How to cite this article:

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Title of article: „Hybrydowe procesy obróbki ubytkowej. Definicje, zasady tworzenia i znaczenie w przemyśle” (“Hybrid machining processes. Definitions, generation rules and real industrial importance”)

Mechanik, Vol. 91, No. 5–6 (2018): pages 338–342

DOI: https://doi.org/10.17814/mechanik.2018.5-6.50

Hybrid machining processes. Definitions, generation rules and real industrial importance

Hybrydowe procesy obróbki ubytkowej. Definicje, zasady tworzenia i znaczenie w przemyśle

WIT GRZESIK *

Some important trends in the development of advanced machining processes with potential applications in Production/Manufacturing 4.0 are presented. In general, both conventional and unconventional machining processes are characterized in terms of potential technological possibilities related to their hybridization allowing the performance of more productive and effective machining processes. This is due to the fact that hybrid processes considerably enhance the advantages of individual processes and minimize potential disadvantages in individual processes. Possible classification systems of hybrid processes including the CIRP terminology are overviewed and some representative examples are provided. In particular, the hybrid machining processes based on the simultaneous and controlled interaction of process mechanisms and/or energy sources leading to the synergic effect (1 + 1 = 3) on the process performance are taken into account. Some conclusions and future trends in the implementation of hybrid processes are outlined.

KEYWORDS: hybrid machining, assisted machining, mixed machining processes, conventional machining, unconventional machining

At present, global expectations towards manufacturing processes boil down to increasing flexibility and efficiency/productivity, and, on the other hand, to maintaining high quality [1]. In the case of parts with complex shapes, the manufacturing cycle may include several stages implemented on different devices (fig. 1). In such cases, subsequent handling and positioning of workpieces is usually ineffective due to the loss of time and an increased risk of machining errors, which increases the cost of maintaining the required quality (or means getting inferior quality). Not without significance is the larger space needed to accommodate several devices. For these reasons, construction and technological activities have been undertaken for many years to integrate many processes in one hybrid manufacturing platform [2, 3].

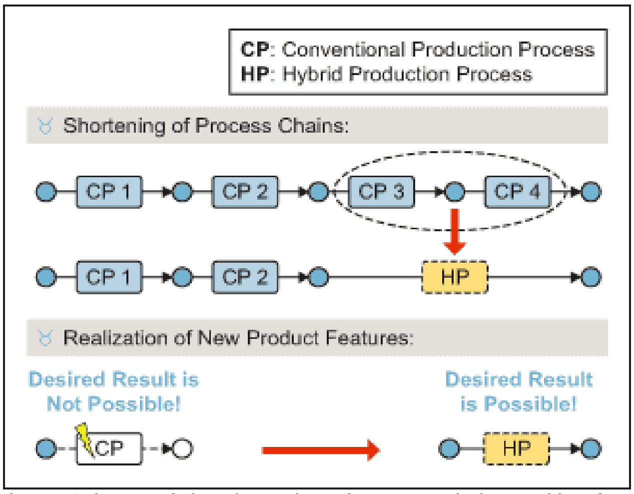

Fig. 1. Scheme of the shortening of process chain resulting from process hybridization [6]. CP – conventional production process, HP – hybrid process

