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Investigations on vibration-assisted EDM-machining of seal slots in high-temperature resistant materials for turbine components

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Abstract

Modern aircraft engines are nowadays designed with the aim of reducing fuel consumption and emission of pollutant gases as well as increasing reliability and competitiveness in the manufacturing and repair costs. These requirements on the engines result in new requirements on components and manufacturing processes, to know: application of new engineering materials, higher component temperatures, increased demands on tightness, 3-D complex shapes as well as new manufacturing technologies. EDM-machining is typically chosen for applications including complex geometries like high aspect ratio cavities in high-temperature resistant materials, since the EDM-process is independent from the mechanical properties of the processed material. This paper addresses the design and utilization of a unit composed of piezoelectric actuators for machining seal slots in turbine components. This aims the optimization of the flushing mechanisms through vertical vibration of the tool electrodes while manufacturing high aspect ratios cavities and therewith the optimization and/or reduction of both process time and electrode wear. Firstly, the piezo-unit was designed and components like piezoelectric actuators and charge amplifier were chosen, in accordance to previous defined requirements regarding vibration frequencies and amplitudes. During the experimental investigations graphite electrodes were applied. A total of twelve cavities with an aspect ratio of 12 are simultaneously machined in the material MAR-247. During the process, a harmonic longitudinal vibration of the electrodes overlapped to the machine’s feed movement is realized. Both vibration amplitude and frequency were varied during the experiments, ranging from 2 μm to 16 μm and from 50 Hz to 1 kHz, respectively. The results are compared to the conventional process without vibration, while the EDM-parameters remain unaltered. By applying longitudinal vibration to the tool electrodes the material removal rate was increased by 11 %. The relative tool electrode wear was reduced by 21 %.

Keywords: die-sinking EDM; vibration-assisted EDM; high aspect ratio cavities; high-temperature resistant materials; turbine components

1. Introduction

The future economic and ecological challenges for the jet-engine industry push for a reduction on the emission of pollutant gases (20 % for CO₂ and 80 % for NOx) as well as reduction on fuel consumption by further 15 % [1]. In addition, the jet-engines producers are permanently in competition and looking for the reduction of manufacturing and repair costs as well as reduction of noise load. These requirements lead to the necessity of developing new materials as well as new or optimized manufacturing technologies [2]. Improvements on the EDM-process also lead to the fulfillment of those requirements, for example in the manufacturing of seal slots. The seal slots consist of high aspect ratio cavities produced in high-temperature resistant alloys, e.g. MAR-M247. The requirements on these are tight tolerances, low influence on the sub-surface and low surface roughness. The EDM-process is typically chosen for the production of complex geometries such as high aspect ratio cavities in hard-to-machine materials [3]. One of the main advantages of this process is the independence regarding the material properties, like hardness and E-module, of the parts to be machined [4].
So far, there are a number of works that studied the micro-EDM process using ultrasonic vibration of electrodes [5, 6, 7, 8, 9]. By the use of a numerical model, Shervani-Tabar [6] showed that induced longitudinal vibrations during the EDM-process had an influence on the expanding and imploding of plasma channel, impacting directly the material removal rate and wear of the tool electrodes. An increase of the material removal rate by using electrode vibration was observed during the experiments. Shabgard [10] studied the ultrasonic vibration during the finishing (0.5 ≤ MRR ≤ 2.5 mm³/min) and semi-finishing (2.5 ≤ MRR ≤ 17 mm³/min) regime machining of tool steel. His work concluded that the ultrasonic vibration increased the material removal rate, reduced arcing and short-circuits as well as improved the flushing conditions between electrodes. Hao Tong [11] and Takashi Endo [12] investigated the micro-EDM with aid of low frequency vibrations and both achieved higher material removal rates or shorter machining times in distinct applications. Prihandana [13] investigated the application of low frequency longitudinal vibration of tools electrodes in the finishing regime machining of stainless steel. He worked with frequencies of 300 Hz, 400 Hz and 500 Hz while applying very small vibration amplitudes of 0.75 μm and 1 μm. He concluded that the materials removal rate can be increased by using vibration-assisted EDM, while the tool electrode wear and surface roughness values become higher than in conventional EDM-machining. Ghoreishi [14] conducted a work comparing vibratory, rotary and vibro-rotary EDM in the roughing regime machining of tool steel AISI 01. He compared low frequency vibration of 50 Hz with high frequency vibration of 19.9 kHz of the tool electrodes and concluded that low frequency has less influence on the material removal rate in comparison to high frequency. He also concluded that there is no need of motions to improve the flushing conditions in the roughing regime.

