Strojniški vestnik - Journal of Mechanical Engineering 52(2006)7-8, 484-494
UDK - UDC 621.914+621.941
Pregledni znanstveni članek - Review scientific paper (1.02)

Mehanska mikroobdelava s frezanjem, žično erozijo, potopno erozijo in diamantnim struženjem

Mechanical Micro-Machining Using Milling, Wire EDM, Die-Sinking EDM and Diamond Turning

Alberto Herrero[1] - Igor Goenaga[1] - Sabino Azcarate[1] - Luis Uriarte[1] - Atanas Ivanov[2] - Andrew Rees[2] -
Christian Wenzel[3] - Claas Müller[4]
([1]Fundacion Tekniker, Spain; [2]Cardiff University, United Kingdom; [3]Fraunhofer Institute for Production
Technology IPT, Germany; [4]Albert-Ludwigs-University Freiburg, Germany)

Med vsemi različnimi mikroobdelavami se ta prispevek osredotoča na tehnike, ki se lahko štejejo kot običajni obdelovalni postopki. Obravnavani so naslednji obdelovalni postopki: zelo natančno rezkanje, obdelava s tanko žično erozijo, potopna erozija ter diamantno struženje. Kljub splošnosti postopkov ima vsaka izmed njih posebno lastnost, ki izboljša njihove zmožnosti obdelave. Postopki so v tem prispevku analizirani, prikazane pa so tudi njihove razlike s splošnimi obdelovalnimi postopki nato pa so prikazane še njihove omejitve. Predstavljene so tudi najnovejše uporabe in potencialni trgi. Čisto na koncu je prikazana še primerjava teh postopkov z drugimi izdelovalnimi postopki, kakor je litografija z namenom poudariti mogoče pristojnosti in dopolnila.

(Ključne besede: obdelave zelo natančne, mikroobdelave, rezkanje, struženje diamantno, obdelave elektroerozijske)

From among all the different techniques currently applied for micro-manufacturing, this paper focuses on those techniques that can be considered as conventional techniques because of their direct relationship with standard machine tools. The following processes are discussed: ultra-precision milling, thin-wire EDM, die-sinking micro-EDM and diamond turning. Despite the mentioned relationship with conventional machine tools, they all have special characteristics that enhance the capability of the machining principle. The processes are analysed, showing the differences with respect to the corresponding conventional processes and stating their current limitations. A review of the state of the art, applications and potential markets is presented. Finally, the capabilities of these technologies and the other micro-manufacturing techniques (lithographic processes) are compared in order to highlight the possible competences and complementariness that they present.

(Keywords: ultra-precision machining, micromachining, milling, diamond turning, EDM)

0 INTRODUCTION

During recent years, the so-called "micro-technologies" have invaded the production of different components in some strategic sectors like automotive, electronics are medical ([1] and [2]). The name has been used during the past 5 years, and brings together all those technologies that are capable of producing small parts. In any case, even today, it has an ambiguous meaning due to the lack of clearly defined dimensions. The discussion about the meaning of "micro-technologies" is not new ([3] and [4]), and the dimensional limits are still fuzzy. The reasonably accepted limits are shown below:

· Micro-technologies: from 0.5 to 499 μm in 2D/3D.
· Nano-technologies: from 0.5 to 499 nm in 2D/3D.

In order to keep these dimensions in perspective: 1 micrometer is 0.001 millimetres, and 1 nanometre is 10^{-6} millimetres (1 nm = 10^{-9} m) or 10 angstroms. An illustrative example is the dimension of a human hair (Fig. 1), with a usual diameter of 80 to 100 μm.

Micro-technologies are capable of achieving tolerances smaller than 0.5 μm and an average sur-

Fig. 1. *A hair machined by a femto-second laser (image captured by x20 confocal microscope)*

face roughness of less than 50 nm. The corresponding conventional processes achieve 1 to 10-µm tolerances (if CNCs are used, 10 to 100 for manual machines) and a 50 to 100-nm average roughness. Micro-technologies are usually divided into two groups:

1) *Lithographic processes:* they have evolved from the 2D technologies applied in the production of circuit boards. They can produce stair-by-stair (referred as 2.5D) structures with very high resolution in XYZ. Most of these technologies must be applied in a clean-room environment. They can machine a limited range of materials (silicon being the most documented material) with a maximum aspect ratio close to 1:100 (which can be improved for some techniques, like LIGA).
2) *Ultra-precision processes:* they are the evolution of the usual industrial production technologies for precision components. They were initially applied by watchmakers, but now other sectors like surgical equipment, aerospace or nuclear vessels make use of them. The applied machinery is adapted for micro-machining: smaller tools, higher resolution, environmental isolation, etc.

Some technologies belonging to the second group are analysed below: micro-milling, diamond turning and EDM.

1 LITHOGRAPHIC VS ULTRA-PRECISION PROCESSES

From searching the available information about micro-technologies, it seems like lithographic and ultra-precision processes are competitors in the production of microsystems. Nevertheless, if a deeper analysis is performed, these technologies are found to be complementary, and only compete in some particular cases; just as happens between different machining technologies.

Analysing the geometry of the obtainable features, ultra-precision technologies can produce complex free-form 3D profiles that cannot be obtained with lithographic processes.

