THE ROLE OF UNCONVENTIONAL MANUFACTURING PROCESSES IN MODERN MANUFACTURING CHAIN

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Abstract: Dynamic development in aircraft, automotive, chemical and medical industry is strictly connected with application of advanced engineering materials. Due to properties, they are classified as “difficult-to-cut” because it is difficult or sometimes impossible to machine them by using the traditional machining processes. The alternative is such case is application of unconventional manufacturing technologies (UMP). The goal of the paper is to present the role of UMP in modern manufacturing chain. The recent developments in area of UMP are driven for two main reasons: properties of the new engineering materials and need for more complex shapes, low-rigidity, high-aspect ratio structures and micro-components.

Keywords: difficult-to-cut, manufacturing, unconventional, hybrid, micromachining

1. Introduction

Among the subtractive manufacturing processes group of traditional and nontraditional (unconventional manufacturing processes, UMP) can be distinguish. These nomenclature has historical background, however it can be related to criteria presented in Table 1. Generally one can state that in UMP instead of traditional tools, energy in its direct form is utilized and the absence of tool-workpiece contact or its relative motion, makes the process a nontraditional one.

The unconventional manufacturing processes can be classified according to the source of energy used to generate machining action to following groups [1]:

– mechanical processes (material removal by mechanical abrasion or shearing),
– chemical or electrochemical processes (material removal due to chemical or electrochemical reaction),
– thermoelectric processes (material removal by melting and evaporation)

Thera are also rapidly developing group of hybrid manufacturing processes (HMP) which combines above mentioned machining actions to remove material [2].

The selection of suitable UMP for given machining job should take into accounts: properties of the work material, geometry to be machined, process parameters and capabilities, cost-effectiveness and environmental impact. It is wort to underline that in majority cases the unconventional manufacturing processes cannot replace traditional methods (they are too expensive). The application of UMP should be taken into account only when economical or process reasons occurs. In the first case, as example machining of difficult-to-cut materials can be specified. In the second case properties of work material or form of geometry to be machined cause that only solution is to apply unconventional process (economic reasons does not play crucial role). In this case one can mention following examples: shaping of ceramics and composites without damages generated during machining, machining of low-rigidity structures, high aspect ratio hole drilling or drilling of thousands of micro-holes in single part.

The idea of the paper is to present the role of UMP in modern manufacturing chain. Generally, the recent developments in area of UMP are driven for two main reasons:

- properties of the new engineering materials made it difficult or sometimes impossible to machine them by using the traditional machining processes,
- need for more complex shapes, low-rigidity and high-aspect ratio structures and micro-components with tight tolerances and fine surface.

Therefore, in the first part of the paper overview of difficult-to-cut materials properties with focus on machinability issue will be presented. The second and third part will include characteristic of selected (the most frequently used) unconventional and hybrid manufacturing processes. The process principle, advantages and limitations with focus on machining of materials presented in previous part will be especially presented. The need for complex, low-rigidity and high-aspect ratio parts made of new advanced engineering materials are typical for aircraft and automotive, therefore presented examples of application will focus in this areas. The fourth part of the paper will present specificity of micromachining and advantages of UMP in this area.

Tab.. 1 Characteristics features of traditional and unconventional (nontraditional) manufacturing processes

Traditional	**Nontraditional (Unconventional)**
– Requires the presence of a tool that is harder than the workpiece to be machined. – Tool should be penetrated in the workpiece to a certain depth. – A relative motion between the tool and workpiece is responsible for forming or generating the required shape.	– Gives possibility to machining a wide spectrum of metallic and nonmetallic materials regardless of their hardness or strength. – The hardness of cutting tools is of no relevance during the process. – In most of unconventional technologies there is no physical contact between the work and the tool. – To obtain complex shapes simple kinematic movements are needed.

