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PAPER

State of the art review on the sustainable dry machining of advanced materials for multifaceted engineering applications: progressive advancements and directions for future prospects

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Keywords: dry machining, milling, drilling, inconel, steel, titanium, sustainable-machining

Abstract

In this article, the comprehensive review on the application, and indeed, a comparative analysis on dry machining of different types of materials (Inconel, steel, aluminum, cast iron, magnesium and advanced materials) used in machining (turning, drilling and milling operations) were carried out in the light of utmost works published in the literature. The work describes the scientific findings of the past twenty years, including sustainable methods (surface texture, solid lubricants, vibration-assisted machining, laser-assisted machining), tool coatings, and geometry of tools. Vibration-assisted machining is another direction that researchers have investigated without the use of cutting coolants, where the complete disposal of coolants is not possible. Various researchers have carried out rigorous experimental work on milling, drilling, and turning operations under dry conditions to machine numerous materials. A significant proportion of experimental data about tool wear, tool wear machining, surface quality, surface integrity, etc, has been analyzed under dry conditions. However, the critical analysis of dry machining for different conventional machining operations for a variety of industrial materials is still lacking for establishing dry machining as a sustainable process for industrial applications. Thus, the critical analysis of various machining parameters and their consequences on tool wear and the surface quality of machined work was carried out in this work. Finally, scientific recommendations based on critical findings were proposed for industrial implementation of dry machining.

Abbreviations

MQL	Minimum quantity lubrication
PCD	Polycrystalline diamond
CBN	Cubic boron nitride

NDM	Near dry machining
CTR	Chip thickness ratio
BUE	Built up edge
BUL	Built up layer
WCCT	Wiper coated carbide tool
SGCC	Straight grade cemented carbide
TiAlN	Titanium aluminium nitride
CrTiAlN	Chromium titanium aluminium nitride
CrN	Chromium nitride
TiCN	Titanium carbonitride
TiAlSiN	Titanium aluminium silicon nitride
MQCL	Minimum quantity cooling lubrication
SEM	Scanning electron microscopy
NCD	Nanocrystalline diamond
MCD	Microcrystalline diamond
RHVT	Ranque-Hilsch vortex tube
EDS	Energy dispersive x-ray spectroscopy
ADI	Austempered ductile iron
CVD	Chemical vapor deposition
SCEA	Side cutting edge angle
MOS_2	Molybdenum disulphide
DSS	Duplex stainless steel
WC-Co	Tungsten carbide-cobalt
MQCL	Minimum quantity coolant lubrication
HSM	High speed machining
GRC	Grey relational coefficient
GRG	Grey relational grade
SS	Stainless steel
PVD	Physical vapor deposition
ANN	Artificial neural network

1. Introduction

The use of cutting coolants in machining operations raises the cost of machining and degrades environmental quality. [1]. Most industries apply cutting liquids/coolants when their use isn't vital. The ultimate goal is to eliminate the use of cutting coolants. The pros of green machining include: non pollute of the air, no harmful to skin, and is allergy free. Dry machining is beneficial to the environment, and industries enforce environmental security laws for health regulations and occupational safety. Dry machining requires the use of high coated tools that can endure high temperatures and of extreme hard material like cubic boron nitride & diamond.

Few reviews have been accounted for on dry machining of advanced materials and sustainable methods so comprehensive review is necessary to bridge gap between the development of dry machining of different materials using coated tools, geometry of tool and sustainable methods. This can provide guidance to researchers who are in search of latest updates about dry machining of different materials and industrial practitioners can gain valuable information too. The scope of review article is shown in figure 1.

2. Lubrication/cooling systems

The use of cutting coolants has drawbacks that necessitate the use of other alternative cooling/lubrication techniques to ensure safety of workers. Cryogenic machining, MQL, wet machining, dry machining, and gaseous machining are the most common cooling/lubricating conditions. Various forms of cutting fluid as

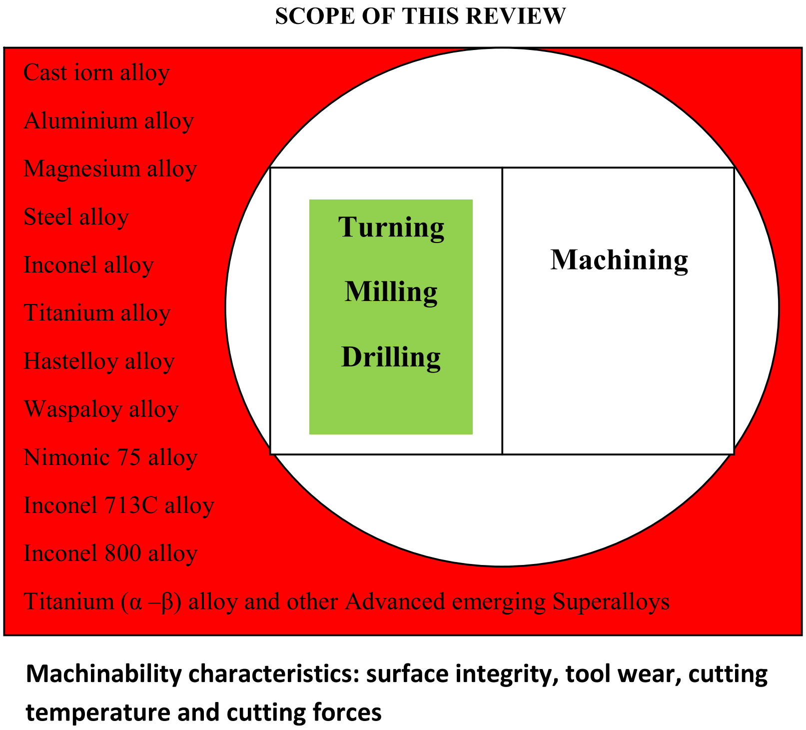

Figure 1. Scope of review article on dry machining of different materials.

Table 1. Characteristics of cooling/lubrication systems [2, 3].

Cooling/Lubrication method	Cutting fluid/Coolant	Flow rate
Dry	Without	N/A
Conventional cooling	Mineral, semi-synthetic, and synthetic based lubricants	0.5–10 l min^{-1}
MQL	Mineral, semi-synthetic, synthetic, and vegetable based lubricants	10–500 ml hr^{-1}
Cryogenic cooling	CO_2 and LN_2	0.3–4 Kg min^{-1}
High Pressure cooling	Mineral, semi-synthetic, and synthetic based lubricants	10–100 L min^{-1}

cryogenic fluid, soluble oil, vegetable oil is supplied into the cutting zone and their flow rate values in range are shown in table 1 [2, 3]. Option of cooling/lubrication systems is illustrated in figure 2.

2.1. Dry machining

Dry machining has been used widely in recent years due to environment regulations, for safety of workers and also saves price related with cutting of fluid. The technique dry machining is highly appealing due to economical and ecological problems. The employ of cutting coolants is eliminated in dry machining. Though coolant is essential to decrease heat generation, enhance tool life, better dimensional tolerance but also increase overhead costs connected with cutting fluid [4]. Investigations showed handling of cutting fluids in many operations higher than tool costs [5]. Dry system requires adequate knowledge and development of tools and materials technology, opening innovative application possibilities. For clean manufacturing and sustainability, dry machining is very useful [6].

2.1.1. Dry machining features

Compact machine structure, requires less floor space.

Chips are simple to recycle and handle, non- polluting and are clean.

Streamlining the production system and reducing production prices by eliminating fluid transport, recovery, filtration and other equipments associates with it.

No environmental pollution.

