Crossing barriers in

With products and components getting smaller and smaller, micro-EDM (Electrical Discharge Machining) is a promising technology for machining micro ceramics components. However, the challenges are formidable. Extremely precise machine tools and machining processes with an ultra-small machining unit are essential. This requires generation of low-energy, ultra-short electrical pulses. And knowledge of physical and mechanical properties is needed to gain insight in the dominant material removal mechanisms. Extended applications for ceramic components with an appropriate material-specific, structural design, as well as feasible and cost-effective manufacturing methods are an absolute must to make micro-EDM applicable to future innovations.

• *Kun Liu, Bert Lauwers and Dominiek Reynaerts* •

Anyone who has ever seen what happens when a bolt of lightning hits the ground, has seen the working force of the EDM process in its most primitive form. EDM, short for Electrical Discharge Machining, also often called spark erosion, is an electro-thermal machining process by which the material is removed through a series of discrete discharges between a workpiece and a tool electrode. Each discharge heats both conductive electrodes locally, which causes mainly the workpiece material to melt and evaporate and leaves a tiny crater on the surface; see Figure 1. Both electrodes are submerged in a dielectric medium which functions as a cooling agent, ejects the resolidified debris, and isolates the gap to assure optimal conditions for subsequent spark generation. Because there is no direct physical contact, the forces due to the spark erosion process are negligible, and any electrically conductive material independent of its hardness or brittleness can be machined by various EDM techniques; see Figure 2.

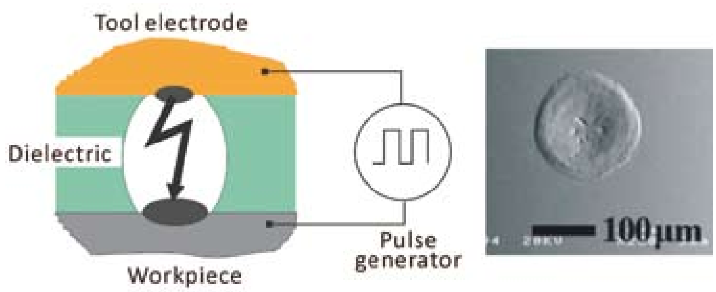


Figure 1. The EDM principle and an image of a crater after discharge.

structuring ceramics

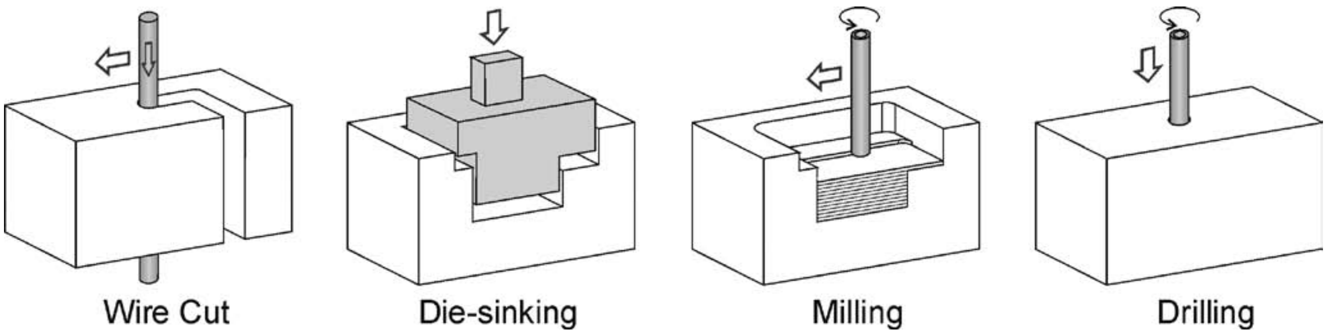


Figure 2. Most commonly used configurations of (micro-) EDM.

