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Review

Energy Saving by Parametric Optimization and Advanced Lubri-Cooling Techniques in the Machining of Composites and Superalloys: A Systematic Review

Rüstem Binali [1,*], Abhishek Dhananjay Patange [2], Mustafa Kuntoğlu [1], Tadeusz Mikolajczyk [3] and Emin Salur [4]

1 Department of Mechanical Engineering, Faculty of Technology, Selcuk University, Konya 42130, Turkey
2 Department of Mechanical Engineering, College of Engineering Pune, Pune 411005, India
3 Department of Production Engineering, Bydgoszcz University of Science and Technology, Al. Prof. S. Kaliskiego 7, 85-796 Bydgoszcz, Poland
4 Technology Faculty, Metallurgical and Material Engineering Department, Selcuk University, Selçuklu, Konya 42130, Turkey
* Correspondence: rustem.binali@selcuk.edu.tr

Abstract: The resources of the earth are being consumed day by day with the increasing population and necessities of humankind in many areas, such as industrial applications and basic needs in houses, workplaces and transportation. As a consequence, careful usage of the energy sources and the conversed energy is of great importance in order to obtain sustainable development. Machining operations have a large percentage of all manufacturing methods in terms of depleted energy which gives them a high potential for reducing the total energy consumption. The approaches handled in the literature for the minimization of the consumed energy in the machining industry were considered in this study. While several machinability characteristics under different machining processes were investigated broadly in the context of composites and superalloys, the comparison of these systems has been given cursory attention in the current literature, specifically for cutting energy saving. The overall performance of these group material systems utilizing widely in numerous significant industrial areas supplies important signs about manufacturing costs, service conditions and environmental impacts. It is highly crucial to monitor the indicators of energy-saving phenomena of the machined parts since the mechanisms behind the energy consumption of these systems is very complex and dynamic owing to different process-induced variables. This well-organized review paper distinguishes itself from previous studies in this field since the comprehensive literature survey paves the way for diverse approaches that regard energy saving, especially for composites and superalloys under different machining operations. This overview paper aims to contribute to the current literature by highlighting the effects of the state-of-the-art approaches in reducing energy consumption in the machining of industrially important materials. This study can also establish a framework in the context of the process-property interactions to comprehend the influence of energy-saving mechanisms through machining in a system of interest.

Keywords: energy savings; machining; optimization; cooling and lubrication

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1. Introduction

Energy saving is an essential matter to protect the environment since overexploitation of non-renewable resources for power generation leads to their destruction which would be unable to replenish [1]. Excessive energy consumption is inevitable because of economic development, growing populace and technology. The usage of energy is not a problem, but the problem originates from the point that the major amount of the energy is harvested from fossil fuels. A certain amount of carbon dioxide (CO_2) is discharged into the environment as fossil fuels are burnt. From the beginning of the first industry transformation, the volume of CO_2 has increased from 280 to over 400 parts per million and it is still rising [2]. This is a serious problem because of greenhouse gasses, which means that heat is released from the atmosphere at a slower than 'normal' rate [3]. Presently, the major requirement for energy comes from high-income countries such as Australia, the USA, and fast developing newly emerging economies such as Nigeria, China and Brazil [4]. In the near future, this demand is probably going to grow in low-income countries, particularly in Africa [5]. Hence, an energy conservation term originated from the concept of reducing energy consumption by using less energy services or saving resources [6]. On the other hand, the efficiency statement comes from using energy in the most effective way possible [7]. Rather than efficiency, one should be trying to consume less energy [8]. There persists a necessity to cut-off excessive energy usage to produce a good quality of life for future generations. According to Jimmy Carter [9], every act of energy conservation is more than just common sense: it is an act of patriotism.

To the extent that the role of industry in power consumption is considered, it accounts for nearly 31% of the overall consumption of energy; wherein the manufacturing process shares almost 60% [10,11]. Particularly considering the energy consumed in actual machining, it appears to be 15% of the overall energy [12]. Energy consumption during various machining operations (milling, turning, grinding, drilling, WEDM, etc.) refers to the energy employed for eliminating a unit of material from a workpiece and can be measured at various units such as the machining center and its subsystems, the spindle motor for rotation of either cutting tools or workpieces and during actual machining activity [13,14]. Among the machinability indicators of machine tools and energy consumption, process variables such as machining parameters (cutting speed, feed rate, depth of cut), properties of workpiece and cutting tool material, tool wear and cutting force, along with processing time can be listed [15]. Increasing the processing time will increase the time required for processing, thus increasing energy consumption. Working with higher feed rates and a higher depth of cut causes higher cutting forces that affect the required cutting power. Thus, with the increasing cutting speed and force, the tool will wear out and the machined surface quality will not be at the desired level. For these reasons, it is important to determine the optimum conditions [16–18]. This situation occurs not only in machining processes, but also in other forming methods. However, a significant amount of energy is consumed to perform the cutting process, which is higher in machining methods compared to other conventional manufacturing methods [19,20]. Nevertheless, by optimizing the cutting parameters, energy consumption in machining processes can be significantly reduced [21,22]. The article is about processing methods made with traditional processes in general. However, it was added in studies on EDM and WEDM. Due to the lack of sufficient study, the energy consumption units for the WEDM center are given in Figure 1. Being a lifeline of the manufacturing industry, the consumed energy contributes a substantial amount to the economics of manufacturing and creates a significant impact on the environment. By moving towards a sustainable machining solution, researchers try a number of attempts for the exploration of a methodology to reduce the consumption of energy during machining activities such as the application of either several optimization approaches or eco-coolants/environmentally friendly lubricants [23].

Specifically speaking about the machining of material groups of super-alloys and composites, they attract a broad range of applications in the automotive, aerospace and ship building industries owing to their improved mechanical behavior at a higher pressure and temperature [24]. However, the machining of super alloys and composites comes across challenging problems because they are 'hard-to-cut' and show poor performance using traditional processes [25]. Therefore, the use of advanced manufacturing techniques such as non-conventional spark-eroding machining or electrical discharge machining (EDM) is tending towards dealing with difficult-to-machine work materials [26]. However, the energy consumption of non-conventional machining such as EDM is 1000 times higher compared to traditional processes, as a result of lower material removal rates [27]. Evidently, as shown in Figure 2, electrical energy takes the chief share of almost 50% of an overall environmental impact of EDM operation of about an hour [28,29]. Thus, this paper aims to contribute to the current literature by highlighting the effects of the methodical approaches to reducing energy consumption in the machining of industrially important materials, particularly superalloys and composites.

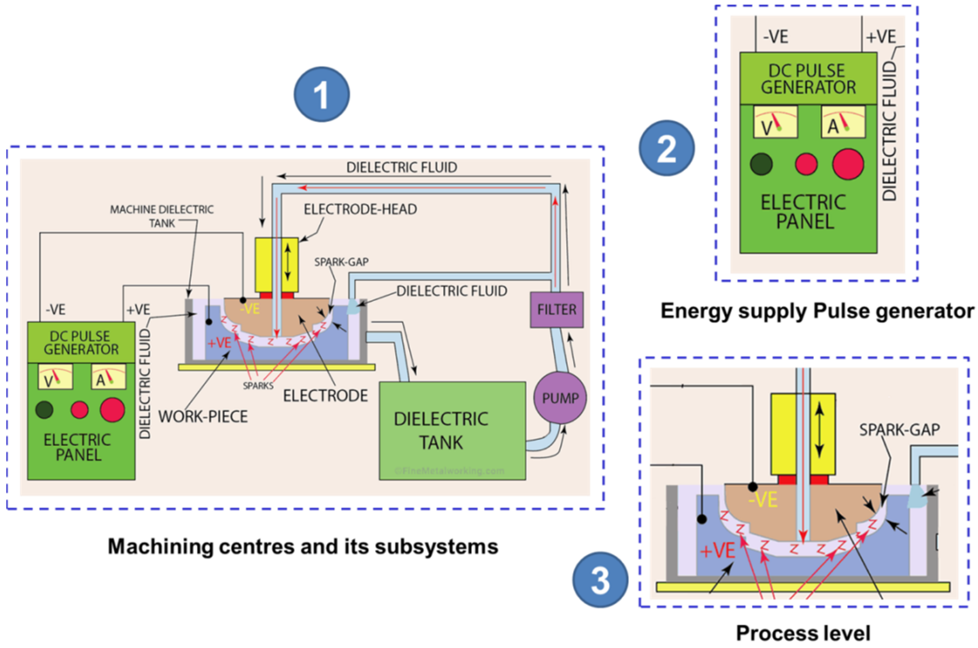


Figure 1. Energy consumption units for WEDM center.

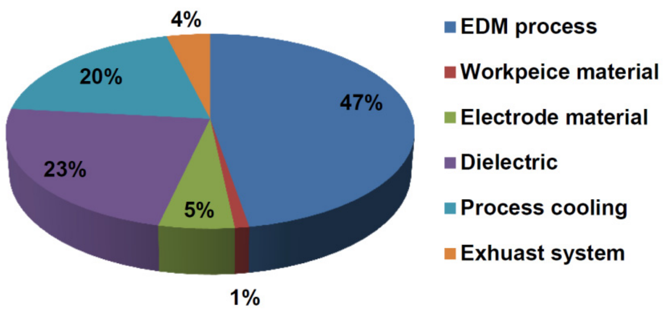


Figure 2. The percentage of energy consumptions in WEDM process [28,29].

2. Classification of Superalloys

Superalloys or high-performance alloys are mainly comprised of nickel (Ni), cobalt (Co) or iron (Fe) elements by combining a large amount of other alloying constituents to provide durability, toughness and strength at high temperatures [30]. They have outstanding heat-resisting characteristics and maintain their dimensional stability, toughness, strength and stiffness for a temperature range much greater than the structural materials used in an aerospace domain [31]. They also possess better resistance to variance with oxidation and corrosion when employed in jet engines at a higher temperature range. They are considered high-temperature alloys which are usually found in the red-hot units of rocket and jet engines with a temperature range from 1200 °C to 1400 °C [32,33].

2.1. Nickel-Based Superalloys

The nickel-based alloys are considered as the main style of superalloys which comprises a rich concentration of cobalt, titanium, iron, chromium and any other alloying constituents. They can be operated for longer time periods at temperature ranges starting from 800 °C to 1000 °C, which makes them appropriate for the red-hot units of engines used for driving gas turbines [34]. They are also extensively utilized in various sections of engines such as the high-temperature and pressure thrust reversers, afterburners, combustion chamber, discs and turbine blades, etc. [35]. Nickel-based superalloys are very hard to machine since they have no weakness to exploit, as well as high thermo-mechanical properties [36,37]. They evenly resist all kinds of forces such as shear, tension and compression. They are suitable for age hardening process; so, as a cutting tool scraps away at a surface and creates the heat, the surface gets harder and harder [38]. In the age-hardening of Ni alloys, aluminum or titanium-alloying constituents are added which are abrasive and sticky constituents [39]. Their abrasiveness creates heat development and accelerates tool edge wear mechanism, which is compounded by the age hardening at the cutting surface [40]. They are also work-hardened, so as a cutting tool attempts to deform a surface, the surface itself becomes gradually harder as there is an increase in the pressure applied by the tool [40,41]. Compared to this superalloy system, heat-treated, high-strength, and high-hardness steels are easier to machine due to the fact that localized deformation of the cutting surface can adequately increase the temperature for lower compression strength, causing a chip to form [42]. The chip carries most of the heat away from the surface, tool and cutting edge. The same feeds, speeds and depth of cut on a Ni-superalloys will not cause chips to form, and will rapidly wear the tool away due to heat transferring to the tool and abrasion of the cutting edge [43]. In addition, high abrasive wear resulting from rapid strain hardening and hard carbide formation in cutting tools during machining operations (such as turning, milling, grinding and drilling), diffusion between the workpiece cutting tool and material stemming from high chemical affinity, frequent adhesion of the material to the cutting tool or welding and chip control occurs as the product of a hard and continuous chip is indicative of the poor machinability of these alloys [44–46]. On the other hand, surface integrity including surface roughness, surface texture, residual stress and microstructure development and machining outputs such as tool life, cutting forces, cutting power or power consumption are directly affected by tool wear [47,48]. Therefore, sustainable machining of the main parameters such as tool material selection, machining method (such as turning, milling, grinding and drilling) selection, tool geometry, machining parameters, cooling/lubrication methods reduces machining costs, power consumption and increase the tool life during machining operations is very important to identify it properly. In order to form a chip at higher pressures, lower speeds/feeds are needed to prevent heat from building up and causing local age hardening [49]. A lower depth of cut is needed to reduce the area of work hardening [50]. In order to resist deflection and vibration, much more rigid tooling and machinery are needed than would be necessary for other alloys [51]. Different combinations of nickel-based superalloys are shown in Table 1.

2.2. Cobalt-Based Superalloys

In consideration of magnetic non-ferrous alloys, cobalt-based alloys are highly popular owing to the properties they possess, such as sustainability at a greater temperature range, excellent resistance to oxidation, wear and corrosion, good toughness and strength [52]. However, they also could be magnetized with suitable processing [53]. Furthermore, they exhibit good resistance to sulfide for the prevention of material sulfidation [54]. They are applicable in components of hot gas turbines and jet-engines, machining tool binders and prosthetic devices [55]. Cobalt (Co) has been recognized to be the most effective alloying constituent for tool steels [56]. In superalloys, the base of cobalt is alloyed with other constituents, such as iron, nickel, tungsten and chromium [57]. Even though they possess higher strength, they encounter some limitations in several applications where heavier loads under repetitive stresses with elevated temperatures are needed. For such cases, the durability of the cobalt-based alloys is generally augmented through the diffusion of BoroCoat in order to regulate high corrosion resistivity and it also increases wear resistance and hardness [58]. Traditionally, cobalt base superalloys were governed by the precipitation of different carbide types in order to achieve good mechanical behavior. The gamma (γ) phase for nickel-base alloys appears to be the matrix phase, however, cobalt base alloys aren't applied in the commercial domain in comparison with nickel base. However, the strengthening mechanism is poorer to the phase formed by precipitating gamma prime (γ') for strengthening, cobalt offers superior melting temperature as compared to present nickel-base alloys, it is superior to resisting thermal fatigue and hot corrosion [59]. Due to these properties of cobalt, it is very difficult to process in machining as it maintains its strength and hardness at high temperatures during processing. In addition, low thermal conductivity, high strain hardening, high hardness at a high temperature and high wear resistance are also reasons for the low machinability of cobalt. For this reason, it causes a short life during chip removal operations. It is important to select the ideal machining parameters and conditions, and to examine the machinability outputs to obtain adequate tool life and surface integrity. However, its poor machinability performance also increases manufacturing costs. It is processed by minimizing the depth of cut, the tool-chip interface and providing a sharp cutting edge [52,60]. However, this is not enough. For this reason, in the current literature, various experimental studies are carried out to minimize the feed rate, cutting speed and heat output. Different combinations of cobalt-based superalloys are shown in Table 2.