Considering the maximum dimensions of the part, the lithographic processes can only machine parts on very flat wafers and cannot take an accurate reference with respect to other features of the part. The ultra-precision technologies have an important market in the machining of small accurate features or textures of bigger parts (moulds, dies, punches, etc.) obtained by conventional machining methods.

Considering the machinable range of materials, the clean-room processes can machine silicon, Pyrex, glass, chrome, nickel, gold, etc., with some of them being brittle and difficult to machine using ultra-precision techniques. On the other hand, ultra-precision techniques can machine most plastics, metals and ceramics. The material of a micro-part is an important specification when choosing the right machining process.

Concerning the part's accuracy, generally speaking, the clean-room processes obtain a better accuracy (one order of magnitude better: ±0.1 µm vs ±1 µm) than the mechanical processes, which are limited by the tolerances of the part-to-tool stiffness loop. On the other hand, this consideration must be carefully analysed, because, despite the high precision of lithographic processes when projecting a mask, the mask accuracy itself should be considered as an error in the process. This error can be very small (<50 nm when using an ion beam, but it is a very expensive process) but sometimes the mask is produced by ultra-precision techniques like laser or milling. Considering the production yield, lithographic processes are easier to apply for high-yield production, but they are very expensive for low-yield production; the ultra-precision processes being more suitable for the production of small series.

The integration of all these technologies in industry is very slow. They are mainly applied by universities and research centres due to the high cost of the required equipment and their low productivity, added to the required skills for the process application, which leads to the important cost of manpower.

Those countries that have an active industry based on microelectronics are more active in the research of lithographic processes; however, those countries with a tradition in the metal-processing industry are more active in the research of ultra-precision technologies.

2 DIAMOND TURNING

Diamond turning is a cutting process capable of producing an absolute accuracy of better than 1 μm, and a 0.002 to 0.005 μm average roughness in some metals, plastics and ceramics [6]. Its application is the production of mirror surfaces in optical-quality components, moulds or reference parts.

The machine must be able to provide high stiffness, thermal and kinematic stability (lack of straightness errors, angular errors or vibrations, hydrostatic bearings are usual for this purpose) and high resolution [7] (~0.01 μm). The tool geometry must be accurate, the control of the edge radius and the tool tip radius being the key parameters to obtaining a mirror finish. The control must be performed with an accuracy of 3 to 75 nm.

2.1 Diamond for Turning

Diamond presents some special features that make it ideal for cutting: high stiffness (E = 700 to 1200 GPa; G = 300 GPa), high thermal conductivity at room temperature (2000 W/mK), easy to work and easy to obtain flat surfaces and sharp edges in its crystallographic directions. Diamond can machine for long periods, keeping the tool geometry and providing both high precision and low roughness (depending on the tool radius and the process parameters). On the other hand, diamond is a brittle material and the tool can break easily if it receives an impact (tool higher than the part's axis, excessive feeds, important variations in the depth of cut, etc.), with this being catastrophic.

As a cutting tool diamond can be found as:
- *Natural Mono-crystalline Diamond:* presents different properties in different crystallographic directions and can have some impurities that reduce the tool's service life.
- *Poly-crystalline Diamond (PCD)*: is a cermet composed of cobalt as a binder and small diamond grains.
- *Synthetic Diamonds*: are obtained using pure graphite that is pressurised (55000 bar) and heated (1500ºC). The obtained diamond has a perfect crystallographic structure with almost no impurities.

In the diamond-turning process, natural and synthetic diamond tools are usually applied, with the latter ones being more expensive (no imperfections). In other processes, like grinding or cutting tools, PCD and synthetic diamond are applied as hard coatings.

2.2 Diamond Machinable Materials

Diamond has a low reactivity with many other materials. At high temperature it reacts with those metals that have an affinity for the carbon in its structure, forming carbides that contaminate the tool, which loses its properties and wears ([8] to [10]).

Favourable materials are:
- *Metals:* aluminium alloys, brass, bronze, copper, gold, silver, zinc, beryllium, lead, tin, indium, plutonium, magnesium
- *Plastics:* metacrylate (PMMA), polycarbonate, Teflon, PVC, polypropylene, polyester
- *Glass:* silicon, germanium

Glass machining produces a higher tool wear [11]. The machining of plastics can introduce some internal tensions that cause the subsequent deformation of the plastics. In all these materials an average surface roughness of 3 to 6 nm and an absolute accuracy of 1to 2 μm can be obtained.

With regard to the materials that have an affinity for carbon, these include: steel, nickel, titanium, molybdenum, cobalt, chrome, vanadium, rhodium and tungsten.

2.3 Diamond Turning Process

The machine configuration and the process concept are similar to a conventional lathe, but the process parameters are different [7]. The part must be pre-machined in another lathe, with an excess of material of around 0.3 to 0.5 mm.

