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Surface Integrity in Hybrid Machining Processes

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Abstract

Hybrid manufacturing processes are based on the simultaneous and controlled interaction of process mechanisms and/or energy sources/tools having a significant effect on the process performance. There are various examples such as laser assisted cutting, vibration assisted grinding and grind-hardening. Hybrid processes have a large influence on the machining characteristics resulting in a higher machineability, reductions of process forces and tool wear, etc. Due to the combined action of processes, it also has an important positive or sometimes negative effect on the surface integrity of machined parts. This key-note/overview paper gives first a definition and classification of hybrid processes. It is then followed by a description of the principles and applications of some common hybrid processes, highlighting the effects on the surface and sub-surface quality. The paper is largely based on the results of an on-going working group within the International Academy for Production Engineering (CIRP).

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1 Introduction

Hybrid production/manufacturing means the combination of processes/machines in order to produce parts in a more efficient and productive way. As stated in [1], a general objective of hybrid manufacturing is the “1+1=3” effect. While the term “hybrid” in manufacturing has a broad meaning, the definition of a “hybrid process” is narrower. Based on numerous discussions within the running collaborative working group of the International Academy for Production Engineering (CIRP), a hybrid process is defined as follows: **“Hybrid manufacturing process are based on the simultaneous and controlled interaction**

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of process mechanisms and/or energy sources/tools having a significant effect on the process performance". The wording "simultaneous and controlled interaction" means that the processes/energy sources should interact more or less in the same machining zone and at the same time. A typical example of a hybrid process is laser assisted turning/milling. According to the above formulation, the definition excludes all kinds of hybrid machines where the implemented processes are still performed in a sequential way.

The development and application of a hybrid process should be as such that it enhances the advantages and minimizes the potential disadvantages found in the individual techniques [2]. The simultaneous effect of process technologies enhances the productivity (e.g. lower process forces, less tool wear) and/or makes machining of materials possible which cannot be machined by a single (conventionally applied) process [3]. Besides the above productivity measures, the simultaneous combination of processes and or energy sources also has an effect on the surface integrity. The latter is sometimes neglected in formulating the potentials of hybrid processes.

After giving a classification of hybrid processes, this key-note paper describes some important/common hybrid processes: vibration assisted machining, laser assisted machining, media-assisted machining processes, grind-hardening and EDM/ECM combinations. Besides a brief description of the benefits and applications, this paper also focuses on the effects of hybrid processes on the surface integrity (surface and sub-surface quality).

2 Hybrid Processes: Classification

Based on the definition given above, Table 1 gives a further classification (grouping) of hybrid processes.

The first group (I) contains processes where two or more energy sources/tools are combined and have a synergetic effect in the machining zone. A further classification is made in "Assisted Hybrid Processes" (I.A) and "Pure Hybrid Processes". In assisting processes, the occurring material removal mechanism is defined by the primary process. The secondary process only assists, while in pure hybrid processes, several material removal mechanisms (originating from the different processes) or even new mechanisms are present. Examples of the different technologies are given in Table 1 as well. To the authors opinion, media assisted machining processes (high pressure jets, cryogenic cooling,..) are also defined as an assisted hybrid process, where the amount of energy applied for the secondary processes (jet) is relatively high compared to the conventional process.

The second group (II) of hybrid processes contains processes where a controlled combination of effects occurs that are conventionally caused by separated processes. For example, in grind-hardening, removal is combined with a controlled hardening due to the induced heat of the grinding process.

Table 1: Classification of Hybrid Processes

| Hybrid Processes | | |
|--|--|---|
| (I) Combination of different energy sources/tools | | (II) Controlled application of Process Mechanisms (conventionally done in separated processes) (e.g. grind-hardening, combination of removal and forming,..) |
| (I.A) Assisted Processes (Laser Assisted Turning Vibration Assisted Grinding Vibration Assisted EDM Media-assisted cutting | (I.B) Mixed Processes (EDM/ECM combination,..) | |

3 Assisted Hybrid Processes

3.1 Vibration Assisted Machining

In vibration assisted machining, a small amplitude vibration (average amplitudes: 1...15 μm , frequencies: 10...80kHz) is added to the tool or workpiece movement. In most systems, the vibration is within the ultrasonic frequency range (18...25kHz) and the vibration itself is generated by piezo's within the tool holder or spindle system. Therefore, the term "Ultrasonic Assisted Machining" is often used. Dependent on the primary process, processes like Ultrasonic Assisted Turning (UAT) [4,5], existing with 1D and 2D (elliptical) vibration, Ultrasonic Assisted Drilling (UAD) [6,7,8], Ultrasonic Assisted Grinding (UAG) [9] and Rotary Ultrasonic Assisted Grinding [10,11,12] have been developed (Figure 1).

