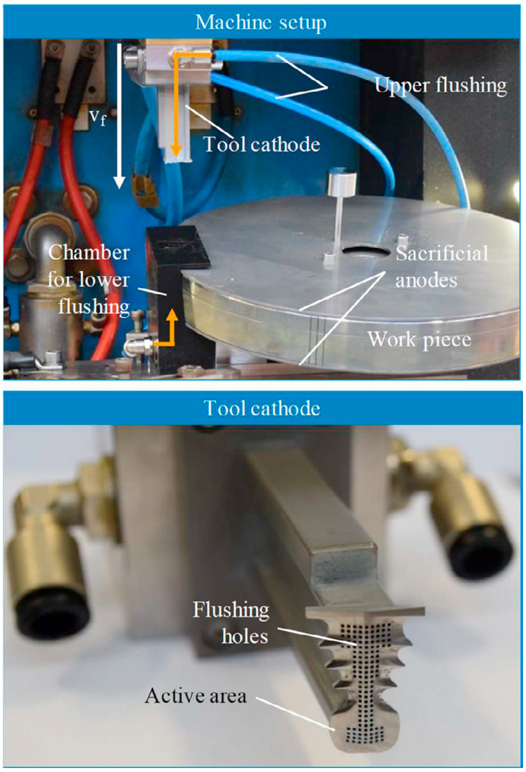


Figure 5: Machining setup for profile grooves in disks and tool cathode

On the one hand it clamps the workpiece and the sacrificial anodes and on the other hand guides the electrolyte flow into and along the machined groove. From the right image, it can be drawn that the flushing of the frontal working gap is realized through the inside of the tool cathode. The principle active area is on the front plate of the cathode around the flushing holes. The lateral contour of the cathode though forms the profile groove. To ensure a stable electrolyte distribution when the tool cathode breaks through the bottom of the lower sacrificial anode, another flushing tube is connected to the flushing chamber. The tool offset and flushing pressure were calculated for a feed rate of 2 mm/min. Hence, the following machining tests were carried out with this feed rate but the first tests started with a slow feed rate to identify weaknesses of the process control.

3. Results

In the first machining test, the tube for electrolyte distribution failed due to the applied pressure and a short circuit occurred. After replacement of the tube, the calculated feed rate could successfully be validated. After machining of the profiled grooves, the geometrical accuracy has been measured with use of a coordinate measurement machine (CMM) Micura 500x500x500 by ZEISS. For the measurement of the inner workpiece radii, a probe with a diameter of 0.5 mm was used.

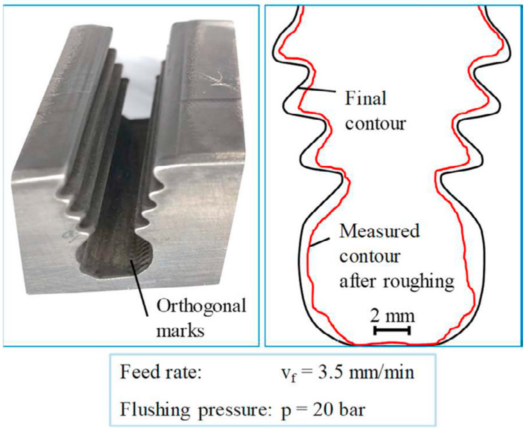


Figure 6: ECM roughed groove, CMM measurement results and tool cathode

The specimen was also mounted under an inclination angle of 12° to make an orthogonal measurement possible. Figure 6 shows the measured groove and the results of the CMM measurement. The measurement shows that the geometry of the profile groove itself is smaller than the final contour by a number of 0.12 mm to 1.16 mm. It was the objective of the rough machining process to machine a groove, which ideally has a constant allowance for the final contour of 0.2 mm to apply the finishing process. It can be seen that the biggest deviation occurs in the area of the outer radii and the smallest deviation at inner radii. In outer radii the current density is lower due to geometrical relationship. At inner radii, the current density increases and respectively the material removal. In addition, it can be drawn from the measurement protocol, that in the base part of the groove, the machined contour has a big deviation.

Compared to the results of the simulation, it can be seen that the flushing velocity on the lateral sides in the bottom area of the groove was too low. Hence, the material removal is lower compared to the rest of the contour what leads to a narrow profile. In the areas of stable flushing conditions, the initial calculation of the tool offset was applicable for the first approach. As it can be drawn from the image, the tool cathode was damaged. This happened during the first machining test before the process could be stabilized. The flushing in the working gap eased up and a short circuit occurred. The negative form of the damages on the tool cathode can be locally as well seen in the machined profile groove as in the measurement graph. Nevertheless, the crucial geometry parts like radii and carrying flanks were machined as calculated before. In the radii it can be seen, that the removal at the inner radii was higher due to higher current density and lower in the outer radii because of lower current density. The clamping of the sacrificial anodes worked well in the bottom area of the groove where sharp leading and trailing edges could be achieved but could also be improved.