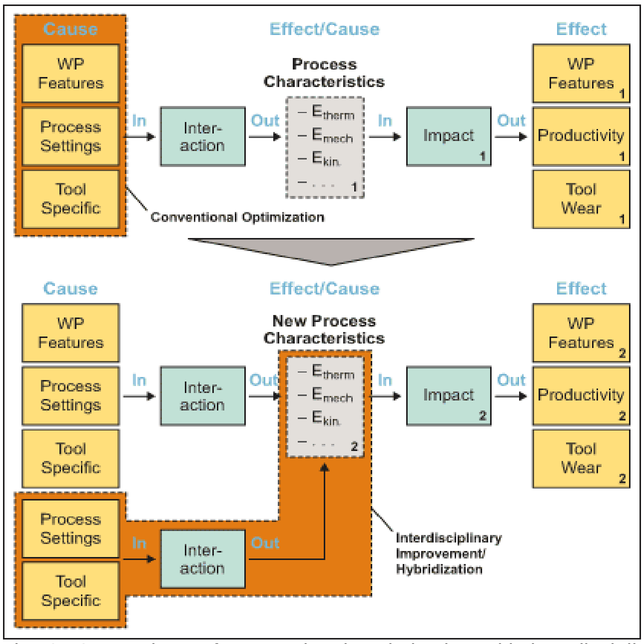

Fig. 2. Comparison of conventional optimization with interdisciplinary effect of process hybridization [6]

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An example of the first such solution can be CNC multifunctional machine tools for integrated (complete) machining – multi-tasking machine tools – which allow for a significant reduction of costs and shortening the machining time. At the next stages of integration of manufacturing processes, devices with a laser source supporting conventional processing appeared.

The concept of a hybrid manufacturing process is currently being developed by integrating multi-axis removal and additive manufacturing (AM) in one device [2]. The AM machining can be used not only to shape additional elements of the part, but also to repair expensive parts, e.g. turbine blades with traces of cavitation pits or cracks on the surface.

TABLE I. Classification of advanced machining processes (AMP) due to the energy used to remove material, giving the source of energy, tool and medium of energy transfer, and material removal mechanism [4, 5]

Energy type	AMP	Energy source	Tool	Transfer medium	Mechanism of material removal
Mechanical	USM	Ultrasonic vibration	Sonotrode	Abrasive slurry	Erosion or abrasion
	AJM	Pneumatic pressure	Abrasive jet	Air	
	WJM	Hydraulic pressure	Water jet	Air	
	AWJM	Hydraulic pressure	Water-abrasive jet	Air	
	IJM	Hydraulic pressure	Ice particles jet	Air	
	AFM	Hydraulic pressure	Abrasive suspension	Suspension	
Chemical	CHM	Corrosive agent	Mask	Etchant	Chemical dissolution
Electrochemical	ECM	High current (I)	Electrode	Electrolyte	Anode dissolution by ion displacement
Thermal	EDM	High voltage (V)	Electrode	Dielectric	Melting and vaporization
	EBM	Ionized material	Electron beam	Vacuum	
	IBM	Ionized material	Ion beam	Atmosphere	
	LBM	Amplified light	Laser beam	Air	
	PAM	Ionized material	Plasma jet	Plasma	

AFM – abrasive flow machining, AJM – abrasive jet machining, AWJM – abrasive water jet machining, CHM – chemical machining, EBM – electron beam machining, ECM – electrochemical machining, EDM – electrodischarge machining, IBM – ion beam machining, IJM – ice jet machining, LBM – laser beam machining, PAM – plasma beam machining, USM – ultrasonic machining, WJM – water jet machining.

Hybridization of manufacturing processes, including material removal process, is an important factor enabling the implementation of the Production/Generation 4.0 strategy, because it promotes innovation. For this reason, hybridization is also an important element in the development of advanced manufacturing processes – it gives a wide range of their improvement and optimization. Tab. I summarized advanced material removal processes that may undergo further hybridization (see tab. II).

Fig. 2 shows that after exhausting the possibilities of optimizing the conventional process, it is still possible to significantly improve its performance by eliminating known limitations by introducing additional, external energy sources. In this way, the interaction of new, additional processes supporting the basic conventional process takes place. Another possibility is to analyze the effect-cause type for all components of the technological chain, leading to process improvement by integrating individual processes or by cumulating several processes in one hybrid process.

Tab. I summarized the industrial processes of material removal using various energy sources (mechanical, thermal, chemical and electrochemical), with full physical and technological characteristics.