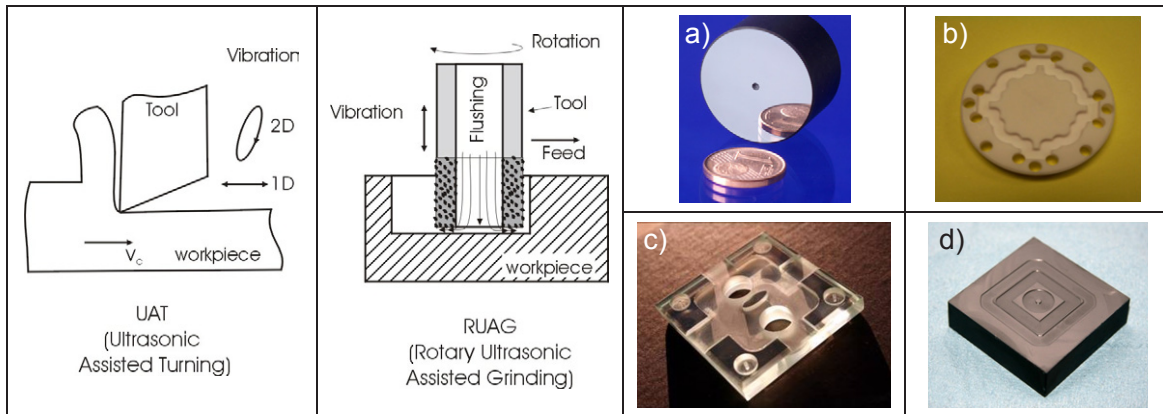


Figure 1: Process configurations of ultrasonic assisted machining and applications: (a) Vibration assisted turning of steel components [IPT], (b) Rotary Ultrasonic Assisted Grinding of Al_2O_3 [Tekniker], (c) Zerodur [Tekniker], and (d) B_4C [K.U.Leuven]

Reduction of process forces and extended tool life are important advantages of ultrasonic assisted machining [11,12,13,14]. It also allows an easier ductile machining of brittle materials (ceramics, glass,...), as the critical depth for ductile machining is increased [15].

For ferrous materials, vibration has mostly a positive effect on the surface roughness (and elimination of burrs). Typical surface textures caused by the machining process are smoothed due to the additional vibration movement [7,16]. The vibration should however be applied in the proper direction. An improvement in UAT of aluminum [16] or aluminum-based metal matrix composites with reinforced SiC particles [7] is only obtained in case the vibration is not along the radial direction. In the latter case, a higher surface roughness is mostly obtained due to the change in depth of cut. The same is seen in the UAG (Ultrasonic Assisted Grinding) of Silicon [9], where an axial vibration (= vibration movement is parallel to the work surface or along the wheel axis (normal grinding wheel)) gives a better surface roughness. In [17], the ultrasonic assisted turning of tungsten carbide (WC) is investigated. It is shown that ductile machining is possible when the depth of cut is below a certain value (critical depth of cut), resulting in fracture free surfaces. This is also the case for the machining of brittle materials (e.g. ceramics) as described in [15].

The effect of vibration is not always positive. When machining pockets by rotary ultrasonic assisted grinding (process kinematics presented in Figure 1), the vibration along the tool direction can result in surface cracks due to the hammering of the tool (Figure 2a). The picture shows the machining of an Al_2O_3 sample machined by RUAG at the K.U.Leuven. In general, surface textures of machined samples of hard materials show mixed material removal mechanisms (MRM): plastic deformation and brittle removal (Figure 2b) [10]. Also in the case of the machining of stabilized ZrO_2 (toughest ceramic material), the effect of the vibration is clearly visible in the surface texture (Figure 2c) [18]. The generation of cracks can have a positive effect on the material removal (MRM based on material break out), but during finishing proper strategies in RUAG should be applied. Due to this negative effect, often no vibration is used for finishing operations.