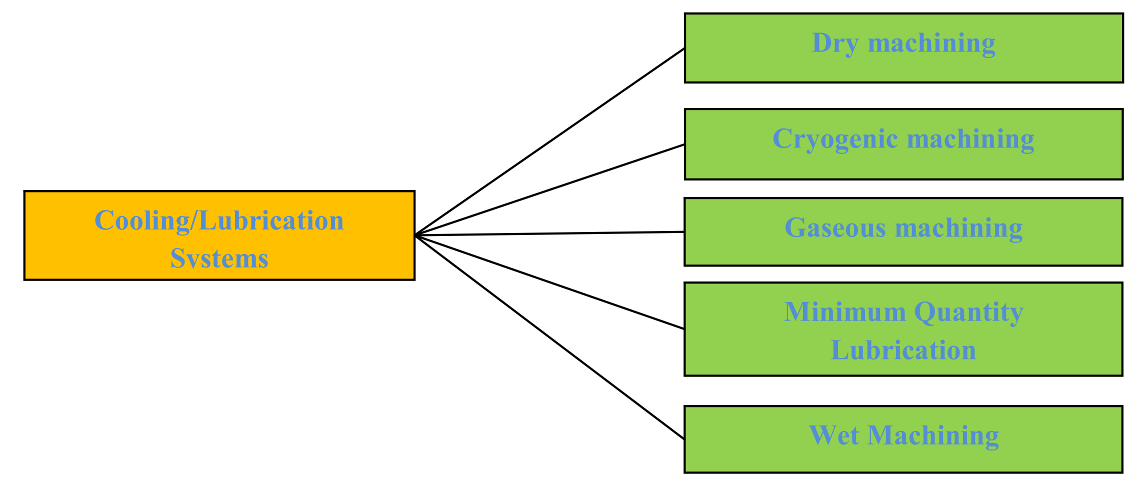

Figure 2. Choice of cooling/lubricants systems.

2.1.2. Selection of cutting tool for implementation of dry machining

2.1.2.1. Dry machining tool technology

The tool ought to have high wear resistance and temperature hardness.

Reduce of coefficient of friction among the spindle and the chip.

2.1.2.2. Tool materials

For dry machining tool materials should have high red hardness, thermal toughness, good resistance to wear and thermal shock. The spindle materials for green machining mainly are:

1. PCD
2. Ultra- fine cemented carbide
3. CBN

2.1.2.3. Coating technology

For an adequate tool life coating is essential. Coated tools can be classified in to two types: hard coated tools and soft coated (self lubricating) tools. Following are the hard coated tools used in machining:

1. Aluminium oxide (Al_2O_3),
2. Titanium carbide (TiC),
3. Titanium nitride (TiN) and other coated tools.

Coated tools (TiN and TiC) have strong resistance to flank wear and crater wear respectively. For dry cast iron castings CBN tool is recommended but after the application of coating can be used to process hard super alloys and aluminium.

2.1.2.4. Tool geometry design

While dry machining, owing to increment in temperature between the tool and chip contact area crater wear occurs in the absence of cutting fluid. Tool geometry has great impact on tool as rake angle, side cutting edge angle (SCEA). For implementing dry machining successfully solutions and strategies is shown in figure 3.

2.2. MQL/Near dry machining

MQL conjointly called NDM is a good option to replace traditional cooling. In MQL process, high pressurized air in combination with oil spayed on cutting zone with help of nozzle. Air helps in evacuation of chips and oil supplies lubrication/cooling. Employ of MQL system due to unique characteristics is an alternate technique to wet machining. Dry cutting isn't continuously possible to materials that are sticky in nature as stainless steel, titanium and nickel- base alloys. MQL utilization brings reduction in cutting coolant which causes less

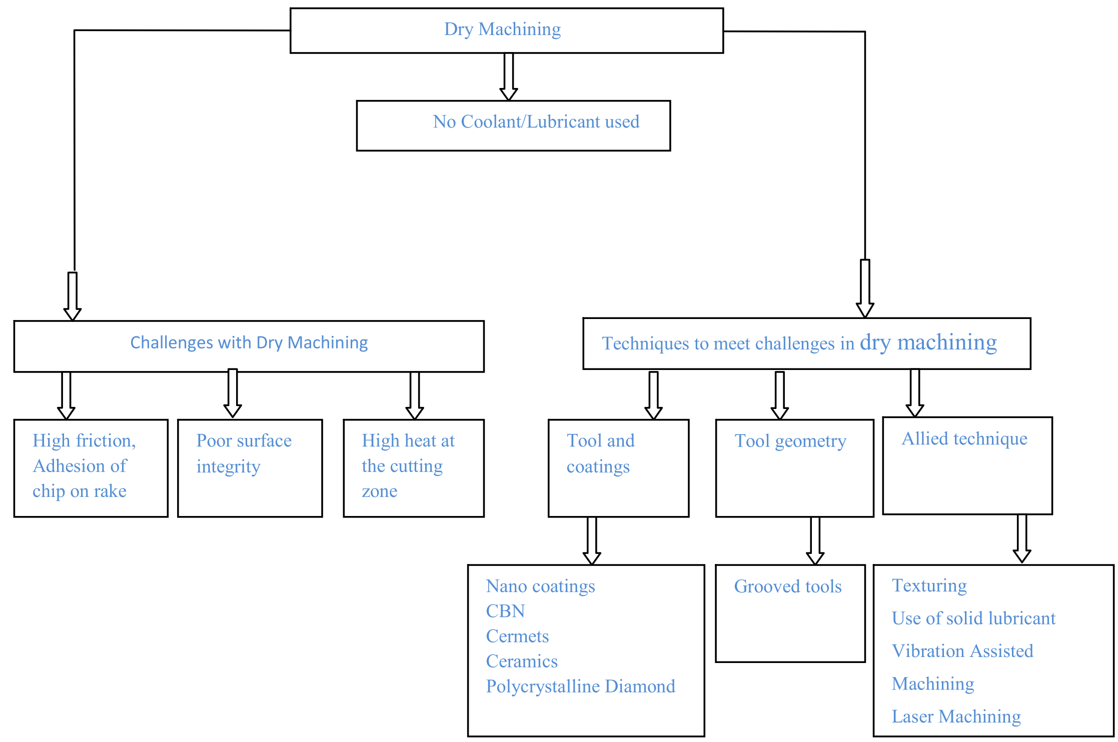

Figure 3. Strategies and solutions for successful dry machining.

environmental impact. MQL improves life of tool, enhance surface roughness than conventional/lubrication system [7–9].

2.3. Cryogenic machining

Cryogenics refers to the use of materials and precise study of same below −150 °C. The use of refrigerants frequently in Cryogenic system is helium, nitrogen or hydrogen. Cryogenic gases possess a huge form of applications in trade like medicine, electronics, and production for cooling functions. In cryogenics LN_2 commonly used and is a odorless, non-toxic, colourless and tasteless gas [10]. From the study and tests of machining [11, 12] the following benefits of cryogenic machining were determined like reducing cutting temperature, enhance surface integrity.

2.4. Gaseous machining

Gas-based coolants are the substances or mixtures that at room temperature are gas types, and are employed in the shape of more over liquefying fluids/cooling and gas compression in machining operations. The most common gas-based coolants are: argon, air, oxygen, nitrogen, and carbon dioxide. Gases additionally give inert atmosphere and lubrication. Air might be a resource and it's promptly accessible everyplace. The methodology which utilized chilled and compressed gas for cooling is tried by a few researchers in machining operations [13–15].

2.5. Wet machining

In wet machining the improved productivity and high material removal rate can be achieved. Wet machining is performed in the presence of cutting coolant. In wet machining rate of heat generation is low for same parameters and material, due to lubricating effect of cutting fluid. Wet machining is recommended in hard metals as steel, titanium etc Agrawal *et al* (2021) carried out machining of Ti-6Al-4V and analysed carbon emissions, power consumption, life of tool and surface roughness under different five cutting speeds. They reported that severe crater wear was observed during cutting speeds beneath wet condition than cryogenic conditions. A reduction in power consumption and surface roughness was observed up to 23.4% and 22.0% under cryogenic environment than wet environment at all cutting speeds [16]. High rate of material removal and reduction in surface roughness was noticed with increased cutting speed, feed rate and depth of cut under both wet and dry cutting environments in machining of LM 25aluminium alloy. [17].