Furthermore, the economy of the process was investigated and optimized. Successively the feed rate could be increased in steps of 0.25 mm/min up to 3.5 mm/min what equals a material removal rate of 882.6 mm³/min. Analogously, the flushing pressure had to be increased to guarantee stable flushing conditions. Hence, the according pressure was 20 bar. On the base of the contour marks can be seen which are orthogonal to the feed direction (see Figure 6). One explanation can be vibrations of the tool cathode that result from the high flushing pressure and resulting influences on the local flushing conditions in the respective area.

4. Comparison of alternative processes

Broaching with HSS is currently the state of the art (SOTA) process for the manufacturing of profile grooves in turbine disks. Hence, it is difficult to compare a single roughing process with the state of the art, where both roughing and finishing are conducted in the same machining step within one movement. With regard to future process chains and meaningful combinations of different processes, it is important to analyze the different processes with their capability for either roughing and / or finishing [21]. In the following comparison, the processes are analyzed with regard to roughing and only for this profile geometry. The costs are calculated with input from the machine tool suppliers as well as with use of the depreciation table (AfA chart). In addition, a full machine utilization is assumed. Cost components were calculated in accordance to Bergs et al. [15]. Figure 7 shows the comparison of different processes that besides ECM have already been investigated for machining of profiled grooves. It can be drawn from the diagram, that ECM is an attractive process that is competitively to already established processes. The machining time per slot is 20 % higher than the state of the art but the costs are 25 % lower, because virtually no tool wear occurs. ECM is also faster than WEDM, one alternative non-conventional manufacturing process but the flexibility is much lower due to the elaborate process development. Also the resulting contour of WEDM machining is closer to the final contour compared to the others, which makes it easier to adapt different finishing processes.

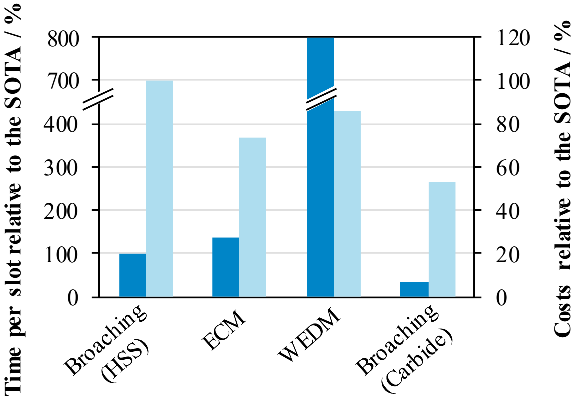


Figure 7: Comparison of different manufacturing processes for roughing of profiled grooves

For the investigated geometry broaching with cemented carbide turned out to be even faster and more economic than ECM machining and similar to WEDM has a high accuracy. The lead time of carbide broaching is comparable with ECM because of the complex tool design low availability of tools [15]. Depending on the following finishing process it can have benefits to use one or another technology because interfaces are easier to handle [22].

5. Conclusion and outlook

Based on fundamental material investigations, a tool cathode has been designed and constructed. A simulation of the stationary machining state proved that the flushing conditions are sufficient to guarantee a stable process under given boundary conditions but also showed critical areas that can be improved in a future redesign of the tool cathode. The calculated feed rate could be established during machining tests. In addition, an increase of the feed rate up to 3.5 mm/min (882.6 mm^3/min) could be realized without final optimization. For future investigations, the flushing pressure should be reduced while the electrolyte volume flow rate stays constant or increases to distribute sufficient electrolyte to the critical areas. Also, the alignment of the flushing holes can be improved to lead the electrolyte straight into the critical areas. With disregard of the contour mistakes due to cathode damages, it can be stated that the process is generally capable to machine a geometry that can be finish machined with an ongoing process.

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References

[1] European Commission. *Flightpath 2050: Europe's vision for aviation*. Publications Office of the European Union, Luxembourg, 2011.

[2] Keramidas, K., Tchung-Ming, S., Diaz-Vazquez, A.R., Weitzel, M., Vandyck, T., Després, J., Schmitz, A., Rey Los Santos, L., Wójtowicz, K., Schade, B., Saveyn, B., Soria-Ramirez, A. *Global energy and climate outlook 2018: Sectoral mitigation options towards a low-emissions economy global context to the EU strategy for long-term greenhouse gas emissions reduction*. Publications Office of the European Union, Luxembourg, 2018.