Basics of hybrid processing – principles of creating machining processes

The evolution of conventional and unconventional machining processes after World War II consisted in combining processes and using various active energy sources or implementing several methods of machining, or even several subsequent stages of the technological process in one production unit with the aim to achieve synergy. This means that as a result of the hybrid process, using a hybrid machine tool or a production device, an effect exceeding the sum of the effects of the component processes, carried out separately.

In a natural way, the definition of hybrid processing has evolved due to the development of techniques and methods of machining that are unfortunately now called technologies. The first definition of the 1970s and later definitions included combinations of two or more processes that can be used simultaneously to remove material (e.g. a combination of abrasion with EDM or ECM), or one of them is only supporting, contributing to a favorable change in the process conditions, e.g. in extreme cases by laser heating of the material or its cryogenic cooling.

At present, hybridization includes various manufacturing techniques, i.e., removal, non-removal (material processing, microstructure change and mechanical properties), additive and their combinations [2, 7, 8]. To unify the terminology, it was proposed to change their names to subtractive machining, transformative (transformative machining) and additive machining [2, 8].

CIRP defines hybrid manufacturing processes that include manufacturing/machining processes [7]: *Hybrid manufacturing processes are based on simultaneous and controlled interaction of process mechanisms and/or energy sources/tools having a significant effect on the process*.

The term "simultaneous and controlled interaction" means that energy processes/sources must interact – more or less – in the same zone of the hybrid process and at the same time. The amplification of the total effect of process hybridization is represented by the "1 + 1 = 3" rule, which indicates an increase in the efficiency of the machining process, e.g. by thermal softening with the laser of the material being processed.

There are distinguished (fig. 3) processes based on combining different energy sources or different tools (different methods and ways of shaping), included in Group I, and processes using controlled mechanisms of various processes that are implemented in conventional component processes (group II). The first group is distinguished by assisted processes (subgroup I.A) and mixed processes (mixed/joint processes – subgroup I.B).

In the case of conventional and unconventional machining processes, the most important is the design of hybrid processes according to the principle of IA (assisted by various vibration energy, thermal laser and liquid and gas media, grinding, polishing, EDM, ECM) and IB (e.g. joining grinding and EDM; joining grinding and ECM, ECM and EDM). Other hybrid processes, also related to plastic deformation, are described in [7].

In group II, one can give examples of combining kinematic features of two cutting methods, e.g. in the form of turn-milling and turn-broaching, surface hardening during grinding (grind-hardening), surface hardening by intensive burnishing a part cooled with frozen CO_2 (cryogenic deep rolling) or combining machining with burnishing.

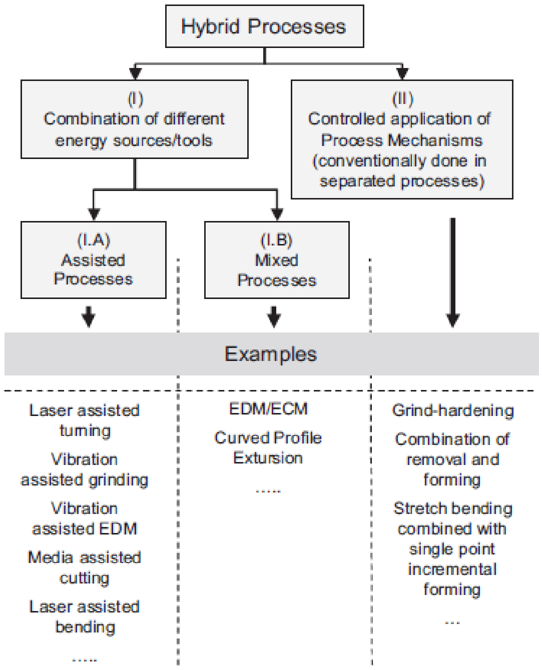


Fig. 3. Classification of hybrid manufacturing/machining processes according to CIRP [2, 7]

Fig. 4 presents the time relations between the constituent processes of different varieties of hybrid processes classified in fig. 3. In variants I and II, the basic and support processes can be implemented simultaneously (case A) or sequentially (case B), while combining two basic processes 1 and 2 takes place sequentially (case C_1), a good illustration of which is the combination of rough cutting with finish burnishing, while case C_2 can be referred to the ECDG process, in which EDM and ECM are abrasive aids, which means that the hybrid process can be assigned to time of the process or to the machining zone [7, 9].

