Chapter 8
Productivity Improvement Through the Application of Hybrid Processes

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Abstract Many parts require high strength materials, exhibiting high temperatures or where formability should be reduced, requiring new processing technologies. The application of hybrid manufacturing processes can answer the needs. This paper gives first a classification of hybrid manufacturing processes, followed by a description of various productivity improvements. The latter is also demonstrated by various examples in cutting, grinding, forming and chemical & physical processes like EDM, ECM and laser.

8.1 Introduction

Advanced mechanical products such as gas turbines, aerospace & automotive parts and heavy off-road equipment, rely more and more on advanced materials to achieve required performance characteristics. Many parts require high strength materials, exhibiting high temperatures or where formability should be reduced, requiring new processing technologies. The application of hybrid manufacturing processes can answer the needs.

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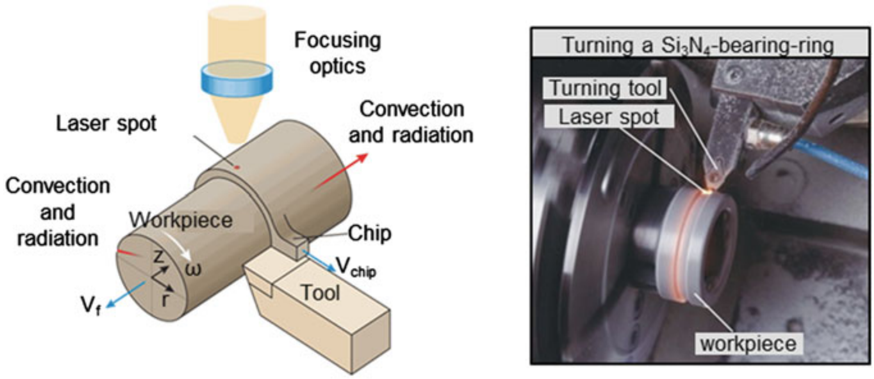

Fig. 8.1 Principle and application of laser assisted turning (Shin 2011)

According to the international academy for production engineering (CIRP), 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 (Lauwers et al. 2014). The wording “simultaneous and controlled interaction” means that the processes/energy sources should interact more or less in the same processing zone and at the same time.

Two distinct examples of hybrid processes are given to better explain what a hybrid process means. First, laser assisted cutting, where the laser beam is directly focused in front of the cutting tool, resulting in easier machining and higher process performance (Fig. 8.1).

In this process, the main material removal mechanism is still the one occurring in conventional cutting, but the laser action softens the workpiece material, so machining of high alloyed steels or some ceramics becomes easier. It is only by applying the laser energy and the mechanical cutting energy at the same time that more efficient machining becomes possible. Due to the softening effect, the process forces decrease drastically and often better surface quality can be obtained.

A second example in the area of forming is curved profile extrusion (CPE) (Klaus et al. 2006), where extrusion and bending is combined within a unique new process. In comparison to the traditional processing route for manufacturing of curved profiles (Fig. 8.2), where first the straight profile is extruded and then in a second process bended, in CPE, the extruded profile passes through a guiding tool, moveable by a linear axes system, naturally bending the profile during extrusion.

Thus, the material flow in the extrusion die is influenced by the superimposed bending moment of the guiding tool and the additional friction force in the bearing areas. Consequently, the material is accelerated at the outside and decelerated at the inside of the profile so that a controlled curvature results from this differing material flow. Due to the bending during extrusion within the die, this new forming process causes no cross-sectional distortion of the profile, no spring back, and nearly no decrease in formability. Compared to warm bending tests, process forces could be

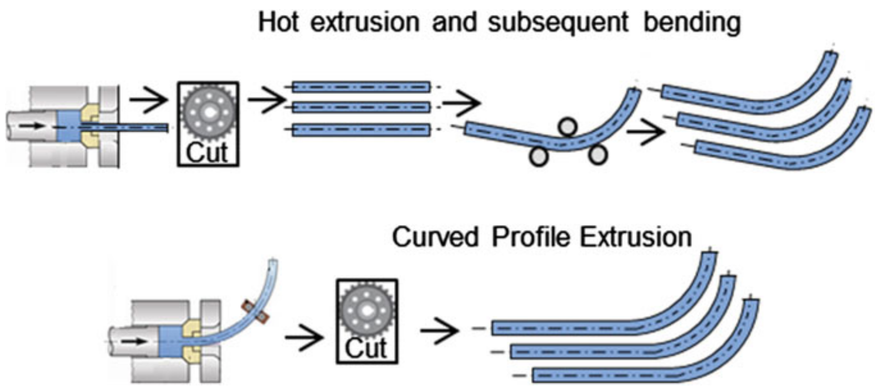

Fig. 8.2 Comparison of traditional manufacturing of curved profiles versus curved profile extrusion (hybrid)

drastically reduced to 10–15 % of the bending force that would be required if only warm bending would have been applied.