3. Machinability

Machinability refers to the easiness a material can be machined to provide acceptable surface finish under a set of given conditions. Materials with excellent machinability can be cut easily, tool does not wear much, need little power to cut and easily obtain a good surface finish. The factors affecting machinability includes (tool material, tool geometry, selection of adequate tool, temperature of chip-tool interface), Machining parameters (feed, cutting speed, depth of cut, and lubrication), Work material parameters (chemical composition, hardness, microstructure, tensile strength shape & dimensions).

Common measures of machinability include:

i. Surface finish

ii. Tool life

iii. Power consumption

iv. Cutting forces

v. Chip control

vi. Machinability rating index

4. Dry turning experimental research

4.1. Cast iron alloy

Cast iron due to excellent machinability, castability, low melting point and good flowability has become an emerging material and has been widely used in automotive industry and machines. The additives nickel and molybdenum can be added to cast iron to improve machinability. Cast iron is an alloy of iron with carbon content ranges from 2%–4% with small amount of silicon and manganese.

Bhattacharyya and his team studied machining of cast iron under dry conditions by employing ceramic tools. Failure modes and reading of the tool life demonstrate that tool life was determined by surface roughness produced on the work piece, fracture and flank face wear. The better performance was observed with mixed ceramics-based tools than nitride and oxide-based ceramics [18]. In another study Sarma and Dixit (2007) executed machining of cast iron by employing ceramic tools. They deduced that cooling air did not benefit at low cutting speed of 100m min^{-1}. Cooled air provides greater surface finish than dry turning. Surface finish was not obtained in dry turning owing to swift tool wear. Air-cooled turning was found effective for reducing the cutting and feed forces. Air- cooled can be a promising environment friendly option. [19]. The silicon nitride (Si_3N_4) cutting tool with increase in speed shows better performance and these tools are appropriate for cutting grey cast iron due to low wear [20]. Textured tools did not benefit surface quality however slight improvement in surface quality was observed with MQL technique [21].

Ghani *et al* (2014) carried out tests of cast iron FCD700 under green machining. The favorable results of cast iron with green machining is possible by employing right type of cutting tool and recommended cutting conditions [22]. Rodzi *et al* (2010) executed machining of cast iron FCD700 under dry (green) machining conditions and deduced that chilled air in comparison with air and without air enhanced the tool life about 30% and 40% respectively. No catastrophic failure was seen under the SEM at low cutting speed and both crater and flank wears were observed. [23]. Polishsetty *et al* (2010) studied effects of machining austempered ductile iron (ADI) by employing ultra hard cutting tools. It has been observed that tool wear was more in roughening operation than the finishing machining operations. The SiC cutting tool was found worthy for both roughening and finishing machining operations. Machining of ADI employing tool TiC does not produce favorable machining results. [24]. Another sequence of experiments studied by employing ceramic tools under dry conditions for machining ADI. The silicon nitride (sialon) tool wear rapid except at low speed 150m min^{-1}. Al_2O_3: Sic fails to meet expectations than Al_2O_3 based tools as far as machining austempered iron. Al_2O_3 and Al_2O_3: TiC performed well in the given conditions. At speed of 150m min^{-1} the addition of TiC improved the life of tool [25].

4.2. Aluminium alloy

Aluminium is a lightweight, recyclable, flexible and easy to machine. BUE formation occurs while machining due to soft grade of aluminium. Poor surface finish results due to formation of BUE. High relief angles, high cutting speed and high rake angles are recommended to improve machinability. The additives copper, lead, bismuth can be added to improve machinability.

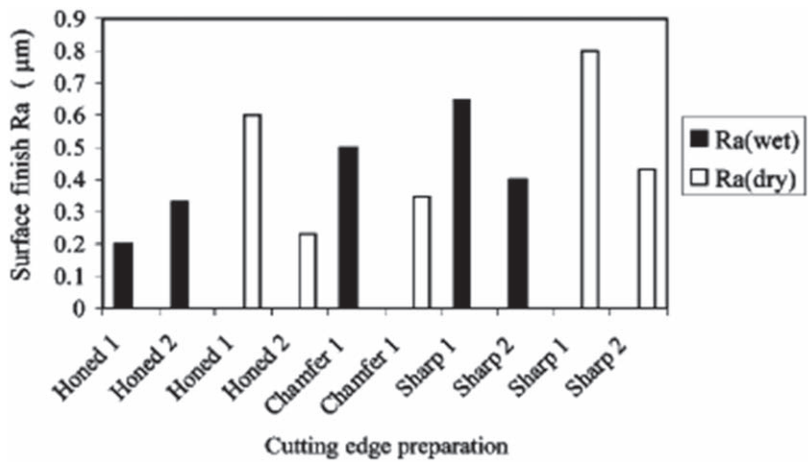

Figure 4. Effect on surface roughness owing to cutting edge [34].

Parra and his team investigated formation of BUE & BUL in turning Al-Si alloys under dry conditions. The outcomes showed that BUE and BUL created by mechanical adhesion and thermo-mechanical causes respectively. BUE is responsible for decrease in surface roughness [26]. A first time estimation to cutting time development of BUL and BUE phenomenon was done on the base of SEM—EDS analysis and noted BUL created by mechanical adhesion [27].

Chen *et al* (2013) assessed performance of Al-Si alloy under dry conditions. They concluded that microcrystalline diamond/nanocrystalline diamond (MCD/NCD) inserts shows low tool wear owing to the application of coating on inserts. Multilayer diamond film deposited on inserts extends the life time of the inserts as compared to uncoated inserts [28]. Bhatt *et al* (1995) performed machining of hypereutectic AI-Si alloy and deduced that CVD diamond coated inserts reduced tool wear, enhanced chip flow and surface finish as compared to unpolished inserts. The thickness of coating was about 20 μm. [29]. Polished CVD diamond inserts during machining enhance life of tool, minimize cutting forces and decrease formation of airborne particles causing health hazards on human in the work atmosphere. Polished CVD diamond coated insert contribute green factor by reducing airborne particles during machining [30]. Zakaria *et al* (2018) observed that crater wear was observed during wet conditions by using CVD coated tool. He recommended low (cutting speed, feed rate) to reduce surface irregularities [31].

Liu and Chou (2005) carried out turning of silicon-aluminium alloy (A390) by employing tungsten carbide. They concluded that vortex tube (VT) cooling efficiency relies on the machining conditions in relation with high spindle speed and low feed [32].

Khettabi *et al* (2007) studied formation of dust and chip in machining of 6061- T6 Al alloy,1018 and 4110 steels using carbide tools. Dust emissions occurrence during machining relies on tool geometry. The tool with a lead angle of 90° generates less dust emission than lead angle of 70° or 110°. It is recommended to avoid miniature lead angle that generates more dust emission during machining of 6061-T6 Al alloy. Ductile chips emit more dust than brittle chips. Dust emission can be minimized by employing lead angle (90°), by machining at high speed or by making chip brittle. The chip-micro band width and formation of micro-band with in chip is responsible for dust creation during machining [33].

4.3. Inconel alloy

Inconel alloys contain high nickel content and belong to a family of super alloys and use in extreme environments and finds applications in marine, aerospace and chemical processing industries and biomedical applications. Inconel's resistance to temperature and high strength poses a challenge to machine operators to machine it but also make idle option to use in extreme environments.

