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Experimental research on the electrochemical machining of modern titanium- and nickel-based alloys for aero engine components

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Abstract

In order to increase the efficiency of jet engines hard to machine titanium- and nickel-based alloys are in common use for blade and disk materials. With Electrochemical Machining (ECM) highest material removal rates can be achieved at best surface qualities. However for tool design, knowledge of local material dissolution is indispensable. This paper deals with basic research on the electrochemical machinability of selected modern titanium- and nickel-based alloys for aero engine components. Therefor experimental results of feed rate as a function of current density for an ECM sinking operation with a cylindrical tool electrode and external flushing are compared to the theoretical dissolution behavior according to Faraday's law. Furthermore surface properties were examined in terms of SEM and EDX analysis of the rim zone.

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Keywords: Electrochemical Machining (ECM); Nickel-based alloy; Titanium-based alloy

1. Introduction

To achieve weight reduction and increased thermal efficiency of jet engines, hard to machine alloys such as Ti-6Al-4V and Inconel 718 are in common use for the manufacture of aero engine components. Beside these standard materials many other high-strength alloys have been developed during the last decades with improved physical properties. Instead of conventional fir-tree design the blisk (bladed disk)-design is no longer only an option for military engines but found its way to latest civil aero engine designs. With this integral component improved aerodynamics can be achieved which lead to higher efficiency and thus less fuel consumption. In blisk production, namely for milled from solid designs, a lot of material has to be removed. Especially the milling process of blisks made of Ni-based alloys reaches its technological and economical limits.

The unconventional manufacturing technology Electrochemical Machining (ECM) could therefore be a cost-effective alternative for these materials and could become more and more important in the near future.

Roughing operations in blisk manufacture are usually carried out by conventional milling. The main economical drawbacks of milling hard to machine alloys are long machining times, high tooling costs and a surface finish which is strongly dependent on cutting kinematics and tool wear [1-3].

Major advantages of ECM are its process specific characteristics of high material removal rates in combination with almost no tool wear. Due to cost-intensive tool pre-developing processes and rather high investment costs for the machine tools, ECM is specifically used in productions with large batch sizes and therefore represents an alternative manufacturing technology for aero engine components. In addition, the high material removal rates can be realised at simultaneously best surface qualities without developing any white layer as well as no mechanically or heat affected zones [4-7].

Independent of the type of ECM process – direct current (DC) or electrically and mechanically pulsed processes (PECM) – the material removal only depends on the basic electrochemistry of the involved materials in combination with the given electrolyte and the impressed current densities. This paper therefor presents a basic analysis of material removal behavior – in terms of feed rate as a function of current density – for the following titanium and nickel-based alloys:

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- Ti-6Al-4V,
- Ti-6Al-2Zn-4Zr-6Mo,
- Ti-5Al-2Sn-4Mo-2Zr-4Cr (abbr: Ti-17),
- Inconel 718,
- Inconel 718 DA,
- Waspaloy,
- Waspaloy gatorized,
- René 88,
- IN 100 and
- MAR-M-247.

The determined effective material removal rates are compared to theory according to Faraday's law. The developed rim zones are analyzed in terms of SEM and EDX pictures. In conclusion the results are discussed and technological capabilities of ECM are shown.

2. Alloys for aero engine components

Figure 1 gives an overview of actual and future aero engine materials. Major materials in constructions are titanium- and nickel-based alloys. Both material groups have continuously been developed through the last decades but are limited in their room for improvement. Nevertheless in future engine concepts those materials are indispensable. Many different types of superalloys have been developed but caused by their tough conventional machinability they often did not made their way into engine concepts up to now.

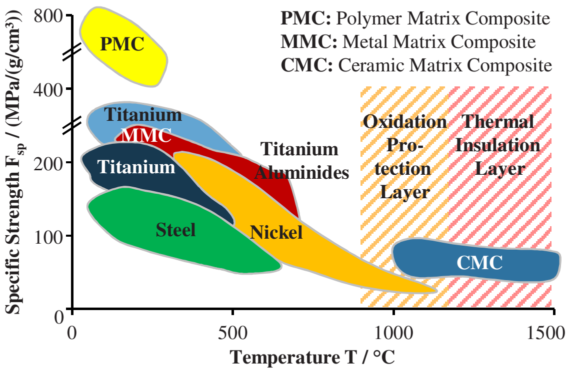


Fig. 1. Specific strength and temperature potential of actual and future aero engine materials [8]

Tables 1 -3 show the examined materials divided into titanium- and nickel-based alloys. In general titanium-based alloys are applied to low pressure compressor (LPC), high pressure compressor (HPC) and as fan material. They combine low densities with high strength, good weldability and high fatigue strength but are limited by their operating temperature. In Table 1 the α-β alloys Ti-6-4 and Ti-6-2-4-6 as well as the metastable β alloy Ti-5-2-4-2-4 (abbr.: Ti-17) are compared to each other in terms of density, operating temperature and tensile strength [9-11].