8.2 Classification of Hybrid Processes

Figure 8.3 gives a further classification or grouping of hybrid processes and some examples. The first group (I) contains processes where two or more energy sources/tools are combined and have a synergetic effect in the processing zone. A further classification is made in "Assisted Hybrid Processes" (I.A) and "Mixed or

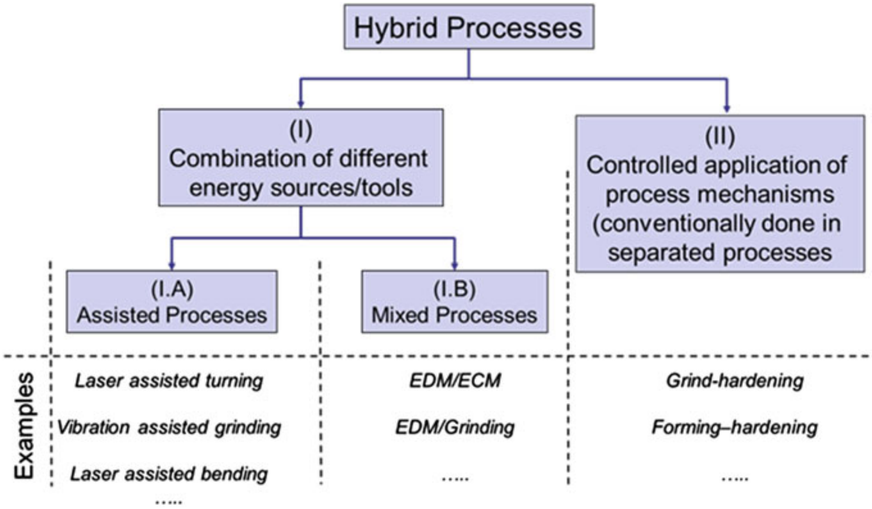

Fig. 8.3 Classification of Hybrid Processes

Combined Processes" (I.B). In assisting processes, a main process (material removal, forming,…) is defined by the primary process. The secondary process only assists, while in pure hybrid processes, several processing mechanisms (originating from the different processes) or even new mechanisms are present. In mixed or combined processes, two or more processes are present, which according to the above definition should occur more or less at the same time. 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 controlled hardening due to the induced heat of the grinding process.

8.3 Assisted Hybrid Processes

Figure 8.4 shows common combinations of a primary process with a secondary assisting process to create a hybrid assisted process technology. It can be concluded that the most important secondary assisting processes are vibration (ultrasonic), laser and media (fluid) assistance. Vibration assisted technologies are used in various primary processes to support the material removal. In these processes, a small vibration (average amplitudes: 1…200 µm, frequencies: 0.1…80 kHz) is added to the tool or workpiece movement. In most systems, especially in cutting and grinding operations, the amplitudes are in the range of 1–15 µm and vibration is within a frequency range from 18 to 25 kHz and the vibration itself is generated by piezoelectric elements within the tool holder, spindle or workpiece holding system. Therefore, the term "Ultrasonic Assisted Machining" (US) is also often used for these kinds of processes.

The use of a laser beam as secondary process is available for various primary processes. The laser beam strongly influences the processing zone (e.g. material

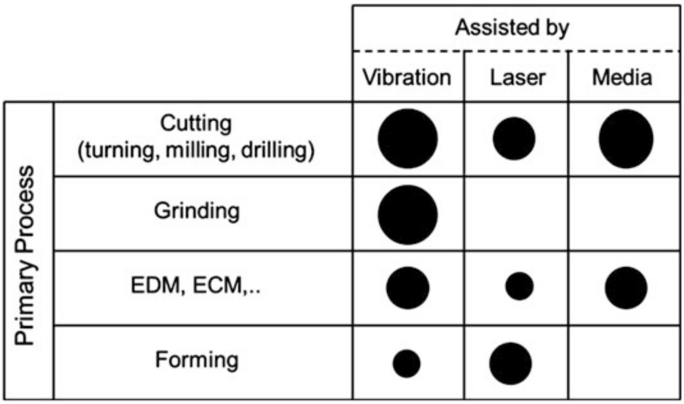

Fig. 8.4 Combinations of assisted hybrid processes

softening in cutting, changing electrolyte conditions in ECM, material elongation and bending in forming, etc.) so processing/shaping/machining becomes easier.

The third very important group of secondary assisting processes incorporates the so called “Media-assisted Processes”. This includes high pressure and cryogenic cooling/lubrication applied by dedicated jets or cooling nozzle systems. It is also used in forming (e.g. the pneumo-mechanical deep drawing process), where a pressurized medium is used to pre-stretch the sheet during the conventional deep drawing process. The borderline to conventional cooling and lubrication applications is not always clearly defined but it can be stated that there must be a significant process improvement initiated by the media assistance. Assisted hybrid processes results in a number of strong positive effects on the process performance. Often, the term “1 + 1 = 3” is used, meaning that the positive effect of the hybrid process is more than the double of the advantages of the single processes. In the following sections, a number of productivity improvements are described and demonstrated by one or two examples (Schuh et al. 2009).

8.3.1 Reduction of Process Force

Various assisted hybrid processes, such as laser assisted turning and ultrasonic assisted grinding show strong process force reductions. An example for major reduction of the drilling torque to a quasi-static value is shown in Fig. 8.5 (left) for the vibration assisted deep hole drilling of electrolytic copper ECu57 (Heisel et al. 2008). A virtually constant value can be reached independent of feed rate for no-load vibration amplitudes (A) in the range of about 5–10 µm. Also a better chip breakage for the ductile material was achieved.