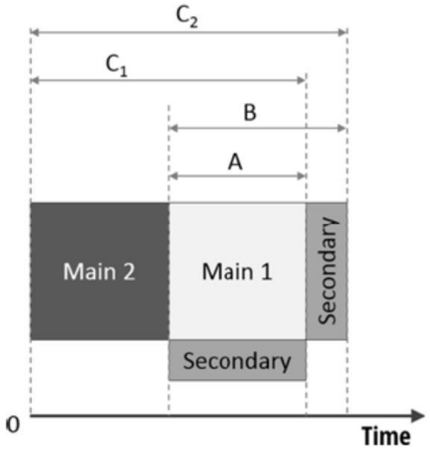


Fig. 4. Time relations in hybrid machining processes [9]. *A* – simultaneous interaction of the basic and supporting process, *B* – sequential interaction of the basic and supporting process, C_1 – sequential interaction of two basic processes, C_2 – sequential interaction of two basic processes and the supporting process

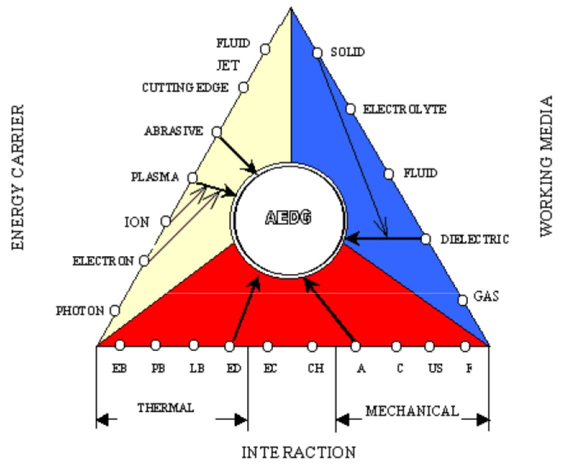
Tab. II presents the combinations of hybrid processes, based on the classification of material removal processes proposed in tab. I. In the group of classic cutting methods consisting in the mechanical interaction of a tool with defined cutting edge geometry (T) for the material being machined, process support belongs to the principle I.A. For this reason, the cutting process is assisted by laser (TLB), plasma (PLB) and ultrasonic vibrations (UST). In turn, grinding support (A) concerns the principle of I.B and that is why it is possible to assist in erosion (AEDM), chemical (MCP), electrochemical (AECH) and ultrasonic vibrations (ultrasound). In contrast, unconventional processes (ED, CH, EC) can be combined, e.g. ECDM, ECAM, and assisted, e.g. EDUSM, USECM, ECML.

A better explanation of the principles of hybridization of machining processes can be made using triple graphs (fig. 5), showing the type of interaction of process mechanisms depending on the working medium and energy carriers used. Fig. 5*a* and fig. 5*b* give examples of assisting abrasive machining with electric discharges (erosion-abrasive machining) and spark erosion machining – with ultrasonic vibrations.