Table 1. Combinations of nickel-based superalloys.

Constitutes	Range of Weight (%)	Function
Nickel (**Ni**), Iron (**Fe**), Cobalt (**Co**)	50–70%	These constitutes create the base matrix γ level. Ni is essential as it creates γ' (Nickel aluminide). Co and Fe has greater melt point as compared to Ni and dissolves one metal into other. Fe is very inexpensive than Co and Fe.
Chromium (**Cr**)	5–20%	Cr is essential to offer resistance to corrosion and oxidation; it creates the protecting oxide Cr_2O_3.
Aluminum (**Al**)	0.5–6%	Al is a major γ' former. It creates the protecting oxide Al_2O_3, that offers resistance to oxidation for a greater temperature range as compared to Cr_2O_3.
Titanium (**Ti**)	1–4%	Ti creates γ'.
Carbon (**C**)	0.05–0.2%	MC and M23C6 (M = metal) carbides acts as a strengthened stage with lack of γ'.
Boron (**B**), Zirconium (**Zr**)	0–0.1%	B and Zr strengthens the grain boundary. This isn't necessary in turbine blades made up of unitary-crystal, since grain boundary is not present.
Niobium (**Nb**)	0–5%	Nb may create γ'', a strengthened stage at a lesser temperature range under 700 °C
Rhenium (**Re**), Tungsten (**W**), Hafnium (**Hf**), Molybdenum (**Mo**), Tantalum (**Ta**)	1–10%	For dissolving one metal into other, refractory metals can be mixed in minor quantities; this also can be done to achieve formation of carbides. It is heavier; however, it has a larger melting point.

Table 2. Combinations of cobalt-based superalloys.

Constitutes	Range of Weight (%)	Function
Nickel (**Ni**)	40–60%	Ni resists the heat and extends elements' temperature resistance
Chromium (**Cr**)	5–20%	Cr adds the strength
Tungsten (**W**), Molybdenum (**Mo**)	10–30%	W and Mo gives more strength

In comparison with iron- and nickel-based alloys, a cobalt base offers a higher melting point. They have a larger resistance to corrosion at higher temperatures [54]. Further, they offer a greater resistance to thermal fatigue than nickel-based alloys. However, when concerning price, Ni-base alloys are favored for applications of higher temperature range due to a considerably lower price than cobalt base alloys [61].

2.3. Iron-Based Superalloys

In consideration of the efficient behavior of materials at elevated temperatures and increasing efficiency to ultimately save energy, iron-based alloys are gaining significant attention [62]. Iron, as a basis, forms a number of combinations including maraging steel, cast iron, stainless steels, alloy steels and carbon steels [63]. They offer high strength even for ambient temperature and great resistivity to wear, corrosion, oxidation and creep [64]. They are widely applicable in tool making and the construction industry with specific applications such as chemical and medical synthesis [65]. Similar to the nickel base alloy, Fe-base alloys exhibit a matrix phase of face-centered cubic austenite iron [66]. There are two main kinds of austenitic stainless steels (SS) and are signified by means of the oxide coating which develops on the steel surface—one is alumina-forming and another is chromia-forming SS [67]. First, chromia-forming SS is commonly found but it does not offer creep resistance for a higher temperature range, particularly in backgrounds of water vapor [68]. The water vapor produced while operating at a higher temperature range results in larger internal oxidation using chromia-forming SS, and the quick creation of explosive Cr (oxy) hydroxides reduces the resilience and life [69]. On the other hand alumina-forming austenitic SS signified by means of the single-phase matrix of face-centered cubic austenite iron where the alumina oxide is on the surface [70]. As compared to chromia, alumina is more stable in terms of thermodynamical aspect [71]. Many precipitate phases were presented towards augmenting creep resistance and strength [72]. Different combinations of Fe-based superalloys are shown in Table 3.

Table 3. Combinations of Fe-based superalloys.

Constitutes	Range of Weight (%)	Function
Aluminum (**Al**)	5–7%	Offers benefits of oxidation; however, weight addition % is kept low in order to stabilize an undesirable phase, i.e., ferritic phase matrix.
Nickel (**Ni**), Aluminum (**Al**), Niobium (**Nb**), Titanium (**Ti**)	15–20%	$\gamma' - Ni_3Al$ adds the strength.
Nickel (**Ni**), Aluminum (**Al**)	20–30%	Al pool for maintaining the protection layer of alumina.
Niobium (**Nb**), Chromium (**Cr**)	5–10%	Nb and Cr assists stabilization of alumina.

Abbas et al. worked the sustainability assessment associated with power consumption and surface roughness characteristics in nanofluid MQL-assisted turning of AISI 1045 steel. As a result of their study, they stated that while a lower feed rate is recommended for a better surface quality, lower control factors are better for lower power consumption [73]. Singh et al. examined the sustainability studies of energy and the environment, considering the carbon emissions from the processing of Ti-3Al-2.5 V. In their study, they investigated the turning of Ti-3Al-2.5 V with coated carbide tools under five different cooling/lubrication environments to determine sustainable and improved cooling/lubrication technology. As a result of their study, it was found that machining under MQL was the lowest for tool wear and surface roughness values, compared to other cooling/lubrication conditions. In addition, they stated that the energy consumption and carbon emissions are at the lowest level in processing with MQL [74]. Anand et al. investigated the feasibility of machining high-chromium tool steel using the electrical discharge machine process to optimize the EDM process according to environmentally friendly aspects such as electrode wear rate, process energy consumption and machining parameter, i.e., processing time. In their study, peak current, pulse duration, flushing pressure and dielectric levels were chosen as control factors in order to minimize the output response. Optimization operations were performed using the Taguchi approach. As a result, they stated that the output responses were greatly affected by the peak current and dielectric level, and minimally affected by the pulse duration [75]. Bagaber and Yusoff conducted research on the sustainable optimization of dry turning of stainless steel based on machining cost and energy consumption. In their study, they examined the effects of cutting parameters such as cutting speed, feed rate and depth of cut. They used the NSGA II algorithm to minimize and optimize energy and processing costs [76]. Sangwan and Sihag investigated the multi-purpose optimization for energy-efficient machining with high productivity and quality for the turning process. In their work, they aimed to maximize the production speed in accordance with the product quality and to minimize power consumption. They used response surface methodology and ANOVA analysis to develop their predictive model [77]. Khanna et al. conducted a study on the energy consumption and life cycle of cutting fluids for titanium alloy during drilling. In their study, they evaluated dry, flood, liquid CO_2 and liquid N_2 conditions according to energy consumption and ecological situation by using a VT20 titanium alloy. As a result of their experimental studies, a cryogenic medium with LN_2 became the most ecological cutting condition after dry processing. They also determined that the effect of the flood environment among all conditions was between 94–99% [78]. Younas et al. have worked on the development of tool wear and energy consumption maps for turning Ti6Al4V (Figure 3). The results of their work show that the increasing temperature and abrasion manipulate the specific cutting energy (SCE). They also stated that the cutting plane angle decreased at increasing cutting speed and an increase in SCE occurred [79].

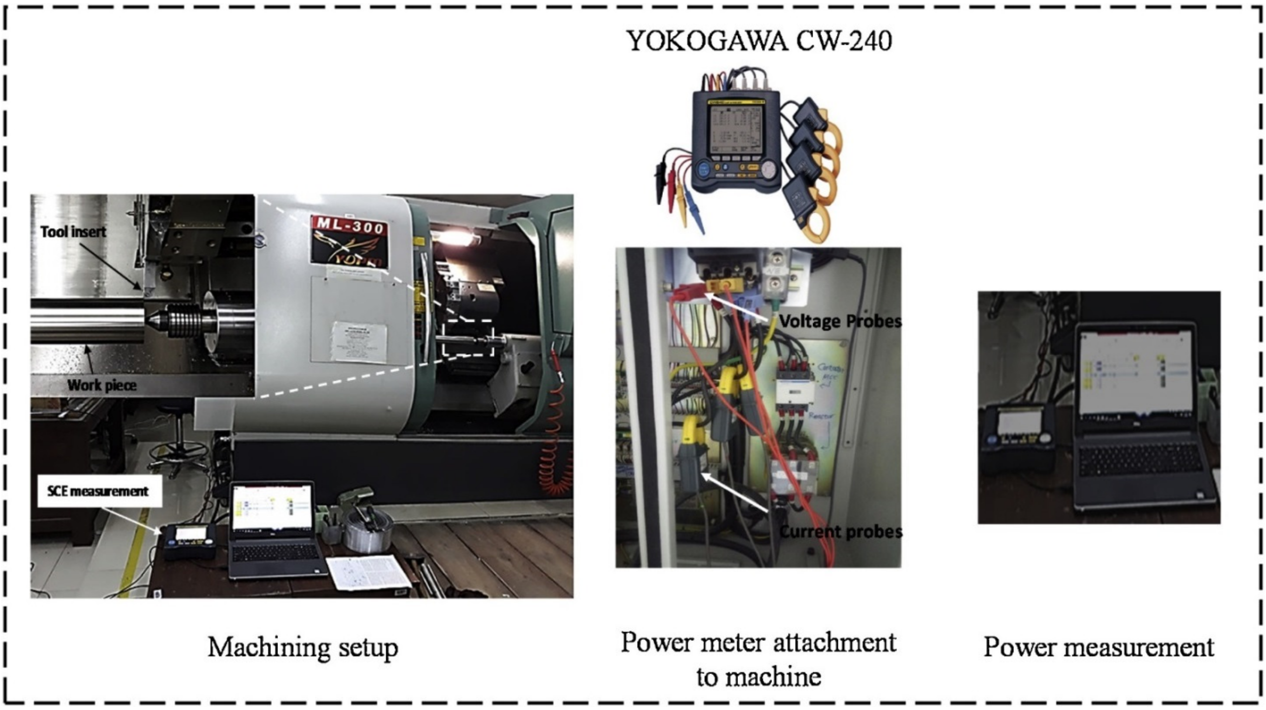


Figure 3. Experimental setups for measurement of cutting power [79].

Liu et al. investigated the energy consumption characteristics of finishing hard milling [13]. Zhang et al. studied the energy consumption in the micro-milling process by considering the optimization of the cutting parameters. They developed an energy model for their work. They stated that the improved optimization method based on the developed energy model reduced the energy consumption by 7.89% compared to the empirical selection. Comparison results of measured and estimated cutting forces are given in Figure 4 [80].

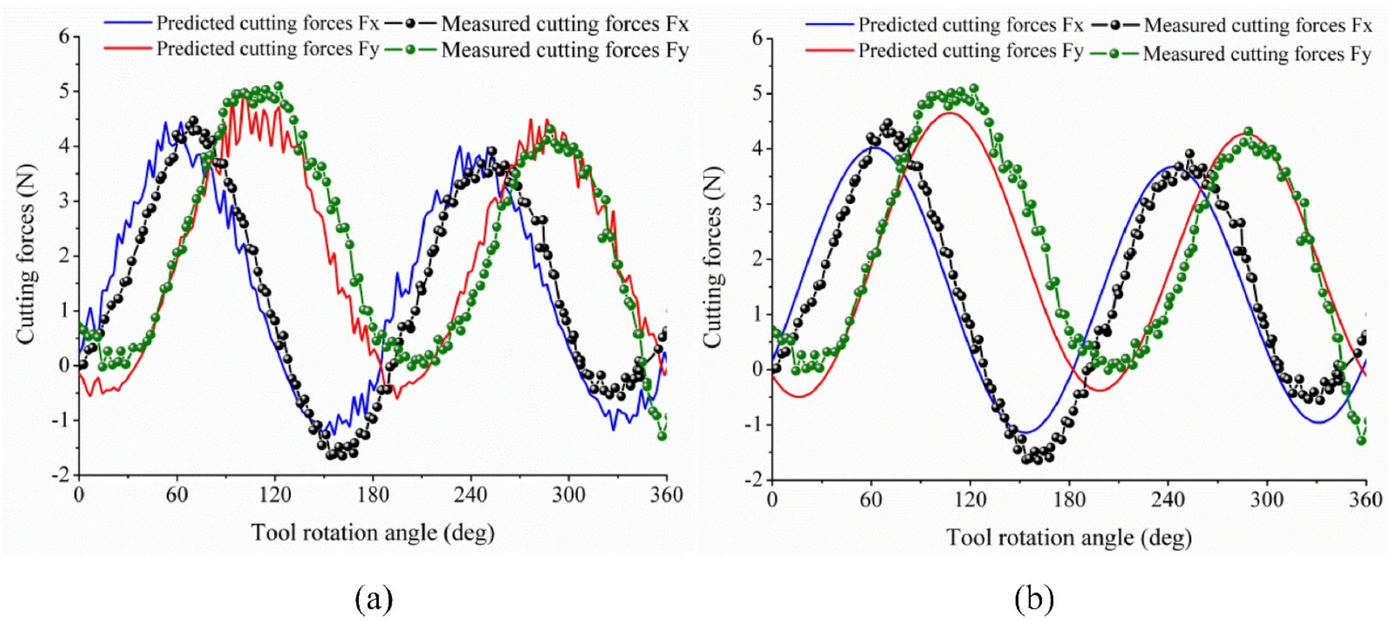


Figure 4. Comparison results of measured and predicted cutting forces (**a**) with considering the effect of stochastic tool wear (**b**) without considering the effect of stochastic tool wear [80].

