Chapter 2

Overview of Hybrid Machining Processes

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2.1 INTRODUCTION

The idea behind hybrid machining is to combine different machining processes/mechanisms to manufacture components with a better machining performance. The general objective of hybridizing processes is the “ $1 + 1 = 3$ ” effect, which implies that the positive effect of the hybrid process is more than double the advantages of the single processes [1]. The trend of developing hybrid processes is due to the advent of novel materials with extreme properties, requirements of enhanced machining precision, and complex shaped parts which were earlier difficult or not possible to machine with existing conventional and nonconventional machining technologies. The term “hybrid process” in machining is specifically related to the combination of different process energies or assisting a specific process by using another media or process energy.

A hybrid process can be used in different terms [1]:

1. Combination of different active energy sources which act at the same time in the processing zone (e.g., laser-electrochemical machining (LECM)).
2. Processes which combine process steps that are usually performed in two or more process steps (e.g., grind-hardening).
3. Hybrid machines, integrating different processes within one machining platform (e.g., sequential milling and electric discharge machining (EDM)).

Fig. 2.1 shows the broad classification of hybrid machining processes [2,3]. In assisted hybrid machining, one process energy or media assists the main process energy which is responsible for material removal. For instance,

FIGURE 2.1 Broad classification of hybrid machining processes. *Compiled from references B. Lauwers, F. Klocke, A. Klink, A.E. Tekkaya, R. Neugebauer, D. McIntosh, Hybrid processes in manufacturing, CIRP Ann. 63 (2) (2014) 561–583, and S.Z. Chavoshi, X. Luo, Hybrid micro-machining processes: a review, Precision Eng. 41 (2015) 1–23.*

in laser-assisted turning a laser facilitates material removal by cutting tool via thermally induced softening. In combined hybrid processes, the process energies react simultaneously with the workpiece and participate in material removal. For example, in mechano-electrochemical machining (MECM) the material removal takes place by both cutting action and anodic dissolution. Other hybrid processing techniques include controlled application of process mechanisms with the objective to reduce the process chain or to combine two different processes on the same machine platform. For example, in grind hardening the two-step processes of grinding and heat treatment are combined at one machine platform by utilizing the heat generated in the grinding operation for hardening of the workpiece.

2.2 DESIGN PRINCIPLE AND METHODOLOGY FOR HYBRID MACHINING PROCESSES

The aim of designing hybrid machining processes and related technologies is twofold. First it can shorten the existing process chains by combining two or

more processes on the same machine platform thereby minimizing problems of referencing, clamping, alignment at different workstations. Second it can combine the process capabilities of different processes into one hybrid process so as to realize complex products and/or obtain contradictory machining performance such as high material removal rate (MRR) and high surface finish simultaneously. Conventional mechanical machining technologies are limited by the strength of the tool and mechanism of chip removal which mainly involves plastic deformation. These technologies are not suitable for machining hard-to-machine materials, including highly brittle materials. Similarly nonconventional machining processes also have limitations, especially due to their process physics and material removal mechanisms. For example, laser machining is limited to certain aspect ratios, EDM and electrochemical machining (ECM) are limited to machining of conductive materials, and the precision of waterjet machining is limited by hydraulic jump of the jet. Therefore, in order to satisfy challenging machining needs, two or more hybrid processes can be combined to meet one or more machining objectives. Advanced machining capabilities can be realized through hybridization of two or more machining processes. Fig. 2.2 shows the opportunities where hybrid processes can improve the production in terms of shortening of process chain or improvement of product qualities [4].

To achieve the above aims design of a hybrid machining process will need to follow at least one of the following principles:

- 1. Broadening existing material processing window of processes (i.e. machinable materials).
- 2. Improving existing process capabilities (i.e. attainable surface finish, surface integrity, tool life, etc.).

FIGURE 2.2 Pictorial representation of the aim of developing hybrid processes [4]. Reprinted with kind permission from Elsevier—License number 4218830257077.