Arunachalam *et al* (2004) investigated that that geometry of tool, coolant, nose radius has major effect on and residual stresses and surface roughness. A reduction in surface roughness values observed with use of round insert as compared to square insert for both wet and dry conditions. A better surface finish was produced by honed cutting edges as compared to chamfered or sharp cutting edges as illustrated in figure 4. Increment in values of surface roughness was observed for sharp cutting edges may be due to too much chipping while cutting. The high values of surface roughness observed in chamfered cutting edge due to increase in cutting forces and unsteadiness whilst cutting. The trend obtained was similar for both dry and wet cutting. surface finish increase with both for wet and dry conditions with increase in nose radius. Positive rake inserts increased surface roughness values in dry cutting and decreased surface roughness values with use of coolant [34]. The impact of inserts was analyzed by Ezugwu *et al* (1995) in turning of superalloy nickel base alloy (718) and G-17 cast iron by employing ($AI_2O_3 + ZrO_2$) and ($A1_2O_3 + TiC$) ceramic tools. They concluded that round inserts as compared to rhomboid inserts provide better surface finish for both nickel base alloy (718) and G-17 cast iron [35]. The effect of C and T type inserts was investigated by Gandhi *et al* (2018) concerning surface roughness and chip thickness ratio. Insert T shape increment surface roughness with with elevated spindle speed from 371–835RPM. C shape inserts at each level of speed performs superior than T shape. With T shape insert large material removal rate was observed as compared with C insert at speed of 835RPM [36].

4.4. Magnesium alloy

Magnesium a light metal consists of magnesium, zinc, manganese, aluminium, copper, silver and ease to machine and provides a good surface finish. They find applications in automotive, aerospace, bicycles and other magnesium alloy applications. In terms of energy requirements magnesium and its alloys are most cost effective.

Rubio *et al* (2014) carried out intermittent turning of Mg pieces under environment friendly conditions (dry and MQL) to assess impact of feed rate. They concluded that the excellent surface quality can be obtained at low feed rates for both cutting conditions. They also identified that sources of surface roughness variability are mainly feed rate and type of interruption [37]. In recent study the influence of feed factor is studied by Viswanathan *et al* (2018) by employing Taguchi method to improve parameters in turning of Mg alloy, They concluded that feed rate is influential factor followed by cutting condition, depth of cut and cutting speed. [38].

The influence of coated tools and formation of flank build–up (FBU) was investigated by Tonshoff and Winkler (1997) in turning Mg alloy. Tools with PCD insert or coating can be used to decrease friction and adhesion within the tool workpiece. PCD tools can extend life of tool, also can help to reduce chip temperature cause for chip ignition in green cutting [39]. Tomac *et al* (1991) analysed formation of FBU in turning MgAlZn alloy. They concluded that FBU leads in in deterioration of surface finish at elevated cutting speed of 600m min^{-1}. The flank build-up cause machining issues associated with vibrations of the machine and product tolerances [40]. None of authors above explained the surface integrity. The factor surface integrity was explained by Wojtowicz *et al* (2013) in turning of wrought magnesium alloy and assessed impact of machining conditions on surface integrity. They deduced that nose feed, feed rate and nose radius relations have important consequences on surface roughness. At low or medium cutting speed round edge radius should be used to get better fatigue strength and low feed to restrict surface defects [41].

4.5. Steel alloy

Machinability is highly affected due to presence of carbon content in steel. The cutting tool is abraded due to presence of carbides. Low carbon steels also causes trouble while machining due to softness. BUE occurs and decreases the tool life in low carbon steels. Therefore, for best machinability medium carbon steels are preferred containing carbon content about 0.2%.

Ekinovic *et al* (2014) analyzed chip metallographically and SEM of alloyed steel. Machining tests were conducted by turning of 3 grades of piece of work material: alloyed steel, pure Al and aluminium bronze. Dry machining carried out in three different methods: machining without utilization of coolant and lubricant, cold air dry machining and with a cooling of piece of work before machining. Analysis of chips demonstrates some benefits of dry machining, primarily within the method of chips segmentation. Using dry machining technology, it's attainable to have an effect on the structure of the chips. In case of Al bronze for all 3 dry conditions, chips are segmented. In case of pure aluminium for all 3 dry conditions, chips are highly plastic deformed. In case of alloyed steel for all 3 dry conditions, chips are continuous. Cooled compressed air can be used for successful dry machining [42]. In a similar study chip mechanism formation was studied out by Mhamdi (2013) in turning AISI D2 (hardened steel) by employing uncoated mixed ceramic tool under dry conditions. The chip formation also depends on cutting speed as revealed by the authors but in case of hard turning it is not true [43]. In a recent study chip formation process and surface integrity is observed by Singh *et al* (2019) by employing (Y-ZTA) ceramic cutting insert. They reported that depth of cut has more impact in minimizing chip reduction coefficient (CRC). In addition, feed rate too along with depth of cut simultaneously influence CRC. Study of chip morphology indicates degree of chip segmentation decrease with elevated speed. i.e., small discontinuous chip support high speed machining. The maximum life of inserts was observed around 20 min of machining [44].

Vasumathy *et al* (2017) assessed the significance of micro textured tools under dry and wet conditions in turning of austenitic stainless steel. Textured tools reduced the avg. cutting force, feed force, friction force and normal force values by 4%–8% 5%–8%, 5%–8% and 4%–8% respectively than conventional tool insert as illustrated in figure 5. However, this is not true for all cases, while using tool IN2 (having grooves at an inclined angle to primary cutting edge) there is increase in frictional and feed force by 0.05 and 0.08% respectively than