Ragai et al. have studied the classification and analysis of machining parameters and energy consumption patterns in turning [81]. Wirtz et al. have studied the simulation-assisted investigation of the electrical power consumption of milling processes and machine tools [82]. Akkuş and Yaka studied the effects of machining parameters on vibration, surface roughness and energy consumption experimentally and statistically in the machining of Ti6Al4V ELI alloy. As a result of their studies, it was determined that the surface roughness and energy consumption increased with the increase in vibration value. They stated that the created Taguchi models made predictions with a high percentage of accuracy (surface roughness about 82%; energy consumption about 98%; vibration about 89%) [83]. Öztürk et al. investigated the effect of surface roughness on energy consumption in X-axis and spindle servo motors in slot milling [84]. Dai et al. studied the grinding temperature and power consumption in the high-speed grinding of Inconel 718 nickel-based superalloy [85]. Ming et al. analyzed the cutting response of SiAlON ceramic tools in the high-speed milling of FGH96 superalloys [86]. Moreira et al. analyzed and optimized the milling of BS EN24T alloy steel on energy efficiency [87]. Liu et al. studied the processing of the Inconel 718 superalloy for the cumulative energy demand and environmental impact on sustainable energy [88]. Zhang et al. evaluated the analysis and optimization of energy consumption and environmental impact in electric discharge machining of titanium superalloys. As a result of the study, they stated that pulse duration and magnetic field intensity are the main factors affecting electrode wear rate and process energy consumption and processing noise [89]. Airao et al. researched the ultrasonic assisted turning under cryogenic/MQL system to reduce tool wear and improve machinability characteristics of Inconel 718. According to the outcomes, the highest power consumption occurred in the MQL condition, while the lowest was achieved in the LCO_2 condition. They stated that LCO_2 significantly reduces tool flank and crater wear by reducing power consumption. The experimental setup of their work and their followed plan are given in Figure 5 [90].

Figure 5. Experimental setup and followed plan [90].

Gupta et al. [91] conducted turning experiments of Ti6Al4V with sustainable hybrid cryogenic MQL cooling/lubrication techniques. They evaluated their experiments according to tool wear, surface roughness, microhardness, SCE and chip morphology and sustainable cooling conditions. Ali et al. [92] have studied new bio-based nano-lubricants for environmentally eco-friendly and improved machinability of Inconel 718 alloys. Jamil et al. [93] have worked to bridge the gaps between sustainability measures (SCE, process time, carbon emissions, energy efficiency) and machining characteristics (tool wear, cutting temperature, surface roughness) in the milling of Ti6Al4V. Kim and Lee [94] conducted an experimental study on the power consumption of the Inconel 718 for laser and induction-assisted machining. Günay et al. [46] evaluated the performance analysis of carbide coated tool in turning of Nimonic 80A superalloy under different cutting environments. Shah et al. [95] conducted a life-cycle evaluation of the Inconel 718 drilling using cryogenic cutting fluids considering sustainability parameters. The experimental setup and methodology of their work are given in Figure 6.

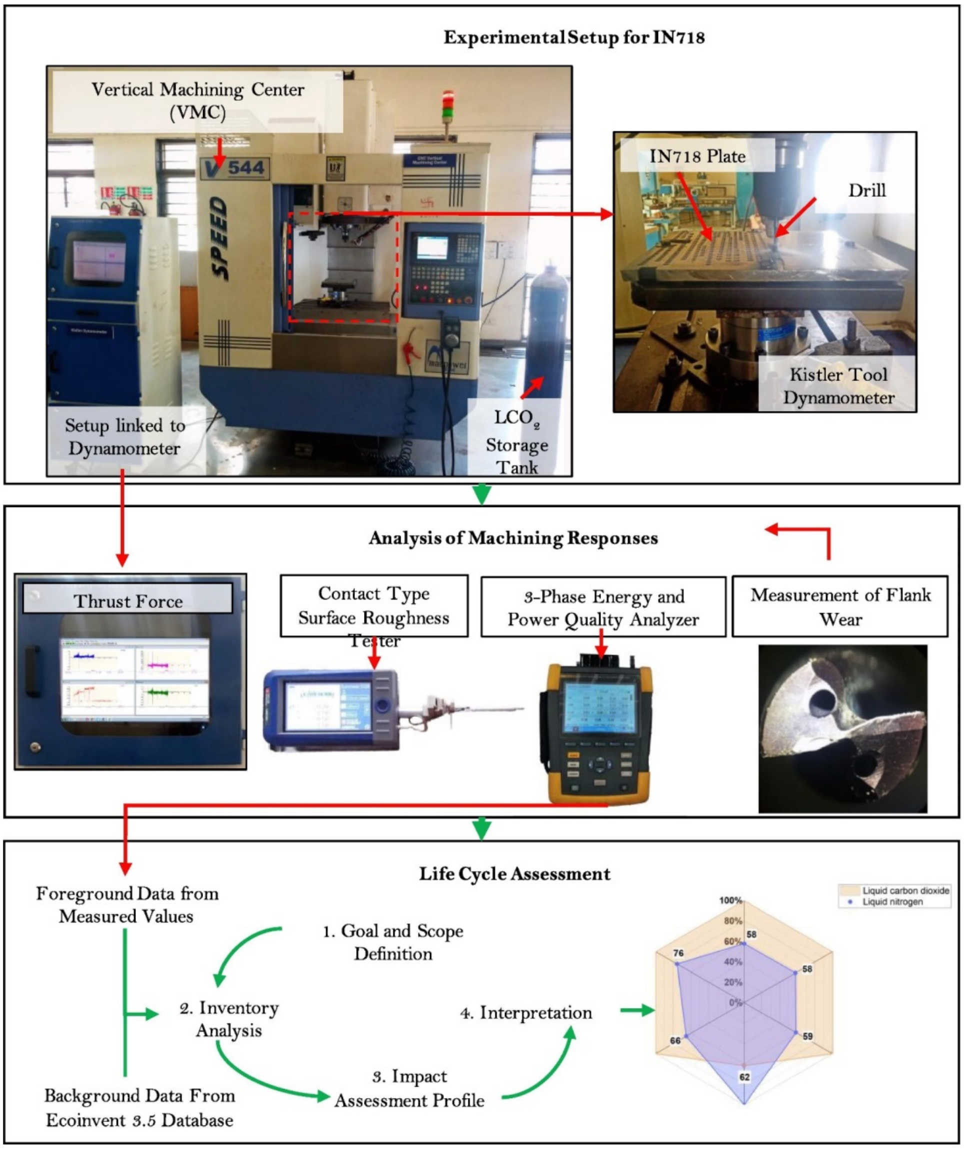


Figure 6. Experimentation methodology followed in the present work [95].

Khanna et al. evaluated energy consumption, tool wear and surface roughness during the turning of Inconel 718 using a sustainable machining technique [96]. Careri et al. studied machining finite element modeling of nickel superalloy produced by a direct energy deposition process [97]. Korkmaz et al. investigated the cutting forces numerically and experimentally in the turning of Nimonic 80A super alloy, since Fc values, which are of primary importance in terms of energy consumption in turning, are primarily considered in the analysis of cutting forces [37]. Bartolomeis et al. evaluated the performance of the Electrostatic Minimum Amount Lubrication system of Inconel 718 in end milling in terms of tool life, SCE and surface roughness [98]. Ross et al. investigated the effects of the milling Nimonic 80A alloy on milling temperature, power consumption, specific cutting energy, burr formation, XRD and grain growth according to various combinations of speed feed [99]. Agrawal et al. studied the tool wear progression of Ti6Al4V in cryogenic-assisted turning and its effects on surface roughness and energy consumption. As a result of their study, they determined that cryogenic turning had reductions of up to 9% and 61% in energy consumption compared to dry and wet turning, respectively [100]. Venkatesan worked on the optimization of surface roughness and power consumption in laser-assisted machining of Inconel 718 with Taguchi-based response surface methodology [101]. Parida and Maity performed hot turning experiments on Inconel 718 to determine the effect of heating on metal removal rate, power consumption, forces, tool life and SCE. As a result of their study, they found an increase in tool life and material removal rate and a reduction in forces, power consumption and specific cutting energy in hot conditions compared to machining conditions at room temperature [102]. Divya et al. studied the performance of micro-hole textured inserts on the power consumption and measurement methodology in the turning process. The focus of their work is to select the appropriate device to measure power consumption and to minimize power consumption. As a result of the study, they stated that the direct measurement of power consumption is an accurate and error-free approach [103]. Khanna et al. evaluated the sustainability and machinability improvement efforts of the Nimonic-90 using cryogenic-ultrasonic-assisted turning and cryogenic-assisted turning. They assessed their observation according to surface roughness and energy consumption. As a result of the study, they determined that up to 20% less energy consumption occurs in the cryogenic-ultrasonic-assisted turning process compared to cryogenic-assisted turning [104]. Khan et al. carried out experimental studies comparing the machinability criteria and economic aspects in the turning Haynes-25 alloy. In their study, they investigated the workability, energy consumption and economic feasibility of a new oil-on-water (OoW) lubrication approach mixed with cryogenic liquid nitrogen (LN_2). As a result of their studies, they determined that the LNOoW lubricated cooling approach reduces the cutting temperature and significantly improves the surface quality of the workpiece. In addition, they found less cutting power and electrical energy consumption in the cooling/lubrication approach used [105]. The literature review of power and energy consumption studies related to superalloys is given in Table 4.

Table 4. Literature review of power and energy consumption studies on superalloys.

Type of Sensors	Machining Operations	Process	Workpiece	Aim	Ref.
Surface roughness tester, power meters, Optical Microscope	CNC turning center	Turning	AISI 1045	Sustainability assessment for turning of AISI 1045 steel in dry, flood and Al_2O_3 nano-fluid conditions, taking into account surface quality and power consumption.	[73]
Tool maker's microscope, three-phase energy analyzer, air quality meter, SEM	Heavy-duty precision lathe	Turning	Ti-3Al-2.5 V	To investigate the turning of Ti3Al2.5 V in different cooling/lubrication environments to determine the cooling/lubrication technology.	[74]
Calculated with formula	EDM machine	EDM	High chromium tool steel	Minimizing the processing time and resources spent on the product during production and processing.	[75]
Surface Roughness tester, Power meter	CNC Turning machine	Turning	AISI 316	Analysis of cutting parameters for energy consumption and machining cost.	[76]
Surface Roughness tester, Power meter	Lathe machine	Turning	AISI 1045	To optimize power consumption and MRR during processing.	[77]
Dynamometer, power-quality analyzer	Vertical Machining Center	Drilling	VT-20 Titanium alloy	To identify the most energy-efficient and environmentally friendly coolant approach.	[78]
Power analyzer, microscope, SEM	CNC Turning machine	Turning	Ti6Al4V	To evaluate the tool wear rate and SCE under different cutting conditions.	[79]

Table 4. *Cont.*

Type of Sensors	Machining Operations	Process	Workpiece	Aim	Ref.
Power meter,	Machining center	Milling	AISI H13	Characterization of process level power profile and energy consumption and machine tool and spindle levels in hard milling.	[13]
SEM, dynamometer, power meter	vertical micro milling machine	Micro milling	Al6061	Develop an improved energy consumption model of micro-milling process based on the effect of team wear.	[80]
Vibration sensor, microphone, and AC current logger	CNC lathe	Turning	AISI 1018	Investigating the use of machine learning techniques to examine the effect of cutting parameters on signal patterns in turning operations.	[81]
Power analyzer	milling machine	Milling	EN-AW 7075 and 1.0577	Simulating the electrical power requirement of machining processes and machine tools.	[82]
Power Quality Analyzer, Roughness measuring device, vibrometer, hardness tester	CNC lathe	Turning	Titanium 6A1-4V ELI	Increasing energy efficiency in the turning process.	[83]
Dynamometer, Power Meter	CNC vertical machining center	Milling	7075	It is the optimization of cutting parameters with minimum surface roughness and energy consumption in the manufacturing process using the Taguchi method.	[84]
Dynamometer, thermocouple, power meter, roughness tester, optical microscope	Grinding machine	Grinding	Inconel 718	Investigation of the effect of grinding speed and grinding temperature on power consumption.	[85]
Dynamometer, infrared thermograph, laser scanning confocal microscope, EDX, SEM	Machining center	Milling	FGH96	Finding the cutting responses of SiAlON ceramic mills during high-speed milling of FGH96.	[86]
Power meter,	Vertical milling machine	Milling	BS EN24T	Making energy-efficient analysis and optimization.	[87]
Optical microscope, power analyzer	CNC milling machine	Milling	Inconel 718	Examination of Inconel 718 flood coolant supply and dry conditions according to energy consumption.	[88]
Oscilloscope, energy detection meter, SEM, sound meter, digital camera	EDM	EDM	Ti6Al4V	To reduce energy consumption and environmental hazards.	[89]
Surface roughness tester, Power analyzer, SEM	Conventional lathe	Turning	Inconel 718	Analyzing the machinability of Inconel 718.	[90]
Energy analyzer, tool maker's microscope, surface-roughness tester, SEM	CNC turning center	Turning	Ti–6Al–4V	Characterization of hybrid cryo-lubrication-assisted turning performance of Ti6Al4V alloy.	[91]