TABLE II. Possibilities of integration of material removal processes (hybridization of energy sources) [4, 5]

		ED	LB	EB	PB	CH	EC	A	T	US	F
THERMAL	ED	EDM					ECDM	AEDG		EDUSM	
	LB		LBM			ELB	ECML		TLB		
	EB			EBM							
	PB				PPM				TPB		
	CH		ELB			CHM		EEM			CHP
	EC	ECAM	ECML				ECM	AECG		USECM	
MECHANICAL	A	AEDM				MCP	AECH	G		USG	
	T		TLB		TPB				T	UST	
	US	EDMUS	LBMUS				USMEC	GUS	TUS	USM	USP
	F					CHP	ECL			USP	JM

a)



b)

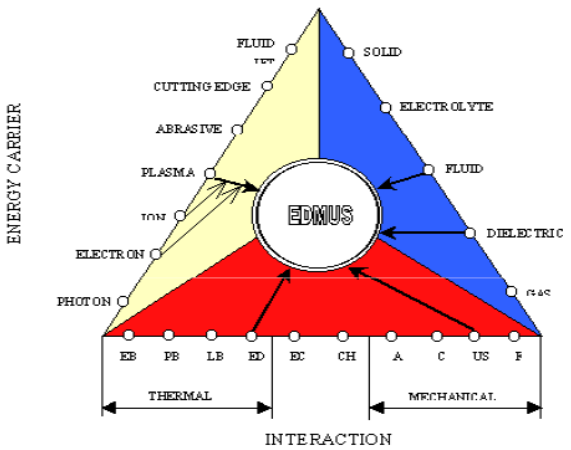


Fig. 5. Examples of energetic structures of hybrid machining processes: a) combination of grinding and EDM (AEDM); b) US vibration assisted EDM (EDMUS) [5]

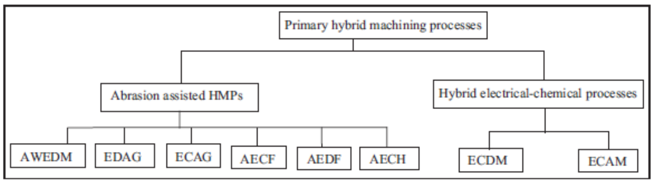


Fig. 6. Primary hybrid machining processes (HMP) [10]: AWEDM – abrasive wire cut electrical discharge machining, EDAG – electrical discharge abrasive grinding, ECAG – electrochemical abrasive grinding, AECF – abrasive electrochemical finishing, AEDF – abrasive electrical discharge finishing, AECH – abrasive electrochemical honing, ECDM – electrochemical discharge machining, ECAM – electrochemical arc machining

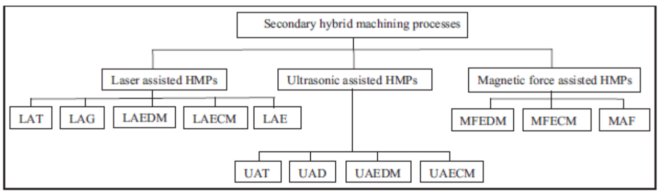


Fig. 7. Secondary hybrid machining processes (HMP) [10]: LAT – laser-assisted turning, LAG – laser-assisted grinding, LAEDM – laser-assisted electrical discharge machining, LAECM – laser-assisted electrochemical machining, MFEDM – magnetic force-assisted EDM, MFECM – magnetic field-assisted ECM, MAF – magnetic abrasive finishing, UAT – ultrasonic-assisted turning, UAD – ultrasonic-assisted drilling, UAEDM – ultrasonic-assisted EDM, UAECM – ultrasonic-assisted ECM

Fig. 6 and fig. 7 present the division of hybrid machining processes into primary and secondary [10], which in principle correspond to the group of assisted processes (group I.A in Figure 3) related to conventional and unconventional processes. However, as Ruszaj [11, 12] points out, abrasive machining processes supported by chemical, electrochemical or electrical discharge interaction – due to the harmful effect of their working fluids (especially electrolytes) on the working environment and the natural environment – have recently been limited to special alloys and composites.

Basics of hybrid processing – supported processes

Fig. 8 presents the combinations of basic and assisted processes used in various manufacturing techniques. The most frequently used assisted energy sources are: vibrations with the frequency of 0.1÷80 kHz and amplitude 1÷200 μm, liquid and gaseous media (CCS under pressure, liquid nitrogen LN_2, cooled CO2) and laser [7, 13]. For this reason, the three most widespread groups of assisted processes (Group IA in fig. 3) are supported by vibrations (vibration/US-assisted machining), thermally-assisted machining and media in various states and under different pressures (media-assisted machining).