The tool-tip radius must be controlled with a very high precision [12], the other parameters of the tool are as follows (Fig. 2): the rake angle is close to 0º (slightly positive for plastics ~5º) and the clearance angle is close to 6 to 10º. Diamond makes it possible to obtain an edge radius close to 20 n be-

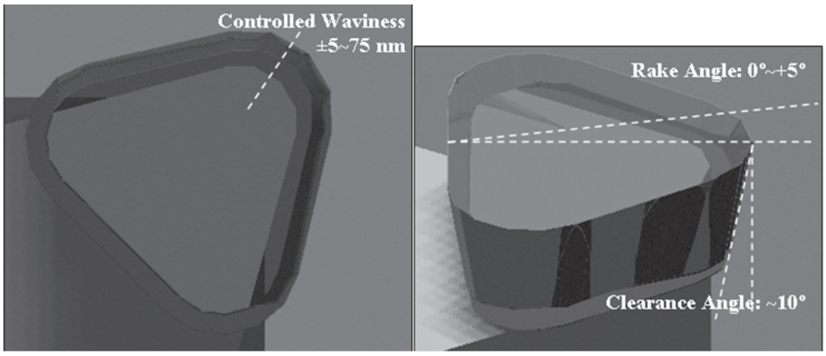

Fig. 2. *Typical tool geometry (solid rendering)*

tween the clearance and the rake planes. Such a small value makes it possible to cut with a very small depth of cut. Rough machining for diamond turning implies a depth of cut of 40 to 50 µm, in finishing it can be 1 to 2 µm. The usual feeds are 5 to 40 mm/rev, and the spindle speed range is 1500 to 2000 rev/min.

The coolant is an air-oil mixture targeted at the tool tip. It will remove the chips, lubricate the cutting area, and cool the tool. The chips must be removed because otherwise they would cause marks if they stayed stuck to the tool edge. Special care must be taken when orienting the coolant nozzles.

2.4 Diamond Turning Applications

The process can be applied for two different purposes:

1) The machines are stiff, stable and can move with very high precision. These specifications make it suitable for micro-machining (Fig. 3, right).
2) Using the correct tools, mirror finishing can be obtained, avoiding several operations (turning-grinding-polishing) (Fig. 3, left).

For micro-machining the process is suitable for producing small diameter shafts (0.2 to 0.02 mm) and small slots (using small tailor-made tools). Part cutting becomes an important issue. Mirror finishing is currently its main market, and some applications are as follows: laser-driving optics, wavelength-filtering surfaces, moulds for components of optical quality, etc.

3 MILLING

The ultra-precision milling process is very similar to conventional milling, being an intuitive process that can easily be assimilated by any operator. Despite cutting chip widths of just a few nanometres, the effect of inter-atomic forces, sometimes considered by other authors, is negligible.

The milling machine has some special characteristics. At present, there are a few commercial solutions ([14] and [15]). Knowledge about the machine is linked to the process knowledge, and it is important to understand what happens at the tip of the tool. Just as with diamond turning, the process parameters, the tools and the cutting process itself have some differences with respect to conventional milling.

3.1 Tools and Auxiliary Systems

Micro-milling depends a lot on the auxiliary components needed for the process, which is why the entire group (machine, components, tools, etc.) must

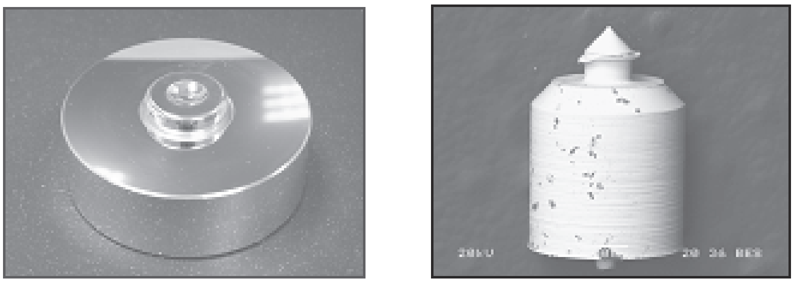

Fig. 3. *Mirror surface machined in aluminium (shape error <0.08 µm in spherical zone, <0.05 µm in flat zone); Miniature Ø0.75 mm brass part.*

be analysed as a whole. Apart from the machine, this includes the tools, the spindle, the collet and the referencing system.

Tools

The tool market is very active in the development of new tools (drills, mills) for micro-machining. In the past several years the minimum diameter of mills has decreased from 0.25 mm to 0.1 mm, the range includes spherical and straight 2-flute mills made of carbide with different coatings (TiAl, TiAlN, CBN, CBD, etc.). In any case, the range is limited and there are no different geometries for different materials. This is an important problem because most of the tools are designed for steel machining. It is important to point out that grain size has a large influence on the tool's performance.

Commercial tools have a well-defined geometry with small tolerances. The tolerances indicated in the catalogues for the sum of the geometrical error plus the run-out error are de ±10 μm. (The tolerance-to-size ratio is poor when compared to conventional high-speed machining mills.) The real errors are usually smaller (±5 μm). A second option is to use tailor-made tools. These tools are provided by specialised companies at a higher cost. These mills can present one (engraving tool) or two flutes with a custom geometry (face angle, helix angle, rake angle) and the diameters can be as small as 0.01 mm. The geometry of the tools has a high dispersion, which is an important issue when changing the tool to continue a machining process.

Spindle and collets

Because of the use of such small tools, the spindle must rotate at high revolutions (120000 to 160000 rev/min) to achieve an appropriate cutting speed for most materials. Apart from the speed, the spindle must be stiff (>25 N/μm) and it must have a small run-out (<1 μm) in order to ensure the high precision of the cutting process. To reach such high speeds, the spindles have ceramic ball bearings that are continuously cooled and lubricated. They are usually low-power electro-spindles (200 to 500 W) or aerostatic spindles.

