

PRODUCTION OF A MINIATURE Si_3N_4 -TiN CERAMIC TURBINE IMPELLER BY DIE-SINKING EDM

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Abstract: This work addresses the high precision manufacture of a miniature gas turbine impeller for the development of 1 kW portable power units. A ceramic composite is chosen to meet the extremely harsh operating conditions. Die sinking EDM (Electrical Discharge Machining) technology is used to machine the complex blade geometry with high accuracy. 3-axis grinding is also applied to the shaft and turbine backside to achieve close tolerances. The dimensional control is conducted on a Coordinate Measuring Machine (CMM), revealing a geometric accuracy within $\pm 50 \mu\text{m}$. The need of surface treatments is finally discussed.

Key Words: micro gas turbine, micro-manufacturing, micro-EDM, micro-milling, ceramic composite

1. INTRODUCTION

Portable fuel-based power units have received increasing attention in recent years. Among the many operating principles, gas turbines are expected to offer the highest power density. Several examples of micro and mesoscopic turbines can be found in literature [1]-[4]. The micro range uses silicon-based technology, enabling the fabrication of very small components with high accuracy, whereas the limited wafer thickness, the 2D blade design and the narrow material choice are the main drawbacks of this solution. On the other hand, mesoscopic devices have a more flexible design as a wide range of fabrication technologies is used (micro-milling, micro EDM, and micro-moulding), and they can be in steel, nickel alloys or ceramics.

In this work, the combined use of advanced ceramic composites and EDM processes is chosen as technological solution for high precision machining of a mesoscopic gas turbine impeller.

The component has a mixed axial-radial design and 8 blades with 3D geometry (Fig.1). It has a diameter of 20 mm and an axial length of 8.5 mm; the integrated shaft is 10 mm long and 8 mm in diameter. It finds final application in the development of a fuel-based power generator with overall size of 1 dm^3 and electrical power output up to 1 kW [4], [5]. To obtain a positive cycle efficiency, the turbine impeller is expected to endure inlet temperatures up to 1200K and rotational speeds of more than 500,000 rpm; the centrifugal stress attains 580 MPa at full speed

(max. principal stress). These thermo-mechanical working conditions make the material choice crucial and put strict requirements on shape accuracy and surface integrity of the final component.

The Kersit 601 Si_3N_4 -TiN ceramic composite (commercially available from Saint-Gobain) is selected because of its good combination of high-temperature mechanical and oxidation properties, low density and electrical resistivity. The complex shaping of this hard material is then solved by die-sinking EDM. In sect. 2, the production approach is presented. Particular attention is paid to the EDM strategy, as the most recent innovative technology to machine brittle materials. The geometric accuracy and surface quality control of the manufactured component are discussed in section 3. Finally, conclusions are drawn.

2. MANUFACTURING

Fig. 2 reviews the production steps involved in the fabrication of the gas turbine impeller.

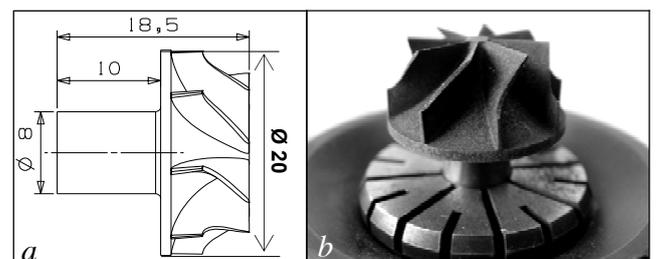


Fig. 1: a) Drawing of the gas turbine impeller; b) image of the produced component.

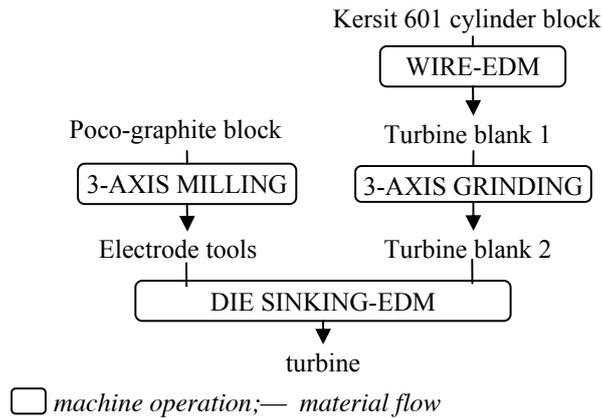


Fig. 2: Flow chart of the production approach

A turbine blank was first pre-shaped with 0.200 mm oversize. Therefore, a Kersit 601 cylinder blank was clamped into a rotational indexing head and cut by wire-EDM along the outside profile of the turbine impeller. Machining was performed in de-mineralized water on a 3-axis Robofil 2000 wire-EDM centre, using standard brass wire (\varnothing 0.250 mm).