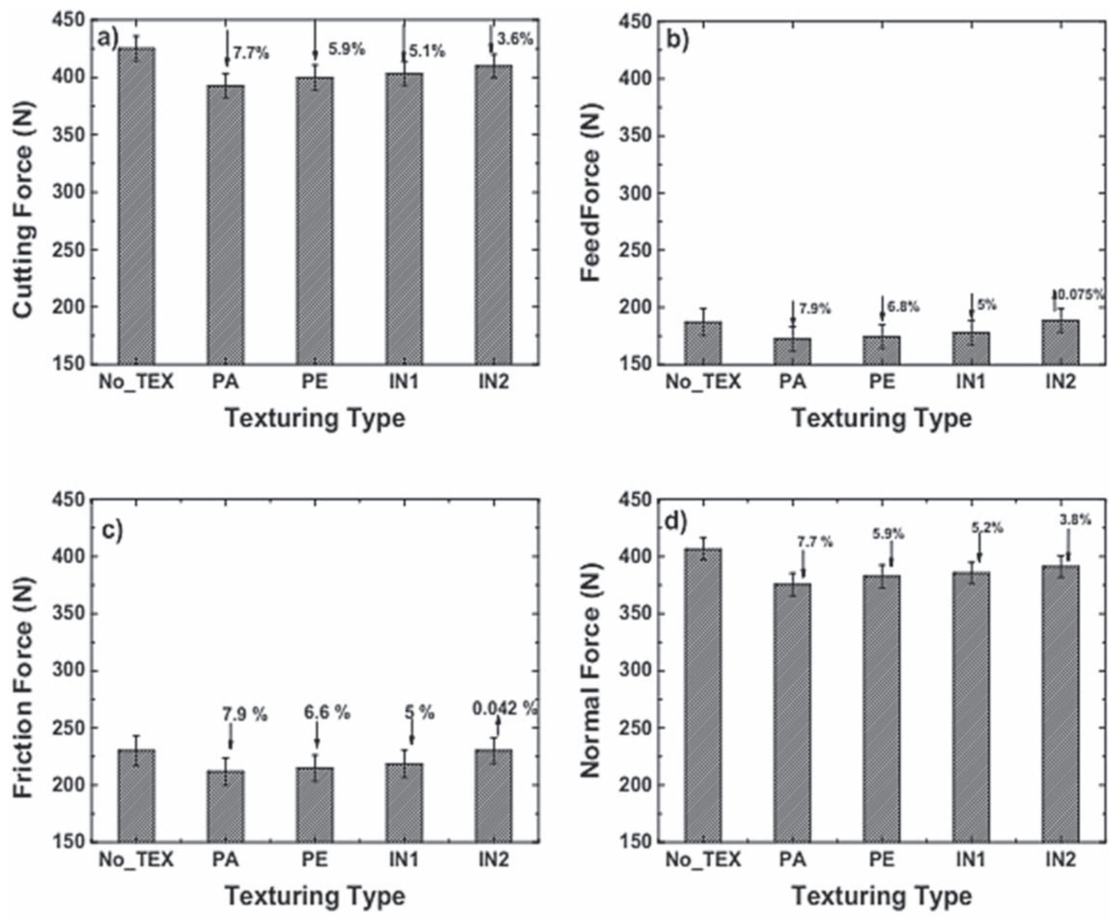

Figure 5. (a) Cutting force, (b) feed force (c) friction force and (d) normal force, forces obtained on dissimilar tools [45].

non textured (No_TEX) cutting insert [45]. In dry orthogonal cutting, surface texturing improved the life of tool and reduced flank wear. Surface quality was enhanced due to decrease in flank wear [46]. Textured tools can be adopted under industrial environment and even results of literature encourage the use of textured prepared through metallurgy in industrial applications.

Gupta *et al* (2015) carried out turning of AISI 140 carbon steel by using LN_2 coolant and dry machining. The results showed that cryogenic fluid reduced the tool wear and improved machining performance than dry machining. Overall tool wear reduction in LN_2 machining was 55.45%, surface roughness reduction 125.90% and force reduction from 61.94 to 96.60% [47].

The influence of LN_2 in machining steel was assessed by Paul *et al* (2001) under dry and soluble oil (wet flood condition). LN_2 (cryogenic cooling) provided better surface finish, enhanced life of tool, reduced tool wear as than dry and wet machining conditions. Maximum tool wear and surface roughness was observed in case of dry machining of steel and in wet machining no significant improvement was observed [48].

The performance of wiper ceramic inserts carried out by Gaitonde *et al* (2010) in turning hard AISI D2 steel through ANN modeling and compared with traditional inserts. They reported that at feed rate of 0.05 to 0.15 mm/rev conventional insert CC650 as compared to wiper inserts is more desirable. At feed rate below 0.09 mm/rev surface roughness is approximately more or less same for all 3 inserts. Feed rate after 0.09 mm/rev surface roughness sharply enhance for conventional insert CC650. Conventional insert CC650 is valuable for reducing cutting force than ceramic inserts regardless of feed rate. In terms of tool wear wiper insert GC6050WH is desirable [49].

He *et al* (2019) investigated TiAlCrN coated tools performance in machining of 20CrMo steel. They reported that TiAlCrN coated tools exhibits excellent surface finish than uncoated tools. The coated tool life about 45 min was observed which was two times that of uncoated tool. The TiAlCrN coated tool provides the better wear resistance [50]. SCEA's impact was not reported by any of the authors above. They remarked that at low cutting speed and feed rate by employing SCEA-5° long life of tool can be obtained for cutting tool KT 315 [51].

Sterle *et al* (2018) evaluated performance of solid lubricant MoS_2 under five cutting conditions as dry, MQL, flooding, combination of (MQL + cryogenic) and cryogenic conditions. They deduced that inclusion of MoS_2 decreased rate of coefficient of friction from 0.6 to 0.28 at high sliding speeds. MoS_2 was suspended in isopropyl

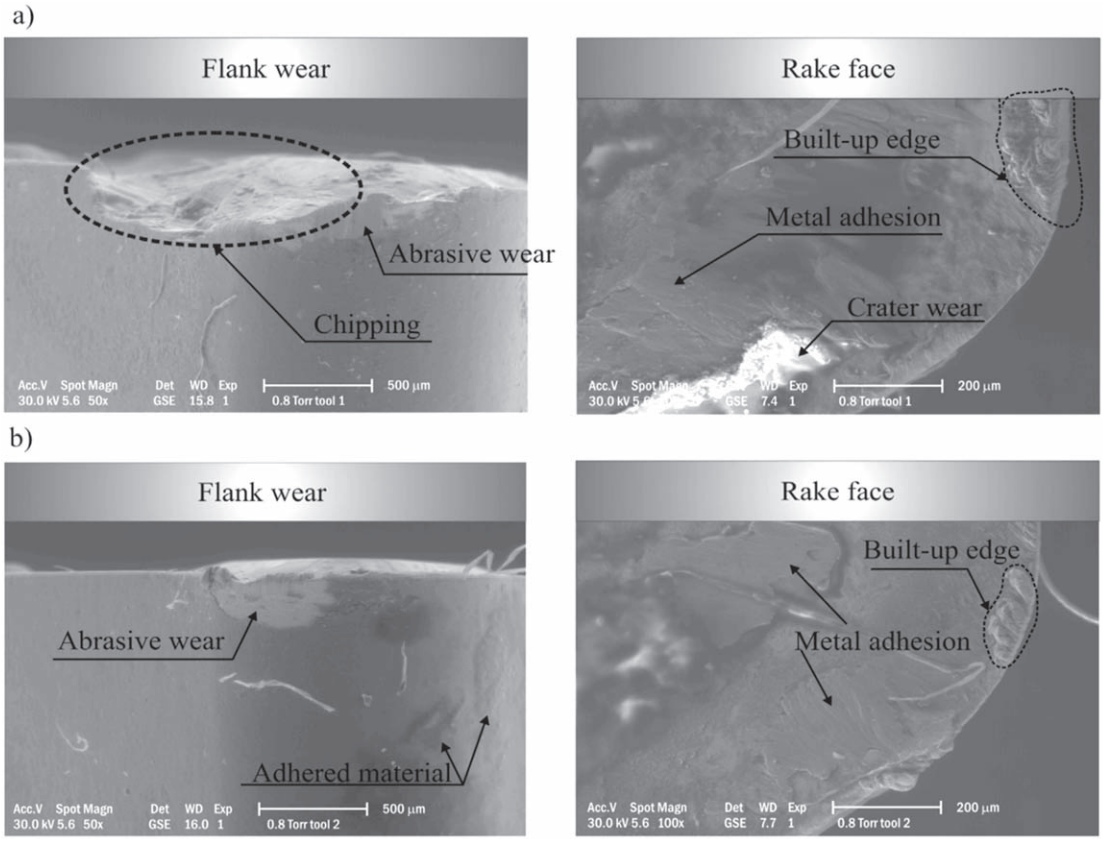

Figure 6. SEM images of tool (a) Dry cutting, (b) lubricating cutting [55].

alcohol (carrier medium) and it is still challenging to supply solid lubricant in to the cutting zone [52]. The solid lubricant MoS_2 reduced cutting forces, flank wear and coefficient of friction than conventional tools [53].

Krolczyk *et al* (2013) assessed surface roughness by developing model in machining of duplex stainless steel (DSS) under dry conditions. They deduced that surface roughness was observed increased with increment in feed rate under given cutting parameters [54]. Crater wear was observed under dry conditions on tool rake's face while for lubricating condition this was not observed. Adhered material was observed under lubricating conditions, while for dry cutting chipping on flank wear was noticed as shown in figure 6 reported by Krolczyk *et al* (2016) [55]. ANN is recommended to save time and cost in conducting experimental studies and model was purposed and gave reasonable results concerning temperature, tool life and wear [56]. In hard turning application of supply of coolant is effective in case of tool life and was not so effective in case of surface roughness as well as main cutting force [57].