Usually, the tool is clamped manually using special collets to reduce the run-out. The most common form of collets are the precision ER type collets (clamp a small range of diameters close to a nominal value) and the super-precision ER type collets (only clamp the nominal diameter). The precision collets can present big run-out errors that depend on the clamped diameter, the super-precision collets have run-out errors smaller than 2 μm.

Tool wear during micro-milling is relatively high, and that is the reason why it is usual to use two or more mills per operation (one for rough machining, the other for finishing). Tool change is a critical operation because the tool run-out, tool height and collet run-out are modified, thus it must be performed carefully, cleaning the cone, collet, tool and nut and applying controlled torques.

Referencing system

In many cases the micro-milling operations must be referenced to other operations, surfaces or part features that have previously been machined. Part referencing is performed in the same way as in conventional milling: the tool is moved until it is "touching" the part in different axes. Commercial touch triggers have errors close to 5 to 10 μm, but this error is very big for micro-machining.

Alternatively, the trigger is done optically. The machine resolution being much better than in conventional systems (approaching micron-by-micron), it is more difficult to identify the first chip that is cut in the part. In order to assist this action, the micro-milling machines are equipped with high magnification (x100 to 200) vision systems that are used for referencing and also to inspect the machining process. Depending on the applied magnification, both the field of view and the depth of view get very reduced, and the working distance must be fixed with higher precision. It is typical to use zoom systems capable of augmenting the image from x60 to x200: the highest magnification is only used for referencing, while the lower magnification provides a greater depth of view that is adequate for process inspection.

3.2 Materials for Milling

The application of different coatings for the tools and different cutting speeds makes it possible to machine metals, plastics and ceramics ([14] and [15]).

The greater limitations of the process are the lack of tool geometries adapted to machine different materials and the high wear produced at the tool tip (specially for hardened steels and ceramics).

3.3 Micro-milling Process

As was mentioned for diamond turning, the machine configuration and the geometrical concept are similar to the corresponding macro-process, although there are some important differences in the machine components and the process parameters ([16] and [17]).

Considering the process parameters, the depth of cut is very reduced for roughing (<10 μm, depending on the part material and the tool diameter) and finishing (2 to 3 μm). These values would cause part sticking and wrong cutting during normal machining. The feeds are reduced (<40 mm/min) and the spindle rotates at high speed (>40000 rev/min). The cutting speeds are close to 25 m/min for steels, and the chip thickness is small (<0.5 μm).

Tool geometry has a large influence on the cutting performance. An important effect that is not usually considered in milling is the edge radius between the rake face and the clearance face. This radius can be the source of important errors during the milling process, because the tool instead of the cutting ploughs the surface material when the depth of cut is very small. The edge radius must be smaller than the chip thickness in order to cut (~0.1 μm, Fig. 4).

Analysing the distribution of the cutting forces acting on the flute of the tool (Fig. 4) it can be appreciated that when cutting a 2-μm depth of cut, the mean rake angle will be different to the nominal value. The mean rake angle will depend on the rake face, the tool edge radius [18], tending to be negative and so plough the material.

The forces acting on the tool will be relatively larger than during normal milling: the specific cutting pressure (p_s) increases as the depth of cut decreases (it is experimentally tested for normal machining). Unfortunately, the values for micro-milling are still unknown. If the values are extrapolated assuming an exponential relation, the cutting forces are close to 5 to 10 mN when milling hardened steels. Considering the tool diameter, these forces cause important deflections that produce higher tool wear and tool breakage.

Micro-milling can obtain an average surface roughness, R_a, close to 0.1 to 0.05 μm, burr formation being a key issue for this technology. Burrs tend to appear on the edges when machining boxes, they are small chips that could not be evacuated and were stuck to the piece walls by the next flute. Deburring is a complex task that can be minimised with optimised tool paths and using a new tool for finishing.

3.4 Micro-milling applications

Comparing micro-milling to other micro-machining technologies, this process is capable of machining freeform 3D shapes (Fig. 5 left) that cannot be obtained with most of the other processes (2D or 2.5D).

In the other processes the machinable range of the materials is limited (electrically conductive