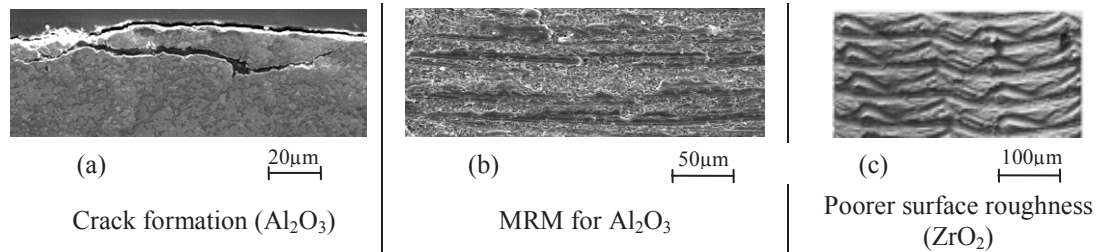


Figure 2: Negative effect of vibration on machined surfaces in RUAG

Vibration also finds its applications in other, non-cutting processes. In ultrasonic assisted EDM [14,19,20,21,22,23,24], vibration is applied between tool and workpiece in order to increase the flushing efficiency, resulting in a higher material removal rate. If process parameters are selected carefully, smooth surfaces can be obtained [19,25]. The vibration supports the removal of re-solidified debris and hence results in a smaller heat affected zone [HAZ], lower thermal stresses and less cracks.

3.2 Laser Assisted Machining

The first implementations of Laser Assisted Machining (LAM) were found in turning of hard materials. The laser beam, focused directly in front of the cutting tool, softens the material so machining

becomes easier (Figure 3). It can be used for the machining of hardened steels, where the addition of heat softens the surface layer of the material, so ductile deformation rather than brittle deformation occurs during cutting.

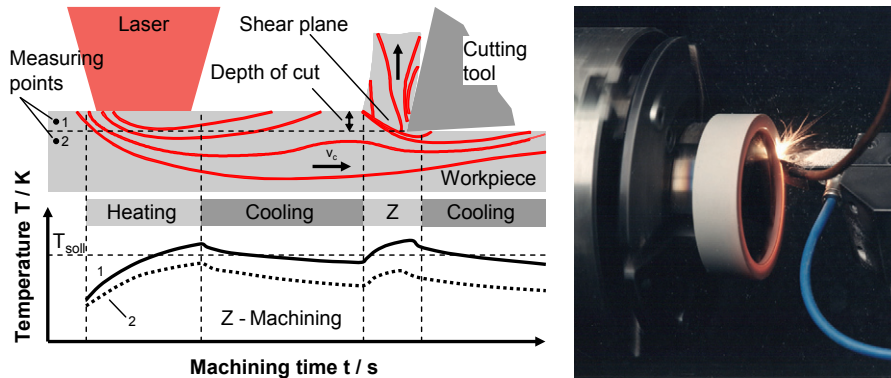


Figure 3: Laser assisted turning of ceramic material [26]

In LAM of hardened steels, residual stresses become more tensile (less compressive) and the stress penetration depth becomes smaller when compared to conventional cutting [27]. An increase in temperature gives often a slightly better surface roughness. Stress and hardness values become more uniform over the surface. In [28], where LAM of Inconel 718 is investigated, SEM analysis and microstructure examination of machined surfaces show an improvement of the surface integrity. Compared to conventional cutting, the plastically deformed surface layer is deeper and more uniform. The absence of smeared material (was present in case of conventional cutting) and the increased plastic deformation zone, are indicative for the favorable compressive residual stresses.

LAM also finds his applications for the machining of ceramic materials (Figure 3, right), which have amorphous boundary phases [26,29,30,31,32,33]. Heating up the glass phase, surrounding the crystals, at temperatures over 1000°C results in a reduction of the deformation resistance and a local softening of the material in the shear zone, enabling machining of the ceramic with a geometrically defined cutting edge. Various ceramic materials (Si_3N_4 , SiC , ZrO_2 , Al_2O_3 ,...) and carbides, under the condition they contain some amorphous glass phases, can efficiently be machined.

For various materials, LAM results in more uniform surfaces with an improved surface roughness. For example in [34], precision ceramic parts are made in Si_3N_4 using LAM. Under normal conditions (moderate temperature levels), the surface is uniformly smeared with a glassy material. LAM samples only showed a 2 to $4\mu\text{m}$ affected zone and no sub-surface cracks were observed. Compared to LAM surfaces, the affected layer in grinding is deeper and sub-surface cracks are present. When applying too high temperatures in LAM, the surface is irregular and cavities are present due to grain fall out. In this case, the surface roughness is mainly defined by the size and the distribution of the Si_3N_4 grains and not by the level of the (too high) temperature. An improvement of the surface roughness is also obtained in the machining of Al_2O_3 ceramics [35], where it is compared to conventional planing. LAM of Magnesia-Partially-Stabilized Zirconia (PSZ) is reported in [36]. Finished LAM surfaces show a smooth texture ($\text{Ra} < 1\mu\text{m}$) without fracture, indicating that plastic deformation is the dominant mode in material removal. However, it is shown that the zone adjacent to the cutting zone (in front) is largely affected (HAZ). This zone is characterized by cracks of which the density increases with increasing temperature.