2. The characteristic of difficult-to-cut materials

Dynamic development in aircraft, automotive, chemical and medical industry is strictly connected with application of advanced engineering materials which have high strength, low specific weight, high ductility and high temperature and corrosion resistance. A group of these materials include Steel, Ti- and Ni-based materials, engineering ceramics and metal matrix composites (MMC). Due to their properties, they are classified as “difficult-to-cut”. Machining such materials using conventional means is very challenging, often resulting in low material removal rates (MRR), reduced precision due to high cutting forces, high tooling costs due to increased wear and consequently low process efficiency [3]. Additionally, in many cases surface integrity is unsatisfactory. Below main problems of machinability of this materials will be addressed

Steel, Ti- and Ni-based materials are materials widely used in the manufacture of aero-engine components. Shaping parts made with these materials is a challenge to manufacturing engineers due to:

- high mechanical strength, which is maintained in high temperatures,
- poor thermal conductivity,
- hardening of the material during machining,
- high chemical reactivity.

Such features makes, that traditional machining of these materials are connected with high stresses generated during machining, problems with heat dissipation (high temperatures at the tool-workpiece and tool-chip interfaces), rapid tool wear, poor surface integrity of machined part and finally high costs. Therefore, to decrease cost of manufacturing of steel, Ti- and Ni-based materials cutting based hybrid processes are dynamically developing (see paragraph 4). Additionally, it is wort to underline, that these alloys are electrically conductive, what prefer to use EDM and ECM as alternative when machining complex and high aspect-ratio shapes.

Advanced engineering ceramic materials such as nitrides, oxides, borides and carbides have superior hardeners, high strength ratio and excellent thermal and chemical stability. Its properties cause that such materials are very attractive for wide range of applications i.e. stamping dies, extrusion tools, combustion engine parts, seal rings, welding nozzles, hip joints and orthodontic implants. However big opportunities ceramics material application in modern industry are limited because of high manufacturing costs. Ceramic components are commonly made in near net shapes and successively machined into the final parts (Fig. 1A). This traditional production chain, which includes powder preparation, shaping, green machining, de-binding, sintering and finishing, is labour and cost intensive, favors medium and large production and does not allows to obtain complex and microsized features. Therefore electrical, chemical and physical shaping techniques are recently intensively investigated to fill this niche and simplifying ceramics manufacturing chain (Fig. 1B). This research especially refer to apply electrical discharge machining (EDM), laser beam machining (LBM, example of application in Fig. 2), ultrasonic machining (USM), waterjet or abrasive waterjet machining (AWJ) and electrochemical hybrid processes [4]. The main goal is to develop manufacturing alternatives and respond to the demand of complex shaping and miniaturization, prototyping, small production and customized solutions. It is wort to mention, that these methods can be applied directly to fully sintered blanks (hard machining stage on the Fig. 1B), therefore its application simplify the entire production chain and reduce the cost of ceramic products.

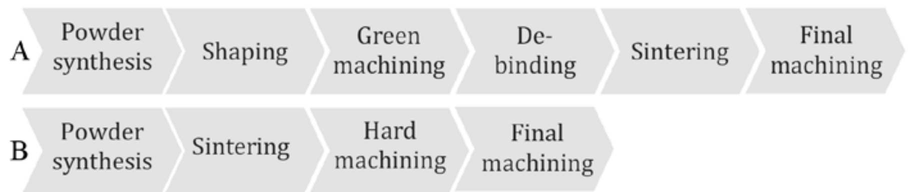


Fig. 1. Manufacturing chains of ceramic components comparing traditional processing routes (A) to hard machining (B)(EDM, USM, LBM and AWJ are collected under the name ‘‘hard machining’’ since they are applied to fully sintered blanks directly) [4]

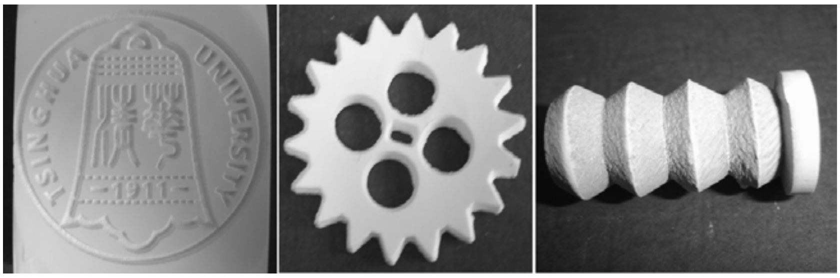


Fig. 2. The complex-shaped sintered Al2O3 ceramic parts prepared by laser-machining [5]