Figure 8.5 (right) shows the results of a superimposing oscillation in sheet bulk metal forming (Behrens et al. 2013). The part itself is manufactured by deep drawing and the gearing is produced by bulk forming in a combination with superimposing oscillation, which leads to significantly reduced process forces. The investigations showed that with increasing process requirements such as lower die clearance, the superimposed oscillation has a greater effect on the reduction of the forming force and the spring back behaviour.

8.3.2 Higher Material Removal Rate

Not only an increase of the feed rate (due to lower process forces), but also the interaction effect between the two energy sources often results in higher material removal rates. Figure 8.6 shows the High-Speed Electro-erosion Milling (HSEM) process where high material removal rates are achieved by promoting controlled electric arcing through the use of a non-dielectric medium and a spinning electrode, enabling simultaneous multiple discharges and arcs to occur. The process starts

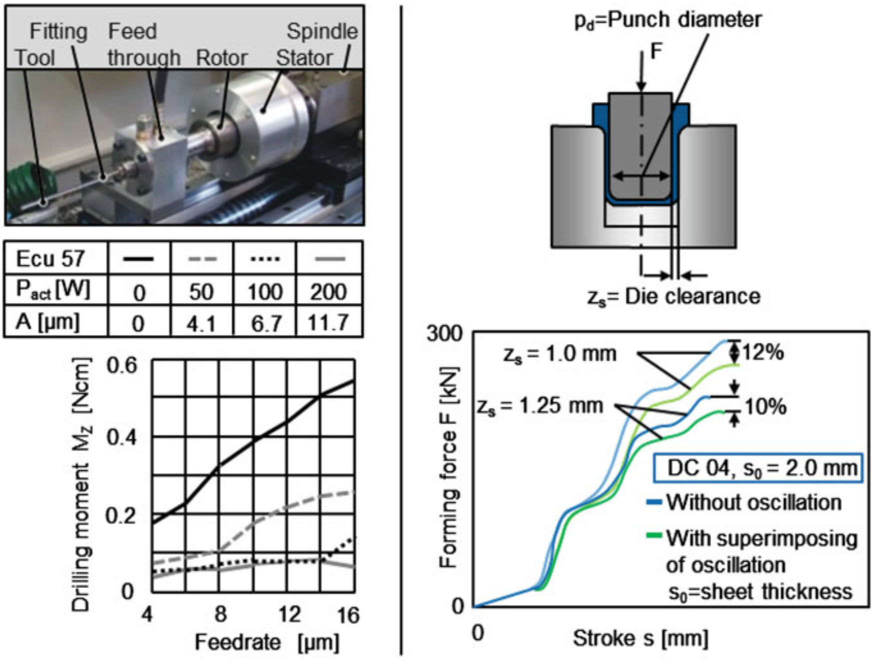

Fig. 8.5 Process force reductions in vibration assisted hole drilling (*left*) and sheet bulk metal forming (*right*)

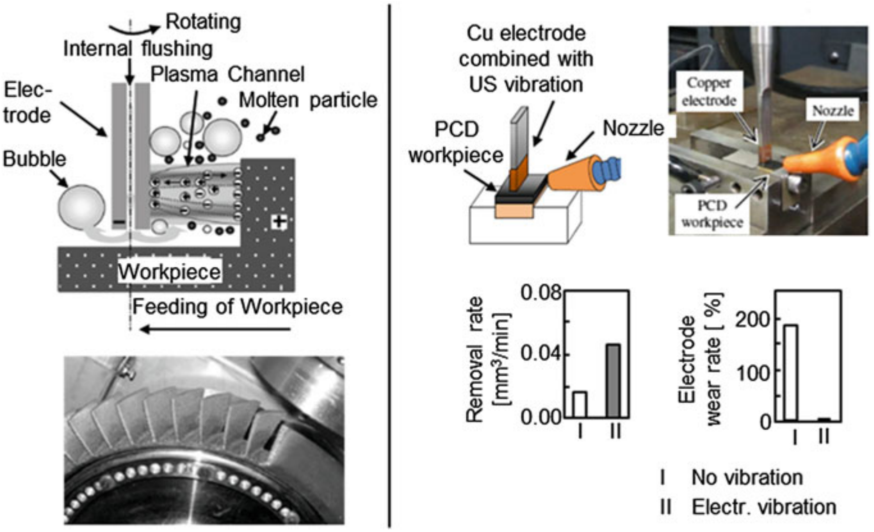

Fig. 8.6 Increase of material removal rate for High-speed Electro-erosion Machining (*left*) and vibration assisted EDM (*right*)

with multiple ionic micro-bridges in the small gap. The applied voltage triggers gas bubble generation and breakdown as well as instantaneous short-circuiting, resulting in rapid metal erosion in many locations. A metal removal rate of approx. 200 cm^3/min has been achieved with a 25 mm thick disk electrode. During blisk milling of Inconel 718 the process achieves a 3 times higher material removal rate compared to conventional cutting (Wei et al. 2010).

In vibration assisted EDM, an additional relative movement is applied in the system tool electrode, workpiece and dielectric fluid in order to increase the flushing efficiency, resulting in a higher material removal rate and better process stability (Fig. 8.6, right) (Ichikawa and Natsu 2013). In addition, the tool wear is drastically reduced by applying tool/workpiece vibration.