Table 1. Comparison of physical properties of titanium alloys for aero engine components

	Ti-6-4	Ti-6-2-4-6	Ti-17
Density ρ / (g/cm³)	4.43	4.65	4.658
Operating temp. T_{op} / °C	300	480	-
Tensile strength at elevated temp.	↓	o	↑
Value	↓ low	o middle	↑ high	- not specified

The mentioned nickel-based alloys are differed due to their primary site of operation in disk and blade materials (Table 2 and Table 3). Except of Inconel 718 all other analyzed superalloys are no longer economically to be machined by conventional milling.

Table 2. Comparison of physical properties of superalloys for turbine disks and blades

	Inco 718	Inco 718 DA	Wasp.	Wasp. gat.	René 88
Density ρ / (g/cm³)	8.19	8.19	8.23	8.15	8.33
Operating temp. T_{op} / °C	650	650	700	705	-
Tensile strength at elevated temp.	↓	o	↓	↑	↑
Value	↓ low	o middle	↑ high	- not specified	

Table 3. Comparison of physical properties of superalloys for rotating blades

	IN 100	MAR-M-247
Density ρ / (g/cm³)	7.8	8.58
Operating temp. T_{op} / °C	1000	1035
Tensile strength at elevated temp.	-	↑
Value ↓ low	o middle ↑ high	- not specified

Inconel 718 itself is the most used nickel-based alloy in aero engine construction. One variant of Inconel 718 is the Direct Aged (DA) material which features higher tensile strength compared to basic Inconel 718. Both materials differ in their heat treatment. Standard Inconel 718 is forged, solution annealed and artificially aged while the DA version is only forged and artificially aged.

Thereby the γ''-Phase is stabilized which leads to a more finegrained microstructure. Thus tensile strength and Low Cycle Fatigue (LCF) are improved [12-15].

Waspaloy, gatorized Waspaloy, René 88 and IN 100 are powder metallurgically (PM) manufactured superalloys. In general PM materials have a more finegrained microstructure compared to wrought alloys so that higher operating temperatures are possible. On the other hand bursting and fatigue strength are lower. MAR-M-247 is a conventionally cast nickel-based alloy with high operating temperature and creep strength for turbine blades. But in comparison with IN 100 it possesses a higher density. In Table 2 and Table 3 the above mentioned superalloys are compared to each other regarding density, operating temperature and tensile strength [8, 14-21].

Caused by their specific properties those alloys are no longer conventionally machinable by milling. Especially regarding the manufacture of aero engine components an alternative is ECM. But the electrochemical machinability of the mentioned alloys has not been examined and published yet.

3. Experimental Setup

The described titanium and nickel-based alloys have been analyzed in terms of their electrochemical machinability on the platform shown in figure 2 and 3. The used ECM-tool operates with an external flushing (flushing diameter d_i = 2 mm) and possesses a cross section with a diameter of d_o = 6 mm.

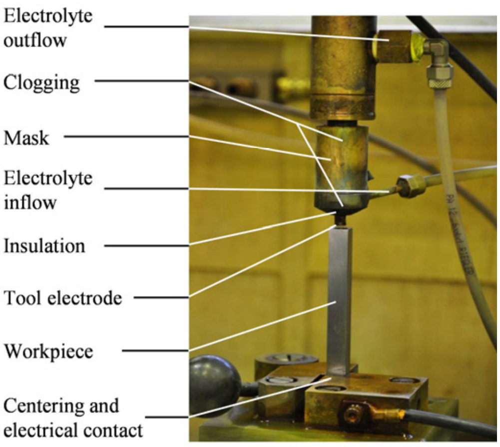


Fig. 2. ECM-tool of basic research platform at WZL

The whole tool is moved towards the clamped workpiece. For calculation reasons the probe has to be balanced before and after each experiment. At first a defined feed rate is set up and a constant pressure ratio (inlet/outlet), temperature and voltage are adjusted. Current and voltage are monitored during the process. In combination with mass difference and process time, the current density for each feed rate can be calculated. Furthermore with the help of this platform different types and concentrations of electrolyte can be examined.

Fig. 3. ECM basic research platform at WZL

4. Results and Discussion

4.1. Comparison with Theory

For tool design in ECM it is indispensable to know the local gap formation during the process. The local gap width can roughly be calculated with a combination of Ohm's and Faraday's law. But especially for complex shaped geometries and long flow lengths the approximation of Faraday loses its validity.