Micro

Micro-EDM (or µ-EDM) refers to the manufacturing of miniaturized components by the EDM process. At first glance, there is no real difference between conventional and micro-EDM except for the drastically reduced geometrical scale. Micro-EDM saw light in the early sixties as a process for small-hole drilling and die-sinking at Philips Research Lab (NatLab, Eindhoven, the Netherlands) and found specific applications such as the objective diaphragm in an electron microscope and high-precision profiled holes in diamond drawing dies. Later in the eighties, it recaptured the attention with the invention of WEDG (Wire Electro-Discharge Grinding, see Figure 3) by Prof. T. Masuzawa (Tokyo University), which allowed fabricating micropins as tool electrodes to a record-breaking diameter of 3 µm and microholes with a diameter less than 5 µm at that time. In the meantime, micro-EDM milling was also introduced by applying a cylindrical CNC-controlled tool electrode moving over a programmed tool path to generate a required geometry on a die-sinking EDM machine.

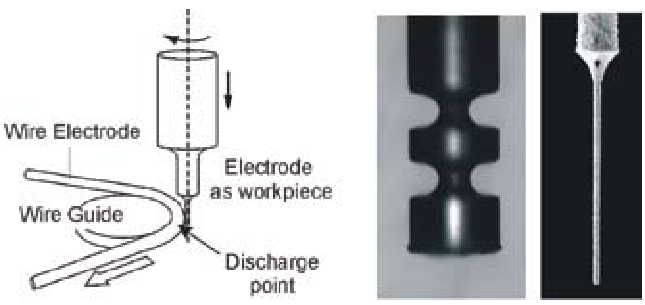


Figure 3. Schematic view of WEDG (Wire Electro-Discharge Grinding) and examples of shaped tool electrodes Ø 0.3 mm (left) and Ø 20 µm with aspect ratio of 20 (right).

Main requirements

Notwithstanding the unchanged working principle, quite a few more factors have to be considered for realizing micro-EDM. First of all, extra precise machine tools and machining processes with an ultra-small machining unit are essential. An extreme positioning resolution of ± 0.1 µm and 1 µm accuracy for some table-top micro-EDM machines can be easily realized thanks to the development in modern drive concepts, motors design and nanopositioning systems (e.g. Sarix S.A., Switzerland; Panasonic, Japan; Smalltec, USA; Makino, Japan; Ocean, Taiwan; etc.).

A small machining unit is defined as the smallest amount of workpiece material which can be removed in a controllable way. Thus the energy input for each discharge is reduced from a few mJ for conventional EDM to a few hundreds or tens of µJ, or even a few tens of nJ for micro-EDM, in order to produce smaller or shallower craters on the surface. More traditional static pulse generators that work through opening and closing of transistors and thyristors are no longer able to provide this condition. Relaxation generators with very small capacitors and a short, solid, and thick cable connection directly to the electrodes are used, to reduce the effects of impedance and inductance. New electronic layout designs are implemented

Table 1. Performance comparison between micro-EDM and alternative micro-manufacturing methods.

	Micro-EDM	Micro-milling	Laser machining	FIB[a] machining	Lithography		
					DRIE[b]	Anisotropic Etching	LIGA[c]
Smallest feature size (μm)	5	50	5	0.005	1-2		0.2
Best surface roughness R_a (μm)	0.05-0.1	0.1-0.2	0.1-0.2	< 0.1	0.2	< 0.1	0.02
Accuracy (μm)	1	1	1	< 0.5	0.1	1	0.3
Maximum aspect ratio	20-40	5-10	1-2	15	30	>> 1	50
Workpiece geometry	3D	3D	2D-3D	3D	2½D	2½D	2½D
Hard and erosive material	++	-	+	++	+	+	-
Applicable materials	++	++	+	++	-	-	-
Process speed	-	+	+	--	++	++	++
Investment (+ being low)	+	+	-	--	--	-	--

[a] FIB = Focused Ion Beam.
[b] DRIE = Deep Reactive Ion Etching.
[c] LIGA = Lithographie, Galvanoformung, Abformung (Lithography, Electroplating, Moulding).

to give extremely short pulse duration (< 30 ns), low discharge current (< 0.5 A) and adaptable pulses. Furthermore, a working gap size typically down to 1-5 μm is essential to attain an adequate accuracy and flushing conditions. In micro-EDM, the demand is for a generator that can generate pulses that are sufficiently short and high in frequency, and for a sensitive servo control for fast reaction to any abnormal gap conditions.