8.3.3 Reduced Tool Wear

Besides vibration assisted EDM processes, tool wear reductions are also observed in other assisted hybrid processes. Figure 8.7 (left) shows the advantageous effects on tool life in cryogenic machining of TiAl6V4 (media assisted process). The cryogenic cooling with liquid nitrogen LN2 or carbon dioxide CO_2 is widely applied for machining of Ni- and Ti-based superalloys.

Also in the case of vibration assisted turning, the periodic disengagement of the cutting tool during vibration assistance offers the opportunity for ultra-precision machining of hardened steel, glass and even other ceramic materials with single crystal diamond tools with reduced process forces and increased surface qualities

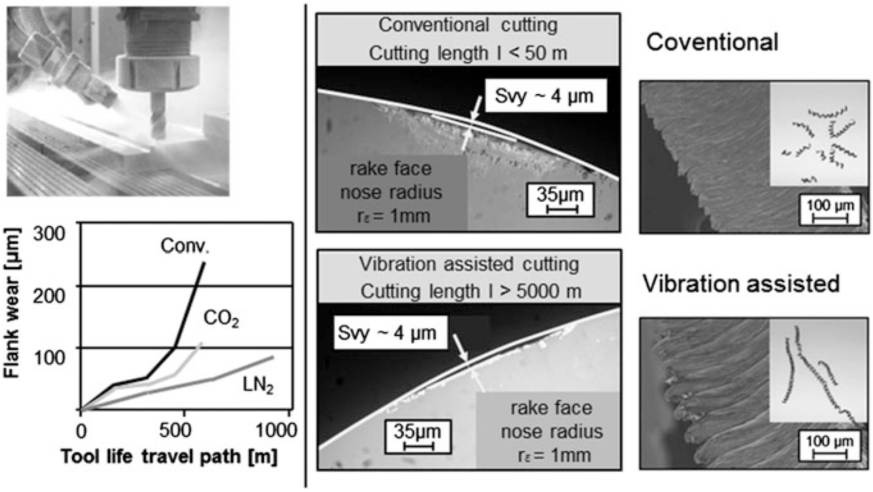

Fig. 8.7 Cryogenic cooling (milling set-up) of TiAl6V4 (*left*) and tool wear behaviour in vibration assisted turning (*right*)

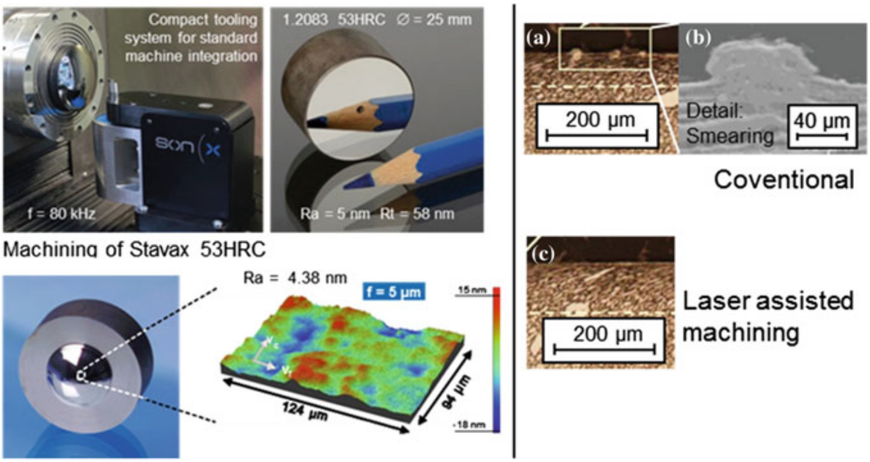

Fig. 8.8 Excellent surface quality in Vibration assisted turning (*left*) and laser assisted machining (*right*)

(at least for ferrous materials) (Bulla et al. 2012). The machining results in drastically reduced tool wear achieving highest geometrical accuracies (Fig. 8.7, right). Also the chip breakage can be positively influenced by the vibration assistance resulting in favourable short or even discontinuous chips.

8.3.4 Excellent Surface Quality

In addition to the above reported advantages, better surface qualities can generally be obtained with assisted processes. Figure 8.8 (left) shows the vibration assisted turning of hardened steel (tool frequency op to 80 kHz) of almost polished surfaces (surface roughness (Ra) values within the nm-range).

Also in laser assisted machining of difficult-to-cut Ni- and Ti-based alloys, better surface qualities can be obtained. Figure 8.8 (right) depicts laser assisted machining of Inconel 718 where SEM analyses and microstructure examinations of machined surfaces show an improvement of the surface integrity (Attia et al. 2010). 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. Other researchers also report on reduced cutting forces (40–60 %) and improved tool life allowing the use of higher cutting speeds during LAM of Inconel alloys (Brecher et al. 2012).