Metal matrix composites (MMCs) usually consist of a low-density metal (i.e. aluminum alloys, titanium alloys, copper alloys, magnesium alloys) reinforced with fibres, whiskers or particles of silicon carbide, aluminum oxide, boron carbide, graphite etc. In comparison to metal matrix MMCs offer higher specific strength and stiffness, higher operating temperature, and greater wear resistance, what makes them an attractive option in many engineering application. However ceramic particles (reinforcements) make traditional machining of composite tougher and more expensive (high tool-wear, poor surface quality). Therefore innovative solution in this area are required. The resent investigation focus on application different unconventional processes, such as electrodischarge, laser, abrasive water-jet, electrochemical or electrochemical discharge machining[6].

3. The characteristic of selected unconventional manufacturing processes

3.1 Electrochemical machining (ECM)

Electrochemical machining is an important technology in shaping free-form surfaces in parts made of conductive difficult-to-cut alloys. In ECM, material is removed by electrochemical dissolution process, and the main advantages of ECM are [3, 7]:

- process specific characteristic of material removal rate which does not depend on material hardness,
- no tool wear during machining (when machining parameters are optimal),
- good surface quality after machining (there is no significant changes in surface layer, no occurrence of white layers, heat affected zones or strain hardening).

The ECM principle cause, that this process is quite complicated and costly in the design and maintenance, therefore is difficult for applying in industry [8]. Additionally, machine tool has to be built from corrosion resistant materials (what means high costs) and the process in non-environmental friendly (negative influence of electrochemical reaction products). Because of above mentioned reasons industrial applications of ECM process are limited for cases, where only ECM process can give satisfactory surface layer quality or metal removal rate. Additionally ECM is specifically used in large batch size production and represents an alternative manufacturing technology for turbomachinery components (i.e. turbine blades of aircraft engines, see Fig 3).

Fig. 3. ECM of blades and vanes for aerospace and stationary gas and steam turbine applications [3]

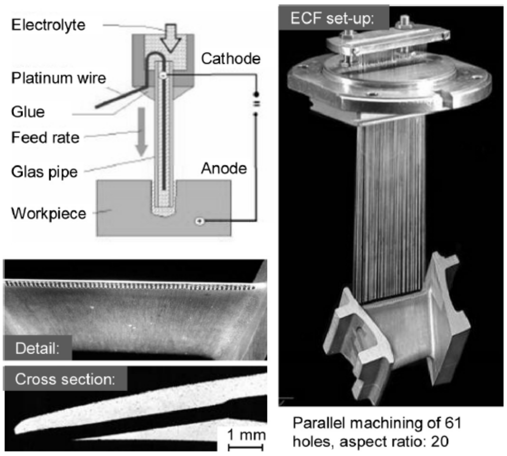


Fig. 4. Electrochemical Fine Drilling (ECF) of cooling holes in nozzle guide vanes – principle and application example [3]

ECM is also widely applied for the production of high-ratio cooling holes in turbomachinery components. In this case the main advantages of applying ECM are the production of smooth, stress- and crack- free surfaces. In this area ECM gives also unique capabilities, i.e. low contour drilling angles can easily be realized, curved elliptical holes can be machined or multiple holes can be simultaneously drilled within one machine set-up (Fig. 4).

3.2 Electrodischarge machining (EDM)

The electrodischarge machining process was introduced to industry in the 1950s. and is one of the most commonly used non-conventional machining methods in all the branches of industry. In EDM material removal takes place as a result of occurring plasma channel (erosion effect) between tool electrode and workpiece surface, separated by dielectric liquid. For every pulse, discharge occurs at a single location where machining material is melted and evaporated. Debris in molten phase are cooled, resolidified and then evacuated by dielectric liquid from the machining gap . As a result of thermal material removal mechanism the heat affected zone occurs in surface layer of workpiece.

The main advantage of using EDM is that it can be used to all materials with an electrical conductivity above 10^{-2} S/cm [4] regardless of the machined material mechanical properties (especially hardness) and chemical structure. EDM is also characterized by very high machining accuracy and achievable surface roughness. With EDM it is possible to get complicated shapes and thin-walled elements, 3-D complex shaped macro, micro and nano features which would be impossible by using conventional machining methods [7].