The shaft and turbine backside were then finished by 3-axis grinding in one single operation, in order to achieve perpendicularity tolerances of few micron. Machining was conducted on a 5-axis Kern MMP 2522 micro-milling centre, equipped with a high-speed spindle (40,000 rpm) and having an accuracy of $\pm 1 \mu\text{m}$. The tool used was an electroplated bond grinding pin, 6 mm in diameter and diamond grit size D91 (75-95 μm). The cutting speed was set to the maximum allowed by the spindle, feed rate to 500 mm/min and cutting depth to 2 μm . The achieved surface roughness was down to 0.10 $\mu\text{m} R_a$.

On the same machine, 10 EDM electrodes were machined (Fig.3) from blocks of copper infiltrated graphite (Poco EDM-C3 with grain size $< 5 \mu\text{m}$), each electrode having the negative shape of a turbine cavity minus a 50 μm undersize. This undersize takes into account the assumed sparking gap and a sufficient material stock to be removed during finishing. A 3-axis layer-by-layer milling strategy was followed, with a 0.1 mm layer thickness, using full hard metal ball mills, 1 mm and 0.5 mm in diameter. Following a similar strategy, two additional EDM tools were shaped to successively erode the outside and top surface of the turbine impeller. On the micro-milling machine, the electrode blanks were fixed in a

system 3R tool holder compatible with the tool interface of the EDM machine. After referencing the tool holder's position in both machines, this approach assured a quick and accurate transfer of the electrodes from the milling centre to the EDM machine, thus overcoming machining errors due to tool alignment and centring.

As a final step, the turbine workpiece was clamped on a 4-axis Roboform 350 γ die sinking EDM centre, and the graphite electrodes were sunk into the ceramic blank to obtain the desired final shape (Fig. 4). Fig. 1b shows the fabricated gas turbine impeller.

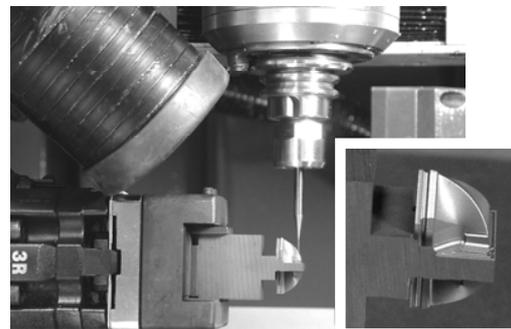


Fig. 3: 3-axis micro-milling operation, and close up view of a cavity electrode tool.

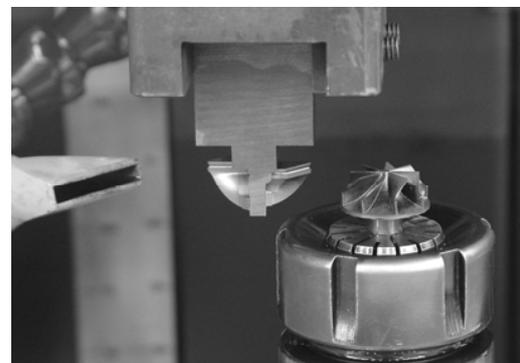


Fig. 4: Tool approach to the turbine cavity describing die sinking EDM process.

2.1 Die sinking EDM strategy

Thanks to new advances in sparking generators and CNC systems, EDM capabilities have been improved to a large extent during the last decades. Meanwhile, new types of electro-erodable materials have been developed.

In principle, all electro-conductive materials can be machined by EDM, once their electrical resistivity limit is lower than 100 Ωcm . Therefore, spark erosion is a potential and attractive

technology for ceramic machining, once sufficient electrical conductivity is provided to the ceramic matrix. In contrast, traditional machining is rather limited due to the high hardness of these materials, while net shape processing may lead to loss of accuracy.

Among ceramic composites, Si₃N₄-based ceramics are the most widely investigated [6], [7], [8]. However, literature is still fragmented with respect to the parameters used. Therefore, tests were conducted before turbine production, to define suitable EDM parameter setting.

Experiments were focused on process parameters, and designed based on the 3-level face centred factorial method [9]. The current (i_e) and the pulse interval (t_i) were varied and respectively set to 8 A-12 A-16 A and 3.2 ms-50 ms-100 ms, while the open voltage (u_i) and the pulse duration (t_o) were maintained constant and respectively set to +160V and 25 ms, taking into account the high electrical resistance of the material and the best achievable surface quality [7]. Experiments were performed in oil dielectric, by sinking Poco graphite rectangular electrodes into a Kersit 601 block. Machining characteristics were evaluated based on material removal rate (MRR), relative tool wear (RTW), sparking gap (SG) and surface roughness. Based on the results, the centre point was selected ($u_i=160$ V, $i_e=12$ A, $t_o=25$ ms, $t_i=50$ ms). Though this is not an optimized combination, highly stable working conditions were achieved, resulting in $MRR = 3.38 \pm 0.63$ mm³/min, $RTW = 0.44 \pm 0.2$ %, $SG = 0.1 \pm 0.04$ mm, $R_a = 2.5 \pm 0.08$ μm. As shown, the actual SG is much larger than the estimated value on which the electrode undersize was based.