3.3 Media Assisted Machining

Within the area of media-assisted processes a very important topic is the supply of high pressure lubrication coolants mainly for an improved machining of difficult-to-machine materials like advanced Ni- and Ti-alloys for aerospace applications or composite materials (Figure 4).

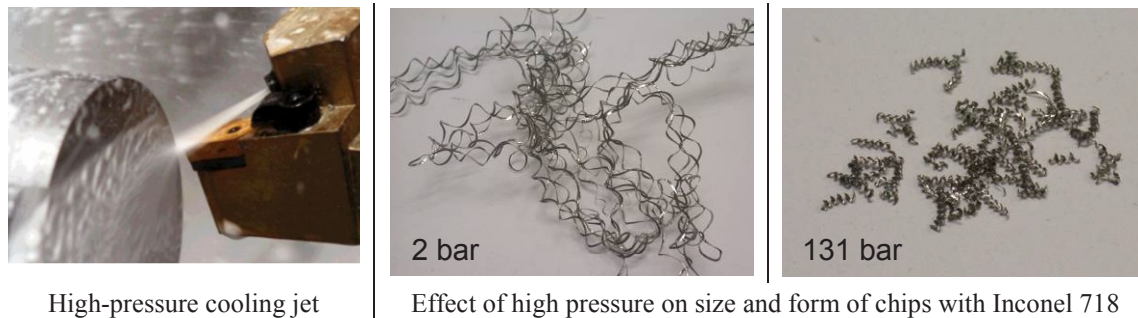


Figure 4: Media Assisted Machining – Application of high pressure cooling and its effect on chip breakage [39]

Flow rate and pressure have a significant influence on tool life and wear behavior as well as on the chip shape and the metallurgical structure of workpiece and chip due to considerable temperature and lubrication changes [37,38,39]. Highly heat resisting super alloys can be machined with improved surface integrity [40] and/or with higher cutting speeds [41] due to reduced heat damage by the better high pressure cooling effect [42,43]. For the machining of alloyed steels [42,44], the surface roughness improves with increasing water jet pressure and the occurrence of burs is significantly lower. The same effects can be noticed in the ultra-high pressure machining of Inconel 718 [40]. There is also a clear reduction in the level of tensile residual stresses developed in the sub-surface layer, which is due to the lower surface temperatures.

Another process is cryogenic machining (also seen as a media assisted process), where cooling fluids are supplied at very low temperatures. The cryogenic machining of Inconel 718 results in a thicker compressive zone beneath the surface (extending the compressive zone from 40 μ m to 70 μ m) [45]. A finer micro-structure is obtained and there is less plastic deformation on the machined surface (1-2 μ m thickness compared to 5-10 μ m in dry and/or conventional MQL machining). Due to the reduced temperatures, reduced wear of cutting tools can be identified [46], hence also having a positive effect on the surface roughness as well. The same effects are seen in the cryogenic machine of steels [47,48] and AISi-4037 [49].

Cryogenic turning is also being applied in the machining of ceramics [50]. Si₃N₄ was used under cryogenic conditions with PCBM tools. A strong reduction in surface roughness could be seen (decrease from 40 μ m Ra (machining length 40mm) down to 3,2 μ m Ra (machining length 160mm)).

4 Mixed Processes

In the area of mixed or combined processes, the integration of grinding and spark erosion processes has gained an important role. Figure 5 shows a Wire-EDM process using a fixed-abrasive wire (AWEDM = Abrasive Wire-EDM), where an enhanced material removal is realized by the synergy between spark erosion and abrasion. In [51], experiments were conducted on a nickel 600 alloy to compare the extent of the recast layer in WEDM and AWEDM, as the machining of recast-free surfaces is of interest in the

aerospace industry. Figure 5 (right) shows the recast layer generated in WEDM to be continuous and of a thickness of $\sim 5\mu\text{m}$. For identical electrical parameters, the recast layer is largely absent in AWEDM.