Up to now, although vibration-assisted EDM-machining has been studied by many researchers, most of the studies focused on micro-EDM operations and on ultrasonic EDM-machining. There is no application of this technology for the machining of high aspect ratio cavities, which present the worst problems regarding bad flushing conditions. Furthermore, there are no results combining the roughing regime, low frequencies ranging from 50 Hz up to 1000 Hz and high vibration amplitudes going up to 16 μm. Finally, no application of vibration-assisted EDM while machining high-temperature resistant materials could be found in the literature as well as no practical application in industry.

Objective of this work is to improve the die-sinking EDM-machining of high aspect ratio seal slots in a high-temperature nickel-based superalloy MAR-M247. Considering the stability of the process, the processing time has to be decreased, also meaning an increase of the material removal rate. For this purpose, a modular piezo-unit for inducing longitudinal vibration on tool electrodes was developed and tested at the applied machine tool. This longitudinal vibration aimed the improvement of the flushing conditions while producing seal slots, which are very critical, and therefore improve the process stability and reduce the total processing time.

2. Machine Tool and Materials

The investigations were carried out at Fraunhofer IPK in cooperation with a producer of turbine components, such as turbine center frames and turbine blades.

For this purpose, the machine tool Genius 1000 THE CUBE from Zimmer&Kreim was applied. IonoPlus IME-MH from Oelheld was used as dielectric fluid and graphite was chosen as tool electrode material. The graphite electrodes presented a specific electrical resistance of 13.6 μΩm ± 2.2 μΩm and a grain size of 2.9 μm ± 0.3 μm, according to manufacturer of the tool electrodes. Electrical resistance of tool electrodes is an important property of these while machining high depth cavities, affecting the machining time and process stability. The grain size of the electrodes influences the tool wear directly. The study was conducted using tool electrodes of three different cross-sectional areas with four electrodes each, totaling 12 electrodes and a total electrode cross-sectional area of 89.50 mm². A total depth of 11 mm was machined, producing an aspect ratio of 13.1. Further details of the experimental set-up will be given in Section 4.1 and 4.2.

3. Design and Construction of the Piezo-Unit

3.1. Specification of technical requirements

The piezo-unit to be developed was to be attached to the sleeve of the chosen EDM machine tool. In order to keep the restrictions on the movement of the machine tool low, the piezo-unit was designed as compact as possible. A total of two actuators should enable the handling of the 12 electrodes simultaneously, meaning therefore 6 tools electrodes per actuator. High stiffness of the components was to be guaranteed, so that the requirements on form accuracy at work piece are respected. The interface between the piezo-unit and machine sleeve had to be implemented using the "Macro-System" from System 3R.

The two identical piezoelectric actuators had to be driven synchronously by a function generator and the corresponding charge amplifier. The vibration frequency in the Z-axis had to range from 0 Hz to 1000 Hz. An adjustable maximum deflection of 30 μm had to be
ensured, which represents a vibration amplitude of 15 μm. The pre-defined frequencies and amplitudes had to be realized under load conditions, considering therefore additional masses like electrode weight, weight of the electrode holder and others. The maximum additional external mass per actuator was fixed at 0.5 kg. Furthermore, due to the working principle of EDM-machines, the piezo-actuators had to be electrically isolated from the machine structure, avoiding therefore alarm messages and process interruption due to short-circuits.

3.2. Selection of piezo-actuators, charge amplifier and function generator

The piezo-actuators to be applied in this study were calculated and designed for this special application and the technical requirements described in Section 3.1 were used as boundary conditions. After definition of the requirements on the piezo-actuators, two actuators model PST1000/16/30VS35 from Piezomechanik GmbH, Germany, were purchased. These had to fulfill the requirements regarding the dynamic operation in the established frequencies, amplitudes and further described boundary conditions. Table 1 presents the technical data of the chosen piezo-actuators.