3. Fulfilling two contrary machining objectives (e.g. high MRR and high quality surface finish).
4. Gaining significant benefits to interactions of different process energies.

In addition, being cost-effective and not causing hazard and toxic waste are also important design principles for a hybrid machining process.

Design for hybrid machining is a multidisciplinary field as it requires the design of a combination of processes, considering their process physics as well as the design of dedicated machine tools. For example, LECM processes need a design for optics as well as ECM peripherals. Furthermore, these two processes can also influence each other through mutual interaction of process energies. On the other hand, combined mechanical milling and EDM process needs dedicated machine tools since milling is a contact-based process, experiencing machining forces, whereas EDM is a noncontact machining process, experiencing no machining force. Fig. 2.3 shows the main elements for design of hybrid machining processes.

The prime consideration in the design of hybrid process is to know the limitations of the existing machining process. Then, it is of utmost

FIGURE 2.3 Elements of design for hybrid machining.

FIGURE 2.4 Design methodology for hybrid processes [4]. Reprinted with kind permission from Elsevier—License number 4218830257077.

importance to know if any other process has the capability to address this limitation. This requires in-depth knowledge of process mechanisms. Based on the knowledge of the process mechanisms and process capabilities of the two processes of interests, hybridization can be conceptualized. After conceptualization, it is critical to know how the two processes will influence each other, the compatibility of the two process energies, and their synchronization. The general design methodology of a hybrid process is outlined in Fig. 2.4 [4].

2.3 ASSISTED HYBRID MACHINING

For assisted hybrid machining, the major machining process is superimposed with input from one or several types of energy such as ultrasonic vibration, laser, fluid, magnetic field, etc. so as to improve the constituent machining process

2.3.1 Vibration-Assisted Machining

Vibration-assisted machining uses vibrations to facilitate material removal and improve process performance. In this process, a small vibration (average amplitudes: 1 – 200 μm , frequencies: 0.1 – 80 kHz) is added to the tool or workpiece movement [5]. The vibrations may be in one or two directions. A small-amplitude high-frequency tool displacement is given to the cutting

- Improvement in surface quality and machining time.
- Improved machining of brittle materials like ceramics and glass.
- During vibrations of specific amplitude, the cutting tool loses contact with the chips and results in reduction in cutting forces and improved tool life [3].
- In case of EDM/ECM, ultrasonic vibration assistance improves flushing of working fluid and assists in evacuation of machining by-products.

The application of a laser beam as a secondary process is advantageous for various primary processes. The laser beam strongly influences the processing zone (e.g., material softening in cutting, changing electrolyte conditions in ECM, material elongation and bending in forming, etc.) so processing/shaping/machining becomes easier [2]. The laser assistance may be applied to both conventional and nonconventional machining processes. In conventional

FIGURE 2.6 (A) Principle of laser-assisted turning [7], (B) mechanical strength as a function of temperature [2].

machining, the laser beam is focused on the workpiece in front of the cutting edge of the tool (Fig. 2.6A) [7]. The flow stress and strain hardening rate of materials normally decrease with the increase of temperature due to thermal softening. Therefore, laser-assisted machining facilitates the material removal when machining hard-to-machine materials (Fig. 2.6B) [2]. The heat from the laser softens the workpiece and the cutting process becomes easier without compromising on hardness and microstructure [3]. In the case of nonconventional machining such as ECM, the laser enhances the precision of material removal by localizing the electrochemical dissolution [8]. The main advantages of laser-assisted machining are as follows:

- Reduction of cutting forces and tool heating while machining hard materials.

- Improved machinability of hard and difficult to cut materials by localized softening of material by laser.
- Reduction of grinding forces and improved surface quality during grinding of ceramics.
- Increase in MRR.
- Localization of material removal, improvement in precision, removal of passivating layer in ECM.
- Improvement in machining precision and MRR in water jet machining [9].