The most popular variants of EDM are die-sink of slots, pockets and grooves, wire-cutting and drilling of cooling holes, however there are a surprising number of alternative machine tool/process configurations that use electrical discharges to remove material. The largest concentration of EDM technology outside general engineering remains in the mould and die industry. The reasons for choosing EDM are that productivity is not limited by the hardness or strength of the workpiece material. One can state that in nowadays manufacturing industry EDM become indispensable process, especially when machining complex shapes with high degree of accuracy in difficult-to-machine materials such as heat-resistant alloys, superalloys, and carbides. However, it is worth to mention, that thermal nature of the electrodischarge machining (heat affected zone in the workpiece surface layer) limits EDM area of application .

3.3 Laser beam machining (LBM)

Laser beam machining belong to the group of thermal non-contact processes. In this process high energy density laser beam (most commonly CO_2 or Nd:YAG laser) is focused on work surface. The laser thermal energy is absorbed by material and transforms the work volume into a molten, vaporized or chemically changed state. In this state material is removed by flow high pressure gas jet. LBM can be used for shaping almost whole range of engineering materials in operations of cutting, drilling, marking, welding, sintering and heat treatment. The lasers are also used to assist other machining processes (see paragraph 4.1). The efficiency of LBM depends on thermal and optical properties rather mechanical properties of the material to be machined. Therefore most favorable for LBM are materials with low thermal diffusivity and conductivity, regardless its hardens and fragility.

The major LBM applications are: drilling (1-D), cutting (2-D) and 3-D machining (grooving, turning, milling). Laser beam drilling has become the most efficient process for drilling thousands of closely spaced holes in structures. Two types of laser beam drilling exist: trepan (drilling involves cutting around the circumference of the hole to be generated) and percussion (‘punches’ directly through the workpiece material with no relative movement of the laser or workpiece). The advantage of laser percussion drilling process is the reduction in processing time but trepanning gives higher accuracy and better hole in/out quality. Laser drilling covers about 5% of all industrial laser material processing and in this area generation of cooling holes in gas turbines for aircraft as well as for power plants is one of the most important, established drilling applications. With this process it is possible to drill hundreds/thousands of cooling holes with high precision and of variable diameter and shape in multi-material blades of complex geometry.

4. The characteristic of selected hybrid manufacturing processes (HMP)

One of the research of unconventional technologies is development of hybrid machining process. HMP can be defined as different machining actions or phases to be used on the material being removed. The reasons for developing HMP are to make use of the combined or mutually enhanced advantages, and to avoid or reduce some adverse effects the constituent processes produce when they are individually applied [2]. Adequate selection of mechanical, thermal, and chemical interaction on the machined material gives the possibility of obtaining beneficial technological solutions. As an example, one can indicate vibration assisted cutting [9], ultrasonically assisted electrodischarge or electrochemical machining [10], abrasive electrochemical or electrodischarge grinding or thermally enhanced machining [11].

Below short description of the thermally and vibration assisted cutting processes will be described. Additionally, in the paragraph 4.3 very attractive technology of Swiss company Synova, which develop waterjet guided laser machining will be presented. The first two examples belong to the category of HMP where only one of the participating processes directly removes the material while the other only assists in removal by positively changing the conditions of machining. While waterjet guided laser machining is typical example of HMP category, where all constituent processes are directly involved in the material removal.

4.1 Thermally assisted cutting

The flow stress and strain hardening rate of materials normally decrease with temperature increase. This relationship is used in thermally assisted cutting process, where external heat sources heat workpiece locally in the front of cutting tool (Fig. 5). It causes reduce of the yield strength and work hardening of workpiece material and result in easier material removal when machining difficult-to-cut materials.