Table 4. *Cont.*

Type of Sensors	Machining Operations	Process	Workpiece	Aim	Ref.
Dynamometer, current data logger, stereomicroscope, SEM, EDX, surface-roughness tester	CNC turning machine	Turning	Inconel 718	To investigate the effect of aluminum oxide, Al_2O_3 nanoparticles dispersed in newly formulated bio-based oils using a minimal lubrication (MQL) approach in turning Inconel 718.	[92]
Optical microscope, surface-roughness tester, infrared thermal image camera, power meter	CNC milling	Milling	Ti6Al4V	To study energy efficiency, carbon emissions and processing characteristics in MQL and cryogenic environment.	[93]
Dynamometer, pyrometer, power logger	5-axis machining center	Milling	Inconel 718	Comparing the machinability characteristics of laser-assisted machining and induction-assisted machining.	[94]
Toolmaker's microscope, SEM,	CNC Turning	Turning	Nimonic 80A	To study the performance of turning Nimonic 80A super-alloy in different cutting environments.	[46]
Dynamometer, surface-roughness tester, power quality analyzer, tool maker's microscope	vertical machining center	Drilling	Inconel 718	To compare tool wear, thrust force, power consumption and surface roughness at cutting speed levels for IN718 drilling using LCO_2 and LN_2.	[95]
Toolmakers microscope, optical profilometer, SEM, power quality and energy analyzer	CNC turning center	Turning	Inconel 718	To evaluate energy consumption, tool wear and surface roughness in the course of turning of Inconel 718.	[96]
Dynamometer, IR camera, thermocouple, SEM	CNC turning center	Turning	Inconel 718	Developing a 3D finite element model of the Inconel 718 turning process.	[97]
Dynamometer, FEM	CNC lathe	Turning	Nimonic 80A	To investigate the machinability of Nimonic 80A superalloy depending on cutting forces in both turning experiments and simulations.	[37]
Optical microscope, power-demand analyzer, profilometer	CNC vertical milling center	Milling	Inconel 718	Investigation of high-speed milling with Electrostatic Minimum Quantity of Lubrication of the Inconel 718.	[98]
Thermometer, dynamometer	Machining Center	Milling	Nimonic 80A	Investigation of the effect of hybrid cooling approach.	[99]
Toolmaker microscope, SEM, optical profilometer, power quality and energy analyzer, surface-roughness tester, a metallurgical microscope	CNC turning center	Turning	Ti-6Al-4V	To evaluate machinability improvements in Ti6Al4V.	[100]
Infrared pyrometer, surface-roughness tester	lathe machine	Turning	Inconel 718	Optimizing cutting conditions.	[101]

Table 4. *Cont.*

Type of Sensors	Machining Operations	Process	Workpiece	Aim	Ref.
Thermocouple, dynamometer, power analyzer	Turning machine	Turning	Inconel 718	Investigation of machinability of nickel-based alloy in heat-assisted machining.	[102]
Dynamometer, Wattmeter and Power Quality Analyzer	CNC turning	Turning	Inconel 718	Minimizing power consumption by using textured inserts and choosing the appropriate device for measuring power consumption.	[103]
Surface-roughness tester, power quality and energy analyzer	Turning machine	Turning	Nimonic-90	Comparison of cryogenic-assisted turning and cryogenic-ultrasonic-assisted turning.	[104]
Thermocouple, surface tester, optical microscope, smart meter	CNC lathe machine	Turning	Haynes-25	Investigation of machining sustainability according to surface quality, tool wear rate, cutting temperature and energy consumption.	[105]

Energy measurement during the machining of super-alloys can be estimated theoretically and experimentally as follows.

Specific cutting energy consumed during the formation serrated chip is specified by E_{spc} considered to be a product of plastic strain and flow stress. Mathematically,

$$E_{spc} = \int_0^{\varepsilon_p} \tau(\varepsilon_p, \overline{\varepsilon_p}, T)d\gamma \tag{1}$$

$\varepsilon_p =$ plastic strain
$\overline{\varepsilon_p} =$ plastic strain rate
$T =$ temperature

The specific friction energy denoted by E_{fspc} is calculated by,

$$E_{fspc} = \frac{\tau_s A_s V_{chip} \sin\beta}{t_0 w V_c \cos(\varnothing + \beta - \varepsilon_{p0})} \tag{2}$$

Further, specific chip kinetic energy denoted by E_{kspc} is calculated by,

$$E_{kspc} = \frac{1}{2}\rho V_{chip}^2 = \frac{\rho V_{chip}^2 \sin^2\varnothing}{2\cos^2(\varnothing - \varepsilon_{p0})} \tag{3}$$

Finally, the total specific cutting energy $E_{totalspc}$ during chip formation is obtained by adding Equations (1)–(3),

$$E_{totalspc} = \int_0^{\varepsilon_p} \tau(\varepsilon_p, \overline{\varepsilon_p}, T)d\gamma + \frac{\tau_s A_s V_{chip} \sin\beta}{t_0 w V_c \cos(\varnothing + \beta - \varepsilon_{p0})} + \frac{\rho V_{chip}^2 \sin^2\varnothing}{2\cos^2(\varnothing - \varepsilon_{p0})} \tag{4}$$

On the other hand, specific cutting energy consumed during the formation of the fragmented chip is specified by $E_{spc}{}'$ and mathematically calculated by,

$E_{spc}{}' = \frac{\rho \overline{\varepsilon}^2}{A'^2} + \frac{E^2{}_{IC}}{2\rho v^2} A'$

The specific energy can also be calculated experimentally as,

$$E_{spc} = \frac{P_{cutting}}{V_{chip} t_0 w} = \frac{F_{cutting}}{t_0 w} \tag{5}$$

$P_{cutting}$ = power during cutting
$F_{cutting}$ = cutting force

Conclusion on the section: When looking at the literature papers, superalloys are widely preferred to manufacture important products in prominent industries. This makes these materials an ideal base material for many sectors; however, such a demand needs serious effort due to the machinability issues. In the context of this paper, the important machinability criteria surrounding energy consumption were addressed several times in addition to the other indexes. According to the comprehensive analyses, depending on the literature papers, alpha-beta titanium and Inconel series are the mostly preferred types among all materials. The researchers preferred to use parametric optimizations, numerical approaches and lubri-cooling strategies to reduce the energy consumption. In addition to the conventional machining processes, EDM and micro-milling as the non-conventional types of machining operations were selected a few times.

3. Classification of Composites

Composites—a derived category of material which is made up of two or more constituents that are very dissimilar from each other—be it organic vs. inorganic compounds, man-made vs. natural, or any other example, these composites display physical or chemical properties that are more than the simple sum of the two, i.e., they are synergistic and they are not integrated microscopically with each other [106]. Composites consist of two or more materials called 'constituents'; each has its own mechanical and physical properties to form an individual material with different properties [107].

Materials in solid forms are categorized into four major types such as metals, ceramics, polymers and carbon. Both matrix-based and reinforced materials are found in all these classes. This provides a capacity for creating numerous new combinations and thus composites exhibit distinctive features which cannot be achieved by any single material. Table 5 states material varieties and possible mixtures currently used in various applications.

Table 5. Varieties of composites.

	MATRIX			
REINFORCEMENT	**Carbon**	**Ceramic**	**Metal**	**Polymer**
Carbon	√	√		√
Ceramic	√	√	√	√
Metal	√	√	√	√
Polymer	√	√	√	√

Composites are typically categorized with respect to the material type used. Principal styles of matrix-based composites are carbon matrix composites (CAMCs), ceramic matrix composites (CMCs), polymer matrix composites (PMCs), and metal matrix composites (MMCs) as shown in Figure 7 [108]. On the other hand, reinforced composites are classified according to reinforced material such as aligned discontinuous and continuous fibers, elongated crystals such as whiskers, small particles and several kinds of fiber structures shaped by textile systems, such as braids and fabrics [109]. A general mode of representing fiber-reinforced composites is to showcase the matrix and fiber segregated via the slash.

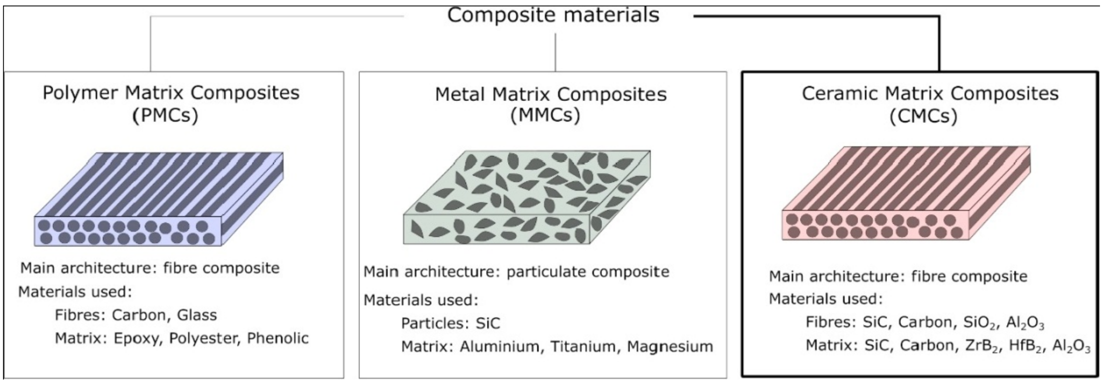


Figure 7. Variations in matrix-based composites [108].

CMCs offer high-temperature competence, a good resistance to wear, oxidation and corrosion behavior. Compliant ceramics are brittle in nature and have very low toughness against fracture, and thus, their strength shows huge scatter resulting in unsuitability for tension or torsional loading. Reinforcing ceramics made up of monolithic fibers turns them competent for the higher temperature range of engines used in aircrafts [110–112]. CAMs are mostly considered as high-performance materials constituted by carbon fibers to be used wherein behavior of machine elements must be robust mechanically and have a lighter weight. Modern sports equipment, wind energy technology and machine elements used in the recreational, military, automotive and aerospace industries require CAMs. Carbon fiber evidently provides one of the best high performances. It offers a high strength-to-weight ratio and has high fatigue resistance, stiffness, toughness, Young's modulus, compressive strength, tensile strength, etc., [113,114]. Plus, carbon fiber composites have a very good aesthetic appeal (those prepared using carbon fiber fabric, woven mat, roving—roving provide a better finish when used in the filament winding process). MMCs typically consist of metal with less density, such as magnesium or aluminum, reinforced with fibers or particulates of ceramics for example graphite or silicon carbide [115]. In comparison with non-reinforced metals, MMCs exhibit more stiffness and specific strength, are sustained over greater temperature ranges and have a higher resistance to wear and tear, and gives chance to adapt this behavior considering specific requirement as well [116,117]. Figure 8 shows the types of CMCs-based applications. Some examples of MMC's are aluminum (Al) with particulates of SiC, aluminum with fibers of graphite or boron, copper reinforced with graphite and steel reinforced with boron nitride, used in making tank armors. Polymer matrix composites (PMCs) have polymers as matrix and usually other strong constituents such as ceramic particles or graphene as dispersed phase [118]. Polymers generally have very good resistance to chemical attacks and have low specific gravity. These properties, when combined with the strength of ceramic particles or other dispersed phases, results in an excellent condition of properties such as a very high strength-to-weight ratio, resistance to corrosion, etc. [119].

To summarise, composites are basically heterogeneous mixtures that influence properties to create the best material for the application. That is, the atoms of the different constituents do not combine with each other, and you can visually see the different constituents distinctly when viewed by a closer look at the composite. Composites are formed by bringing together different materials and making a third product that is different from the original constituents but has the properties of both of them. The product formed is of much better quality and greater usage than the single material. Some of the properties of composites are listed as: they have a high strength-to-weight ratio, offering high resistance to corrosion, greater fatigue life, high dielectric strength and inherent durability [120]. As previously stated, composites have a high strength-to-weight ratio, which is critical in weight-limited applications, such as spacecrafts, aircrafts and sports equipment [121]. Some composites are impact-energy absorbing, so can be used in the armor industry.

Some composites have consistent frictional characteristics across a very wide temperature range, so they are useful for high-performance brake discs (race cars, F-16, Space Shuttles). Some have high-temperature resistance, so can be used for spacecraft heat shields and jet engine parts.