The effect of vibration when machining slots or pockets is not always positive. For example in rotary ultrasonic assisted grinding (Fig. 8.9), a tool vibration perpendicular to the feed direction can result in surface cracks due to the

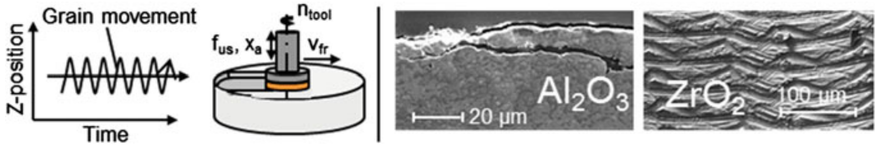

Fig. 8.9 Negative effect of the vibration on the surface quality in rotary ultrasonic assisted

hammering of the tool (see for example the machining of a Al_2O_3 (Vanparys 2012)). In general, surface textures of machined hard materials by vibration assisted grinding show mixed material removal mechanisms (MRM): plastic deformation and brittle removal. The type of material removal mechanism depends on the material properties, the amplitude of vibration and the machining parameters. Brittle removal certainly increases the material removal rate, additionally supporting lower process forces, but should be avoided in finishing processes.

Also in the case of machining of stabilized ZrO_2, the effect of the vibration is clearly visible on the surface texture (Lauwers et al. 2010). As ZrO_2 is a tough material (among all ceramic materials), no brittle removal is observed, but the impact of the grain movement is clearly visible.

8.3.5 High Precision

As process force reductions is a main advantage, hybrid assisted processes find interesting applications in micro machining such as micro EDM and micro laser assisted milling.

But high precision is also obtained for example in laser assisted single point incremental forming (Duflou et al. 2007; Göttmann et al. 2011) (Fig. 8.10). The laser softening effect not only extends the formability limits, the spring back is also reduced. The figure shows two set-ups, left performed on a classical milling

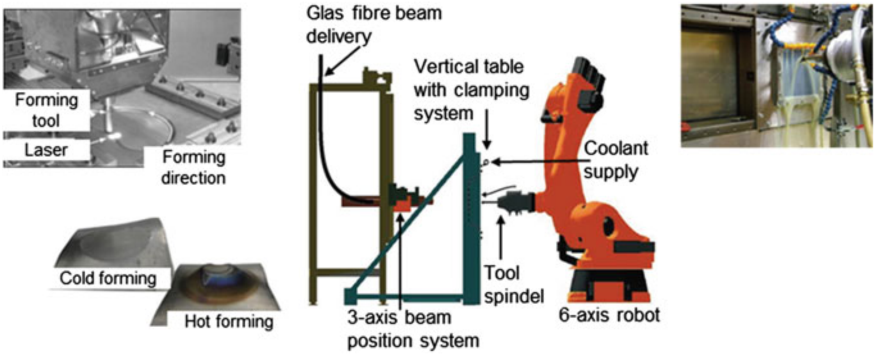

Fig. 8.10 Laser assisted single point incremental forming of sheet metal parts

machine (Göttmann et al. 2011), right with a robot system (Duflou et al. 2007). For the robot set-up, the sheet metal plate is clamped in a vertical table system. The shaping tool is moved by a robot, while the material is locally heated in front of the moving tool by a laser beam (Nd-YAG laser) acting at the back side of the sheet metal plate.

8.4 Mixed Processes and Process Mechanisms

In mixed or combined processes, two or more processes are present, which according to the definition should occur more or less at the same time. Research and development is focused on the investigation of new combinations, enhancing process performance. Figure 8.11 shows an overview of the most important process combinations.

The size of the bullets is related to the number of process combinations found in literature (Lauwers et al. 2014). Grinding and polishing is combined with EDM as well as ECM. Also the combination between grinding and hardening is coming up as an interesting hybrid process. Many process combinations exist between physical and electro-chemical processes (EDM, ECM, laser). Also in forming, processes like extrusion, spinning, bending are often combined to increase the process performance. In general, processes are combined to enhance advantages and to minimize potential disadvantages found in an individual technique (Rajurkar et al. 1999).

8.4.1 Combinations with EDM

In the area of process combinations with EDM the integration of grinding and spark erosion processes has gained an important role (Kozak et al. 2002). Figure 8.12 (left) shows the basic principle and the application of a EDM-Grinding hybrid

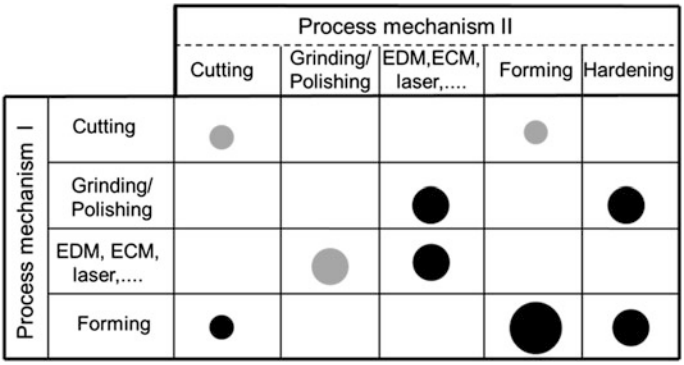

Fig. 8.11 Mixed processes and process mechanisms—possible combinations

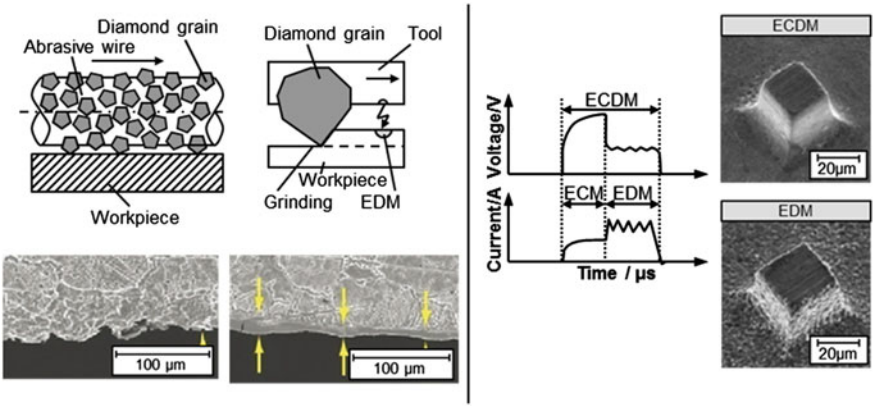

Fig. 8.12 Combinations with EDM: with grinding (*left*), with ECM (*right*)