The heat source should be local, gives possibility to rapid heating and easy controllable, therefore the more popular solution is to apply laser beam [11]. The laser heats the workpiece locally in front of the cutting tool and only the volume of material to be removed is effectively heated. The laser beam has high power density and controllable spot size, therefore the heat affected zone and thermal distortion by the laser beam during preheating are small. The laser assistance improves the machinability of variety of hard-to-machine materials such as ceramics, metal alloys and metal matrix composites. This process offers lower cutting forces and lower specific cutting energy, longer tool life, a better surface finish and higher material removal rate. However it is worth to mention, that laser action may result in high tool–chip interface temperatures which may lead to accelerated dissolution–diffusion and adhesion tool wear. Therefore, laser assisted cutting process needs more effective methods of cooling the cutting tool without affecting local heating of the workpiece.

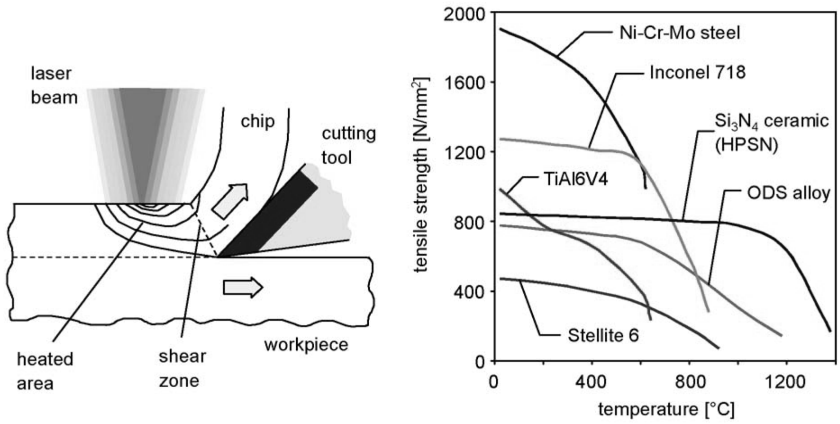


Fig. 5. Principle of laser assisted machining (left) and effect of temperature on the ultimate tensile strength for various hard-to- machine materials (right) [9].

4.2 Vibration assisted cutting

In vibration-assisted cutting process motion of the tool is imposed with small-amplitude, high-frequency tool vibration. Depending on the vibration trajectory in relation to the tool main motion several types of vibration assisted machining processes can be distinguished (Fig. 6). Appropriate combination of cutting velocity and vibration frequency and amplitude cause, that tool periodically loses contact with the chip resulting in machining force reduction and decrease of chip thickness. This leads to extended tool life (especially for diamond tools used to machine ferrous metals and when machining hard and brittle materials), improved surface integrity and form accuracy (Fig. 7), increase of depth-of-cut for ductile regime machining of brittle materials and almost burr-free machining process.

(a) (b)

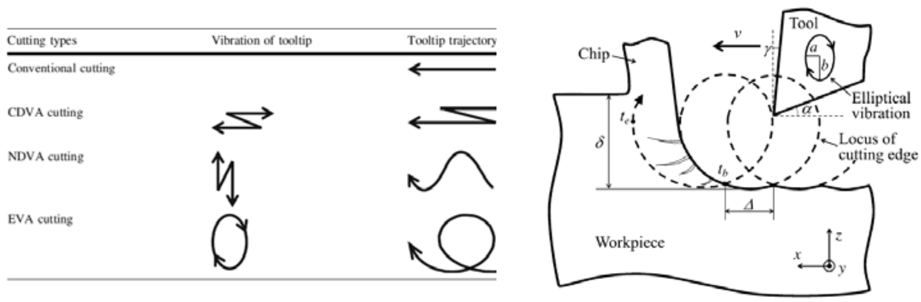


Fig. 6. Cutting types (a) and schematic illustration of vibration assisted cutting (b)

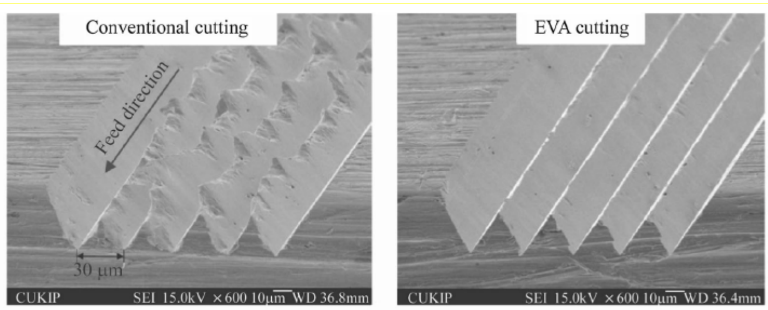


Fig. 7 Image of micro v-grooves machined by conventional cutting (left) and vibration assisted cutting (right) [12]