For mass production, micro-tool electrodes can be acquired commercially with minimum outer diameter of 40 μm or tubular tool electrodes down to an outer diameter of 80 μm, covering a wide range of materials including tungsten carbide, graphite, brass, copper, etc. Special attention has to be paid to the precise mounting of the miniature tool electrode. In order to assure the accuracy of the process, this calls for measures such as the development of high-precision clamping devices with a repeatability of less than 1 μm, adding ceramic guides to the electrodes, reducing the number of clamping procedures caused by tool electrode wear, integration of measurement devices into a machine tool such as CCD cameras, chromatic confocal microscopes, etc. The implementation of a WEDG unit on the machine gives more versatility and benefits to the micro-EDM process: the electrodes can be shaped to a diameter of a few tens of micrometers, with an aspect ratio up to 40; see Figure 3. Without reclamping the tools, eccentricities and run-out errors can be avoided. A variety of electrodes can be made to axisymmetrical or non-axisymmetrical shapes, even non-prismatic or customized geometries.

Comparisons

Compared to mechanical machining methods like micro-milling, the ability of micro-EDM to machine hard and brittle materials is one of the strongest points in favor of applying this highly accurate technique. Though other contactless micro-fabrication techniques like laser machining or lithography are also able to machine a variety of materials, their drawback is, however, that the ability to produce very high aspect ratio structures is limited. Furthermore, lithography has such a limitation on fabricating three-dimensional free-form components. With a view on cost-effectiveness, micro-EDM becomes an excellent alternative choice for prototyping and small batch production. Table 1 lists comparisons between the micro-EDM process and alternative micro-manufacturing techniques.

Ceramics

Engineering ceramics like ZrO_2, Al_2O_3, SiC, and Si_3N_4, processed from fine powders, are becoming more and more popular and important in modern engineering because of their outstanding mechanical and physical properties. Therefore they find tremendous applications such as cutting inserts and tools, bearings, engine and heat components, gas turbines, and even dental prostheses, synthetic bones and joints, etc. These diverse ceramics and their composites provide hardness, toughness, wear resistance and chemical stability at high temperature and extreme conditions; see Table 2.

However, those high-performance ceramic materials also bring along difficulties in directly structuring them into desired sizes and shapes. Traditional economic casting and sintering, or even more complex methods such as injection moulding or 'hot wax moulding', can satisfy most of the demands in precision yet with flaws like shrinkage, demoulding and debinding defects, not to mention the very limited capability in producing three-dimensional and micro-parts. Mechanical processing like grinding which is often applied as the finishing technique, gives very good

Table 2. Comparison of physical and mechanical properties of steel, hard metal, ceramics and their composites.

	Composition	**Density** (g/cm³)	**Hardness**[a] (GPa)	**Thermal conductivity @ 20°C** (W/m·K)	**Fracture toughness K_{ic}** (MPa·m$^{1/2}$)	**Young's Modulus** (GPa)	**3-Point flexural strength @ 20°C** (MPa)
HSS (e.g. Böhler S590)		8.1	62-64 [HRC]	24	20-50	242	
WC-Co	Balance/ 12 wt% Co	14.08	12.8 [HV_{10}]	95	> 15	563	4,280
Si_3N_4		3.17	16 [HV_{10}]	29	6.8	309	900
Si_3N_4-TiN	64/36 vol%	3.95	15 [HV_{10}]	28	8.7	333	980
SiC		3.22	26 [$HV_{0.5}$]	125	4.6	456	670
SiSiC	88 vol% SiC	3.05	12-28 [$HV_{0.5}$]	150	4.1	360	320
Al_2O_3		3.98	18 [HV_{10}]	30	5.2	380	420
Al_2O_3-TiCN	60/40 vol%	4.45	21.2 [HV_3]	–	2.5	417	700
ZrO_2		6	13 [HV_{10}]	3	10	220	900
ZrO_2-TiN	66/34 vol%	5.81	13.7 [HV_{10}]	8	12.5	290	1,500
TiB_2		4.5	25 [$HV_{0.5}$]	96	6.2	240	400
B_4C		2.5	32 [$HV_{0.5}$]	40	3.0	450	400