2.3.3 Magnetic Field-Assisted Machining

The assistance of a magnetic field in machining is beneficial for certain processes as it influences their process physics. In laser-induced plasma machining, the external magnetic fluid is used to manipulate the plasma shape for special geometries [2]. In conventional mechanical machining, application of a magnetic field helps in directing crack propagation in any direction in a controlled way. This is achieved through the combination of mechanical force with the Lorentz forces [10]. The magnetic field assistance is also advantageous for the EDM process since it helps in debris evacuation. The process implements magnetic force perpendicular to the electrode's rotational force which produces a resultant force that is efficient in transporting debris out of the hole during machining [11]. In the case of dry EDM [12], the process suffers from low stability of arc column and low MRR. The application of pulsating magnetic field assists will increase the plasma ionization and allow control of the plasma expansion. Furthermore, when the pulsating magnetic field is applied tangentially to the electric field (Fig. 2.7A–C) it increases the movement of electrons and degree of ionization in the plasma leading to productivity improvements of 130% and zero tool wear as compared to conventional dry EDM [12]. The increase in MRR in dry EDM with magnetic assistance is due to the following reasons [12]:

1. The magnetic force prevents plasma expansion. It acts tangentially to the plasma and prevents expansion. It increases the plasma pressure (P) and reduces mean free path (λ) and increases the plasma density:

$$\lambda = \frac{RT}{2^{0.5} \pi d^2 N_A} \quad (2.1)$$

where R , T , d , and N_A are universal gas constant, temperature of gas, diameter of a gas molecule, and Avogadro number, respectively.

2. A decrease in mean free path of the ions (Fig. 2.7D) leads to an increase in the number of ionization events (α) in the interelectrode gap given by:

$$\alpha = PA \exp\left(\frac{-BP}{E}\right) \quad (2.2)$$

FIGURE 2.7 (A) Schematic of tangential magnetic field and forces. (B) Schematic of pulsating electromagnetic field application. (C) Experimental setup. (D) Illustration of reduced mean free path and more ionization in MFA dry EDM [12]. Reprinted with kind permission from Elsevier—License number 4218831208989.

where A and B are constants for a particular gas. P and E are plasma pressure and electric field in the interelectrode gap, respectively.

3. The magnetic field increases the intermolecular collisions and contributes to the ionization, which helps faster breakdown given by the breakdown criteria:

$$\gamma = \frac{1}{e^{\alpha \cdot V_B/E} - 1} \quad (2.3)$$

where e is number of electrons emitted from cathode due to initial ionization and V_B is breakdown voltage. Therefore, J of the plasma increase can be described as:

$$J = \pi r_c^2 j_e V \quad (2.4)$$

where r_c , j_e , and V are radius of a micropeak on cathode-emitting electrons, electronic current density, and voltage across cathode and anode, respectively.

Therefore, the application of a magnetic field controls the plasma expansion and leads to an increase in energy at the anode thereby increasing MRR in magnetic field-assisted dry EDM.

2.3.4 External Electric Field-Assisted Machining

The generation of debris in machining process has adverse effects on the surface quality of the machined surface. Especially during machining with ultrashort pulsed lasers, plasma cloud generation is a frequently occurring phenomenon. At ultrashort pulse durations (fs), the laser pulses with high pulse energy produce very high peak power which results in ionization of substrate material and plasma formation takes place. This plasma cloud may redeposit on the machined surface as debris. The application of an external electric field in short pulsed laser machining facilitates removal of debris and minimizes redeposition on the surface. Fig. 2.8A shows the schematic of the experimental prototype for external electric field-assisted laser machining.

The principle of debris removal by application of electric field resembles that of a charged particle being removed by electric force. To accomplish

FIGURE 2.8 (A) Sketch of prototype setup for external electric field-assisted laser micromachining. fs laser micromachining of Si (B) without external electric field, (C) with external electric field and applied voltage of 150 V (laser power: 10 mW, scanning speed 10 $\mu\text{m/s}$). Adapted from H.Y. Zheng, Z.W. Jiang, *Femtosecond laser micromachining of silicon with an external electric field*, *J. Micromech. Microeng.* 20 (2010) 17001–17004.

this, the weight of the particle should be less than the electric forces. The electric force is defined by Eq. (2.5).

$$F = \frac{V \times q}{d} \quad (2.5)$$

where F , q , V , and d are electric force experienced by the particle, charge on an electron (i.e., -1.602×10^{-19} C), the applied voltage between two plates, and the distance between two plates, respectively.