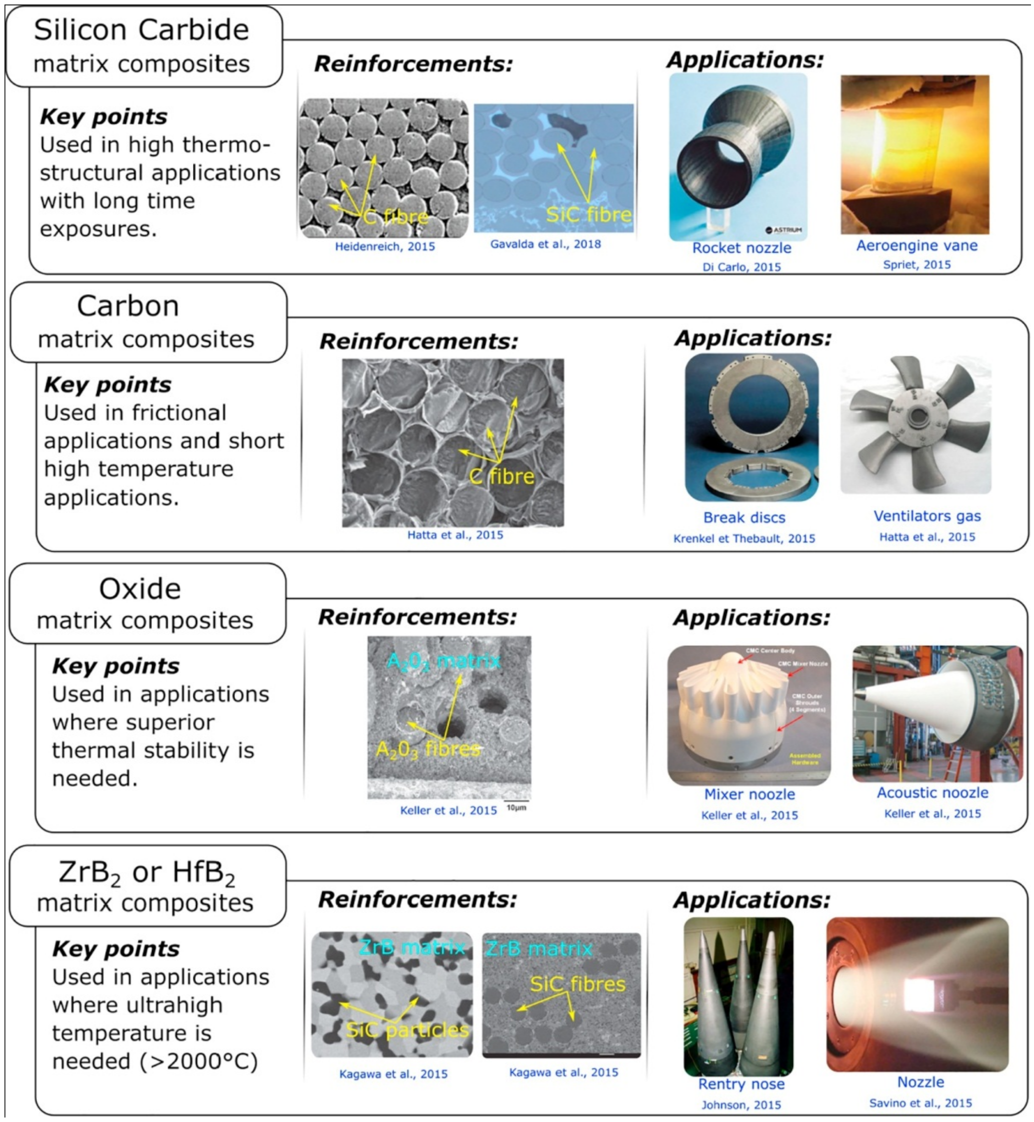


Figure 8. Types of CMC-based applications [108].

Usca et al. evaluated tool wear, surface roughness, cutting temperature and chip morphology of Al/TiN-coated carbide cutting tools in the milling of CuBCrC-based ceramic matrix composites in order to enable businesses to minimize energy consumption on an industrial scale [122]. Ji et al. investigated the effects of different cooling methods on specific energy consumption when drilling CFRP/Ti6Al4V stacks. As a result of their study, they stated that the use of vegetable-based lubricating oil can effectively reduce the energy consumed, resulting in a reduction in drilling torque and specific cutting energy [123]. Chen et al. examined the mechanism and feasibility of ultrasonic-assisted milling to improve the machined surface quality of 2D Cf/SiC composites. A schematic diagram of the experimental setup, machining center and online test equipment, tooling and milling used is given in Figure 9 [124].

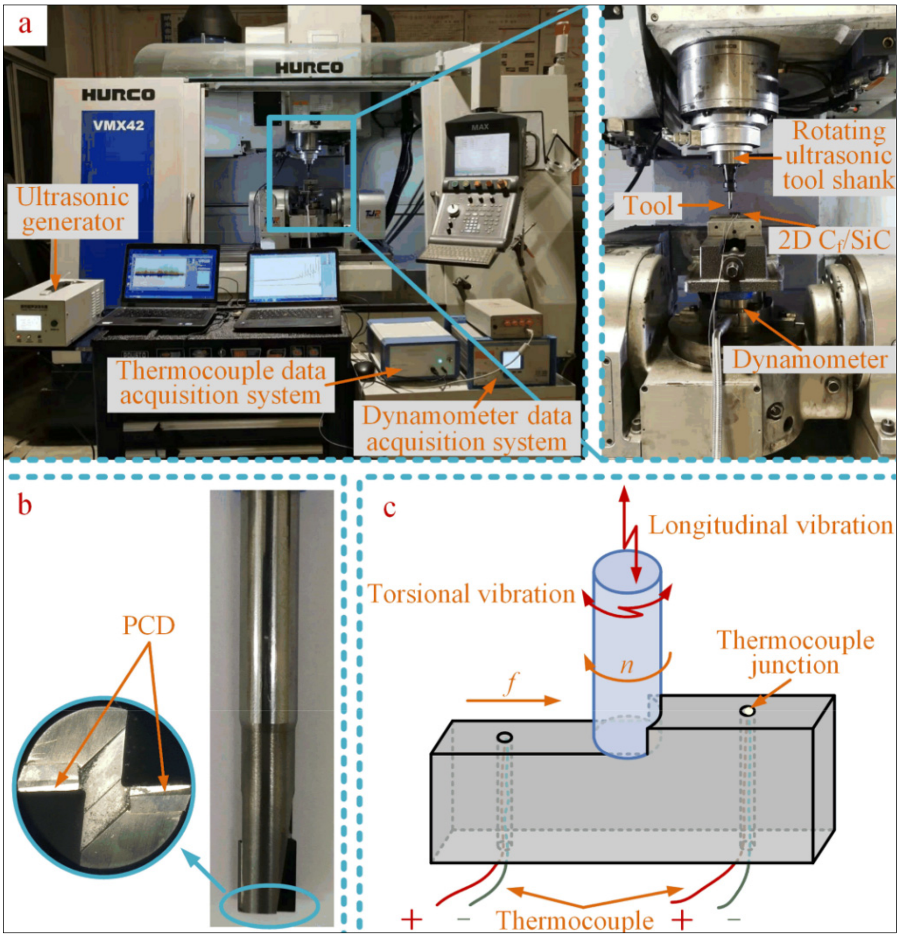


Figure 9. Experimental setup, (**a**) machining center and online testing equipment, (**b**) PCD tool, (**c**) schematic diagram of milling [124].

Arulkirubakaran et al. studied the performance of surface textured tools during machining of Al-Cu/TiB_2 composite. They evaluated their work with material hardness, cutting force, tool wear and specific cutting energy. They made the specific energy with the empirical formula. The formula is given in Equation (6) [125].

$$U_c = F_c/wt \tag{6}$$

Peng et al. conducted an experimental study on laser-assisted ultrasonic elliptical vibration turning of 70% wt. SiCp-reinforced Al-based composites [126]. Wei et al. conducted research on high-speed, high-power density laser-assisted machining, productivity and surface quality of Al-SiC metal matrix composite [127]. Karabulut et al. investigated the effect of B_4C particle reinforcement on the mechanical and processing properties of Al6061/B_4C composites according to surface roughness and energy consumption. As a result of the study, they stated that power consumption and surface roughness increased when cooling with compressed air [128]. Salur et al. conducted an experimental study of the machinability properties of metal matrix composites during drilling. In their study, they stated that by reducing the forces, there is less energy consumption during drilling. For this reason, they evaluated their work according to cutting forces and surface roughness. In their study, analysis of variance was used to determine the effects of production parameters on the thrust force and surface roughness of metal matrix composites drilled at different feed rates. In addition, the effects of each production parameter were determined according to the Taguchi design and the S/N ratio approach [129]. Bhushan investigated the effect of SiC particle size and weight percentages on power consumption during the turning of AA7075/SiC composites. He used the ANOVA analysis in his study to obtain the optimum processing parameters. In this study, the minimum power was consumed at 90 m/min cutting speed, 0.15 mm/rev feed, 0.20 mm cutting depth and 0.40 mm nose radius [130]. Reddy et al. have worked on the experimental investigation and optimization of energy consumption and surface defects in Al-Si and Al-based metal matrix composite's wire-cutting electric discharge machining. Optimization processes were performed with the controllable parameters of pulse on time, current, pulse off time, voltage and wire tension, using graph theory, utility concept and teaching–learning based optimization algorithm [131]. James and Annamalai evaluated the developed composite AA6061-ZrO_2 with lubricants and power consumption. They made their studies according to the L27 orthogonal index. Turning experiments were carried out in dry and minimally lubricated conditions. ANOVA and S/N ratio graphs were used in the evaluation processes [132]. Xu et al. carried out experimental studies on drilling machinability and hole quality of CFRP/Ti6Al4V stacks under different cooling conditions. As a result of their study, they found that the stacks of MQL on the CFRP/Ti6Al4V reduced the drilling torque and minimized the specific cutting energy consumption during drilling [133]. Agrawal et al. studied the effect of dry and multi-jet cryogenic cooling on the machinability and hole accuracy of CFRP composites. As a result of the study, they stated that the specific cutting energy was reduced by up to 35% using cryogenic drilling compared to dry drilling. They also stated that the use of a multi-jet cryogenic cooling system provides improved composite machinability and sustainability for industrial usage. The experimental set they used in their studies is given in Figure 10 [134].

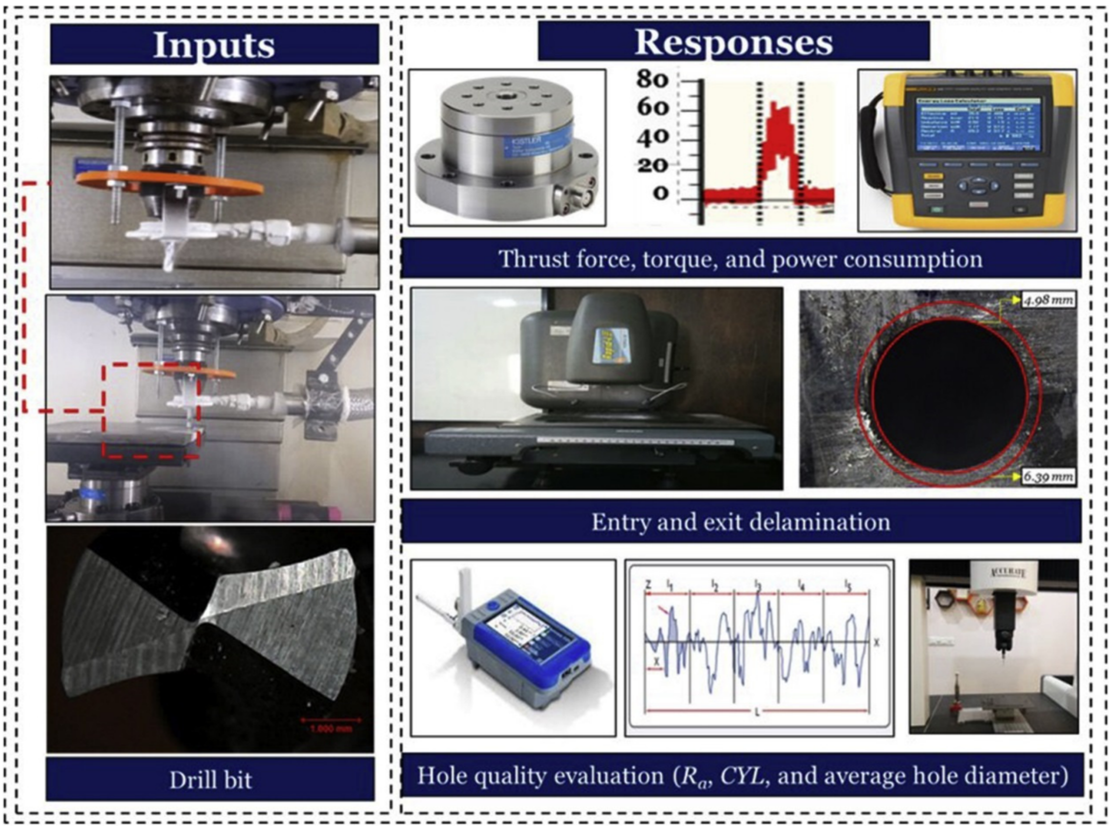


Figure 10. Inputs, experimental setup and responses [134].

Kayihan et al. have studied the drilling of Al/Ti/CFRP hybrid composites. In their study, they investigated the effect of machining parameters on cutting force, consumed energy and torque. As a result of their studies, they determined that the lowest amount of energy was consumed at 62 m/min drilling speed and 0.1 mm/rev feed rate. They also observed that energy consumption increased with increasing cutting speed [135]. Ic et al. optimized the turning parameters for SiC^- or $Al_2O_3{}^-$ reinforced aluminum matrix composites according to surface roughness, power consumed and material surface hardness. They stated that the optimum parameters were 1668 mm/rev feed rate, 1 mm depth of cut, cutting tool material KNUX 1605X and SiC reinforced the Al alloy [136]. Kumar et al. have studied the optimization of machining parameters of Al7075–ZrO_2–C Metal Matrix Composites using Grey relations analysis and ANOVA [137]. Shoba et al. performed turning experiments of Al/SiC/RHA hybrid composite under different conditions. They evaluated their work according to the cutting force, power consumption, surface roughness and metal removal rate during the process [138]. Suneesh and Sivapragash used Mg/Al_2O_3 hybrid composite material in their study. They carried out their experimental studies in dry and MQL conditions on a lathe. Parameter optimization evaluations were made by combining low energy consumption and high surface integrity [139]. Zou et al. evaluated the machinability criteria and machined surface quality of milling CFRP laminate composites under dry and supercritical CO_2-based cryogenic conditions [140]. In their study, they made the specific cutting power and energy with the following equations [140,141].

$$E_s = F * v/MRR \tag{7}$$

$$P_s = F * v \tag{8}$$

Zhu et al. have studied the optimization of machining parameters by considering the energy efficiency of milling wood plastic composite material [142]. Yu et al. studied the cutting-specific energy and surface roughness values during the milling of TiB_2/Al composites and Al alloys [143]. Xu et al. evaluated their diamond-coated tools for drilling CFRP composites based on cutting force, energy consumed and machined surface quality [144]. Energy measurement during the machining of composites can be estimated theoretically and experimentally as follows.