Cavity no.		1	2	3	4	5	6	7	8
Tool Electrode no.	1	N	R	R	R	R	R	R	R
	2	N	R	R	R	R	R	R	R
	3	N	R	R	R	R	R	R	R
	4		N	R	R	R	R	R	R
	5			N	R	R	R	R	R
	6				N	R	R	R	R
	7					N	R	R	R
	8						N	R	R
	9							N	R
	10	R	R	R	R	R	R	R	R

Legend: N=new tool; R=reused tool

Table 1: Die sinking EDM tool strategy used for the turbine cavity machining.

According to [7], the achievable R_a is limited to around 2 μm. Therefore, this parameter setting is useful for a semi-finishing regime.

Table 1 reviews the tool strategy used for machining the turbine cavities. A total of 10 new tools were used, each tool successively reused to machine all cavities in sequence, before starting with the next one. While using tool no. 9, almost no sparks occurred. The same tool was sunk in all cavities again to check where sparks occurred, and a last tool was necessary to finish the first cavities. The operation took approximately 15 hours. By running milling and die sinking EDM jobs in parallel, this duration gives also an estimation of the whole production time.

3. CHARACTERISATION

3.1 Geometric accuracy

The dimensional control of the manufactured turbine was done on a Mitutoyo FN 905 CMM system, with accuracy up to ± 4,2 μm. The system was equipped with a Renishaw touch probe (Ø 0.7 mm).

Measurements on the shaft were taken over 3 circumferences with 24 points each. The map reveals a conical shape with a cylindricity deviation of 15 μm, when tolerance of 1 μm is required to obtain predictable bearing characteristics. Clearly, this result must be dramatically improved.

In a similar way, the backside of the turbine was scanned (3 circumferences with 12 points each), showing a conical shape as well. The maximum flatness deviation is 7 μm. As a reference, bearing clearance specifications impose a backside flatness tolerance of 2 μm. The adoption of different grinding tools (as for instance cup-shape tools) and new path strategies is currently in discussion, in order to meet this requirement.

Each side of the turbine cavities was scanned over 10 lines with 20 points each. The coordinates were extracted from the turbine CAD model, and converted into the CMM reference system. A CNC code was finally created to execute the measurements automatically. The data obtained were fitted, translated and tilted, in order to compensate for alignment errors. Fig.5 shows the deviation between the CMM data and the CAD

model. All cavities look very similar. Maximum deviations are located near the cavity tips. Specifically, the tip of cavity no. 8 has an overcut up to 50 μm , which suggests to improve the EDM tool strategy and to equally distribute the amount of tools among the cavities. As expected, almost no material stock is observed, with exception of a single point repeated in each cavity (undercut up to 36 μm), whose reason is still unknown to the authors.

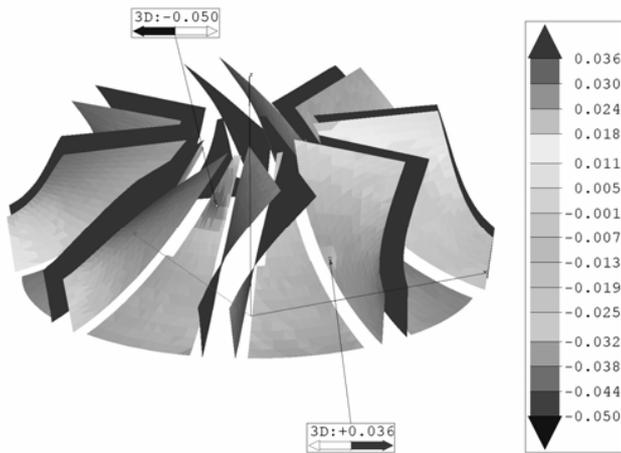


Fig. 5: Deviation map (mm) between the CMM data and the CAD model of the turbine.

3.2 Surface quality

Surface roughness of the turbine cavities was examined on a TalySurf 120L profilometer (Taylor Hobson). A slight improvement was observed ($R_a=2.3 \mu\text{m}$) with respect to the tests described in section 2.1. This may be attributed to better flushing due to enhanced tool retraction and a more favourable “tapered” electrode geometry. However, no significant further improvements are expected, even by decreasing the pulse energy [7]. It is widely recognized that limited surface quality on $\text{Si}_3\text{N}_4\text{-TiN}$ samples is caused by decomposition of Si_3N_4 at high temperature (1700°C). The formation of nitrogen gas bubbles leads to a foamy and porous layer, with an estimated thickness of 20 μm [8]. The presence of micro-cracks is also observed, which could lead to the material strength loss during service [6]. Therefore, a surface treatment is required.

As finishing process, Abrasive Flow Machining (AFM) and 3-axis grinding are currently under evaluation. AFM finishing is fast and simple, while grinding can further enhance the accuracy of the EDM part, but at an additional cost (time

and tools). The application of pure Si_3N_4 and SiC coatings to inhibit oxidation of the bulk material during service is under evaluation as well [8].

4. CONCLUSION

High precision manufacturing of a miniature $\text{Si}_3\text{Ni}_4\text{-TiN}$ ceramic turbine impeller by die-sinking EDM has been proved. To achieve reliable components for the development of portable power units, further improvements are needed. The next step is to apply post-processing techniques to achieve smoother surfaces and tighter tolerances.

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