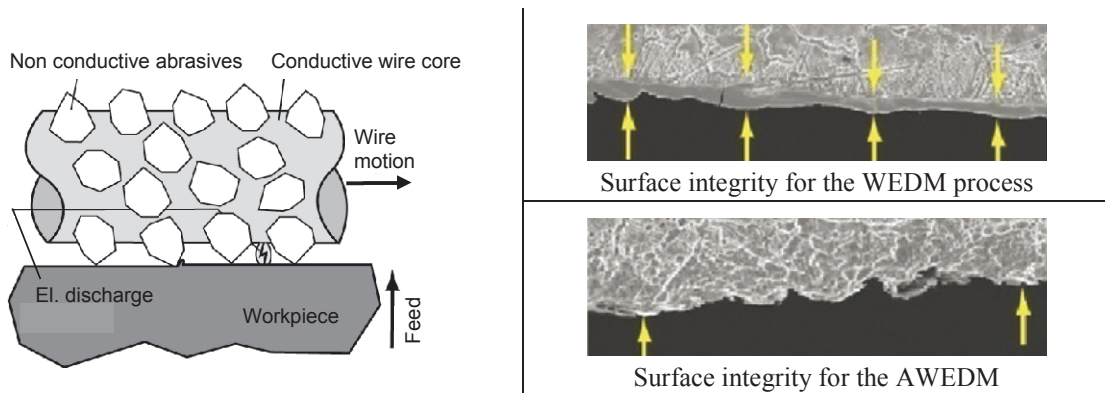


Figure 5: AWEDM: combination of EDM with an abrasive process [51]

Another process combination is the rotary EDM process [52], where a metal-bonded diamond grinding wheel is used (Figure 6). The surface textures in the figure shows the decrease of the role of the grinding process with an increase of the current ($0.4\text{A} \rightarrow 2.1\text{A}$). For a current of 0.4A , the grooves generated by the abrasives are clearly visible, while this is not for a current of 2.1A .

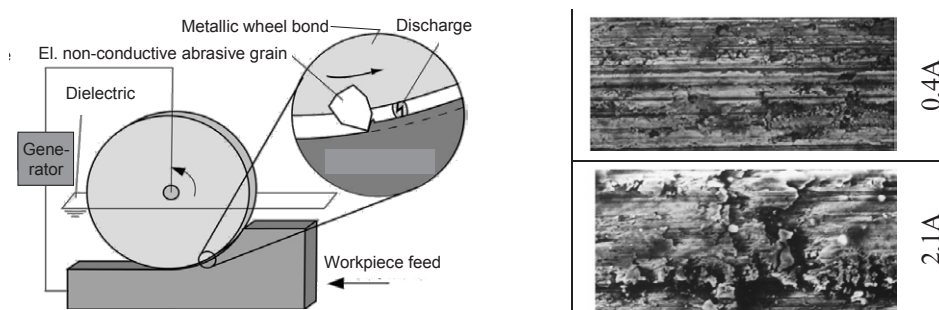


Figure 6: Rotary EDM with metal-bonded wheels: principle (left), effect on the surface integrity (right) [52]

Electrolysis (ECM) assisted Wire-EDM is investigated for the machining of low resistance silicon wafers. High efficiency of slicing ingots with low wire consumption is achieved by the use of a specific detergent capability of the electrolyte [53]. The presence of chemicals influences the surface texture, as micro-holes (sub-micron level) can be formed due to the electrochemical corrosion on the silicon surface. However, using proper process parameters, these micro-holes can be avoided. The electrochemical mechanical polishing uses the process combination of ECM and mechanical abrasion to effectively machine copper and other metals with low pressure, high removal rates and defect-free surfaces [54].

Electric and magnetic field-assisted finishing/polishing represent another area of combined processes in order to enhance material removal and surface finish. By the field assistance an active control of the polishing process is achieved due to dedicated electric or magnetic forces acting on the specific tools [55]. The surface roughness of machined wafers can be further reduced (from $1,14\text{ nm Ra}$ to $0,58\text{ nm Ra}$), but

also in this case a proper selection of process parameters is required. The use of too large grains (e.g. 0-1/2 μm diameter grains instead of 0-1/4 μm) gives a rougher surface (2,04nm Ra).

5 Combination of process principles

The second group of hybrid processes (Table 1) represents process operations where a controlled combination of effects occurs, which are normally performed in sequential operations. An interesting example is grind-hardening. It utilizes the induced heat of the grinding process for local surface hardening of the workpiece. For achieving the high heat input rate the grinding process is applied with higher depth of cut and slow feed speeds (Figure 10), [56,57]. Figure 7 shows the results of hardness measurements as reported in [56].

6 Conclusions

This keynote paper gave a brief overview of some existing and upcoming hybrid processes. Process combinations are used to considerably enhance advantages and to minimize potential disadvantages found in individual techniques. Advantages such as lower process forces, reduced tool wear, increasing the productivity, mostly have a positive effect on the surface integrity (surface roughness,...). However, based on a good understanding of the process-material interaction, process parameters should be selected in a proper way. If not, there can be a strong negative effect by the hybrid process on the surface integrity (rough surface, micro cracks,...).