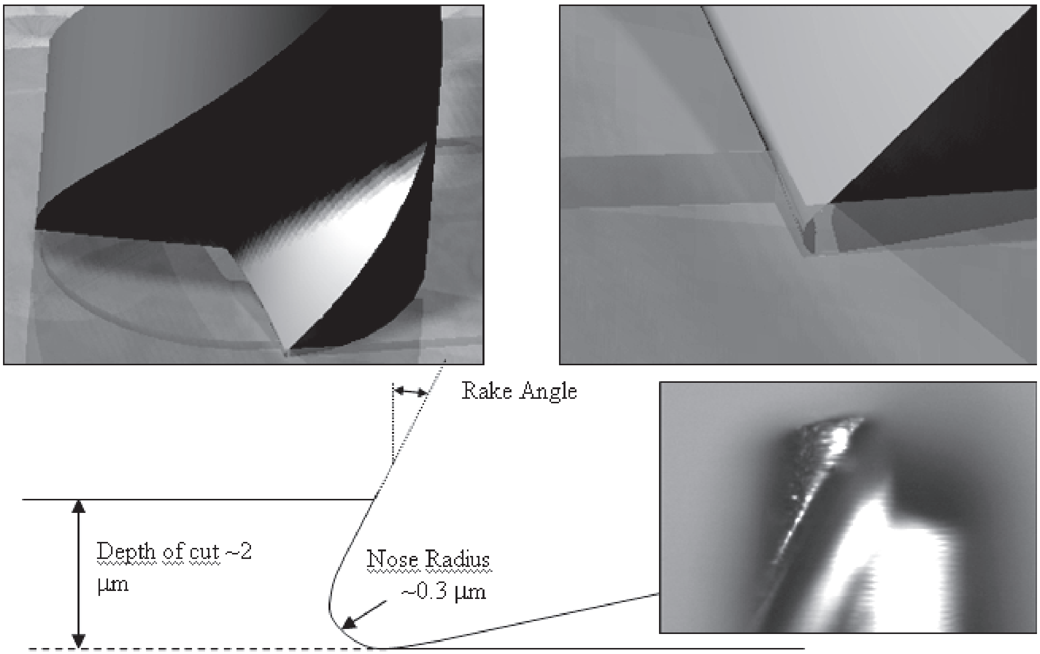

Fig. 4. *Geometry of a 2-flute straight mill, detail of the edge radius. Ø 0.2 mill captured by confocal microscope (x100)*

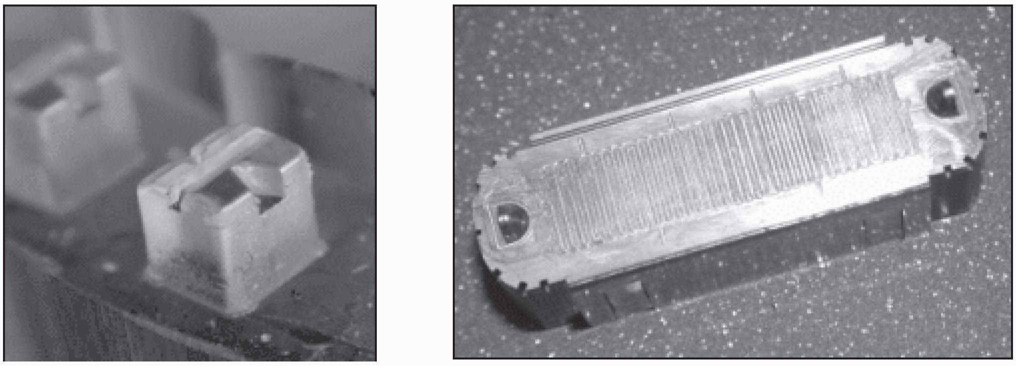

Fig. 5. *Bracket made of polysulfone (3x3x2 mm); mould for a drug-delivery system (channel height 0.1 mm; channel width 0.3 mm; wall thickness 0.2 mm; accuracy ±2 µm; roughness 0.15 µm Ra).*

materials for EDM, diamond-compatible materials for diamond turning, etc.), but micro-milling can be applied to a wider range of materials by using mills with different coatings. This is also important because it can process not only miniaturised parts, but also precision features in big parts.

Another advantage of micro-milling is its similarity with the conventional process. This makes the process easier to introduce in industry. Many applications of micro-milling involve the machining of medical parts (Fig. 5, right) and surgical tools (the sector in which this technology has opened new opportunities), moulds and dies, scientific research, etc.

5 DIE-SINK EDM AND MICRO-EDM

The lack of cutting forces and the capability of removing small portions of material per spark makes EDM a perfect process for micro-machining. The die-sinking EDM process was studied by many companies and institutes, with new machines and auxiliary systems capable of machining smaller features appearing. Comparing the process to conventional EDM, the main differences are the electrode dimensions, the higher resolution of the machine and the capability to produce less energetic pulses (~100 nJ). As T. Masuzawa explained [19], the pulse energy is proportional to the voltage, the intensity and the spark duration. The process is also different in terms of sludge removal, process parameters and electrode wear.

The current and voltage must have some minimum values to overcome the resistance of the cables and connections and produce the spark. Thus, to reduce the pulse energy, the time must be controlled. Transistorised generators can reduce the pulse interval to 0.5 ms, while the relaxation circuits (RC circuits) can produce pulses of some microseconds. Most of micro-EDM machines use RC generators with small condensers (<10 pF), reducing pulse time and energy.

One of the most important applications for micro-EDM is micro-drilling with small electrodes (Ø0.1 mm, with an aspect ratio 50:1) made of tungsten. These can be used for fuel injectors, air injectors, precision dispensers, ink-jet printing, filters, etc. Smaller holes can be made by electrode-dressing techniques (Fig. 6 left). Among these techniques are the following: slab milling and wire electro-discharge grinding (WEDG – Wire Electro Discharge Grinding, developed in 1985, by T. Masuzawa of Tokyo University). WEDG is a technique that incorporates a wire electro-discharge unit horizontally in the sinking EDM working area. Changing the electrode polarity, it can be dressed against the wire electrode, decreasing its diameter to 10 to 20 µm. Controlling the Z axis rotation, it is possible to produce form electrodes [22].