Previous applications of assisted processes and the state of advancement of research are shown in fig. 9.

Relative frequency of publications in the analyzed literature: ● Very frequent, ◐ Frequent, ○ Partly (US: Ultrasonic)

Secondary processes	Primary processes: Turning	Milling	Drilling	Grinding	Polishing/Lapping	EDM	ECM	Laser	Forming	Shearing	Etching
Vibration/US-assisted	●	○	◐	●	◐	●	◐	○	○		
Laser-assisted	●	◐	◐	○		○			◐	○	○
Water-jet assisted								○			
Pressure-fluid assisted	◐			○					●		
Magnetic-field assisted	○				◐	○	○		○		
Conductive-heat assisted									◐		

Fig. 8. Combinations of assisted hybrid processes [7]

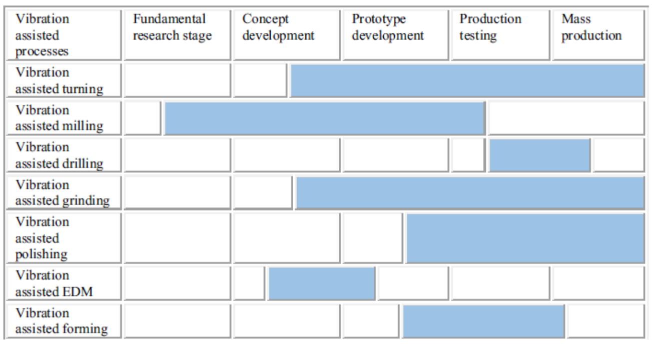


Fig. 9. Advances in assisted machining processes [7]

Basics of hybrid processing – combined processes

As mentioned, the combination of two or more subtractive machining processes is – as defined – conditioned by their simultaneous influence to a greater or lesser extent on the material removal mechanism (group I.B in fig. 3). So far, the widest application has been found in the processes combining the abrasive grinding mechanism and the thermal effect of electrical discharges, i.e. AEDG (EDG) or electrochemical dissolution, i.e. AECG (ECG), and the combination of EDM and ECM, i.e. ECDM. In the latter case, a third abrasive mechanism may occur, i.e. in the ECDG hybrid process. During the electrochemical grinding process, not only grinding (ECG) is performed, but also honing (ECH) and superfinishing (ECS). The principles of combining component processes in hybrid processes are presented in fig. 10.

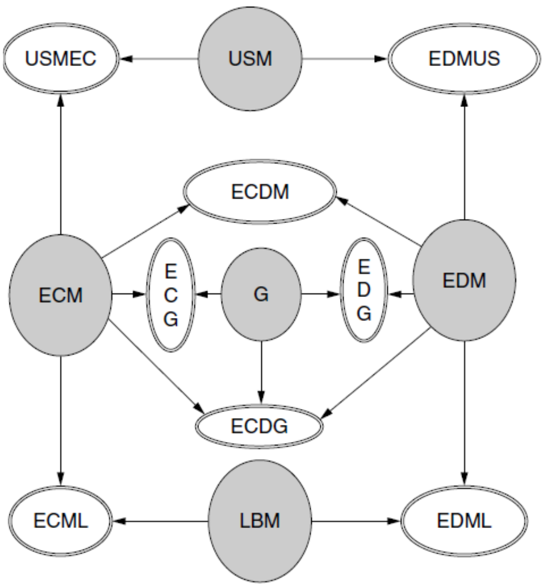
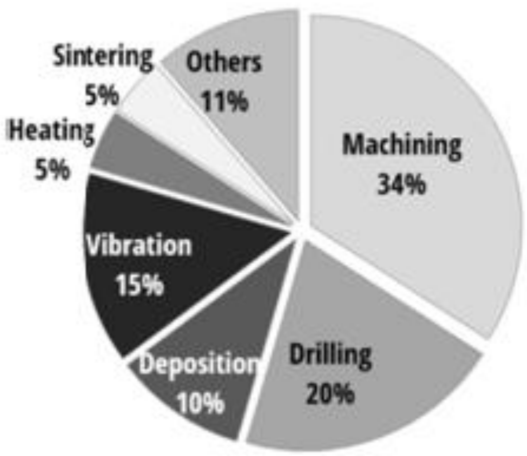