4.6. Titanium alloy

Titanium is widely used in industries owing superb corrosion resistance, potential to resist high temperature, high tensile strength, light in weight and find applications in rockets, missiles, airplanes and where resistance to high temperature is important. Due to inherent material and mechanical properties titanium alloys possess poor machinability.

Jawaid *et al* (1999) machined Titanium alloy (Ti) with use of uncoated cemented carbide tool to assess wear characteristics under dry conditions. They reported that inserts with refine grain size have an extended tool life than a honed edge. For machining titanium alloy WC-Co are beneficial [58]. The successful use of WC-Co in turning titanium Ti alloy is investigated by Che-Haron *et al* (2011) under dry cutting conditions. The author concluded that at nose rake face wear was less than flank wear. The inserts with refine grain size increased the life of tool. For machining titanium alloy straight grade cemented carbides are beneficial [59]. The coated carbide tools shows favorable results in machining of Ti-6Al-4V ELI under dry conditions to assess surface integrity. They investigated that nose radius and feed rate affects surface roughness values. Coated cemented carbide tools are usually acceptable in machining Ti-6Al-4V ELI and surface generated freed of damage such as cracks and tears [60]. Sun *et al* (2014) investigated that PCD cutting tool showed higher performance than PCBN tool. The lifetime of PCBN insert was remarked less than PCD tool underneath similar cutting environment. The main causes of PCBN tool failure were chip, adhesion, crater and nose. The PCD tool failure main causes were crater, dissolution-diffusion and adhesion [61]. The PCBN and PCD tool for machining titanium alloy found more appropriate as compared to CBN tools. The ultra-hard tools enhanced quality of machined surface and wear resistance as compared with Carbide tools [62]. Ren *et al* (2019) explored that PCD insert shows better performance than PCBN tool in dry turning of Ti alloy TC7. For machining TC7 PCD tool is reliable [63].

5. Dry milling experimental research

5.1. Cast Iron alloy

Jaharah *et al* (2009) conducted machining of cast iron in dry end milling condition using coated carbide cutting tool. They concluded depth of cut and feed rate are the influential factor affecting tool life. Wear crater is predominantly controlled at elevated cutting speed as well as flank wear on flank face at all ranges of cutting speed [64]. The coated tool provides better machined surface roughness and reduction in tool temperature as compared to uncoated tool. The TiAlN coating with carbide based tool provides high processing efficiency and surface quality and can be selected in dry milling of CGI [65]. The coating MoS_2/Ti (MoST) is suitable at normal cutting speed in dry machining, but its advantages of coating reduced at very high temperatures because of the very high cutting temperature [66].

5.2. Aluminium alloy

The WC/C (tungsten carbide/carbon) coating and diamond recommended for dry machining of (AlZnMgCu1.5) alloy. The WC/C coating and diamond increased the life of tool and enhanced surface quality [67]. Dhanalakshmi *et al* (2020) studied parametric influence of LM 25 Al alloy under dry and wet environments by using PCD insert. Increased cutting speed, feed rate and depth of cut increase material removal rate and decrease surface roughness in both dry and wet conditions [17]. The favorable results were noticed with increment in flow rate of MQL as it results in decrease of cutting forces together with surface roughness at low cutting speed. If particle emission is considered the dry machining will be better option as compared to MQL [68].

5.3. Inconel alloy

Zheng *et al* (2013) investigated failure execution of spindle during ultra HSM of Inconel 718 beneath dry environment. The results revealed that Si_3N_4 showed much higher resistance as compared to other tools. The main failure patterns were notch wear, flaking and chipping [69].

Le Coz *et al* (2014) measured the temperature during machining of Inconel 718 under dry conditions with the thermocouple. They concluded 60 m min^{-1} a cutting speed is a optimal value for machining Inconel 718 employing coated carbide tool. At cutting speed 60 m min^{-1}, a low temperature gradient value was noticed. A high temperature gradient values were observed at higher speeds [70].

Zhang *et al* (2012) investigated life of spindle and cutting forces during milling of Inconel beneath dry and MQCL conditions. The life of tool increased 1.57 times under MQCL conditions than dry conditions. Reductions in cutting forces were remarked under MQCL conditions than dry conditions. [71]. MQCL under appropriate cutting conditions can be used for milling processes as favorable results in machining productivity and life of tool were obtained by using MQCL technique in machining of stainless steel [72].

5.4. Magnesium alloy

Shi *et al* (2016) executed milling of Mg alloy using carbide tools. Increment in cutting speed in the limits of 50–400 m min^{-1}, the feed force and radial force were decreased. The cutting temperature between the spindle and a piece of work rises with further increment of cutting speed, causing softening effect of material. The surface quality is steady between 100 and 200m min^{-1}. The surface quality decreased with increase in speed commencing from 50–100m min^{-1}, may be due to accumulation of mass chips at rake face of tool. The surface quality deteriorates with increment in cutting speed as of 200 to 400m min^{-1} may be due to softening of material [73]. Zagórski *et al* (2020) assessed surface quality during milling of magnesium alloy. The good surface quality was observed by using PCD tools during milling AZ91D magnesium alloy. They observed that milling efficiency can be improved with axial depth of cut without affecting surface components [74].

5.5. Steel alloy

Li *et al* (2014) studied cutting performance and microstructure for CrTiAlN coating for in milling of hardened steel. The CrTiAlN coating improves life of spindle and reduces the cutting forces than uncoated ones. The CrTiAlN coating due to excellent mechanical properties can be employed on the carbide tools for HSM [75]. The AlCrN coating shows improved machining performance and resistance to wear than AlTiN coating. The cryogenic conditions improved the tool life, reduced the cutting forces as well as surface roughness than dry and wet conditions [76]. The coatings (TiN, CrN, TiCN, TiAlN, CrTiAlN) can reduce cutting edge chipping as well as edge radius wear than uncoated tools. TiN performs most excellent in micro milling spindle steel based on surface finish, flank wear, edge radius wear, chipping and burr size [77].

Cryogenic machining using liquid nitrogen has effectively reduced 14%–24% average surface roughness than dry machining. During machining generation of temperature depends on cutting speed [78].

5.6. Titanium alloy

Liu *et al* (2020) conducted milling of Ti alloy employing coated carbide inserts. Titanium TiAlSiN coating shows better cutting performance, better oxidation resistance, longer tool life, smaller and more uniform chips and fewer thermal cracks than aluminium titanium nitride (AlTiN) coating. The tool lives of TiAlSiN coating exceeds than AlTiN coating with increment in speed from 150 to 200m min^{-1} [79]. The use of nanostructured coatings minimizes brittle fracture, chipping and increases the tool life [80]. The cutting speed 60 m min^{-1} combined with radial depth of cut 0.6 mm are suggested when $f_z = 0.1$ mm per tooth and $a_p = 2$ mm in milling of titanium alloy under dry conditions to improve cutting efficiency. Dry Trochoidal milling shows potential for machining Ti alloy [81]. Cryogenic technique increased life of tool as than dry and conventional machining. The price for cutting tool is reduced and productivity is boosted due to long life of tool. The time of machining in dry and conventional mode is more than cryogenic mode [82].

6. Dry drilling experimental research

6.1. Cast iron alloy

Li *et al* (2019) carried out drilling of cast grey iron (CGI) beneath dry and MQL conditions. Severe abrasion wear was noticed under dry conditions owing to the hard dust chip during drilling CGI. Dry drilling with compressed air is feasible in drilling of CGI due to carbon which originated from CGI. Dry drilling of CGI with combination of compressed air together with MQL 5 ml h^{-1} is feasible. [83].