[3] Bräunling, W.J.G. *Flugzeugtriebwerke: Grundlagen, Aero-Thermodynamik, ideale und reale Kreisprozesse, Thermische Turbomaschinen, Komponenten, Emissionen und Systeme,* 3rd edn. Springer-Verlag Berlin Heidelberg, Berlin, Heidelberg, 2009.

[4] Rolls-Royce Plc. *The Jet engine,* 6th edn., London, 2005.

[5] Kennedy, R.L. Allvac 718Plus, Superalloy for the Next Forty Years, in *Superalloys 718, 625, 706 and Various Derivatives (2005)*, TMS, 2005. p. 1.

[6] Kushan, M.C., Uzgur, S.C., Uzunonat, Y., Diltemiz, F. ALLVAC 718 Plus™ superalloy for aircraft engine applications. Recent advances in aircraft technology. InTech, Rijeka (Croatia), 2012, p. 75.

[7] Pöhls, M. *Untersuchungen zum Räumen mit Feinstkornhartmetall und Cermet*. Dissertation. RWTH Aachen, Aachen, 2000.

[8] Klocke, F., Gierlings, S., Brockmann, M., Veselovac, D. Influence of Temperature on Surface Integrity for Typical Machining Processes in Aero Engine Manufacture. Procedia Engineering, 2011; 19, p. 203.

[9] Vogtel, P., Klocke, F., Lung, D. High Performance Machining of Profiled Slots in Nickel-Based-Superalloys. Procedia CIRP, 2014; 14

[10] Aspinwall, D.K., Soo, S.L., Curtis, D.T., Mantle, A.L. Profiled Superabrasive Grinding Wheels for the Machining of a Nickel Based Superalloy. CIRP Annals - Manufacturing Technology, 2007; 56, p. 335.

[11] Klocke, F., Vogtel, P., Gierlings, S., Lung, D., Veselovac, D. Broaching of Inconel 718 with cemented carbide. Production Engineering, 2013; 7, p. 593.

[12] Welling, D. *Wire EDM for the manufacture of fir tree slots in nickel-based alloys for jet engine components*. Dissertation. RWTH Aachen University, Aachen, 2015.

[13] Klocke, F., Welling, D., Klink, A., Perez, R. Quality Assessment through In-process Monitoring of Wire-EDM for Fir Tree Slot Production. Procedia CIRP, 2014; 24, p. 97.

[14] Klocke, F., Herrig, T., Zeis, M., Klink, A. Experimental Investigations of Cutting Rates and Surface Integrity in Wire Electrochemical Machining with Rotating Electrode. Procedia CIRP, 2018; 68, p. 725.

[15] Bergs, T., Smeets, G., Seimann, M., Doebbeler, B., Klink, A., Klocke, F. Surface integrity and economical assessment of alternative manufactured profiled grooves in a nickel-based alloy. Procedia Manufacturing, 2018; 18, p. 112.

[16] Klocke, F., Klink, A., Veselovac, D., Aspinwall, D.K., Soo, S.L., Schmidt, M., Schilp, J., Levy, G., Kruth, J.-P. Turbomachinery component manufacture by application of electrochemical, electro-physical and photonic processes. CIRP Annals - Manuf. Techn., 2014; 63, p. 703.

[17] Klocke, F., Zeis, M., Klink, A., Veselovac, D. Experimental Research on the Electrochemical Machining of Modern Titanium- and Nickel-based Alloys for Aero Engine Components. Procedia CIRP, 2013; 6, p. 368.

[18] Klocke, F., Zeis, M., Klink, A., Veselovac, D. Technological and Economical Comparison of Roughing Strategies via Milling, EDM and ECM for Titanium- and Nickel-based Blisks. Procedia CIRP, 2012; 2, p. 98.

[19] Pollock, T.M., Tin, S. Nickel-Based Superalloys for Advanced Turbine Engines: Chemistry, Microstructure and Properties. Journal of Propulsion and Power, 2006; 22, p. 361.

[20] Schreiber, A., Rosenkranz, C., Lohrengel, M.M. Grain-dependent anodic dissolution of iron. Electrochimica Acta, 2007; 52, p. 7738.

[21] Klink, A., Hlavac, M., Herrig, T., Holsten, M. Technological and Economical Assessment of Alternative Process Chains for Turbocharger Impeller Manufacture. Procedia CIRP, 2018; 77, p. 586.

[22] Klocke, F., Schmitt, R., Zeis, M., Heidemanns, L., Kerkhoff, J., Heinen, D., Klink, A. Technological and Economical Assessment of Alternative Process Chains for Blisk Manufacture. Procedia CIRP, 2015; 35, p. 67.