4.3 Water jet guided laser machining

The water jet guided laser technology is cutting process which combines advantages of water jet cutting (low temperature, relatively large working distance) with the precision and speed of laser cutting. In this process the laser beam is guided by transparent water jet (in similar way to optical fibers), which enables to overcome limitations of laser beam machining (Table 2). Following main advantages of this technology can be mentioned [13]:

- cutting with almost parallel and very thin (up to 20 µm) kerf with absolute precision of +/- 3 µm
- significantly decreased heat affected zone (no heat impact due to water cooling, water jet removes melted material).

The water jet guided technology allows to machine of a broad range of materials such as metals (stainless steel, titanium, nickel, super-alloys), hard materials (PcBN, PCD, MCD), ceramics (ZrO_2, $Al2O_3$) and semiconductors (Si, SiC, GaAs) and can be used mainly in operation of cutting and drilling.

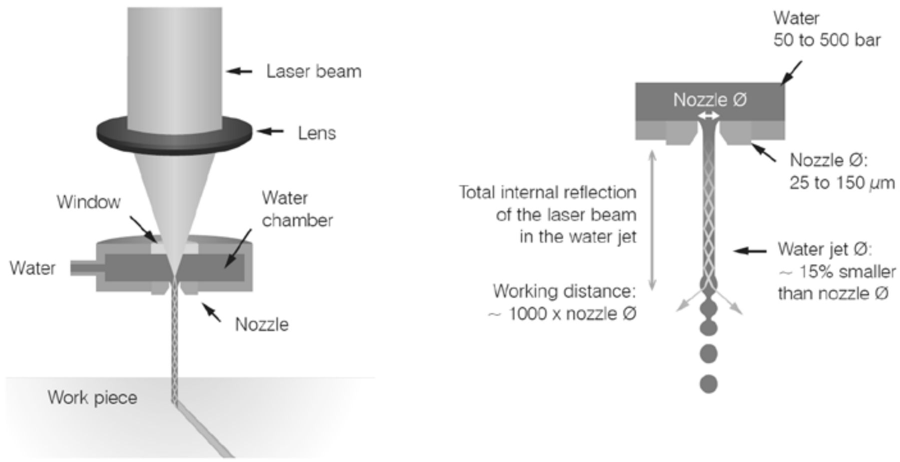
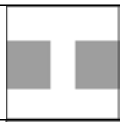
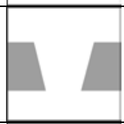
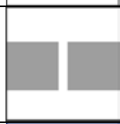
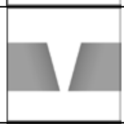
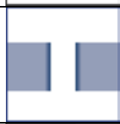
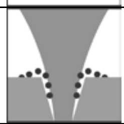
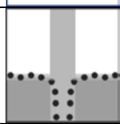
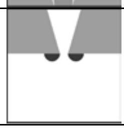
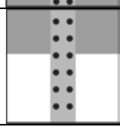


Fig. 8. The scheme of water jet guided laser technology [13]

Table 2. Comparison of technological capabilities of laser beam cutting and water jet guided laser cutting [13]

Laser beam cutting		Water jet guided laser cutting	
Requires precise focus adjustment			No focus adjustment required, non-flat surfaces are not an issue, 3D cutting possible, variable cutting depth of up to several cm
Conical laser beam leaves non-parallel kerf walls			Cylindrical beam results in parallel kerf walls, consistent high quality cutting
Limitations in cutting aspect ratio			High aspect ratio, very small kerf width (>20 μm), minimal material loss, with simultaneous deep cuts possible
Heat affected zone			Water-cooling process avoids thermal damage and material change, high fracture strength is maintained
Particle deposition			A thin water film eliminates particle deposition and contamination, no surface protection layer required
Inefficient material removal leaves burrs			High kinetic energy of the water jet expels molten material, no burrs form

5. Micromachining

In aspect of machining parts miniaturization, manufacturing methods in which material is removed by electrical, thermal, or chemical interaction have a number of advantages in comparison to cutting. The most important of them are: no mechanical contact between tool and workpiece (smaller deformations and vibrations in machining area, less chance to damage tool and workpiece), machinability does not depend on mechanical properties of material (it depends on thermal, electrical, optical, or chemical properties of material), possibility of machining broad range of materials, and efficiency in the production of prototypes and small series (flexibility).