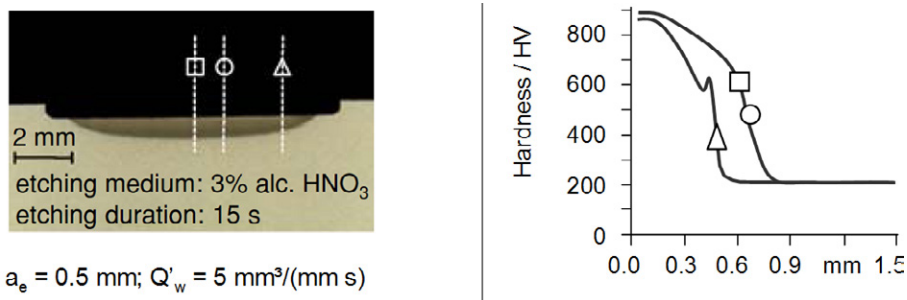


Figure 7: Measured hardness results for grind-hardening process [56]

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References

- [1] Schuh G, Kreysa J; Orilski S. Roadmap ”Hybride Produktion” – Wie 1+1=3-Effekte in der Produktion maximiert werden können. *ZWF*; 2009, 104:385-391.
- [2] Rajurkar K.P., Zhu D, McGeough J.A., Kozak J., De Silva A. New Deve-lopments in ECM. *CIRP Annals – Manufacturing Technology*, 1999, 48/2: 567-579.

- [3] Lauwers B, Klocke F, Klink A. Advanced manufacturing through the implementation of hybrid and media assisted processes. *Int. Chemnitz Manufacturing Colloquium*, 2010, 54:205-220.
- [4] Klocke F, Dambon O, Bulla B, Heselhaus M. Direct Diamond Turning of Steel Molds for Optical Replication. *Proceedings of SPIE*, 2009; Vol: 7283.
- [5] Lauwers B, Van Gestel N, Vanparys M, Plakhotnik D. Machining of ceramics and ecological steels using a mill-turn centre equipped with an ultrasonic assisted tooling system. *Proceedings of the MTTRF 2009 meeting*, 2009; Shanghai, China, p.183-200.
- [6] Neugebauer R, Stoll A. Ultrasonic application in drilling. *Journal of Materials Processing Technology* 2004; 149:633-639.
- [7] Heisel U, Wallaschek J, Eisseler R, Potthast C. Ultrasonic deep hole drilling in electrolytic copper ECu 57. *CIRP Annals – Manufacturing Technology*, 2008; 57/1:53–56
- [8] Schopf C, Rascher R. Ultrasonic assisted drilling of brittle hard materials. *Proceedings of the 9th International Conference of the European Society for Precision Engineering and Nanotechnology*, 2009; San Sebastian, Vol 1:455-458
- [9] Liang Z, Wu Y, Wang X, Zhao W. A new two-dimensional ultrasonic assisted grinding (2D-UAG) method and its fundamental performance in monocrystal silicon machining. *International Journal of Machining Tools & Manufacture*, 2010; 50:728–736.
- [10] Vanparys M, Liu W, Lauwers, B. Influence of machining parameters and tool wear on the material removal mechanisms in the ultrasonic assisted grinding of Al₂O₃. *Proceedings of the 3rd CIRP International Conference High Performance Cutting, Dublin*, 2008; p. 849-858.
- [11] Vicario I, Gonzalo O, Bengoetxea I. Rotary ultrasonic machining of aluminium oxide ceramics: designed experiments. *International Journal of Machining and Machinability of Materials*; 2007, 2/2: 233-243.
- [12] Uhlmann E, Hübert C. Ultrasonic Assisted Grinding of Advanced Ceramics. *Proceedings of the ASPE Spring Topical Meeting*, 2007; Raleigh, N.C., USA.
- [13] Brecher C, Wenzel C, Schug R, Weber A, Hannig S. New systematic and time saving procedure to design cup grinding wheels for the application of ultrasonic assisted grinding. *International Journal of Advanced Manufacturing Technology (IJAMT)*, 2010; 47:153–159
- [14] Suzuki K, Uematsu T, Iwai M, Ninomiya S, Sano S, Nakagawa T. A New Complex Grinding Method for Ceramic Materials Combined with Ultrasonic Vibration and Electrodischarge Machining. *Key Engineering Materials*, 2007; 329: 439-444.
- [15] Dornfeld D, Min S, Takeuchi Y. Recent Advances in Mechanical Micromachining. *CIRP Annals – Manufacturing Technology*, 2006, 55/2:745-768.
- [16] Schubert A, Nestler A, Pinternagel S, Zeidler H. Influence of ultrasonic vibration assistance on the surface integrity in turning of the aluminium alloy AA2017. *Mat.-wiss u. Werkstofftech*, 2011, Vol. 42.
- [17] Liu K, Li P, Rahman M. Characteristics of ultrasonic vibration-assisted ductile mode cutting of tungsten carbide. *International Journal of Advanced Manufacturing Technology*, 2008, 35:833–841
- [18] Lauwers B, Bleicher F, Ten Haaf P; Vanparys M, Bernreiter J, Jacobs T, Loenders J. Investigation of the process-material interaction in ultrasonic assisted grinding of ZrO₂ based ceramic materials. *4th CIRP International Conference on High Performance Cutting*, 2010, 2:59-64.
- [19] Jahan M.P, Saleh T, Wong Y.S, Rahman M. Study of micro-EDM of tungsten carbide with workpiece vibration, *Advanced Materials Research*, 2011; 264-265:1056-1061.
- [20] Yeo S.H, Tan L.K, Effects of Ultrasonic Vibrations in Micro Electro-Discharge Machining of Microholes. *Journal of Micromechanics and Microengineering*, 1999; 9:345–352.
- [21] Zhao W.S, Wang Z.L, Di S.C, Chi G.X, Wei H.Y. Ultrasonic and Electric Discharge Machining to Deep and Small Hole on Titanium Alloy. *Journal. of Materials Processing Technology*, 2002; 120: 101–106.
- [22] Yu Z.Y, Zhang Y, Li J, Luan J, Zhao F, Guo D. High aspect ratio micro-hole drilling aided with ultrasonic vibration and planetary movement of electrode by micro-EDM. *CIRP Annals – Manufacturing Technology*, 2009; 58/1: 213–216.
- [23] Sundaram M.M, Pavalarajan G.B, Rajurkar K.P. A Study on Process Parameters of Ultrasonic Assisted Micro EDM Based on Taguchi Method. *Journal of Materials Engineering and Performance*, 2008, 17:210-215.