Fig. 10. Rules for integration of machining processes based on EDM and ECM [6]

Basics of hybrid processing – processes in micro and nanoscale

Fig. 11 shows differences in the structure of hybrid processes in micro (fig. 11*a*) and nanoscale (fig. 11*b*).

a)



b)

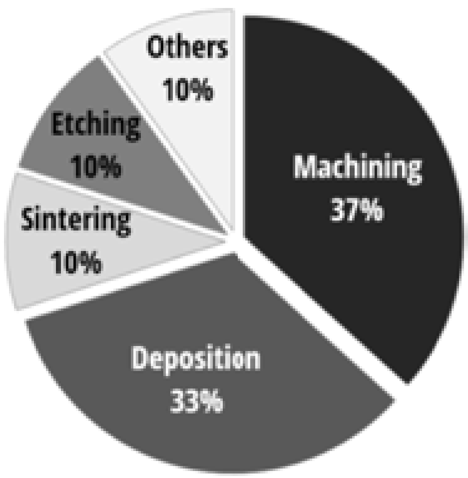


Fig. 11. Manufacturing processes used in micro- (*a*) and nano- (*b*) scale hybrid manufacturing [9]

It is clearly visible that the largest share in the micro-machining (about 64%) are subtractive and additive processes. In turn, in nano-machining, the additive process is still important (despite the significant share of cutting) (layer deposition – share of approx. 33%). In micro-machining, 55.8% are assisted subtractive processes carried out simultaneously, and 47.7% – processes carried out sequentially. In nano-machining, 30.7% of processes have the C2 structure, i.e. the third supporting process occurs, and 69.2% of the total hybrid processes are carried out sequentially [9].

Conclusions

- Implementation of the Production/Generation 4.0 strategy is closely related to the hybridization of manufacturing processes, including the material removal process, due to the large role in achieving a high level of manufacturing innovation. Hybridization applies not only to normal machining processes, but also to processes in the micro and nanoscale.
- Hybrid machining processes contribute, due to the synergy effect, to the resulting effect exceeding the sum of the effects of component processes performed separately. Therefore, there are additional possibilities to optimize the process.
- In practice, hybrid processes based on supporting an additional source of energy, combining various energy sources and/or tools, and controlling various mechanisms of component processes (removal, metal forming, heat treatment, additive machining) can be used.
- In the group of conventional cutting methods (turning, drilling, milling) the most important is the support of vibration energy US, laser and technological media (liquid under high pressure, liquid nitrogen).
- In the group of conventional abrasive methods (grinding, honing, polishing, lapping) the most important is the strengthening of the abrasive effect by electro-erosive and electrochemical interactions and magnetic forces. However, the development of this group of hybrid processes limits ecological restrictions.
- Due to ecological reasons and under the influence of requirements on the functionality of the surface of machine elements, hybrid processes are developed in which the mechanisms of constituent processes are controlled, e.g. controlled heat flow in grind-hardening, intensive deformation of the surface layer combined with cryogenic cooling and phase change of the material.
- Rapid development of hybrid processes and devices that combine additive shaping and CNC machining is also observed.

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Translation of scientific articles, their computer composition and publishing them on the website www.mechanik.media.pl by original articles in Polish is a task financed from the funds of the Ministry of Science and Higher Education designated for dissemination of science.

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