Specific cutting energy consumed during the plastic deformation in the shear zone ($E_{spcshear}$) in the machining of composites is mathematically expressed as

$$E_{spcshear} = \int_0^{\varepsilon} \sigma_{max} d\varepsilon \tag{9}$$

σ_{max} = syntactic foam peak stress
$d\varepsilon$ = incremental strain in the shear zone

$$E_{spcshear} = \int_0^{\varepsilon_p} [2F_M\sigma_y + F_{CB}\hat{u}B_{fw}] \left(\frac{\varphi_a}{\varphi_b}\right) [1 + Cln\dot{\varepsilon}] \left[1 - \left(\frac{T - T_r}{T_m - T_r}\right)^m\right] d\varepsilon_p \tag{10}$$

ε_p = equivalent plastic strain
F_M = matrix fraction
σ_y = yield strength
F_{CB} = ceramic microsphere area fraction
B_{fw} = fracture strength of the hollow microsphere wall
$\hat{u}$ = pores on thewall of the ceramic microspheres
$\frac{\varphi_a}{\varphi_b}$ = changes in shear stress due to microsphere diameter variations

On the other hand, experimentally, specific cutting energy (E_{spc}) consumed during the machining of composites depends on cutting force ($F_{cutting}$), cutting velocity ($V_{cutting}$) and material removal rate (MRR) and is expressed as

$$E_{spc} = \frac{F_{cutting}V_{cutting}}{MRR} \tag{11}$$

$$E_{spc} = \frac{F_{cutting}V_{cutting}}{A_{undeformed}V_{cutting}} \tag{12}$$

$$E_{spc} = \frac{F_{cutting}}{A_{undeformed}} \quad (13)$$

where

$$F_{cutting} = -F_x \sin\ \theta + F_y \cos\ \theta \quad (14)$$

Here, θ is the engagement angle of a tool and is calculated as

$$\theta = \tan^{-1}\left(\frac{\cos\beta}{1-\sin\beta}\right) \quad (15)$$

$F_x,\ F_y =$ force in x and y direction, respectively.

Further, $A_{undeformed}$ expresses an undeformed area of a chip which is calculated as

$$A_{undeformed} = t_{chip} + t_{unidirectional\ laminate} \quad (16)$$

where $t_{unidirectional\ laminate}$ is the thickness of the unidirectional laminate and t_{chip} is chip thickness.

Chip thickness t_{chip} is calculated as

$$t_{chip} = F_z \sin\theta \quad (17)$$

Fz = force in z direction

The literature review of power and energy consumption studies related to composites is given in Table 6.

Table 6. Literature review of power and energy consumption studies on composites.

Type of Sensors	Machining Operations	Process	Workpiece	Aim	Ref.
Thermal camera, surface-roughness measurement, SEM	Milling machine	Milling	CuBCrC-based ceramic matrix composite	It aims to investigate the machinability properties during the milling of new material CuBCrC composites using Al/TiN-coated carbide tools.	[122]
SEM, dynamometer	CNC machining center	Drilling	CFRP/Ti6Al4V Stack	To investigate the effect of cooling methods on the energy distribution in the course of the drilling of multi-material.	[123]
TEM, laser displacement sensor, dynamometer, thermocouple	Machining center	Milling	Cf/SiC composite	To examine the mechanism and effectiveness of ultrasonic-assisted grinding in improving the surface integrity of Cf/SiC.	[124]
SEM, hardness tester, dynamometer, optical microscope	CNC turning	Turning	Al-4 wt% Cu/TiB_2 composite	Investigation of the performance of surface-textured tools.	[125]
EDS, SEM, microhardness tester, dynamometer, infrared thermometer	CNC lathe	Turning	70% SiCp/Al composite	Investigation of the removal mechanism of materials and the effects of different laser heating temperatures and ultrasonic vibration.	[126]
Pyrometer, infrared thermal camera, thermocouple, surface-roughness tester, power meter	Mini lathe	Turning	Al-SiC MMC	Increasing productivity in the laser-assisted turning of Al/SiC MMC material.	[127]

Table 6. *Cont.*

Type of Sensors	Machining Operations	Process	Workpiece	Aim	Ref.
SEM, microscope, power-quality analyzer, surface-roughness measurement instrument	Vertical machining center	Milling	Al6061/B4C composite	To investigate the mechanical and machinability properties of aluminum 6061 reinforced with boron carbide (B4C).	[128]
Dynamometer, surface-roughness measurement instrument	Vertical machining center	Drilling	Metal matrix composite	To determine the optimum machining parameters of tin bronze matrix composites produced by hot pressing of waste metallic chips.	[129]
Wattmeter	CNC Turning Machine	Turning	AA7075/SiC composite	Investigation of the power consumption of AA7075/10 wt% SiC during the turning process.	[130]
Wattmeter, stereo zoom microscope, Surftester	CNC Wire cut EDM	WEDM	Al-Si is an Al-based MMC	Minimizing energy consumption and improving machine performance.	[131]
Surface-roughness tester, dynamometer	CNC Turning	Turning	AA6061-ZrO_2	Analysis of MQL effect on improved composite AA6061-ZrO_2 machinability.	[132]
Dynamometer, SEM, digital microscope, CMM	Five-axis machining center	Drilling	CFRP/Ti6Al4V	To compare the processing behavior of CFRP/Ti6Al4V stacks under different cooling conditions.	[133]
Dynamometer, power-quality energy analyzer, CMM, surface-roughness tester	CNC vertical machining center	Drilling	CFRP	To analyze the drilling performance of CFRP composites under cryogenic cooling conditions.	[134]
Stereo optical microscope, dynamometer, profilometer	Vertical machining center	Drilling	Al/Ti/CFRP hybrid composite	To create a new perspective by considering the energy consumption of drilling hybrid composite materials.	[135]
Phertometer, electrical panel, hardness tester	Conventional lathe	Turning	Al matrix + 10% SiC Al matrix + 10% Al_2O_3	Optimizing turning parameters for minimum surface roughness, energy consumption and minimum hardness of the workpiece material.	[136]
Dynamometer, Surface-rough-ness tester	Vertical milling center	Milling	Al7075–ZrO_2–C MMC	Determination of good surface quality, minimum cutting force and optimal machining parameters in milling.	[137]
SEM, EDX, Optical microscope, Surface roughness tester	Medium duty lathe	Turning	Al/SiC/RHA	Investigation of Power Consumption, tool wear, surface roughness and MMR.	[138]
Surface roughness tester, Dynamometer, infrared thermometer	Lathe machine	Turning	Mg/Al_2O_3	Minimizing surface roughness, cutting force and specific power consumption.	[139]

Table 6. *Cont.*

Type of Sensors	Machining Operations	Process	Workpiece	Aim	Ref.
Confocal laser scanning microscope, SEM, infrared thermal imager, optic microscope	Vertical milling center	Milling	T800/X850 CFRP laminates	To investigate the effect of cryogenic cooling methods on the processing of CFRP laminates.	[140]
Power analyzer	CNC Milling	Milling	Wood Plastic Composite	Optimizing milling conditions according to energy efficiency.	[142]
Dynamometer, laser confocal microscope, surface-roughness tester	Machining center	Milling	TiB_2/Al	Investigation of cutting-specific energy and cutting force coefficients according to machining parameters.	[143]
SAM, SEM, dynamometer	CNC machining center	Drilling	CFRP	To evaluate the performance of diamond-coated tools on the machining properties of CFRP composites.	[144]

Usca et al. [145] investigated the influence of the addition of particles on the consumption of energy in the milling of the ceramic-based (CuBCrC) composites and the main results of their comparative study are presented in Figure 11. Higher cutting speed and feed rate improve the consumption of energy that increases particularly for 10–15 wt.% reinforced materials considering the extreme material removing rate however reinforcement of 5 wt.% was established to be the best resolution for minimal consumption of energy for this application.

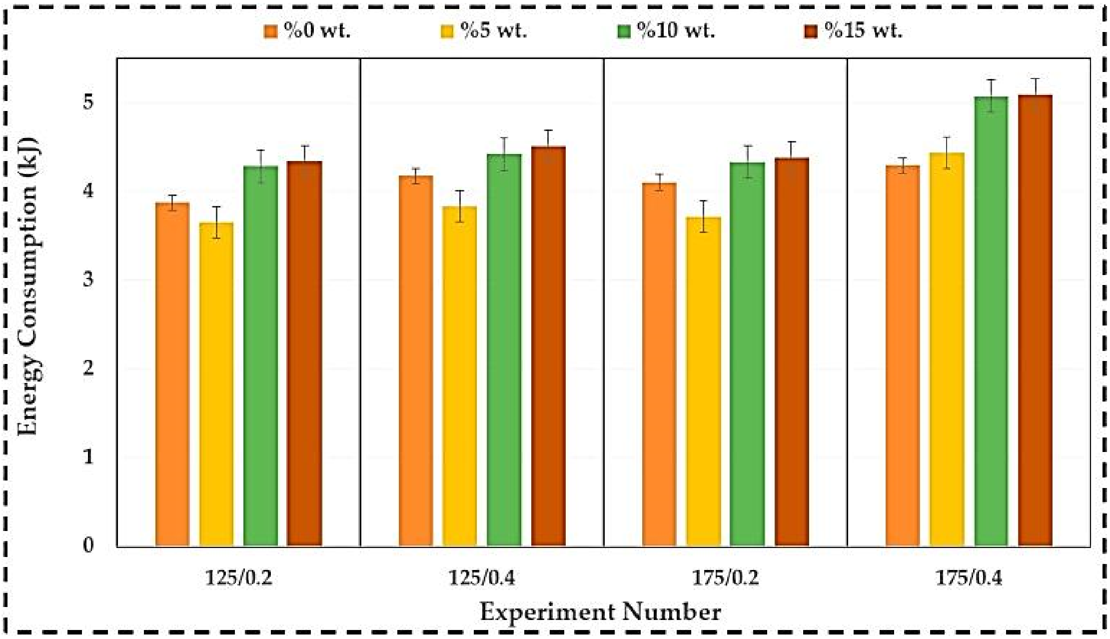


Figure 11. Comparison of reinforcement ratio on energy consumption [145].

Furthermore, the influence of machining parameters (cutting speed and feed rate) on the consumption of energy is depicted using 3D illustrations as shown in Figure 12. According to this, an augmented tendency can be observed for the consumption of energy with the rise of machining parameters.

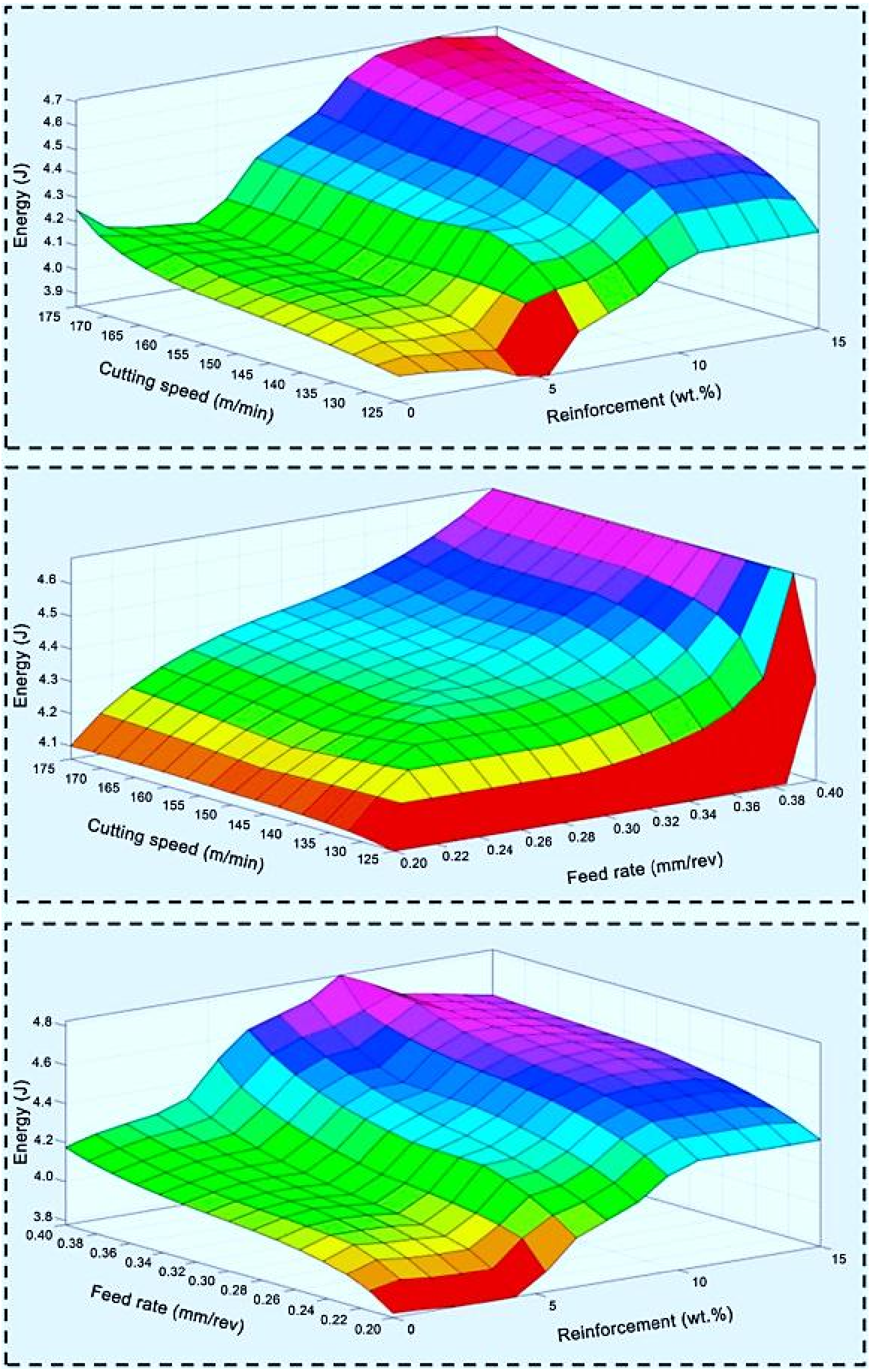


Figure 12. Influence of machining parameters on consumption of energy [145].