Equation 1 shows the effective material removal rate according to Faraday's law reduced by the current efficiency η [4]. Especially the fact that in the pure form of Faraday's law for each element only one electrochemical valency is considered the equation has to be corrected by η which also can be understood as efficiency factor.

$$V_{eff} = V_{sp,alloy} \cdot \eta = \frac{\eta}{\rho_{alloy}} \cdot \sum_{i=1}^{n} \frac{w_i}{100} \cdot \frac{M_i}{z_i \cdot F} \qquad (1)$$

Furthermore the calculation of local gap forming by the combination of Ohm's and Faraday's law is only applicable in the frontal gap [4]. Complex shaped geometries can roughly be corrected by the angle of inclination of the workpiece contour α (equation 2).

$$s_{eff,\alpha} = \frac{(U - \Delta U) \cdot V_{eff} \cdot \kappa}{v_f \cdot \sin \alpha} \qquad (2)$$

Therefor it is necessary to determine the effective material removal rate by analyzing the behavior of feed rate as a function of current density in experiments. Results of these examinations are shown in Figure 4 for Ti-6-2-4-6 and Figure 5 for MAR-M-247 respectively. The strictly linear behavior showed for all experiments and almost no dependence of electrolyte`s concentration on effective material removal rate was discovered.

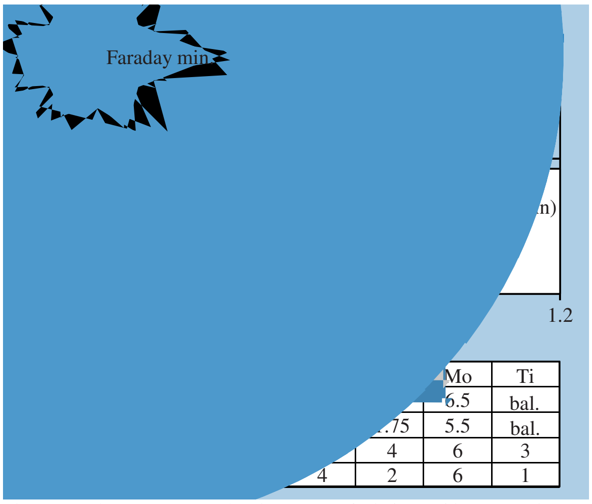
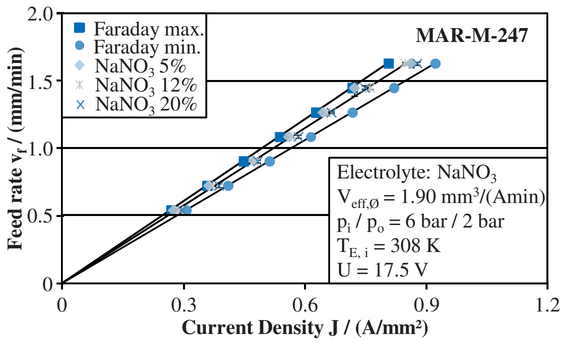


Fig. 4. Feed rate - current density curve of Ti-6-2-4-6 in comparison to Faraday's law

In case of Ti-6-2-4-6 the deviation to Faraday's law caused by a large variance in possible electrochemical reduction processes is high. This means that minimal electrochemical valencies lead to highest specific material removal rates. Each experiment has been repeated three times and the overall largest deviation amounted less than 3% and so current efficiency η was well recorded.



Element	W	Co	Al	Cr	Ni
wt.% max.	9.7	9.5	5.7	8.5	bal.
wt.% min.	9.3	9.0	5.4	8.0	bal.
z max.	6	3	3	6	2
z min.	6	2	3	3	2

Fig. 5. Feed rate - current density curve of MAR-M-247 in comparison to Faraday's law

4.2. Effective Material Removal Rates (v_f - J Curves)

Figure 6 summarizes the averaged effective material removal rates of all tested alloys. Due to almost no difference in the results for different electrolyte concentrations, the linear curves were combined to one function named $V_{eff,Ø}$, the averaged effective material removal rate. For all titanium alloys an almost identic $V_{eff,Ø}$ with 1.78 mm³/(Amin) adjusted.

In case of the nickel-based alloys more finegrained microstructures lead to a better electrochemical machinability and dissolved faster. Thereby the powder metallurgically manufactured superalloys showed the best electrochemical machinability. Generally the nickel-based alloys dissolved faster than the titanium ones.