A second research field in the sinking EDM process has started to use the electrode to sculpt complex 3D shapes, controlling its position in space (similar to the milling process) (Fig. 6, right). This process is named EDM-milling. In EDM-milling the tip of the electrode wears and loses its initial shape. Adjusting the process parameters, the modified shape is maintained within the process and only the tool height must be compensated. The compensation depends on process parameters and part material; electrode wear characterisation and trajectory planning being the key issues ([23] and [24]). It is a slow process (depth of cut ~20 µm in roughing, 3 µm in finishing) that obtains an accuracy of ±2 µm.

The difference with respect to conventional EDM machines, apart from the machine precision, is

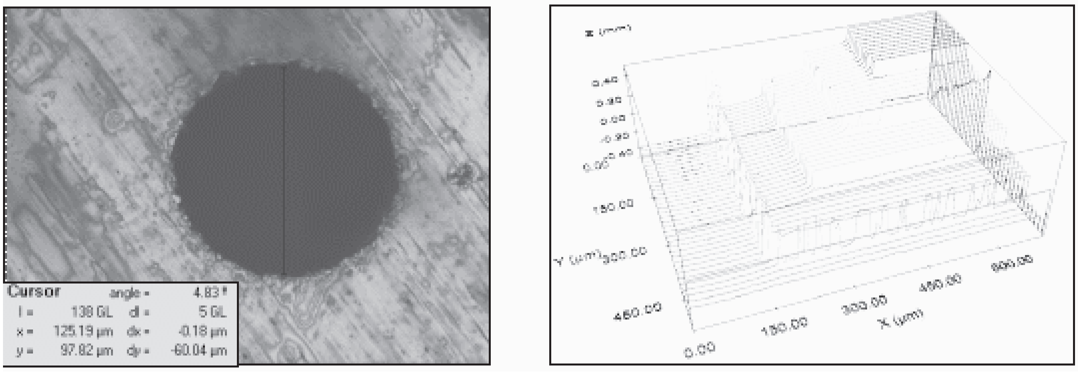

Fig. 6. *Ø0.060 mm hole by s-EDM (Ø0.2 mm tungsten electrode dressed to Ø0.036 mm). 1x1 mm EDM-milled pyramid with 0.2 mm stairs (captured by confocal microscopy x20).*

that micromachining systems can interpolate in 3D and erode in any spatial direction, controlling the gap width. Commercially the range of such systems is limited [25], and only two companies offer products focused on micro-EDM.

The process limitations are that vertical walls and sharp edges cannot be produced (unless special shaped electrodes are used for finishing) and the electrode wear/part wear ratio is higher than in conventional EDM because finishing parameters are applied during the whole process (positive polarity, high frequency and low energy).

The combination of electrode dressing and EDM-milling makes it possible to machine very small freeform surfaces in conductive materials. The electrode can be dressed to diameters not obtainable with cutting tools, making it possible to machine smaller features.

4.1 Electrodes and Auxiliary Tools

The applied electrodes are made of different materials and the machine is equipped with some special systems that are different from normal EDM.

The most used material for micro-EDM electrodes is tungsten, due to its high stiffness and fusion temperature. On the market there are cylindrical electrodes down to Ø0.06 mm and tube electrodes (holed) down to Ø0.1 mm. Handling electrodes below Ø0.1 mm is almost impossible, but there are feeding systems for this purpose.

The manual collets are specially designed to clamp small diameters and have fine-regulation systems to reduce the rotation run-out. Apart from the collets, it is common to use ceramic guides that make it possible to work with longer electrodes that minimise the need for manual feeding. Optical microscopes are another usual accessory for micro-EDM machines, apart from being used to reduce the electrode run-out, they are also used to align the collet and the ceramic guide.

The machines have rotary spindles to ensure the highest circularity when drilling (<2 µm for Ø0.2 mm electrodes). In some cases the spindle rotation can be controlled (C axis) to produce shaped electrodes. The dielectric is usually oil, but some machines apply de-ionised water to drill higher aspect ratios in steel.

4.2 Micro Die-sinking EDM Applications

The main application for this process is the machining of high-aspect-ratio small holes (>Ø0.15 mm) for injection. A second important application is performing drills for subsequent wire threading in the WEDM process. Concerning the EDM-milling process, the application is mould machining in hard-to-machine materials.

5 THIN-WIRE EDM

The thin-wire EDM process (sometimes call micro-WEDM) is very similar to the conventional WEDM process. The wire electrodes that are used have smaller diameters (<0.050 µm) making it possible to machine miniaturised complex ruled surfaces with an aspect ratio greater than 10:1, and micrometric accuracy [26]. The machining systems are an evolution of conventional WEDM machines that achieve higher accuracy (1–3 µm, depending on the part height) in small travels and fine adjustable wire traction [27]. All those wires with a diameter smaller than 0.05 mm are considered thin wires. The spark generator is usually an RC type generator that can provide high-frequency and low-energy pulses.

The applied dielectric fluid is oil because it has a higher resistivity than water, reducing both the energy of the spark reaching the part and the gap width. Thus, it is possible to reach a higher precision and a smaller surface roughness. A disadvantage is that by using oil the productivity is 10 times lower.

The thin wires, due to their small section and mass, cannot be tensioned with high forces to reduce the effect of the process forces. All these forces cause wire vibration and deformation levels that are larger than in conventional WEDM. Process optimisation can be done choosing the right cutting strategies, parameters, dielectric flow and wire tension for each kind of material and each part height.