Application of unconventional manufacturing methods for microparts shaping is connected with application of appropriately modified production systems which are commonly used in macromanufacturing. These modification relate to increase of machining resolution and improvement of machine-tools and tooling accuracy. As an example of such adapted unconventional processes one can state micro electrodischarge machining, micro electrochemical machining, micro laser machining and micro water jet machining. They can be characterized by high efficiency in shaping 3D, therefore as main area of application of these processes one can state MEMS parts prototypes, technological tooling and microtools manufacturing (Fig. 9). In some cases, when machining of microdetails made of special materials or with complicated 3D shape it is necessary to apply hybrid or sequentional processes [14], i.e. integration of micro-ECM and micro-EDM processes on one machine-tool gives possibility of increasing accuracy, metal removal rate and surface quality of final part (Fig. 10)

(a) (b)

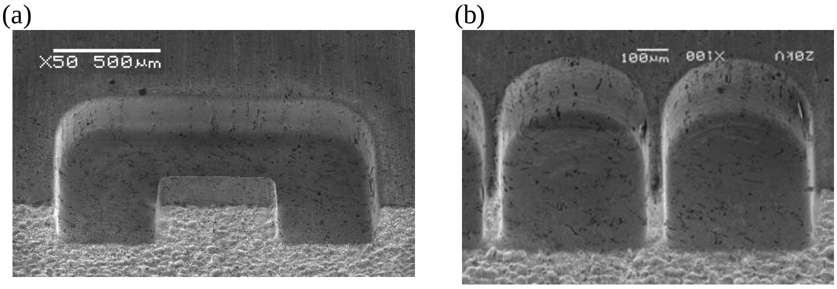


Fig. 9. Examples of electrocheimcal micromachinign application

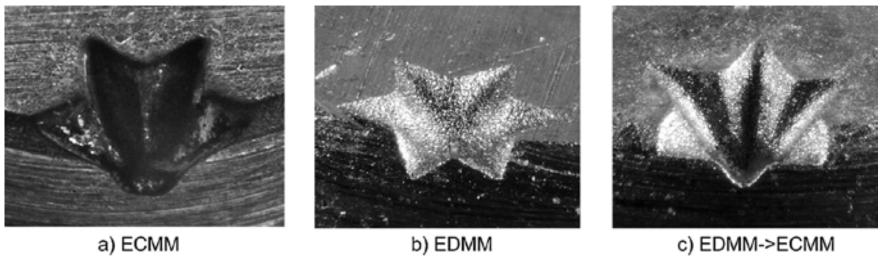


Fig. 10. Photographs of cavities machined during electrochemical sinking (a), electrodischarge sinking (b) and sinking when using the EC/EDMM sequence (c) [14].

5. Summary

Outlined in the paper capabilities and areas of application of unconventional manufacturing processes showing the broad potential of these methods when machining advanced and difficult-to-cut materials with relatively high removal rate, high geometrical accuracy and acceptable surface integrity. There are also a number of process reasons for using UMP in manufacturing process chain. The most frequently examples are application when machining without mechanical interaction brings benefits (low-rigidity, high-aspect ratio structures and micro-components) or hole drilling. For example application of EDM or ECM gives possibility to drill impossible to obtain with traditional methods high aspect-ratio holes with diameter less than 1 mm and L/D ratio higher than 100, while application of LBM gives possibility to drill several hundred of micro-holes per second in thin-walled aircraft parts.

It is wort to mention that in each case of UMP application detailed technological and economic analysis of each operation is needed to identify optimal processes and process chain to minimize production costs.

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