The particle weight can be estimated from Eq. (2.6).

$$G = \left(\frac{r_p}{r_a} \right)^3 m_a g \quad (2.6)$$

where r_p , r_a , m_a , and g are radius of particle, radius of the Si atom (i.e., 0.117 nm), mass of Si atom (i.e., 4.66×10^{-26} kg), and acceleration due to gravity (i.e., 9.8 m/s^2), respectively.

Higher voltages produce higher electric forces and attract larger charged particles and facilitate efficient debris removal. This leads to improvement in surface quality of the machined surface and minimizes the surface contamination [13]. Fig. 2.8B and C show the comparison between the surface machined using fs laser without external electric field and with external electric field (150 V). It can be observed that the Si surface processed with external electric field-assisted laser micromachining is much cleaner and has a higher surface quality.

2.3.5 Fluid-Assisted Machining

In fluid-assisted machining, different types of fluids, such as water, chemicals, cryogenic fluids, gas, or methanol, are applied in the machining zone to improve the performance of a specific process [3]. A high pressure fluid is usually supplied for improving the material removal for hard and difficult-to-cut materials. The flow rate and pressure of the fluid are critical parameters. The application of cryogenic cooling with liquid nitrogen or carbon dioxide is suitable for machining of Ni- and Ti-based superalloys as it improves surface finish and tool life [2]. In mechanical machining such as turning and milling, the application of a high pressure waterjet facilitates cooling of the machining zone and hence reduces the cutting edge temperature, minimizes the burr formation, and improves the surface finish. This is particularly useful in machining of low thermal conductivity alloys such as nickel-based superalloys, Ti-6Al-4V, alloy steels, etc. [2]. Besides the high-pressure cooling applications, cryogenic cooling has also been developed for machining of different materials. Cryogenic cooling and its positive effects on tool life during machining are self-explanatory in Fig. 2.9 [14]. The main challenge for fluid-assisted machining processes is to effectively supply pressurized

FIGURE 2.9 Cryogenic cooling (milling setup) and evolution of flank wear in conventional, CO₂ and LN₂-turning of Ti6Al4V [14].

fluid to the machining zone. This is normally done through specially designed tools, collets, and sealing systems.

2.4 COMBINED HYBRID MACHINING

In combined hybrid processes, two or more processes are combined together and they act simultaneously or in a synchronized manner on the workpiece. Table 2.1 gives an overview of combined hybrid machining processes, suitable workpiece materials, and process characteristics [3]. Some of the combined hybrid machining processes are discussed in the subsequent sections.

2.4.1 Electrochemical Discharge Machining

Electrochemical discharge machining (ECDM) stands for the combination of electrochemical and electrodischarge process energies. According to the principle of ECDM, the discharge delay time of the EDM process is utilized for electrochemical dissolution which is followed by melting through spark discharge. Fig. 2.10 shows the nature of ECDM pulse. The optimal adjustment of process parameters can give high surface finish, reduced heat affected zone, and dimensional precision in ECDM process as shown in Fig. 2.10. In ECDM process, the electrochemical activity produces hydrogen bubbles which are positively charged. When a DC voltage is applied to tool and workpiece electrodes, the breakdown of the insulating layer of hydrogen bubbles leads to spark discharge. As a result, localized material removal occurs by virtue of melting and evaporation.