5.1 Wire Electrodes and Auxiliary Tools

The minimum machinable feature depends on wire diameter, wire tension, wire guiding and the skills of the operator to thread it correctly. Usually, the wire electrode is made of tungsten (Fig. 7, left), although there are wires made of molybdenum or brass-coated steel. The minimum market-available wire diameter was 0.030 mm (±1 µm), until last year, when two smaller dimensions entered the market: Ø0.025 and Ø0.020 mm. The limit is not in the wire manufacturing (Bedra presented some demonstrators of Ø0.015 mm wire in ISEM XIV) but in the machine's capability to work with such small wires (guides and tension). It is important to point out that the dimensional tolerances are similar to conventional wires (±2 µm for Ø0.25 mm wires), the tolerance/diameter ratio being worse for thin wires.

Wire guides are another important issue; most machines are designed to work with Ø0.030 mm, there are no existing consumables to use thinner wires. The wire guides are machined by laser and cannot be controlled better than conventional ones, the diameter and roundness errors being 1 to 2 µm. This makes the process less accurate than expected. Finally, wire threading is difficult to perform. In most commercial machines the automatic threading is only reliable up to Ø0.05 mm (some companies like Agie or Makino have a threading system for Ø0.020 mm), making manual threading a complex task that can last for ±10 minutes; this limits the industrialization of the process.

5.2 Thin-Wire EDM Applications

In thin-WEDM, the wire is continuously renewed and the process achieves high accuracy. It can machine any ruled surface but, when the machining is performed inside a part, a threading hole must be machined previously. The process can machine hardened materials and is used in the machining of precision features of moulds, dies and punches. It can also machine mechanical components (Figs.7 and 8), small connectors, etc.

6 CONCLUSIONS

All these technologies present important capabilities that can be applied mainly to the development of precision miniaturised moulds, punches and dies. Most of them keep a strong relationship with the corresponding conventional technologies, and this makes it easier for them to be assimilated by the metal-processing industry.

The limits of these technologies are not in their positioning accuracy, but in the development of improved tools and referencing systems. At present, all these processes are being actively researched and their introduction in some industrial sectors (surgical tools, car sector, etc.) has started the initiation of a strong market around them.

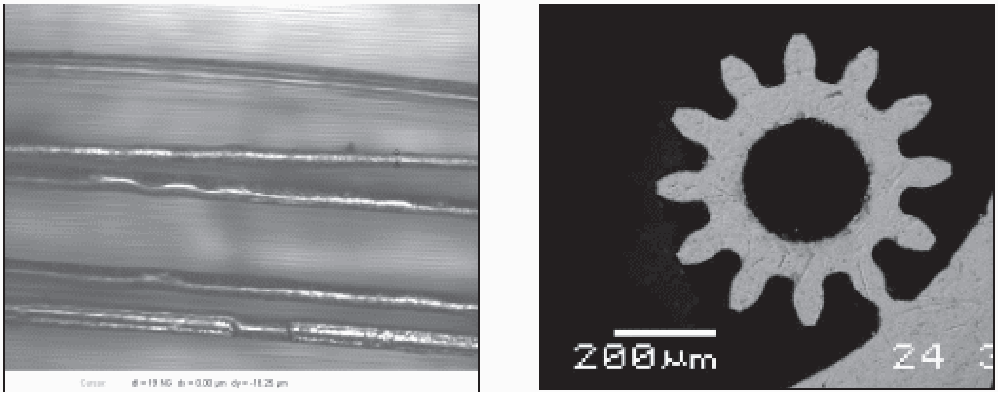

Fig. 7. *Used and new Ø0.030 mm tungsten wire; Ø0.5 mm nominal diameter gear cut by Ø0.030 mm WEDM.*

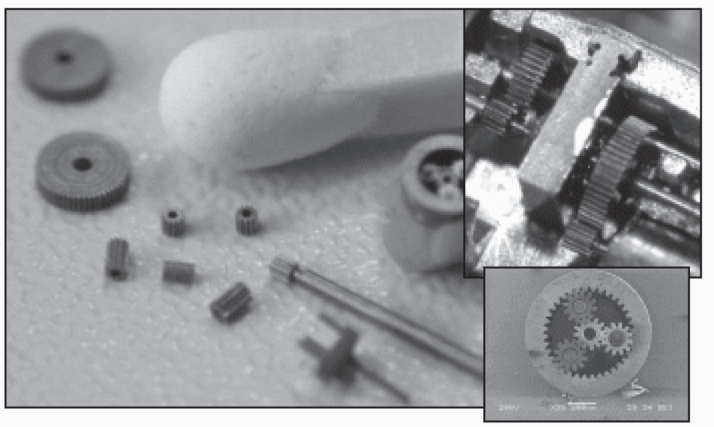

Fig. 8. *Thin-Wire EDM-ed components for a micro-car transmission*

7 REFERENCES

[1] Wechsung R. et al. (1998) Market analysis for microsystems, 1996-2002, A NEXUS Task Force Report. *Nexus Office* (eds). Grenoble.

[2] Wechsung R. et al. (2002) Market analysis for microsystems II, 2000-2005, A NEXUS Task Force Report. *Nexus Office* (eds). Grenoble.