processes, more specifically Abrasive-Wire-EDM where enhanced material removal is realized by the synergy between spark erosion and abrasion.

During EDM grinding of difficult-to-machine but electrically conductive materials like cemented carbides with metal bonded diamond grinding wheels, the grinding performance is enhanced by both effectively removing material from the workpiece and declogging the grinding wheel surface.

The combination of ECM and EDM has been widely investigated by many researchers (Lauwers et al. 2014). According to the principle of ECDM (Fig. 8.12, right), the discharge delay time of the EDM process is used for electrochemical based broad surface abrasion followed by local thermal material removal in consequence of discharge formation. By adjusting the process parameters smooth surface finishes with reduced thermally influenced rim zones and high geometrical precision can be achieved during machining of micro features.

8.4.2 Combinations with Grinding

The hybrid process combination of grinding and ECM (Fig. 8.13, left) was already developed in the 1960s in order to get a high-efficient and burr-free material removal process for difficult-to-machine aerospace alloys and cemented carbides (Becker-Barbrock 1966). This hybrid process allows for example the burr-free grinding of honeycomb structures for turbine applications (Fig. 8.13, left). Process variants were also developed for ECM-honing applications (Scholz 1968). Nowadays, alternative technologies have been developed, largely reducing the application of this process because of the high complexity of process control and environmental concerns. Figure 8.13 (right) shows another application, the precise machining of small holes (Zhu et al. 2011).

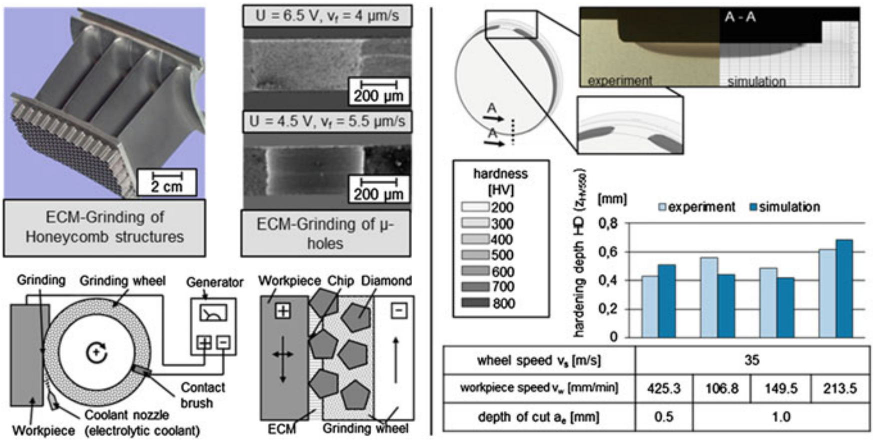

Fig. 8.13 Combinations with grinding: grinding and ECM (*left*), grinding and hardening (*right*)

The grind-hardening process utilizes the induced heat of the grinding process for local surface hardening on the workpiece. For achieving the high heat input rate the grinding process is applied with higher depth of cut and slow feed speeds. For the process combination the additional hardening process and the logistics are completely eliminated saving time, energy and production costs (Zäh et al. 2009). Figure 8.13 (right) shows the results of hardness measurements as reported in Kolkwitza et al. (2011).

8.4.3 Process Combinations with Hardening

Besides grind-hardening, there are other processes which are combined with hardening. An example is the hot stamping process used for the manufacturing of high strength components for lightweight construction (Karbasian and Tekkaya 2010). Within the direct hot stamping process (Fig. 8.14, left) an aluminum–silicon coated blank is heated up above the Ac3-temperature of the material and dwelled for a certain time to ensure a homogeneous austenitic microstructure. Afterwards, the blank is transferred to a press in which it is formed and simultaneously quenched by tool contact. With cooling rates above 27 K/s the commonly used boron-manganese steel 22MnB5 develops a martensitic microstructure with an ultimate tensile strength of 1500 MPa and an ultimate elongation of 5–6 % (Lechler 2009). The hybrid character is given since the quenching of the workpiece material is applied in the calibration phase of the hot forming operation which leads to reduced springback. The combination of forming and hardening makes 22MnB5 steel an ideal solution for the construction of structural elements and safety-relevant components in the automotive industry, in particular in view of the implementation of