2.4.2 Electrochemical Grinding

The motivation behind the development of combined ECM and grinding (Fig. 2.11) was to obtain a burr-free material removal process for difficult-to-cut aerospace alloys and cemented carbides. The combination of ECM

TABLE 2.1 Overview of Combined Hybrid Machining Processes [3]

Combined hybrid machining processes	Suitable workpiece materials	Characteristic of process
ECDM	Glass, Pyrex glass, soda lime glass, steel, quartz, 100 Cr6 steel, silicon nitride, borosilicate glass, copper, tantalum, SS304, Al ₂ O ₃ , E-glass-fiber-epoxy composite, silica glass	<ul style="list-style-type: none">• Suitable for micromachining of nonconductive materials• Achieved surface roughness (<i>Rq</i>) for Pyrex glass is nearly 0.08 μm
ECDM milling	Glass, pyrex glass	<ul style="list-style-type: none">• Suitable for 3D microstructuring of nonconductive materials.• Achieved surface roughness (<i>Ra</i>) for glass is 0.099 μm
Simultaneous ED-EC milling	SUS304, T1 copper, 1Cr18Ni9Tistainless steel	<ul style="list-style-type: none">• Achieved surface roughness for SS304 is <i>Ra</i> 22 nm
ECM-grinding	SS321	<ul style="list-style-type: none">• Achieved surface roughness, <i>Ra</i> 0.21 μm
EDM-electrorheological fluid polishing	SUS304, aluminum alloy	<ul style="list-style-type: none">• Achieved surface roughness, <i>Ra</i> 0.06 – 0.08 μm
Laser drilling-jet ECM	321 stainless steel	<ul style="list-style-type: none">• More than 90% reduction in recast

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FIGURE 2.10 Principle of ECDM (combined machining with ECMD and EDM) and example of an application [15]. Reprinted with kind permission from Elsevier—License number 4218850076487.

FIGURE 2.11 Sketch showing principle of ECM grinding [16].

and grinding is more advantageous than conventional grinding due to low residual stresses, large depths of cut, and increased wheel life. Furthermore, the combined process also performs better than ECM process as it removes the passivation layer and higher MRRs can be realized by combined grinding and ECM. In electrochemical grinding (ECG), a rotating grinding wheel is made the cathode [17]. When the wheel comes closer to the workpiece, its abrasive particles touch the workpiece surface and a gap is formed between the workpiece and the wheel. The electrolyte flow takes place in this gap. At first, the material removal occurs due to electrochemical dissolution and this leads to formation of a passivating layer.

This passivation layer is removed by abrasive action of the grinding wheel and it facilitates ECM process by exposing a fresh workpiece surface every time. The use of pulsed power supply in ECG is better than conventional ECG as it helps in adjusting the balance between electrochemical and mechanical actions. The pulse parameters such as pulse-on-time and duty cycle act as additional parameters for better control of the material removal process.

2.4.3 Electrodischarge Grinding and Abrasive-EDM Processes

In electrodischarge grinding and other variants of abrasive-EDM processes, the material removal is accomplished by synergistic combination of spark erosion and abrasive action. Fig. 2.12 shows the basic principle and application of hybrid processes during EDM grinding and abrasive-wire-EDM. The combination of EDM and grinding is particularly useful in machining of electrically conductive cemented carbides with a metal bonded diamond grinding wheel. This is because of the dual benefit of enhanced material removal by combined action and the declogging of the grinding wheel surface [18]. The material removal due to abrasive action and spark erosion depends on process parameters. As shown in Fig. 2.2, there is a decrease in grinding/abrasive action with an increase of current from 0.4 to 2.1 A. This

FIGURE 2.12 Combination of EDM with abrasive processes: principle and application in EDM-grinding and abrasive-wire-EDM [18,19]. Reprinted with kind permission from Elsevier—License numbers 4218840185713, 4218840377112.

can be visualized clearly from SEM images where the grooves machined by abrasive action are clearly visible at 0.4 A. However, in the case when the current is 2.1 A, the surface shows dominantly EDMed characteristics. Additionally, the spark of EDM process results in thermally induced softening of the material in the grinding zone. Thus, the process is benefiting from reduced cutting forces and the requirement of the low spindle power [18].