- [24] Sundaram M.M, Billa S, Rajurkar K.P. Generation of High Aspect Ratio Micro Holes by a Hybrid Micromachining Process. *ASME 2007 International Manufacturing Science and Engineering Conference (MSEC2007)*, 2007, Paper no. MSEC2007-31078 pp. 243-248
- [25] Abdullah A, Shabgard M, Ivanov A, Shervanyi-Tabar M. Effect of ultrasonic-assisted EDM on the surface integrity of cemented tungsten carbide (WC-Co). *International Journal of Advanced Manufacturing Technology*, 2009, 41:268-280.
- [26] Klocke F, König W. *Fertigungsverfahren 3 – Abtragen, Generieren und Lasermaterialbearbeitung. Neu bearbeitete Aufl.*, 2007; Springer.
- [27] Ding H, Shin Y. Laser-assisted machining of hardened steel parts with surface integrity analysis. *International Journal of Machine Tools & Manufacture*, 2010; 50:106-114.
- [28] Attia H, Tavakoli S, Vargas R, Thomason V. Laser-assisted high-speed finish turning of superalloy Inconel 718 under dry conditions, *Annals of the CIRP*, 2010; 59/1:83-88.
- [29] Brecher C, Emonts M. LaserPunch - Entwicklung eines laserunterstützten Scherschneidverfahrens. *WT-Online*, 2008; 98:815-824.
- [30] Brecher C, Rosen C.-J. Processing of Advanced Ceramics by Laser-Assisted Milling and Laser Polishing. *Konferenzbeitrag: Internationales VW-Symposium über funktionale Oberflächen*, 2008; Bremen.
- [31] Brecher C, Rosen C.-J, Bausch S, Wenzel C. Fräsen von Hochleistungskeramik. *Werkstatttechnik online*, 2009, p. 177-185.
- [32] Zaboklicki A. Laserunterstütztes Drehen von dichtgesinterter Siliziumnitrid-Keramik. Dissertation RWTH Aachen University, 1998.
- [33] Bergs T. Analyse der Wirkmechanismen beim laserunterstützten Drehen von Siliziumnitridkeramik. Dissertation RWTH Aachen University, 2002.
- [34] Lei S, Shin Y.C. Experimental Investigation of Thermo-Mechanical Characteristics in Laser-Assisted Machining of Silicon Nitride Ceramics. *Journal of Manufacturing Science and Engineering*, 2001, 123:639-646.
- [35] Chang C, Kuo C. An investigation of laser-assisted machining of Al_2O_3 ceramics planing. *International Journal of Machine Tools & Manufacture*, 2007, 47:452-461.
- [36] Pfefferkorn F, Shin Y, Tian Y. Laser-Assisted Machining of Magnesia-Partially-Stabilized Zirconia. *Journal of Manufacturing Science and Engineering*, 2004, Vol. 126:42-51.
- [37] Wertheim R, Ber A. Influence of High Pressure Flushing through the Rake Face of the Cutting Tool. *Annals of the CIRP*, 1992, 41/1:101-106.
- [38] Ezugwu E. O. High Speed Machining of Aero-Engine Alloys, *Journal of the Brazilian Society of Mechanical Science & Engineering* 2004, Vol. XXVI/1:1-11.
- [39] Sanz C, Fuentes E, Gonzalo O. Turning Performance Optimisation of Aeronautical Materials By Using High Pressure Cooling Technology. *5th Int. conference on High Speed Machining*, 2006, Metz, p. 269-280.
- [40] Sharman A.R.C, Hughes J.I., Ridgway K. Surface integrity and tool life when turning Inconel 718 using ultra-high pressure and flood coolant systems. *Proc. IMechE, Part B: J. Engineering Manufacture*, 2008, 222: 653-664.
- [41] Lopez de Lacalle L. N, Perez-Bilbatua J, Sanchez J. A, Llorente J. I, Gutierrez A, Alboniga J. Using High Pressure Coolant in the Drilling and Turning of Low Machinability Alloys. *International Journal of Advanced Manufacturing Technology*, 2000; 16: 85-91.
- [42] Kaminskia J, Alvelid B. Temperature reduction in the cutting zone in water-jet assisted turning. *Journal of Materials Processing Technology*, 2000; 106:68-73.
- [43] Dahlmann P. A comparison of temperature reduction in high-pressure jet-assisted turning using high pressure versus high flowrate. *Proc. Instn. Mech. Engrs., Part B – J. Engineering Manufacture*, 2002; 216: 467-473.
- [44] Kovacevic R, Cherukuthota C, Mohan R. Improving Milling Performance with High pressure Waterjet Assisted Cooling-Lubrication. *Journal of Engineering for Industry*, 1995; 117:331-339.
- [45] Pusavec F, Hamdi H, Kopac J, Jawahir I.S. Surface integrity in cryogenic machining of nickel based alloy-Inconel 718. *Journal of materials Processing Technology*, 2011, Vol. 211:773-783.