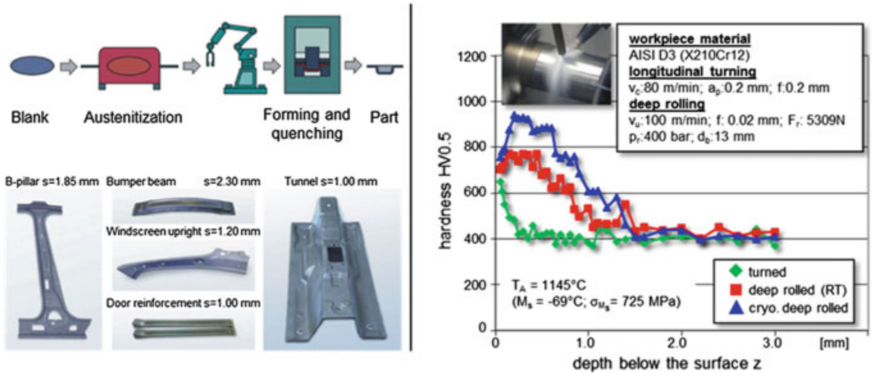

Fig. 8.14 Other process combinations with hardening: hot stamping and hardening (*left*), deep rolling and hardening (*right*)

penetration protection in the areas of the passenger cabin or motor (N.N. 2008). Figure 8.14 (left) also shows some automotive applications of hot stamping: A-pillars, B-pillars, side impact protections, frame components, bumpers, bumper mounts, door pillar reinforcements, roof frames, tunnels, rear and front end cross members. The sheet thickness in these parts varies between 1.0 and 2.5 mm.

Another hybrid processes combining with hardening is surface hardening by cryogenic deep rolling (Meyer et al. 2011). In this hybrid process (which could be seen as a kind of media assisted process), workpieces are exposed to the mechanical loads of a deep rolling process and a cryogenic treatment cooling applying CO$_2$-snow simultaneously. The hybrid process causes plastic deformation and strain induced martensitic transformations into depths of up to 1.5 mm (Fig. 8.14, right).

8.4.4 Combination of Forming Processes

Some examples of combinations of forming processes are presented in Fig. 8.15. The first process is a combination of a tube spinning and a tube bending process (Fig. 8.15, left) (Becker et al. 2012). A tube is being clamped on a feeding device and is transported through a sleeve to the spinning tool. The three spinning rolls of the spinning tool are rotating around the tube at a defined rotational speed. The spinning process creates a diameter reduction of the tube. To manufacture a bent structure a freeform bending process is superposed. Due to this process setup the production of bent structures can be realized with variable tube diameters. In this hybrid process, the spinning process significantly influences the bending results, which is shown by reduced process forces and reduced springback. Figure 8.15 (left) also shows a prototype machine and industrial manufactured samples. Tube diameters up to 90 mm can be processed as well as tube lengths of 3000 mm. Also the bending of three dimensional parts is possible due to a change of the bending plane by rotation of the pusher device.

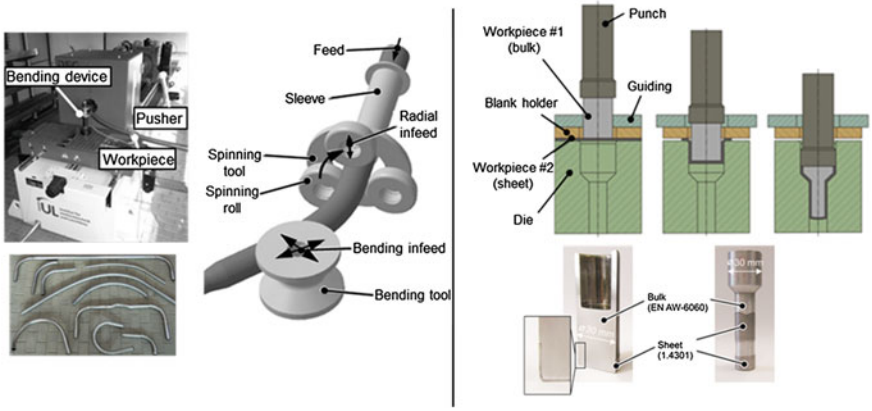

Fig. 8.15 Other combinations of forming processes: extrusion and spinning (*left*), deep drawing and cold forging (*right*)

The combined process of deep drawing and cold forging is a new hybrid metal forming process to produce composite products from different combinations of materials (Jäger et al. 2012). As presented in Fig. 8.15 (right), a one side coated circular sheet is positioned centrally above the contour-shaping die. The opening of the die has a small radius, which serves as a drawing edge (die radius). By substituting the deep drawing mandrel by a cylindrical bulk metal workpiece, the sheet is deep drawn into the shape of a cup which partly covers the bulk component. With increasing stroke the bulk metal workpiece starts to be cold forged, while the sheet component is additionally formed or even calibrated. At the end of the cold forging process, the punch moves upwards and the workpiece is pressed out by an ejector from the bottom of the tool. Depending on the diameter of the sheet in relation to the height of the bulk part, there is a partial or a complete cladding of the component. Composite metal structures with a cold forged bulk material in the core partly covered with a deep-drawn sheet material can be produced (Fig. 8.15, right). It is expected that the use of a bulk part instead of a conventional mandrel allows a greater drawing ratio because of the simultaneous movement and deformation of the sheet and the bulk part. Furthermore, due to the cold forging process an additional reduction of the cross section can be carried out.

8.5 Conclusions

This paper gave a brief overview of advanced manufacturing through the implementation of hybrid processes. The process combinations are used to considerably enhance advantages and to minimize potential disadvantages found in individual techniques. Within hybrid production processes different forms of energy or forms of energy caused in different ways are used at the same time at the same zone of impact.