Another variant of abrasive-EDM process is abrasive-wire-EDM process (AWEDM). This process is particularly useful for the aerospace industry as it produces machined surfaces with a minimal or negligible recast layer [19]. The AWEDM process makes use of a fixed abrasive wire. The process can be considered as a combined action of wire-EDM and wire sawing particularly at low wire speed. The process has similar kinematics as the wire-EDM process. The gap between wire core and workpiece surface is filled with dielectric. The wire is electrically conductive and the abrasives are nonconductive. Fig. 2.12 shows the comparison of surface integrity of wire-EDMed and AWEDMed surface. It can be observed that the surface machined by wire-EDM shows the presence of a 5- μ m-thick recast layer whereas on the AWEDMed surface, the recast layer is almost absent [19].

2.4.4 Laser-Chemical/Electrochemical Machining

The laser-chemical and electrochemical machining processes have been developed with a multifold objective of increasing MRR and precision of chemical/electrochemical material removal as well as minimizing thermally induced defects of laser machining. In laser chemical machining the etchant is injected coaxially to the laser beam as shown in Fig. 2.13 [20,21]. The reaction rate of etching is temperature dependent and the laser increases dissolution kinetics. Furthermore, there is no thermal damage to the workpiece. The velocity of etchant also plays an important role as at higher velocities, better surface roughness and higher aspect ratios can be obtained. The SEM images in Fig. 2.13 show the improvement in machining quality of Nitinol when machined with laser-chemical etching as compared to direct laser ablation [21]. In LECM [8,22], the electrolyte jet is injected coaxially to the laser beam. The machining is mainly due to electrochemical dissolution and the laser serves multiple functions depending on the fluences. The laser can help removal of passivation layer, local heating of workpiece to improve kinetics of dissolution [8,22], and it can also participate in material removal if high pulse energies are used [22]. The combination of LECM generates better surface finish, negligible thermal defects, and better precision as compared to stand-alone ECM and laser machining processes.

FIGURE 2.13 Principle of laser chemical machining and resulting performance of material removal rate and surface finish on Nitinol. Comparison of machining quality after (A) direct laser ablation, and (B) laser chemical machining. [20]. Reprinted with kind permission from Elsevier—License number 4218840729413.

2.4.5 Laser-Waterjet Machining

In laser-waterjet machining (LWJM), the thermally induced defects induced by laser machining are minimized and material removal by waterjet impact is facilitated [9]. By combining laser and waterjet, the laser heats the workpiece material locally and softens it. The impacting waterjet then expels the softened material. The waterjet also serves the function of cooling the laser heated region. The technique has been found useful for the cutting of silicon substrates as it produces surfaces which are free from a heat-affected zone. Fig. 2.14 is a sketch of LWJM along with the main process parameters.

2.4.6 Mechano-Electrochemical Machining

The mechano-electrochemical machining (MECM) process exploits dual benefits by a combination of mechanical and electrochemical material removal. Fig. 2.15 shows a sketch of a hybrid MECM setup. The process is realized by design of a special ECM tool with a cutting edge. The process is

FIGURE 2.14 Sketch showing principle and parameters of hybrid laser-waterjet machining [9]. Reprinted with kind permission from Elsevier—License number 4218840869109.

FIGURE 2.15 Principle of hybrid MECM [25]. Adapted from D. Van Camp, J. Bouquet, J. Qian, J. Vleugels, B. Lauwers, Investigation on hybrid mechano-electrochemical milling of Ti6Al4V, Proc. ISEM XIX, 2018.

especially useful for machining hard metals such as Ti-6Al-4V, which suffer from surface passivation during ECM process. The mechanical process facilitates removal of the passivation layer by a cutting edge, thereby enhancing surface quality and process stability. The process needs a dedicated tool design and machine tool.