The multilayered coating shows the excellent performance at cutting speed 150m min^{-1}. The Cr-based coatings improved the life of tool in view of flank wear at 80m min^{-1}. The holes drilled showed best circularity for TiSiN/AlCrN coating at cutting speed of 150m min^{-1} [84]. The carbide tools show the best performance than ceramic tools when tested for same conditions in terms of too life [85].

6.2. Aluminium

Mydin . (2020) conducted drilling of aluminium alloy 7075 under dry conditions. They deduced that the life of carbide cutting tool can be enhanced with the merger of reduce (cutting speed feed rate) while drilling of 7075 alloy. The optimal parameters for drilling aluminium 7075 were found cutting speed of 4000rpm and feed rate 0.001 mm/rev [86]. Muhammad *et al* (2020) executed dry drilling of Al2024, Al5083 and Al6061 alloys using carbide tools. The results showed that Al2024 shows promising results like less BUE on tools, less burrs around the hole edges and broken chips [87]. The low cutting speeds with small feed rate recommended for machining of AA2024 alloy using uncoated cemented coated carbide tool. HSS drills are not suggested for drilling AA2024 alloy [88].

6.3. Inconel alloy

Kivak *et al* (2012) assessed tool wear and cutting parameters effects on hole quality during dry drilling of Inconel alloy using uncoated, TiN and TiAlN carbide drills. They recommended uncoated carbide tools under dry conditions due to hole quality. Furthermore, low feed rates improved the hole quality [89]. The AlTiN coated tool enhances the roundness accuracy of holes under dry, wet and cryogenic conditions. Cryogenic technique improves the hole quality than dry and wet conditions by reducing burr formation and roundness error. High thrust values were observed under cryogenic technique at low temperatures. Cryogenic cooling is not beneficial for cutting condition for drilling of Inconel alloy owing to rapid tool wear [90]. The life of tool was increased 87.5% under cryogenic drilling than dry drilling. Drilling of Inconel at elevated temperature is not feasible under dry conditions owing high chemical reactivity of material and coating as reported by Khanna *et al* (2019) [91].

6.4. Magnesium alloy

Bhowmick *et al* (2010) conducted drilling of Mg alloy (AM60) beneath dry and MQL conditions. They identified that cause of tool wear in drilling of magnesium alloy is due to adhesion on edge insert. The results showed that HSS drill fails before drilling 80 holes. Higher thrust force and torque were observed under dry conditions may be due to softening of work material. MQL conditions improved the cutting performance, attained smooth hole surface, chip segments short and reduced thrust force and torque [92]. Garibaldi also identified cause of tool wear in drilling of magnesium alloy (AM60B) owing to adhesion on the edge of insert. He recognized a range of feed rates that promised to produce favorable results concerning life of tool and surface roughness [93].

Shivasankar et al (2017) studied performance characteristics of tool in drilling of Magnesium AZ61 alloy under dry conditions. The results showed optimal value of machining under dry conditions using GRC and GRG were spindle speed of 1200rpm, drill diameter 7 mm and feed rate 1.5 mm. Drill Cutter is the most influential parameter followed by spindle speed and feed rate [94].

6.5. Steel alloy

Shrivas et al (2020) executed drilling of stainless steel (17–4H) under dry conditions using carbide drill bits. They concluded that variable feed rates could not improve surface finish of drilled surface using TiAlN solid carbide drill as compared to uncoated carbide drill. They recommended feed rate 0.1 mm/rev or lower with combination of 2000 spindle rpm and coated drill for drilling 17-4H stainless steel [95]. The coated tool shows promising results than uncoated tool related to surface finish. The optimal parameter for drilling hole in D2 steel were spindle speed of 680 rpm and feed rate 206.25 mm by using HSS drill TiCN coated [96].

Sultan et al (2020) evaluated tool wear during drilling of (AISI 316L) SS under MQL, flood cooling and dry conditions by using uncoated carbide drill. They concluded that flood coolant outperformed MQL and dry in terms of lives of tool, which resulted 68% and 5% respectively. Flood coolant exhibit less surface roughness than that of MQL and dry drilling [97]. Sinha et al (2020) conducted drilling of EN31 steel under dry and wet conditions. They concluded that wet machining is best than dry machining for drilling EN31 steel. Feed rate an influential factor noticed for drilling of hole in both dry and wet conditions as concerned with surface roughness [98].

6.6. Titanium alloy

Joy et al (2020) studied machining parameters during drilling of Ti alloy under dry conditions. They reported that tool wear fast owing to generation of high temperature and adhesion between piece of work and spindle. The chip observed was ductile and continuous at low feed rate [99]. The low cutting parameters are beneficial for increasing tool life while drilling titanium alloy. The cutting parameters spindle speed 2387 rpm with combination of feed speed 29 mm minute^{-1} recommended to increase tool life [100].

Samsudeensadham et al (2020) assessed surface quality during drilling of titanium alloy under dry condition. They deduced that feed rate has higher significance on surface quality as compared to drilling speed but speed has higher significance when circularity error is considered [101].

7. Drilling of carbon-fiber-reinforced-plastics (CFRP) and metal matrix composites (MMCs)

CFRP contain carbon fibers, can be expensive used in aerospace, automotive, superstructure of ships, and civil engineering. In CFRP machining the tool wear relies on machining condition of the cutting process and fiber orientation. Zitoune et al (2012) evaluated performance of nano-coated tool on drilling of Al alloy and CFRP. They reported that thrust force increased up to 72% (115–198N) after 70 no. of holes drilled as illustrated in figure 7. The thrust force rised to 92% (114–278N) in case of uncoated tool may be due to high wear. In case of aluminium thrust force increase about 11% in spite of of the type of tool from first hole to last hole (70th hole). During drilling flank wear is observed while drilling CFRP the wear caused owing to carbon fibers adhered on cutting edges [102]. The increase in thrust force observed for both CFRP and Al during dry drilling using uncoated tools may due to high wear [103]. In compressed air environment, lowest thrust forces were found (1.46 times) for 30° inclination as compared to dry cutting in drilling of CFRP reported by Parvez et al (2020) [104]. Cryogenic fluid between–the-holes shows favorable results with respect to drilling of CFRP concerning hole quality, thrust force and energy consumption while a reduction in surface roughness and energy consumption in case of drilling of titanium alloy [105].

MMCs are a relatively new group of materials that are lighter in weight and have higher wear resistance than conventional materials. Because of the highly abrasive nature of the ceramic particulate reinforcement, machining MMCs is extremely difficult. These materials have been considered for use in automotive brake rotors and a variety of internal combustion engine components. Haq et al (2008) used grey relational analysis and reported that point angle influences more followed by cutting speed and feed in drilling of Al/SiC metal matrix composites [106]. A significant improvement was observed in surface roughness, tool wear, heights of burrs produced and cutting forces using coolant as compared to dry drilling. When compared to dry drilling, the use of coolant had no advantage in terms of cutting [107]. A good surface quality was observed with coated carbide tools as compared to HSS tools. The effect of cutting speed on surface roughness is dependent on boron carbide (B_4C) content, and this effect may be ignored when the particle's B_4C content is less than 25% [108].