Navneet Khanna et al. [96] studied energy consumption during the turning operation of Inconel-718 considering different MRRs for dry, wet and cryogenic configurations and their results are shown in Figure 13. It is evident that the consumption of energy decreases with an increase in MRRs for all three configurations of turning owing to saving in time of machining. For the case of wet configuration, the consumption of energy is highest due to the requirement of more energy for running of the coolant system. In the comparison of the dry and cryogenic configurations, the consumption of energy is higher for the lower intensity of MRRs (11.25–30 mm^3/s) by reason of rise in the hardness and strength of work in the case of cryogenic configuration. Consumption of energy in the case of cryogenic was observed by 27% lesser in comparison with wet configuration. This demonstrates that lesser consumption of energy in the case of cryogenic configuration encourages sustainability in manufacturing.

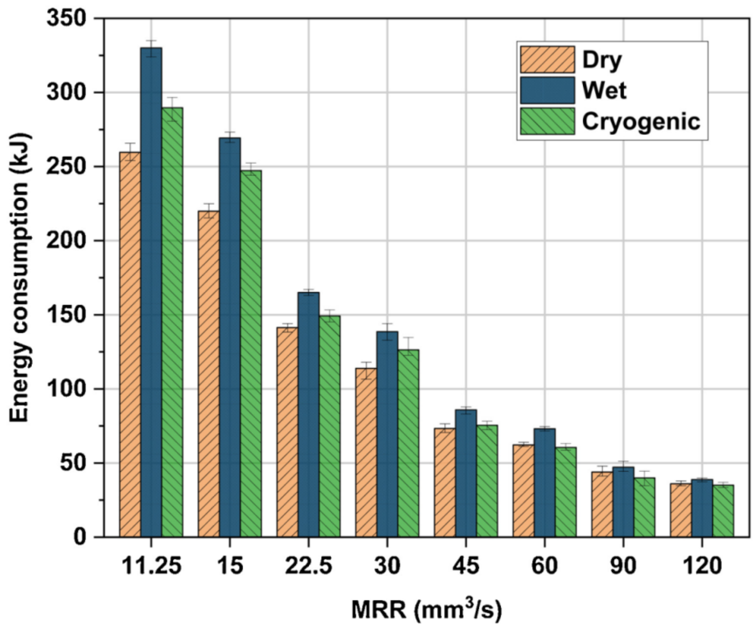


Figure 13. Effect of variation in MRR on energy consumption in turning of Inconel-718 [96].

Asmatulu et al. [146] summarized the energy utilization necessary for the grinding process for various kinds of composites in which FRP sandwich requires utmost power during machining and GMRT requires the lowest power as shown in Figure 14. In total, 400 MJ is essential for producing 1000 g of virgin CF, out of which 200 MJ/kg arises from electric power and the left-over is for the consumption of oil.

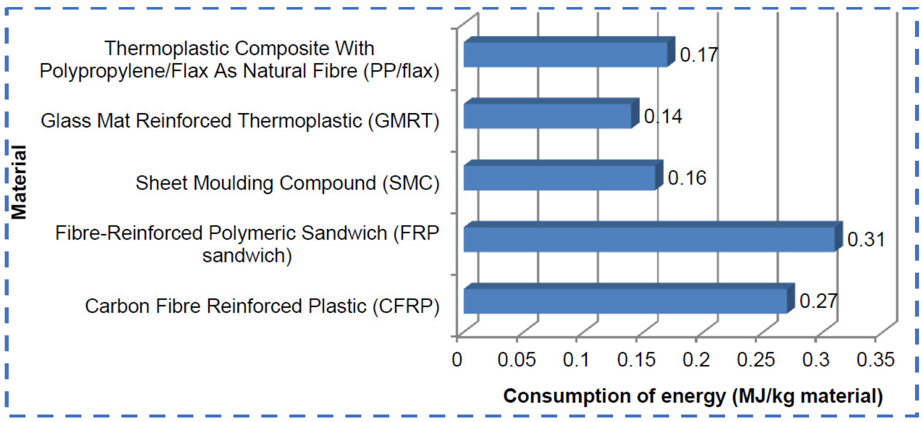
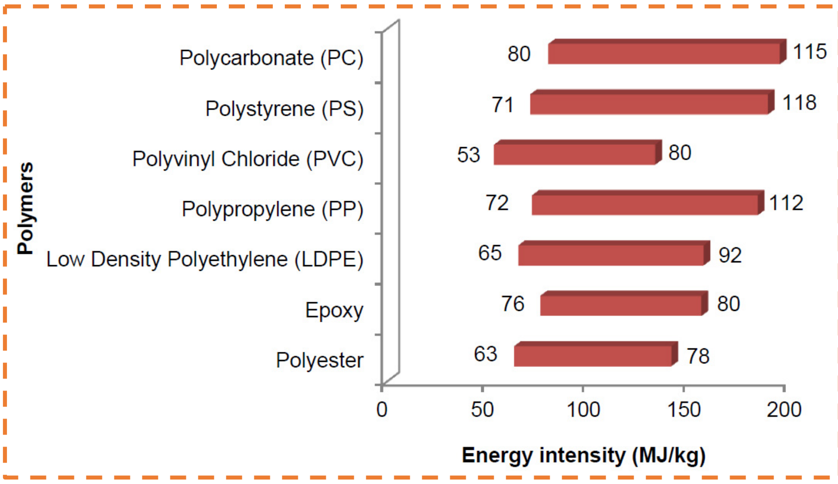


Figure 14. Consumption of energy in grinding of composites [146].

Song et al. [147] listed different constituents used for the development of composites and their energy contents as depicted in Figure 15. Amongst the family of polymers, thermosetting plastic includes epoxy resins and polyester which is the main constituent in the development of fiber-reinforced-based composites which owe lower energy contents. Glass fibers have a broad range of production energy contents. Natural fibers require 45% less energy; however, they cause greater water emissions because of the application of fertilizers in the agricultural domain. Carbon fiber which is a classic reinforcing constituent in poly-based composites has a higher energy intensity among the remaining fibers; however, it involves high economics and thus, it limits its widespread use despite exceptional mechanical and physical behavior.



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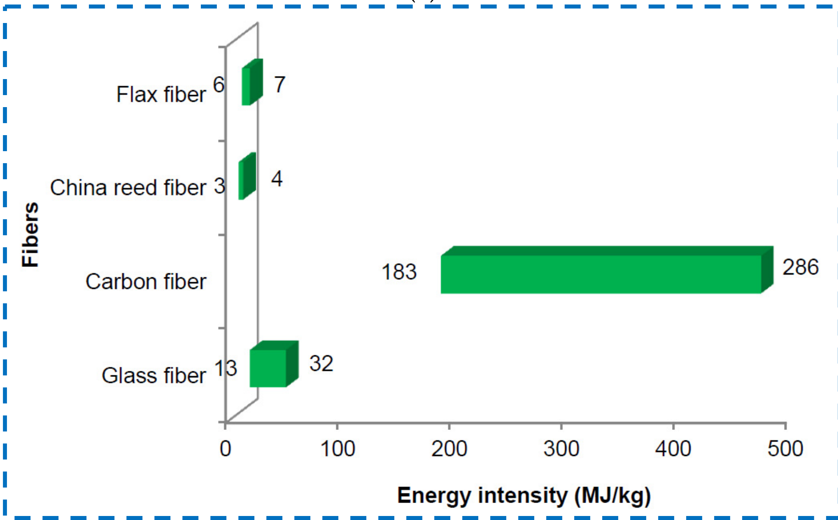
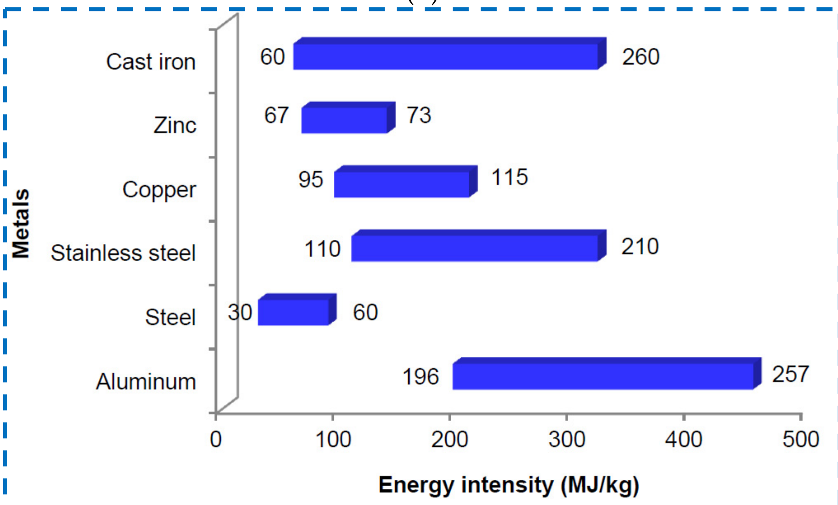


(**b**)



(**c**)

Figure 15. Energy intensity of various constituents used in development of composites [147]. (**a**) Polymers; (**b**) Fibers; (**c**) Metals.

Further, Song et al. [147] listed various composite manufacturing techniques and corresponding energy intensity representing power related to machining as shown in

Figure 16. Although fiber-reinforced composite material has been shown to be competent towards automotive components in some of the previous years, the deployment is yet to be undertaken on a mass scale because of a number of disadvantages such as major costs, rates of automation, and lower production. As composites are combinations of different materials, their machining methods are reasonably different, and thus, require substantial energy conversion. For example, once polymer matrices and reinforcing fibers are prepared, additional processing is often required, such as the manufacturing of textiles and the preparation of prepreg before its integration with polymer resins and fibers. Such processing also requires additional power, even if less energy is consumed in processing in the primary phase. Further, the use of additives and solvents consumes some part of the energy. Overall, a noteworthy volume of power is employed to deliver the pressure and heat essential for curing. It can be observed from Figure 16 that partially automated methods, such as the pultrusion and filament winding, require lesser energy. On the other hand, fully automated methods such as performing matched die, SMC molding and filament winding, require higher energy.

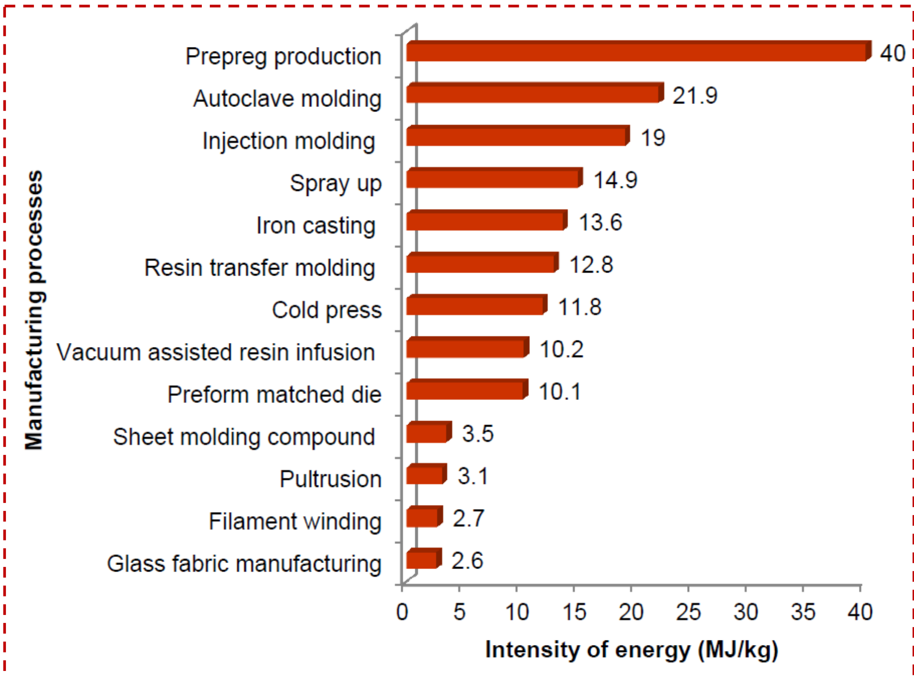


Figure 16. Energy intensity of composite manufacturing techniques [147].

Machine tools convert electrical energy into mechanical energy, allowing the cutting tool to remove chips from the workpiece material and give it the desired shape. For this reason, low energy efficiency and maximum work efficiency are desired in machining processes. In machining operations, the improper selection of machining parameters seriously affects energy loss. In order to reduce energy consumption in machining, first of all, the effect of machining parameters on energy consumption should be examined. As a result of the research literature, processing parameters for energy consumption were optimized and experimental data were compared. According to the literature, energy efficiency can be achieved by optimizing the processing parameters and conditions. Statistical approaches are generally used in optimization processes. The operating conditions were carried out in both dry and cutting fluid environments. By optimizing the machining parameters, the energy consumed in machining operations can be reduced and energy conservation can be achieved. Tool stresses can be eliminated by chip removal in coolant conditions, and energy consumption can be kept to a minimum. In addition, it is possible to increase the efficiency of the energy consumed by optimizing the chip removal processes by increasing the feed rate appropriately and reducing the cutting speed appropriately in both dry and cutting fluid cutting conditions.

The Office of Energy Efficiency and Renewable Energy (EERE) presented the estimation of two 'hypothetical opportunity bandwidths' for the saving of energy. First is the current prospect and second is the research and development prospect. In the first one, it proposes that yearly energy savings of 1.21 TBtu would be possible if all-inclusive practices and technologies are installed [148]. Secondly, additional yearly energy savings of 3.43 TBtu would be achieved if the research and development techniques are effectively set up universally, as shown in Figure 17. These two opportunity bandwidths are illustrated with the help of Figure 17 where the practical and impractical area is also clearly highlighted. Talking particularly about saving energy consumption in the processing of CFRP composites, there exists the requirement for the advancement carbonization/oxidation apparatus and methods. Other factors such as minor alterations in the fraction of fiber considerably modify the intensity of energy in the material owing to energy-intensive manufacturing. Vigilant consideration of application-specific element design is desirable for understanding the supplementary potential energy savings prospects.