[a] HRC: Rockwell scale hardness; HV: Vickers scale hardness.
Sources: Saint-Gobain ceramics; Böhler Special Steel; K.U.Leuven.

results regarding surface quality and geometrical accuracy, but the slow machining speed leads to a rise in production costs and unit price. Thus, (micro-) EDM as a flexible, inexpensive and precise method is called in for filling in the gap.

Solving difficulties

The most obvious problem is the electrical conductivity. Experience shows that the boundary of electrical conductivity for the EDM process is around 10^{-2} S/cm. Therefore, conductive ceramics like TiB_2, TiN and tungsten carbide (WC) can be directly structured using EDM. Some silicon carbides and B_4C, however, are on the transition zone and their machinability by EDM largely depends on the applied technology. Nevertheless, a large variety of ceramic materials like alumina, zirconia, and silicon nitride are too resistive to be machined; see Figure 4. For that reason, by mixing one or two electrical conductive phase(s) such as borides, nitrides or carbides of transition metals into the ceramic matrix at the powder stage, some composites show greatly improved electrical conductivity. The most popular applied secondary phases are TiN, TiCN or TiC, since they also help further improving the mechanical properties such as toughness, strength and hardness of the composites.

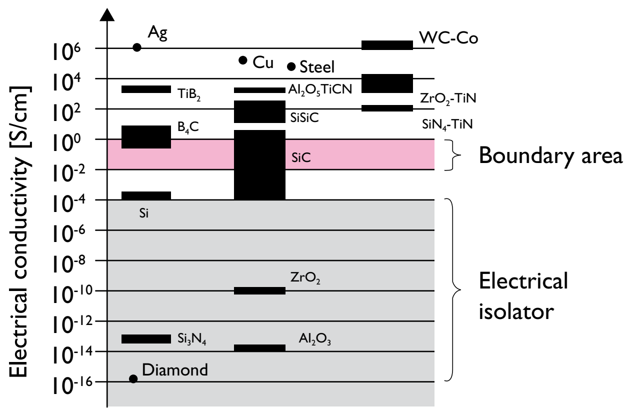


Figure 4. Overview of materials with their electrical conductivity.

Quite a few ceramic processing companies like Saint-Gobain (France), ESK (Germany) and FCT-Keramik (Germany), etc., commercialize a range of electro-conductive materials such as ZrO_2-TiN, Al_2O_3-SiC_w-TiC (subscript w stands for whiskers reinforced Al_2O_3-TiC ceramic composite), SiSiC (silicon infiltrated SiC) and Si_3N_4-TiN, etc., for specific industrial applications. At K.U.Leuven, the effects of a variety of secondary phases on physical and mechanical properties as well as the EDM machining performances of the ceramic composites are being investigated by varying electrical conductive phases with different percentages, grain sizes, sintering aids, binding materials, processing techniques, etc.

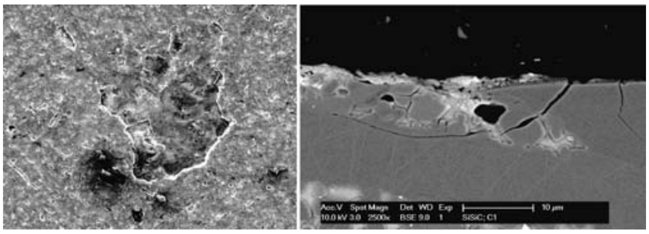


Figure 5. Spalling effects of micro-EDM on SSiC (left) and SiSiC, respectively.