2.4.7 Abrasive-Waterjet Milling

Abrasive-waterjet machining (AWJM) is widely used in the cutting of hard and low machinability materials like titanium alloys, ceramics, metal–matrix composites, concrete, rocks, etc. The process makes use of the impact of a waterjet as well as the impact of abrasives for improving the machinability of certain materials. Fig. 2.16 shows a sketch of a setup for AWJM [23]. The main element of an abrasive-waterjet setup is the reciprocating pump which is used to pump pure water at extremely high pressure of 4000 – 6000 bar. The abrasive particles are introduced into the waterjet from a hopper in the mixing chamber. The combined impact of waterjet and abrasives is useful in cutting or machining of composites, Kevlar polymer, toughened steels, and some ceramics. The main challenge in abrasive-waterjet machining lies in controlling the depth of cut. The advantages of abrasive-waterjet machining over conventional cutting/machining methods are listed below [23]:

1. The AWJM process produces very small stresses and negligible heat and is suitable for heat-sensitive materials such as plastics.
2. The process is suitable for cutting complex contours on wide range of materials.
3. The process has the capability to cut thin pieces with least bending.

FIGURE 2.16 Sketch of abrasive-waterjet machining setup [23]. Reprinted with kind permission from Springer—License number 4218841341855.

4. The process is comparatively faster due to combined action of waterjet and abrasive action.

The main disadvantages of this process include the limited range of surface finish, the expensive equipment, as well as safety issues.

2.5 COMBINATION OF CONTROLLED PROCESSES

In this group of hybrid processes, the processes are developed where a controlled combination of effects occurs that are conventionally caused by separated processes.

2.5.1 Grind Hardening

Grinding is a machining process which removes material in a finishing regime. Heat treatment is the final step of many process chains, and it is usually expensive and time-consuming. To shorten these process chains, the concept of grind-hardening has come up [24]. The idea consists of substituting a conventional hardening process with the “grind-hardening” process. Grind-hardening has the advanced capability for process integrated surface layer hardening by grinding with a subsequent finishing in one clamping. In grinding process, ample heat is generated in the contact zone between the grinding wheel and workpiece due to deformation, shearing, and friction. This heat can be utilized for short-time surface hardening of the machined part. In order to achieve high heat input rate, the grinding operation is performed with a higher depth of cut and slow feed speed [24]. Fig. 2.17 reports the hardness results for grind hardening process. The cross-section image depicts the characteristic of surface hardening and shows the location of hardening depth distributions.

FIGURE 2.17 Hardness results for grind-hardening process [24]. Reprinted with kind permission from Springer—License number 4218870457356.

2.6 SUMMARY

This chapter gave an overview of hybrid machining processes. The motive behind developing a hybrid machining process is discussed and the advantages of hybrid machining processes are highlighted. The design principle and methodology for hybrid machining technologies are also discussed comprehensively. The hybrid machining process combinations are considered to give a “ $1 + 1 = 3$ ” effect and to address the limitations of individual machining processes. Three different categories of hybrid machining processes are discussed in this chapter i.e., assisted machining, combined machining, and controlled application of process mechanisms. With the developments in hybrid machining technologies, machining issues with novel materials and complex shapes can be addressed effectively. The development of hybrid machining processes is still continuously evolving, starting from basic research to industrial implementation.