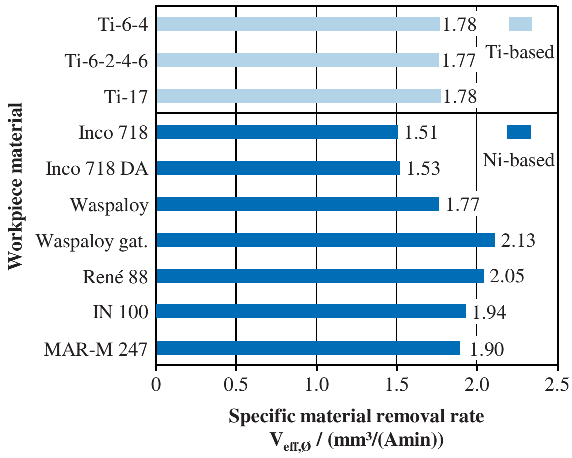


Fig. 6. Effective material removal rates of analysed alloys

4.3. Rim Zone Analysis

Figure 7 shows the cross section of Inconel 718 and Inconel 718 DA. The more finegrained microstructure is clearly recognizable. As often described in literature no influence of the process on the rim zone can be identified.

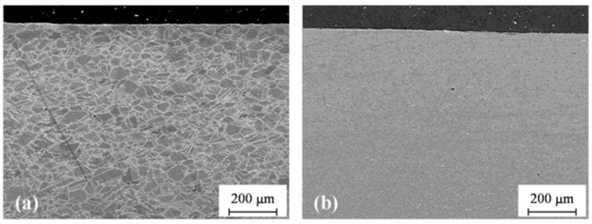


Fig. 7. (a) SEM picture of Inconel 718; (b) SEM picture of Inconel 718 DA

Although no influence of the cross-section can be seen at the SEM pictures, it could happen that elements of the electrolyte diffused into the workpiece. To prove this for three depths from surface an EDX analysis has been made. The results of this measurement are exemplary shown in Figure 8 for IN 100. For all other materials no residue of the electrolyte could be found as well.

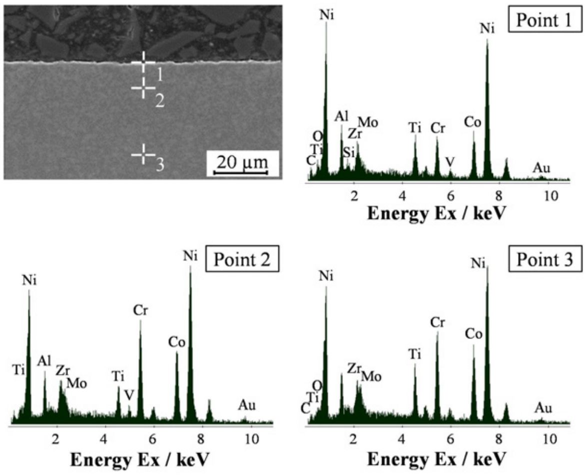


Fig. 8. EDX analysis of rim zone composition of IN 100

5. Conclusions and Outlook

In this paper modern hard to machine alloys for aero engine components were analyzed in terms of their electrochemical machinability. Therefor at first the basic research platform at WZL with the associated ECM-tool has been presented. With the help of this platform the feed rate - current density curves for several titanium- and nickel-based alloys have been examined. Experimental results were compared to theory according to Faraday's law and among each other by effective material removal rates. For all analyzed titanium materials the effective material removal rates were almost equal to $V_{eff,Ti} \approx 1.78$ mm³/(Amin). In case of nickel-based alloys it turned out that the more finegrained the microstructure of the material the better its electrochemical machinability. All analyzed superalloys showed good machining behavior by ECM and effective material removal rates were in the range of 1.51 mm³/(Amin) $\leq V_{eff,Ni} \leq$ 2.13 mm³/(Amin).

As often described in literature for other material groups no influence on the rim zone by ECM could be recognized. SEM and EDX analysis showed no kind of affected zone or foreign atoms diffused from the electrolyte.

The generator of the actual platform setup did not allow machining of larger areas with high feed rates because of its maximum current limit of 40 A. Thus it was not possible to measure surface roughness, what should be investigated in further work.

Moreover – in comparison to standard analytical models according to Faraday's law in combination with the angle correction – a more complex simulation model should be built up. With the help of this model it should be possible to forecast local gap forming even for complex geometries like blisks with arrow-shaped leading and trailing edge.

In terms of material machinability investigations, one promising kind of titanium alloys are gamma titanium aluminides (abbr.: γ-TiAl). This class of material with improved tensile strength at lower densities in comparison to α-β titanium alloys should be analyzed concerning its electrochemical machinability as well.

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