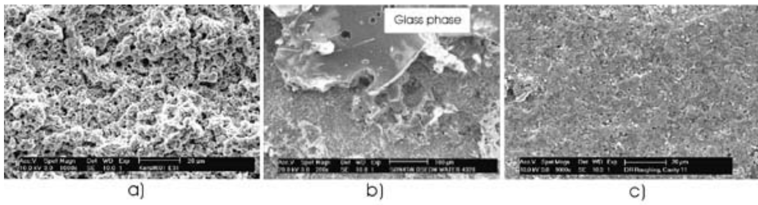


Figure 6. Various material removal mechanisms of µ-EDM on Si_3N_4-TiN, as explained in the text.

Technology drives

The practical difficulties can be credited to the fact that the efficiency of EDMing ceramic materials is largely depending on the proper knowledge of the ‘process-material interaction’. Each ceramic or its composite will react distinctively under diverse discharge conditions during the EDM process. As a result, the cross-linking of the material properties with the process characterization is most important but also very difficult. In micro-EDM, extreme-low-energy and ultra-short-duration pulses would give unexpected performances thus requiring additional investigation.

Variations in material removal mechanisms

As we all know, in EDM of metallic materials, melting and evaporation are the only forms of material removal from the workpiece. However, the machining phenomena are not exactly identical when EDMing ceramics. Research has shown that other types of material removal are coexistent with melting and evaporation under variable machining conditions, for example ‘spalling’ and chemical reactions. Spalling is removal of solid particles due to thermal shocks and disintegration of structural elements because of the melting of the binder phase. It is often related to the generation of large micro-cracks (perpendicular and parallel to the top surface) during the EDM process. These big micro-cracks make the separation of a (larger) volume during successive discharges much easier. These effects are noticed more frequently on the ceramic composites with lower toughness, strength and thermal conductivity, e.g. materials such as SiSiC and SSiC (Sintered SiC), Al_2O_3-TiCN, and B_4C. Even with small pulse energy and short pulse duration during micro-EDM, this phenomenon persists and sometimes dominates as the main material removal format; see Figure 5.

The conductive phases in the ceramic composite matrix are often chemically unstable at high temperature and in oxygen-rich conditions. Chemical reactions such as decomposition and oxidation thus become another important type of material removal mechanism (MRM) during (micro-) EDM. For example, TiN, TiCN and TiB_2 are easily oxidized into gasified TiO_2 and B_2O_3, etc., accompanied with nitrogen gas bubbles. When the EDM process is happening in a water environment, the oxidation gets even more dominant. The generation of these gases, in most of the cases, leads to a porous, foamy and sponge-like surface structure; see Figure 6a.

On the other hand, materials like Si_3N_4 are already experiencing decomposition at relatively low temperature around 1,700°C:

$$Si_3N_4 \rightarrow 3\ Si + 2\ N_2\ (g)$$

The liquid Si quickly reacts with oxygen to SiO_2 and contributes to the generation of more gas. When using deionised water as dielectric, the Si also reacts with O_2 forming a glassy and non-conductive SiO_2 phase, preventing further EDM machining; see Figure 6b.

Chemical reactions as material removal mechanism often have a very high impact on the machining performance, regarding speed, surface quality, as well as tool wear. Comparing to micro-EDM of metal, simply reducing the input discharge energy for improving the surface quality on a ceramic composite sometimes is not adequate. For example, when machining Si_3N_4-TiN, experiments confirm that by finetuning the discharge pulse duration, the dominant material removal mechanisms can alter from decomposition and oxidation to melting and evaporation, and a better surface quality can be obtained even with moderate discharge energy input; see Figure 6c.

Adapted machining parameters

Apart from a variation in MRMs, another important issue for machining some ceramics is the voltage drop on the workpiece during a discharge because of their lower electrical conductivity. The impedance of the material consumes energy and changes the shape of discharge pulses. This might be in a favor of improving the surface quality but apparently part of the machining speed is sacrificed, along with possibly more tool consumption (electrode wear). More importantly, the traditional servo-feed control needs to be adjusted for overcoming the elevated discharge voltage, avoiding abnormal machining conditions and further improving the machining efficiency. Table 3 presents comparisons of machining performances of a few frequently-used engineering ceramics and ceramic composites by micro-EDM.