[3] Bueno R., Corta, R., Herrero, A. (1999) Microtechnologies in Spain. *Semaine Nationale des Nano et Micro Technologies*. Menrt, París. Noviembre 1999.

[4] Bueno R., Corta R, Herrero A. (1999) MICROMACHINE: Perspectivas en torno a las máquinas, microfabricación y fabricación de precisión, *Fundación Tekniker*. Eibar.

[5] Masuzawa T. (2000) State of the art micromachining. Colibri A.G. (eds) *Annals of the CIRP 49-2*. Uitendorf, Switzerland, pp 473–488.

[6] Benjamin, R. J. (1983) Diamond machining applications and capabilities. *SPIE* Vol. 433, pp. 24-31, 1983.

[7] Weck M. et al. (1988) Performance assessment in ultraprecision micro-machining.*Annals of the CIRP*, 37/1/1988, p. 499.

[8] Moriwaki T. et al. (1990) Effect of cutting heat on machining accuracy in ultra precision diamond turning. *Annals of the CIRP*, 39/1/1990, p. 81.

[9] Evans C., Bryan J.B. (1991) Cryogenic diamond turning of stainless steel. *Annals of the CIRP* 40/1/1991, p. 571.

[10] Shimada S. et al. (2000) Suppression of tool wear in diamond turning of copper under reduced oxygen atmosphere. *Annals of the CIRP*, 49/1/2000, p. 21.

[11] Nakasuji T. et al. (1990) Diamond turning of brittle materials for optical components. *Annals of the CIRP*, 39/1/1990, p. 89.

[12] S. Asai S. et al. (1990) Measuring the very small cutting edge radius for a diamond tool using a new type of SEM having two detectors. *Annals of the CIRP*, 39/1/1990, p. 85.

[13] Herrero A., Bueno R. (2001) Development of a three axes travelling column ultra-precision milling machine, *Proceedings of the 10th ICPE*. Yokohama. Japan. 18-20 July, 2001.

[14] Spath D. et al. (2000) Micro-milling of steel for mould manufacturing - influences of material, tools and process parameters. *EUSPEN 2000*.

[15] Takeuchi Y. et al. (1996) Ultraprecision 3D machining of glass. *Annals of the CIRP*, Vol. 45/2/1996.

[16] L. Uriarte, A. Herrero, R. Oñate (2004) Fresadora de ultraprecisión de 3 ejes de columna móvil. XV Congreso de Maquinas-Herramienta y Tecnologias de Fabricacion. ISBN 931828-7-7. San Sebastian, October 2004.

[17] Weck M., y Fischer, S. (1997) Development of an ultraprecision milling machine. P*roceedings of the 9th IPES/4th UME*. Braunschweig. Alemania. 26-30 Mayo, 1997.

[18] Lucca D.A., Seo Y.W., Komanduri R. (1993) Effect of tool edge geometry on energy dissipation in

ultraprecision machining. *Annals of the CIRP*, 42/1/1993, p. 83.
[19] Masuzawa, T. (2001) Micro EDM, *Proceedings of the ISEM XIII* Vol I., p.3-19
[20] Masuzawa T., Tsukamoto J., Fujino M. (1989) Drilling of deep microholes by EDM. *Annals of the CIRP*, 38/1/1989, p. 195.
[21] Masuzawa T., Fujino M. Et al. (1985) Wire electro-discharge grinding for micro-machining. *Annals of the CIRP*, 34/1/1985, p. 431.
[22] S Piltz S., Uhlmann E. (2004) Micro machining of cylindrical parts by electrical discharge grinding. *ISEM XIV*.
[23] Zhao W., Yang Y. et al. (2004) A CAD/CAM system for micro ED-Milling of Small 3D Freeform Cavity. *ISEM XIV*.
[24] Bleys P., Kruth JP., Lauwers B. (2004) Sensing & compensation of tool wear in milling EDM. *ISEM XIV*.
[25] Beltrami I. (2004) Micro and nano electride-discharge machining. *ISEM XIV*.
[26] Klocke F., Lung D., Antonoglou G.. (2004) Using ultra thin electrodes to produce micro-parts with wire-EDM. *ISEM XIV*.
[27] Mu-Tian Y., Huang CW. Et al. (2004) Development of a prototype micro wire-EDM machine. *ISEM XIV*.

Authors' Address: Mag. Alberto Herrero
Mag. Igor Goenaga
Mag. Sabino Azcarate
Fundacion Tekniker Micro & Nano
technologies Dep.
Avda. Otaola, 20
20600 Eibar, Spain

Mag. Luis Uriarte
Fundacion Tekniker Mechatronics Dep.
Avda. Otaola, 20
20600 Eibar, Spain

Dr. Atanas Ivanov
Mag. Andrew Rees
Cardiff University
Queen's Building
PO Box 925
Cardiff CF24 3AA, Wales

Mag. Christian Wenzel
Fraunhofer-Institut für
Produktionstechnologie IPT
Steinbachstrasse 17
52074 Aachen, Germany

Dr. Claas Müller
IMTEK
Alber-Ludwigs Universität Freiburg
Georges Köhler Allee 103
79110 Freiburg, Germany

Prejeto:
Received: 2.11.2005

Sprejeto:
Accepted: 22.6.2006

Odprto za diskusijo: 1 leto
Open for discussion: 1 year