<table>
<thead>
<tr>
<th>Actuator designation</th>
<th>PST1000/16/30VS35 thermostable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating voltage</td>
<td>-200 V / + 1000 V</td>
</tr>
<tr>
<td>Deflection (ΔL) - 200V/1000V</td>
<td>33 μm</td>
</tr>
<tr>
<td>Actuator stiffness</td>
<td>200 N/μm ± 20 %</td>
</tr>
<tr>
<td>Ceramic dimension</td>
<td>16 mm x 30 mm</td>
</tr>
<tr>
<td>Capacity (C)</td>
<td>300 nF ± 20 %</td>
</tr>
<tr>
<td>Max. pressure and tensile stresses</td>
<td>15000 / 2500 N</td>
</tr>
<tr>
<td>Mass of actuator (without cable)</td>
<td>301 g</td>
</tr>
<tr>
<td>Mass of additional parts</td>
<td>18 g</td>
</tr>
<tr>
<td>Special specification</td>
<td>Housing electrically isolated from internal ceramic</td>
</tr>
</tbody>
</table>

The movement characteristics and dynamics of the piezoelectric system are essentially determined by the design of the electronic control or charge amplifier. The specification of the charge amplifier was carried out after choosing the appropriate piezo-actuators. The calculations considered the factors supply voltage, capacity of the actuators, average and maximum charge current, band width as well as the output power. In this case, the charge amplifier RCV 1000/3 from Piezomechanik was chosen. The function generator FG 501 A from company Tektronix was applied for generating the sinus signals for the piezo-actuators.

3.3. Design of the piezo-unit

The design of the piezo-unit can be divided into the following steps: design of the adapter to the 3R-system, design of the electrode holders and finally design of spacing sleeves. The adapter to the 3R-system was designed as a robust and solid block, which guaranteed the stiffness of the whole system. The distancing sleeves were produced in aluminum, avoiding therefore further mass to be moved by the piezo-actuators and were responsible for avoiding that actuators get in contact with the dielectric fluid. The selection of the electrode holders considered four distinct designs, and these were prioritized utilizing a value benefit analysis. For that, following criteria were analyzed: production expenditure, number of parts, flexibility, effort in fixing the electrodes, maximum utilization of work pieces, accessibility to produced cavities as well as finally transmission of clamping force to the electrodes. This analysis resulted in the piezo-unit presented in Fig. 1.

![Fig. 1. 3D-view of the piezo-unit (a) and examples of seal slots in turbine components (b)](https://example.com/fig1.png)

4. Verification and Validation of the Piezo-Unit

The piezo-actuators had to be tested after the development and construction of the unit. This consisted in checking the piezo-actuator responses in terms of
frequencies and amplitudes while clamped to the machine tool (verification). Some experiments were carried out to determine the influence of the vibration-assisted EDM-machining on producing high-depth seal slots in the high-temperature resistant material MAR-M247 (validation). The Section 4 describes the procedures and results regarding the verification and validation of the piezo-unit.

4.1. Design verification of piezo-unit

The measurement of the piezo-actuators response in the machine tool was carried out by using a Laser Doppler Vibrometer sensor. This aimed not only the verification of the vibration behavior of the piezo-actuators, but also the verification of possible influence of the machine tool on this behavior. Besides the equipment already presented for operating the actuators (Section 3.2), the software and hardware presented in Table 2 were applied during the verification procedure. These measurements were carried out at the machine tool utilized for the experiments, presented in Section 2.

Table 2. Equipment used for piezo-actuator verification

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Digital oscilloscope</td>
<td>TDS 5032 B (Tektronix)</td>
</tr>
<tr>
<td>Laser Doppler Vibrometer</td>
<td>Laser head: OFV-353; Objective: mid-range (Polytec)</td>
</tr>
<tr>
<td>Vibrometer Controller</td>
<td>OFV 3001 (Polytec)</td>
</tr>
<tr>
<td>DAQ-Module</td>
<td>NI 9215 BNC (National Instruments)</td>
</tr>
<tr>
<td>Evaluation software</td>
<td>LabVIEW Vers. 8.2.1 (National Instruments)</td>
</tr>
</tbody>
</table>

Prior to the verification of the actuators at the machine tool, these were calibrated on a rigid granite table using a laser interferometer. This calibration enabled the determination of the voltage to be applied at the charge amplifier for each pre-determined vibration amplitude.

Frequencies ranging from 100 Hz to 1000 Hz and amplitudes varying from 2 μm to 16 μm were tested during the verification experiments. High vibration amplitudes at high frequencies are critical for the actuators due to the highest dynamic loads that occur and the biggest errors regarding vibration behavior are to be expected in this range. Fig. 2 presents a schematic representation of the experimental set-up for the verification of the piezo-unit mounted at the machine tool. The oscilloscope was used as measuring/setting device for setting the correct amplitudes and frequencies for the piezo-actuators. The actuators were operated and measured simultaneously, applying therefore two laser heads.