Table 3. The optimized micro-EDM milling performances on ceramics and ceramic composites.

Material	Dielectric/ tool	Energy scale[a] (μJ)	Material removal rate (mm³/min)	Tool wear ratio (%)	Surface roughness R_a (μm)	Main material removal mechanisms
SiC	Oil/WC	24.5×10^3	0.12	19	0.82	Spalling
		320	0.03	13	0.20	Melting and Evaporation
SiSiC		400	0.65	19	1.50	
		12	0.05	10.5	0.43	
Si_3N_4-TiN		215	0.36	1.8	2.45	Foamy surface; chemical reactions
		8	0.05	6.0	0.70	
		600	0.32	5.4	2.10	Non-foamy surface; melting and evaporation
		8	0.04	8.3	0.54	
		16	0.003	~ 20	0.25	Non-foamy surface with modified RC generator
ZrO_2-TiN		150	0.20	5.2	1.08	Melting and Evaporation
		3	0.012	7.7	0.31	
Al_2O_3-TiCN		150	0.20	8.1	0.72	
		3	0.02	8.3	0.24	
TiB_2	Oil/Brass	150	0.09	69.2	1.20	Oxidation
		3	0.005	27.3	0.29	
	Water/Brass	150	0.09	31.0	1.26	
		3	0.014	19.4	0.33	

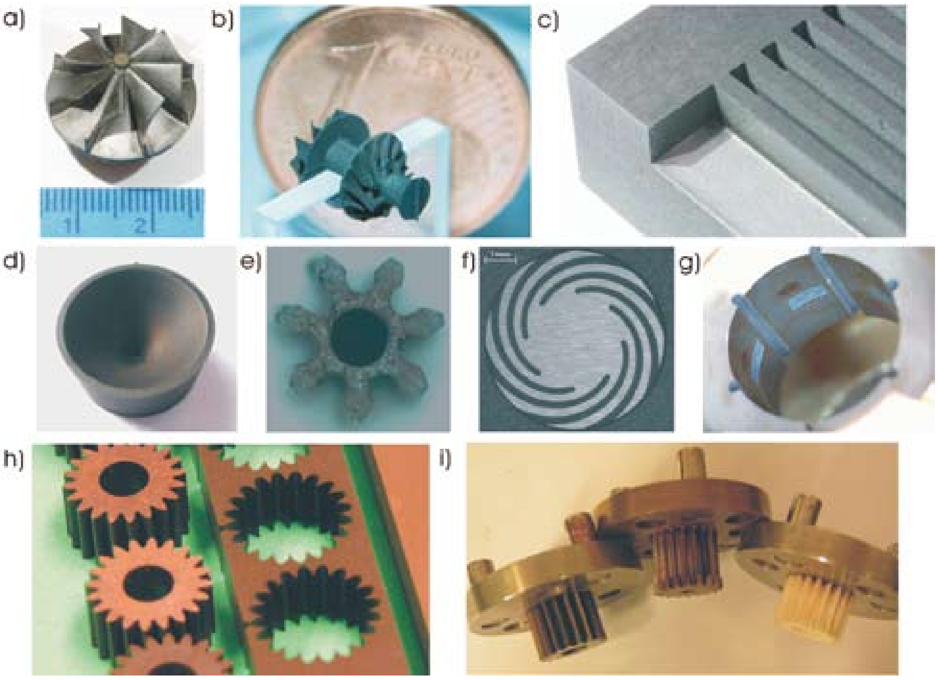
[a] Total energy consumption including voltage drop in the material and discharge.