REFERENCES

- [1] G. Schuh, J. Kreysa, S. Orilski, S. Roadmap, *Hybride Produktion*, ZWF Zeitschrift für wirtschaftlichen Fabrikbetrieb, Hanser Verlag 104 (5) (2009) 385–391.
- [2] B. Lauwers, F. Klocke, A. Klink, A.E. Tekkaya, R. Neugebauer, D. McIntosh, Hybrid processes in manufacturing, *CIRP Ann.* 63 (2) (2014) 561–583.
- [3] S.Z. Chavoshi, X. Luo, Hybrid micro-machining processes: a review, *Precision Eng.* 41 (2015) 1–23.
- [4] F. Klocke, A. Roderburg, C. Zeppenfeld, Design methodology for hybrid production processes, *Proc. Eng.* 9 (2011) 417–430.
- [5] D.E. Brehl, T.A. Dow, Review of vibration-assisted machining, *Precision Eng.* 32 (3) (2008) 153–172.
- [6] S. Skoczypiec, Research on ultrasonically assisted electrochemical machining process, *Int. J. Adv. Manuf. Technol.* 52 (5–8) (2011) 565–574.
- [7] Y. Shin, Laser Assisted Machining with Distributed Lasers, US patent 8053705 B2, 2011.
- [8] P.T. Pajak, A.K.M. Desilva, D.K. Harrison, J.A. McGeough, Precision and efficiency of laser assisted jet electrochemical machining, *Precision Eng.* 30 (2006) 288–298.
- [9] V. Tangwarodomnukun, J. Wang, C.Z. Huang, H.T. Zhu, Heating and material removal process in hybrid laser-waterjet ablation of silicon substrates, *Int. J. Machine Tools Manuf.* 79 (2014) 1–16.
- [10] P. Kumar, A. Mishra, T. Watt, I. Dutta, D.L. Bourell, U. Sahaym, Electromagnetic jigsaw: Metal-cutting by combining electromagnetic and mechanical Forces, *Proc. CIRP* 6 (2013) 600–604.
- [11] S.H. Yeo, M. Murali, H.T. Cheah, Magnetic field assisted micro electro-discharge machining, *J. Micromech. Microeng.* 14 (11) (2004) 1526–1529.
- [12] S. Joshi, P. Govindan, A. Malshe, K. Rajurkar, Experimental characterization of dry EDM performed in a pulsating magnetic field, *CIRP Ann.* 60 (1) (2011) 239–242.
- [13] H.Y. Zheng, Z.W. Jiang, Femtosecond laser micromachining of silicon with an external electric field, *J. Micromech. Microeng.* 20 (2010) 17001–17004.

- [14] F. Klocke, H. Sangermann, A. Kraemer, A.D. Lung, High performance cutting of difficult-to-cut materials through targeted selection of the lubricoolant strategy, *Proc. 9th Int. Conf. High Speed Machining*, 2012.
- [15] M.D. Nguyen, M. Rahman, Y.S. Wong, Enhanced surface integrity and dimensional accuracy by simultaneous micro-ED/EC milling, *CIRP Ann.* 61 (1) (2012) 191–194.
- [16] Verein Deutscher Ingenieure-VDI-Richtlinien, 2009.
- [17] D. Zhu, Y.B. Zeng, Z.Y. Xu, X.Y. Zhang, Precision machining of small holes by the hybrid process of electrochemical removal and grinding, *CIRP Ann.* 60 (1) (2011) 247–250.
- [18] P. Koshy, V.K. Jain, G.K. Lal, Grinding of cemented carbide with electrical spark assistance, *J. Mater. Process. Technol.* 72 (1997) 61–68.
- [19] I. Menzies, P. Koshy, Assessment of abrasion-assisted material removal in wire EDM, *CIRP Ann.* 57 (1) (2008) 195–198.
- [20] A. Stephen, F. Vollertsen, Mechanisms and processing limits in laser thermochemical machining, *CIRP Ann.* 59 (1) (2010) 251–254.
- [21] A. Stephen, Mechanisms and applications of laser chemical machining, *Phys. Proc.* 12 (Part 2) (2011) 261–267.
- [22] H. Zhang, J. Xu, J. Wang, Investigation of a novel hybrid process of laser drilling assisted with jet electrochemical machining, *Optics Lasers Eng.* 47 (11) (2009) 1242–1249.
- [23] M. Shukla, Abrasive water jet milling BT, in: J.P. Davim (Ed.), *Nontraditional Machining Processes: Research Advances*, Springer, London, 2013, pp. 177–203.
- [24] M.F. Zäh, E. Brinksmeier, C. Heinzel, J.W. Huntemann, T. Föckerer, Experimental and numerical identification of process parameters of grind-hardening and resulting part distortions, *Prod. Eng.* 3 (3) (2009) 271–279.
- [25] D. Van Camp, J. Bouquet, J. Qian, J. Vleugels, B. Lauwers, Investigation on hybrid mechano-electrochemical milling of Ti6Al4V, *Proc. ISEM XIX*, 2018.