The analysis of the results showed that the two piezo-actuators present similar behavior while vibrating at low frequencies and amplitudes. At high frequencies and high amplitudes, as indicated at the upper diagram in Fig. 3, the actuators of the piezo-unit presented a distinct behavior concerning the amplitude. Actuator 1 achieved vibration amplitude of 13 μm while actuator 2 achieved amplitude of 14.5 μm, while the frequencies were the same and the actuators were running synchronously. This was the maximum observed difference between actuators. By reducing one of the parameters or both of them, this error decreases considerably. The lower diagram of Fig. 3 shows that by reducing the frequency from 1000 Hz to 150 Hz and increasing the amplitude to 16 μm, the amplitude deviation could be decreased from 1.5 μm to 0.5 μm.

The measurements were considered satisfactory, since the waveforms did not present any noise and operate synchronously. Apart from the operation at high frequencies (> 800 Hz) and amplitudes (> 700 μm), the
actuators presented a total difference in the amplitudes < 0.5 μm.

![Graph showing vibration behavior of actuators](image)

Fig. 3. Verification of vibration behavior of the two actuators at distinct frequencies and amplitudes

4.2. Validation of the piezo-unit through experimental investigation on vibration-assisted EDM-machining of seal slots

After verification of vibration behavior, experiments were carried out to test the designed piezo-unit during the machining process. The electrical and control parameters at the machine tool were kept constant and are presented in Fig. 4. The frequency and amplitude vibration of the piezo-unit have been varied and are also presented in the Fig. 4. The results show that high amplitudes of 16 μm (parameter setting 2) reduced the material removal rate by 14%. By reducing the vibration amplitudes to 6 μm and 2 μm, and by applying frequencies higher than 150 Hz, the material removal rate has been increased and the relative tool electrode wear has been reduced. The best results were achieved with high frequencies (700 Hz and 800 Hz) with short vibration amplitudes (2 μm). In comparison with the process without vibration, the material removal rate has been improved in 11.1%, while applying a vibration frequency of 700 Hz and amplitude of 2 μm. The best results regarding the tool electrode wear were achieved applying a vibration frequency of 800 Hz and amplitude of 2 μm, corresponding to a reduction of 21% in the electrode wear.

![Graph showing material removal rate and relative wear](image)

Fig. 4. Influence of vibration on the EDM-machining of high-depth seal slots

An analysis of the machining time necessary for machining a 1-mm-step in function of the depth of electrodes inside of the work piece material was carried out. This aimed the identification of best parameters settings depending on the depth of the electrodes in the material. Fig. 5 presents these results. This diagram shows that the studied high vibration amplitudes of 6 μm and 16 μm possess a negative influence on the process at the beginning of the machining. From 4 mm depth towards, a vibration amplitude of 6 μm improved the process speed and therefore material removal rate when compared to the process without vibration, by applying both 150 Hz and 500 Hz. The use of high frequencies, as already presented in Fig. 4, improved the process regarding the total machining time or material removal rate. This behavior can be observed from the beginning of the erosion process until a final depth of 11 mm. An alternative for further improvement of the total machining time can be the combination of distinct vibration parameters, which can be varied in function of the depth of electrode in the work piece, so-called multi-step technology. In the diagram (Fig. 5) the arrows
indicate the fastest machining parameters for each 1-mm-step. The combination of these can be tested as a multi-step technology.

**Fig. 5. Machining time for a 1-mm-step for distinct depths in the workpiece**

### 5. Summary and Outlook

This study focused in the design of a piezo-unit, working in the range from 0 Hz up to 1000 Hz and with amplitudes ranging from 0 μm up to 16μm, to be used in the manufacturing of seal slots in high-temperature materials. This piezo-unit was developed, piezo-actuators and charge amplifiers were designed and selected at the market and the synchronous vibration behavior of the actuators could be verified through measurements at the machine tool. The results of the EDM experiments confirmed that the designed piezo-unit for EDM-machining can be used effectively in combination with the appropriate processing technology to obtain elevated material removal and reduced tool electrode wear. The relative tool electrode wear could be reduced by 21 %. The material removal rate was improved by 11 %. High vibration frequencies and low amplitudes increase the machining efficiency. These improvements lie on the improved flushing conditions, which lead to the improvement of process stability. It is assumed, the number of electrical arcs can be reduced applying the longitudinal vibration of the electrodes. The tool electrode wear was reduced in these experiments, meaning that the longitudinal vibration can influence positively the tool wear during the EDM-machining of deep cavities. A multi-step technology can be tested in the future for further improvement of material removal and electrode wear.

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### References