Application examples

Nowadays, a tremendous amount of applications for ceramic components can be found in industry. The high hardness, wear resistance, thermal and chemical stability make these modern engineering materials an excellent choice for applications such as adhesive spray nozzles, cutting tools, medical devices, heat exchangers, even turbine impellers in micro-scale power-generation systems (see www.powermems.be), and of course gears, die inserts and moulds. A few examples in various ceramic materials and dimensions are shown in Figure 7. The versatility of the micro-EDM process allows machining prototypes and parts in a much more economic way. For example the ZrO_2-TiN planetary transmission gears from maxon motors (Germany) have a 50% longer lifetime than pure ZrO_2 gears made by classical methods. By combining different EDM machining processes like micro-EDM milling, (micro-) wire EDM and (micro-) sinking EDM, very complex-shaped structures can be produced, and even with improved machining efficiency. For example, by combining EDM die-sinking and EDM milling for making B_4C spray nozzles, processing-time reductions up to 50% can be obtained. Besides, instead of using its original material (metal alloy), the lifetime of the nozzle is increased by a factor of at least five. Another recent high-tech example – the micro-turbine impeller shown in Figure 7a – is a result of sinking EDM and wire EDM or can be directly machined by micro-EDM milling; see Figure 8.

Challenges for future research

With the future perspective that products and components are getting smaller and smaller, plenty of challenges still exist for the micro-EDM process and structuring of micro ceramics components. On one side, for most conventional EDM machine tool builders, micro-EDM is inevitably an additional domain for competition in the market. The development of ultra-high-precision machines not just requires a thermal- and vibration-isolated, extremely stable base, or simply 'down-scaling' the conventional machine. The requirements on the pulse generator, servo control, the ability to machine free-form products, and automation for clamping/unclamping of tool/workpiece, are difficult and intricate tasks for the machine builders, uniquely so for micro-EDM. On the other hand, the process knowledge base is often still restricted to metal and cermets manufacturing. A rich database for ceramic materials requires a vigorous investigation as mentioned before regarding material variations and their effects on the machining processes. The lack of a proper knowledge database and experience in the current situation and the large variety of choices in materials make this task an exceptionally challenging one. Extended applications for ceramic components with an appropriate material-specific, structural design, as well as feasible and cost-effective manufacturing methods are an absolute must to make micro-EDM applicable to future innovations.



(a) Ø 20 mm Si_3N_4-TiN turbine impeller aiming at rotation speed of 500,000 rpm and service temperature of 1,200 K.
(b) Si_3N_4-TiN turboshaft with a Ø 5 mm compressor and a Ø 5 mm turbine impeller.
(c) Partial image of a heat exchanger component in SiSiC with a grid width of 1 mm.
(d) B_4C nozzle with a spray hole Ø 0.7 mm.
(e) Ø 1 mm miniature gear wheel in AlN-TiN by wire EDM.
(f) Ø 6 mm ZrO_2-TiN aerodynamic thrust bearing.
(g) Ø 6 mm Si_3N_4-TiN journal air bearing with micro-EDMed pockets and Ø 0.2 mm air feeding holes, reached working speed at 438,600 rpm.
(h) ZrO_2-TiN transmission gears by wire EDM.
(i) Assembled ZrO_2-TiN transmission gears (SMS & WTS, the Netherlands; maxon motors, Germany).

Figure 7. Application examples of ceramics and ceramic composites manufactured by micro-EDM.

Figure 8. Three-dimensional micro-EDM milling of a Si_3N_4-TiN turbine impeller in progress.

Authors' note

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Acknowledgement

Part of the research was sponsored by the Institute for the Promotion of Innovation by Science and Technology in Flanders, Belgium. It was carried out within the framework of the EC Network for Excellence 4M (Multi-Material Micro Manufacture: Technologies and Applications) and the EU FP6 projects Moncerat and EuroTooling. The authors would like to thank Prof. J. Vleugels from MTM, K.U. Leuven, dr. P. Bleys, dr. J. Peirs, and dr. E. Ferraris from PMA, K.U.Leuven, for their contributions to the research; and J. Wijers for reading and correcting this article.

Information

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