- [46] Ezugwu E.O, Bonney J. Finish Machining of Nickel-Base Inconel 718 Alloy with Coated Carbide Tool under Conventional and High-Pressure Coolant Supplies. *Tribology Transactions*, 2005 48:76-81.
- [47] Paul S, Dhar N.R, Chattopadhyay A.B. Beneficial effects of cryogenic cooling over dry and wet machining on tool wear and surface finish in turning AISI 1060 steel. *Journal of Materials Processing Technology*, 2011, 116:44-48.
- [48] Paul S, Chattopadhyay A.B. Effects of cryogenic cooling by liquid nitrogen jet on forces, temperature and surface residual stresses in grinding steels, *Cryogenics*, 1995, 35:515-523
- [49] Dhar N.R, Kumrazzaman M. Cutting temperature, tool wear, surface roughness and dimensional deviation in turning AISI-4037 steel under cryogenic condition. *International Journal of Machine Tools & Manufacture*, 2007, 47:754-759.
- [50] Wang Z.Y, Rajurkar K.P, Murugappan M. Cryogenic PCBN turning of ceramic (Si_3N_4), *Wear* 195, 1996, 195:1-6
- [51] Menzies I, Koshy P. Assessment of abrasion-assisted material removal in wire EDM. *CIRP Annals – Manufacturing Technology*, 2008, 57/1:195-198.
- [52] Koshy P, Jain V.K, Lal G.K. Grinding of cemented carbide with electrical spark assistance *Journal of Materials Processing Technology*, 1997; 72: 61-68.
- [53] Wang W, Liu Z D, Tian Z J, Huang Y H, Liu Z X. High efficiency slicing of low resistance silicon ingot by wire electrolytic-spark hybrid machining. *Journal of Materials Processing Technology*, 2009 , 209:3149-3155.
- [54] Jeong S, Jeong H. Effect on Two-Step Polishing Process of Electrochemical Mechanical Planarization and Chemical-Mechanical Planarization. *Journal of Japanese Applied Physics*, 2009, 48.
- [55] Yamaguchi H, Yumoto K, Shinmura T, Okazaki T. Study of finishing of wafers by magnetic field-assisted finishing. *Journal of Advanced Mechanical Design, Systems, and Manufacturing*, 2009, 3/1: 35-46.
- [56] Foeckerer T, Huntemann J.W, Heinzl C, Brinksmeier E, Zaeh M.F. Experimental and Numerical Identification of Process Parameters of Grind-Hardening and Resulting Part Distortions, *Production Engineering Research and Development*, 2009; 3:271-279.
- [57] Salonitis K, Chryssolouris G. Thermal Analysis of Grind-Hardening Process. *International Journal of Manufacturing Technology and Management*, 2007; 12, Number 1-3:72 – 92.