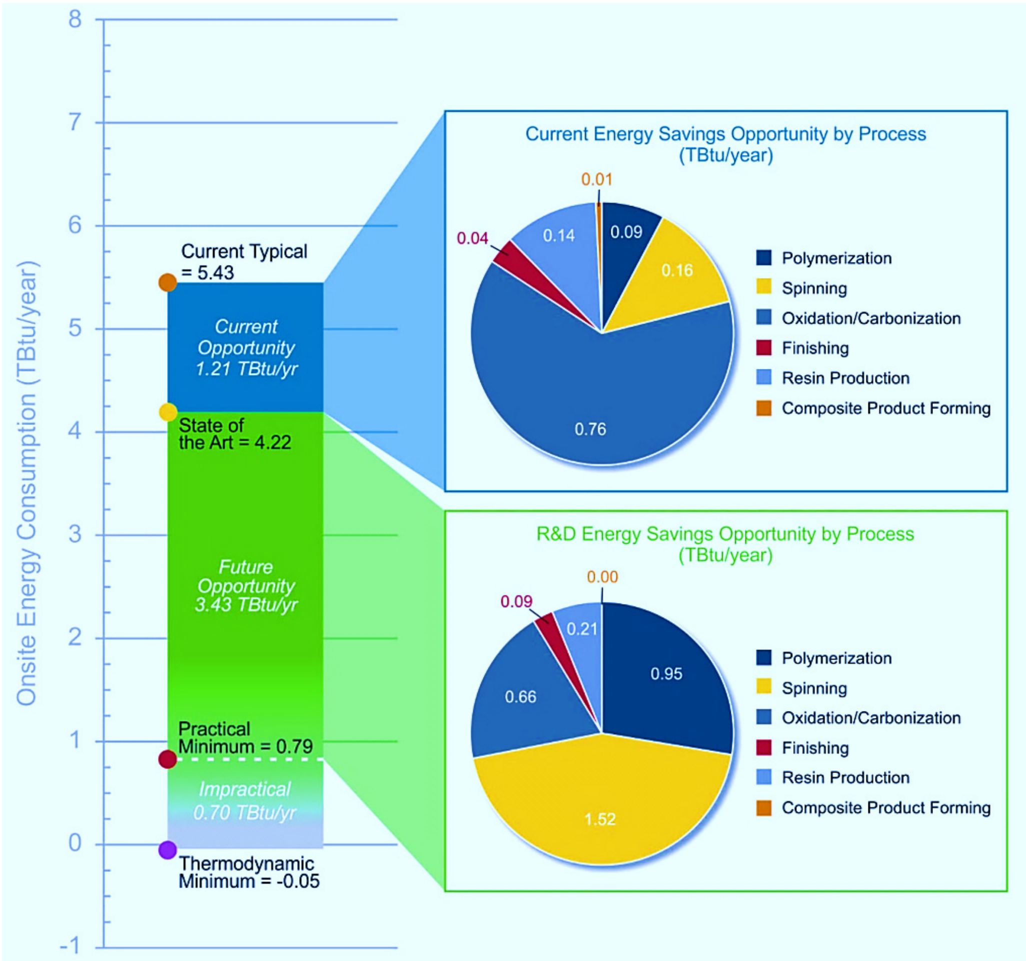


Figure 17. Opportunities for energy savings in manufacturing of CFRP composite [redrawn from reference [149]].

4. Discussion

This comprehensive review study aims to have a discussion on the energy consumption of some specific material groups, i.e., superalloys and composites during various machining operations. The main motivation here is to investigate the feasibility of reducing the cutting energy through machining these materials. The secondary thing is the broad application of superalloys and composites in prominent sectors such as aerospace, medical, medicine, bioengineering, aviation, etc. Therefore, these two special types of industrial materials are abundantly welcome, mostly thanks to their extraordinary mechanical and physical properties even in the harshest environmental conditions. Despite these positive sides during run-time, the pre-process until manufacturing the ultimate product can be highly challenging due to poor machinability. As a consequence, machinability improvements of industrially important materials are of great importance in the present situation of today's rival engineering world. However, a wide range of published studies have been conducted on other machining parameters rather than energy aspects and most of them deal with the conventional machining of traditional material systems. Figure 18 shows the percentage range of energy measurements between superalloys and composite in terms of their main material types according to examined studies in this review paper. The examined articles regarding energy saving on the superalloys and composites in this review paper are nearly ignorable compared to the cutting of other material systems in the open literature. Moreover, one of the primary goals of metal-cutting companies, such as material groups, is to make the manufacturing procedure cost-effective and fertile. Considering that these initiatives have great potential in consuming natural resources for high energies, it would be reasonable to analyze the amount of energy depletion. Such an approach will be directly influential on the environmental impacts such as carbon emission rate and usage of sustainable energy resources. From this point of view, this review paper is confined to the papers entitled the optimization and reduction approaches in energy consumption of superalloys and composites.

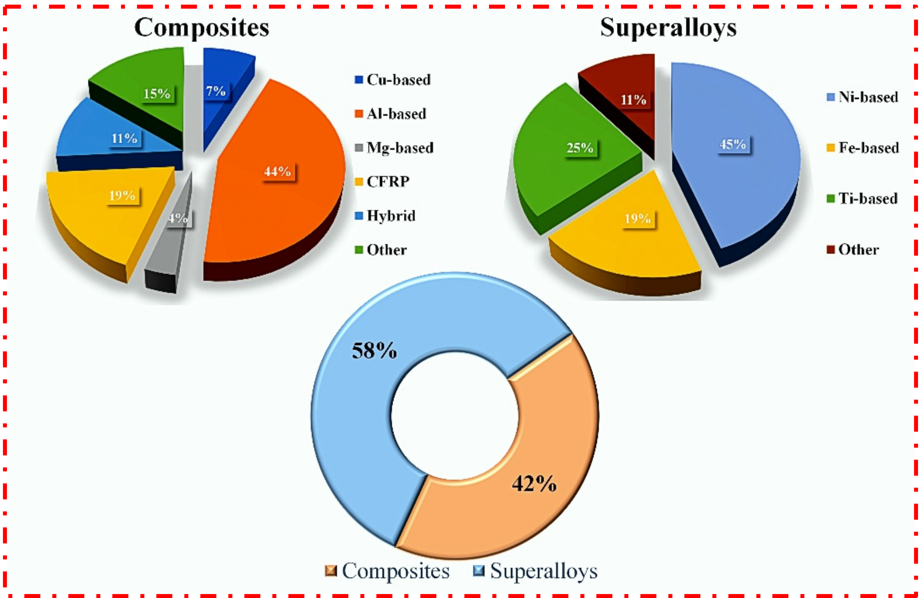


Figure 18. The percentage range of energy measurements between superalloys and composite machining according to their main material type.

The energy consumption in the machining operations is chiefly divided into two parts. The first one is the required energy for elastoplastic deformation of machined material. The second one is the energy overcoming the friction forces of the material pairs (tool and workpiece) interface [150]. According to the equation [151], the cutting energy is mainly the function of cutting power and material removal rate. In addition, these parameters depend on other machining variables such as cutting force, feed rate, moment, angular velocity, spindle speed, depth and width of cut [152]. Moreover, grain sizes, different phase types, carbide developments and their fraction and distribution behavior in the superalloys structure show a discernible impact on the strength/hardness and structure [153]. As for composites, the mechanical performance of these groups is mainly influenced by several concurrent factors: the strength of the matrix and reinforcement element, wettability, distribution and demolition of reinforcement phases and concomitant structural integrity [154]. Above we have mentioned all of the alterations, along with different cooling–lubricating or traditional cutting strategies that exhibit an appreciable influence on machined material's integrity, microstructural changes and mechanical and tribological aspects. However, available published studies in the current literature about the differences in energy consumption between superalloys and composites are very limited. Yu et al. [143] declared that the required cutting energy is generally larger than that of the metals or traditional metal alloys due to the fact that the existence of hard reinforcement phases in the matrix makes the composites hard-to-cut material, resulting in an increment of cutting force. In another notable study, Ji et al. [123] reported that almost the half of cutting energy of CFRP/Ti6Al4V composites during drilling at constant machining parameters is consumed by the CFRP phase. They also announced that as the feed rate is elevated, the specific cutting energy is increased due to easier congestion of the Ti chips, resulting in an increment in drilling torque and resultant cutting energy consumption. Such observations are ascribed to the diverse chip removal mechanisms and physical/mechanical aspects of the two different stacked material properties. Moreover, they observed that the cutting energy consumption is remarkably decreased when the application of MQL methods since the reduced frictional forces at interfaces of workpiece/tool materials act as a hole wall.

When looking at the literature papers, turning, milling and drilling are the popular approaches during the investigation of the energy consumption of composite materials. This is understandable considering the irregular constructions of the composites which make the steady cutting [122,127]. However, superalloys are preferred as the workpiece material in non-conventional manufacturing processes such as EDM and micro-machining [75,80]. It is highly important to adapt these materials for the production of small parts, which can be especially useful for the dentistry and medical sectors. After determining the usage of the energy consumption data in machining operations, it is important to decide how to collect this information or measure the required energy. Seemingly, literature studies prefer to use several approaches in such goals: (i) using a power meter or power analyzer [76,87], (ii) calculation by the equations which mainly depend on the cutting forces and current [80,130]. It is noteworthy to mention that open literature papers prefer to use multiple sensors in cutting both composites and superalloys. This situation comes from the fact that such materials cause excessive tool wear patterns in short cutting times. Therefore, high cutting forces, chatter vibrations and low surface qualities with high roughness and distorted topographies reveal almost all machining operations. Studies dealing with the energy consumption of these materials are also interested in these variations, which require other types of sensors such as dynamometers, accelerometers, rough meters, thermocouples, perthometers, etc. [88,128]. According to the notes of the scientists in the field, parametric optimization for several cutting operations such as turning, milling and drilling are extremely important [136,142]. Since the basic cutting parameters such as cutting depth, feed and cutting speed plays the key role in total cutting time, cutting forces and, naturally, the current drawn, they determine the required cutting energy. Moreover, analyses of the coefficient of friction effect during the machining of the composites and superalloys are of great significance since their machinability requires high cutting forces [132]. To overcome this problem and make the cutting performance better, sustainable cutting environments were adopted for machine tools in the past many times [145]. Such strategies can be regarded as the key factors in reducing the frictional forces and make easier the chip evacuation from the surface. Therefore, energy consumption can be minimized when compared with dry mediums.

On the basis of the above discourses, it can be clearly said that the phenomenon behind the energy consumption of superalloys or composites during machining is a very dynamic and complex issue; hence, these circumstances should be thoroughly analyzed by researchers. It is also inevitable that industries now and in the near-future need to take responsibility for saving resources and supervising the environmental results of machining processes. In this concept, maximum attention will be needed for the minimization of the outcomes for achieving a better sustainability index. For this purpose, this study is expected to be a cornerstone as it includes an important aspect of the machining industries by highlighting a significant machinability parameter namely energy consumption for industrially important materials.

5. Conclusions

Saving energy is an important topic especially today due to the fast-growing amount of consumption of natural resources of the world. Machining operations cover a large part of the consumed energy in the industry, which makes them a valuable and potential option in reducing total energy loss. Optimizing energy consumption directly or indirectly regulates the total manufacturing costs and environmental impacts, such as the carbon footprint. On the other hand, there is a relationship between total machining time and energy consumed which also create an opportunity to minimize both for achieving successful results. Therefore, all factors affecting energy consumption should be considered in machining operations to succeed in sustainable and technological tasks. This paper handles some of the industrially important material groups to evaluate their influence on the energy consumed during several machining tasks. The important outcomes of the current review study regarding energy aspects in the machining of superalloys and composites are listed below:

1. There are over one hundred published papers in the last five years in open literature regarding energy optimization and reduction during machining of the superalloys and composite materials. Compared with the numerous papers in the field, such numbers show that this part of the machining studies still needs more research.
2. The measurement of the energy consumption on the machine tools is an easy task considering the diversity of the sensor systems that are capable to determine the amount of the depleted energy. Such tasks can be fulfilled by the cutting force, current, power and energy measurement sensors.
3. Seemingly, superalloys have gained popularity in the last five years, which is understandable when thinking about their place in prominent sectors such as energy, space and automotive. In this direction, most of this research paper is about the energy optimizations of the superalloys. As for composites, limited studies, of which more than half of them are about Al-based and CFRP composites, have been encountered. The main reason for this situation can be deduced from that the energy aspects of composite cutting operations depend on various process and structure-induced variables and different behavior of matrix and reinforcement phases. Such observations pave the way for diverse researchers to fill the blind spots in the current literature studies, which makes the present review study more innovative.
4. Drilling, milling and turning are the most encountered machine tools for calculating energy consumption, which is logical since these operations are widely applied in the world. However, a handful of research has been performed on the effect of different cooling/lubricating strategies on energy saving, which has proven itself in increasing energy efficiency and reducing costs.
5. Composites are considered a workpiece material when looking at energy-based machining studies; however, it should be noted that their number is highly low compared with different types of materials. In this direction, it is recommended that future projects about machinability studies should be directed into composite materials. One of the reasons is that composites are powerful materials that gather the several material properties needed to meet the physical and constructional expectations.
6. This study is expected to make a contribution to the literature in the field of the machining industry for the ones who work on superalloys and composites.

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Nomenclature

SEM	Scanning Electron Microscope
EDM	Electric Discharge Machining
CNC	Computer Numerical Control
EDS	Energy dispersive spectrometer
EDX	Energy dispersive X-ray
MMC	Metal matrix composite
CFRP	Carbon fiber reinforced polymer
SCE	Specific cutting energy
SAM	Scanning acoustic microscope
MRR	Material removal rate

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