The combination of processes result various advantages that often occur at the same time: lower processes forces, higher precision, higher productivity,… The development of hybrid processes is continuously evolving, from basic development towards industrial implementation. Further developments are driven on the one hand by industrial needs to manufacture highly engineered mechanical products made of advanced materials and on the other hand to process parts in a more productive and energy efficient way.

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References

Attia H., Tavakoli S., et al (2010), Laser-assisted high-speed finish turning of superalloy Inconel 718 under dry conditions, CIRP Annals—Manufacturing Technology 59/1:83–88

Becker-Barbrock, U. (1966), Untersuchung des elektrochemischen Schleifens von Hartmetall und Schnellarbeitsstahl, Dissertation RWTH Aachen

Becker C., Staupendahl D., et al (2012) Incremental Tube Forming and Torque Superposed Spatial Bending—A View on Process Parameters, Proceedings of the 14th International Conference "Metal Forming 2012", steel research international, 159–162.

Behrens B., Hübner S., et al (2013), Influence of superimposed oscillation on sheet-bulk metal forming, Key Engineering Materials, 554–557:1484–1489

Brecher C., Emonts M., et al (2012), Laserunterstützte Fräsbearbeitung, wt Werkstattstechnik online, 102,6: 353–356

Bulla B., Klocke F., et al (2012) Influence of different steel alloys on the machining results in ultrasonic assisted diamond turning, Key Engineering Materials, 523–524:203–208

Duflou J.R., Callebaut B., et al (2007) Laser Assisted Incremental Forming—Formability and Accuracy Improvement, CIRP Annals—Manufacturing Technology, 56/1:273–276

Göttmann A., Diettrich J., et al (2011) Laser-assisted asymmetric incremental sheet forming of titanium sheet metal parts, Prod. Eng. Res. Devel., 5:263–271

Heisel U., Wallaschek J., et al (2008), Ultrasonic deep hole drilling in electrolytic copper ECu 57, CIRP Annals—Manufacturing Technology, 57:53–56

Ichikawa T., Natsu W., (2013) Realization of micro-EDM under ultra-small discharge energy by applying ultrasonic vibration to machining fluid, Procedia CIRP, 6:326–331

Jäger A., Hänisch S., et al (2012) Method for producing composite parts by means of a combination of deep drawing and impact extrusion, Patent application PCT/DE2011/00001053.

Karbasian H., Tekkaya A.E. (2010) A review on hot stamping, Journal of Materials Processing Technology, 210/15:2103–2118

Klaus A., Becker D., et al (2006) Three-Dimensional Curved Profile Extrusion—First Results on the Influence of Gravity, Advanced Materials Research, 10:5–12

Kolkwitza B., Foeckerer T., et al (2011), Experimental and Numerical Analysis of the Surface Integrity resulting from Outer-Diameter Grind-Hardening, Procedia Engineering 19 (2011) 222–227

Kozak J.; Rajurkar K.P.; et al (2002) Self-Dressing and Performance Characteristics in Rotary Abrasive Electrodischarge Machining, Transac. of the North Amer. Manuf. Res. Institution of SME, Vol.30, (2002), p. 145–152

Lauwers B., Klocke K., et al (2014) Hybrid processes in manufacturing. CIRP Annals—Manufacturing Technology, 63:561–583

Lauwers B., Bleicher F., et al (2010) Investigation of the process-material interaction in ultrasonic assisted grinding of ZrO_2 based ceramic materials, 4th CIRP International Conference on High Performance Cutting 2:59–64

Lechler J. (2009) Beschreibung und Modellierung des Werkstoffverhaltens von presshärtbaren Bor-Manganstählen, Meisenbach (Verlag), 978-3-87525-286-6 (ISBN)

Meyer D., Brinksmeier E., et al (2011) Surface hardening by cryogenic deep rolling, Procedia Engineering, 19:258–263

N. N. (2008), Steels for hot stamping—very high strength steels, ArcelorMittal

Rajurkar K.P., Zhu D., et al (1999) New Developments in Electro-Chemical Machining, CIRP Annals—Manufacturing Technology 48/2:567–579

Scholz E. (1968) Untersuchung des elektrochemischen Honens, Dissertation RWTH Aachen.

Schuh G., Kreysa J., et al (2009), Roadmap "Hybride Produktion", Zeitschrift für Wirtschaftlichen Fabrikbetrieb, 104/5:385–391

Shin Y. (2011) Laser assisted machining, www.industrial-lasers.com/articles, 26/1.

Vanparys M. (2012) Ultrasonic Assisted Grinding of Ceramic Components, PhD thesis, KU Leuven, ISBN 978-94-6018-600-4

Wei B., Trimmer A.L., et al (2010) Advancement in High Speed Electro-Erosion Processes for Machining Tough Metals, Proceedings of the 16th International Symposium on Electromachining, 193–196

Zäh M.F., Brinksmeier E., et al (2009) Experimental and numerical identification of process parameters of grind hardening and resulting part distortions, Prod. Eng. Res. Devel. 3:271–279

Zhu D., Zeng Y.B., et al (2011) Precision machining of small holes by the hybrid process of electrochemical removal and grinding, CIRP Annals—Manufacturing Technology, 60/1:247–250