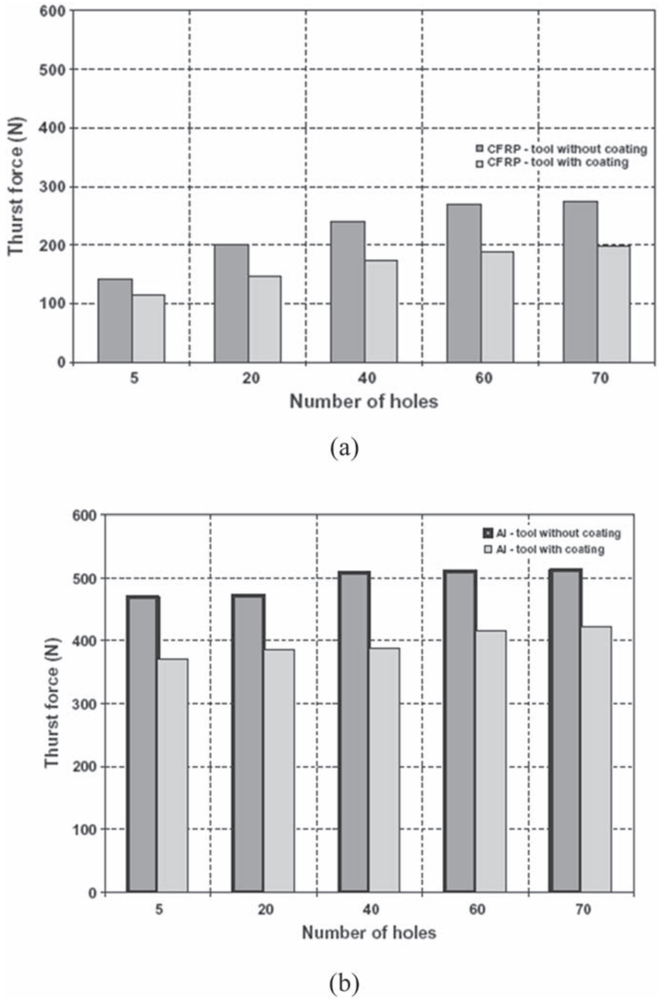

Figure 7. (a), (b) Measurement of thrust forces in CFRP and Al respectively on number of holes drilled [102].

8. Recent developments in the dry machining of advanced materials

8.1. Hastelloy alloy

A nickel molybdenum alloy, resistance to corrosion and oxidizing solutions, finds applications in pharmaceutical, oil & gas, aerospace, marine and chemical processing industries. Hastelloy when used in metal applications they provide strong durability in reducing environments.

Kesavan *et al* (2020) examined the impact of dry and MQL conditions while turning the Hastelloy C-276 concerning cutting temperature and cutting forces. They noticed that machining forces were decreased under cryogenic conditions as compared to dry conditions. Under cryogenic condition a reduction about 57% of temperature was observed as compared to dry conditions [109]. Higher forces, flank wear and roughness was noticed under dry condition than MQL conditions in machining of Hastelloy X. Results reveal that PVD with 0.25wt% with Hexagonal Boron Nitride (HBN) has potential to cut hard materials and an environment friendly option [110].

8.2. Waspaloy alloy

Waspaloy alloy is a nickel-based superalloy, offers oxidation resistance, high hardness and high temperature strength. Waspaloy can be used in variety of applications as gas turbine, fasteners, shafts, rotor discs, missile systems and airframe assembly.

Velmurugan and Venkatesan (2020) carried out machining of waspaloy alloy under coated PVD and CVD inserts. They noticed that from point of view of chip morphology, golden color was obtained for CVD insert and silver color for CVD. The Serrated chips were obtained for CVD inserts owing to high tool wear and high temperature. Less segmented chips were obtained for PVD inserts due to less heat toward tool-chip edge as depicts in figure 8 [111].

Figure 8. (a) PVD; (b) CVD insert shows optical images of chips [111].

Yıldırım *et al* (2019) conducted milling of waspaloy under different cooling/lubrication conditions using ceramic tools. MQL method provides the minimum surface roughness and tool wear than dry and wet method under given machining parameters. In all cutting tools dominant wear type observed was notch wear and flank wear [112].

8.3. Nimonic 75 alloy

A nickel-chromium alloy is strengthened by the additives of carbon, titanium and aluminium. Nimonic 75 alloy shows good heat resistance, mechanical properties and corrosion resistance. They find applications in gas turbine, nuclear engineering, aerospace and industries.

Swain *et al* (2017) executed milling of Nimonic 75 alloy employing coated and uncoated tungsten carbide tools. TiAlN coated micro-tools shows better performance concerning burr formation and tool life as than uncoated ones [113].

Sivakumar *et al* (2019) performed machining of Nimonic 75 alloy beneath dry and wet conditions using ceramic tools. The main type of wear observed was notch wear under both cutting environments, while it occurred generally at time of dry process. A better wear behaviour was observed using SiAlON insert as compared to other insert under wet conditions [114].

8.4. Inconel 713C alloy

A nickel-chromium cast alloy offers resistance to thermal fatigue, high ductility, high-temperature strength and possesses excellent rupture strength at 1700°F. They find applications in industrial turbines, extrusion dies, jet aircraft etc This alloy is difficult to machine due to high rate of work hardening.

Kurniawan *et al* (2020) investigated machinability in turning of modified Inconel 713C using coated WC-TiAlN tool. Modified tools and base Inconel was scrutinized under dry and wet conditions. The surface roughness was observed reduced under wet conditions for base Inconel 713C while, surface roughness of modified tools remains equally for dry and wet environments. The cutting temperature was observed reduced for modified tools as compared to Inconel 713C [115]. WC-Co tools cryogenically treated with oil lower surface roughness as well as cutting force magnitude than dry conditions while turning of Inconel 713C as reported by Vijayakumar *et al* (2020) [116].

8.5. Titanium (α-β) alloys

A combination of both β and α stabilizer and can be strengthening by heat treatment. They are used for manufacturing marine components, jet engine parts, airframes, steam turbine blades etc These alloys have poor machinability and consume more cost and time to machine the material.

Jamil *et al* (2019) evaluated economic performance and machinability in machining of Titanium (α-β) alloy under different cutting conditions. Results revealed that low cutting cost and long life of tool was observed under cryogenic environment followed by MQL and dry machining. On contrary, swift tool wear and high temperature was observed under dry conditions [117]. A reduction in tool performance about 40% was observed for Ti5553 alloy as compared to Ti6Al4V because of β rich in Cr, Mo and V than α phase in Ti6Al4V. At low cutting speed, mechanical wear was dominant, while at high cutting speed, diffusion wear mechanism is determined [118].

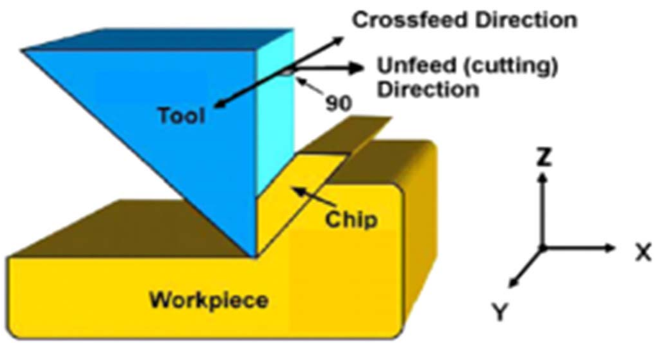

Figure 9. Coordinate System [120].

8.6. Inconel 800 alloy

Inconel 800 is an alloy recommended by manufacturers for high pressure and extreme temperature applications. Applications of Inconel 800 include marine engineering, chemical processing industries, aerospace, and beverage industry.

Gupta *et al* (2019) investigated machinability of Inconel 800 alloy beneath dissimilar cutting environments. MQL strategy helps in decrease of cutting forces, tool wear, tool-chip contact length, surface roughness as than dry and flood cooling while turning Inconel 800 alloy. They recommended cutting speed 215 m min^{-1}, cutting tool angle 82°, and federate 0.10 mm/rev to generate superior quality in terms of surface roughness and tool-chip contact length [119].

9. Vibration assisted machining , laser machining and laser assisted drilling

Vibration assisted machining (VAM) is a cutting technique combines with precision machining in which vibrations with high frequency and small amplitude to get better fabrication process. VAM has been applied in processes as turning, drilling and grinding. The centroid of tool tip is propelled in a tiny elliptical (2D VAM) or reciprocating (1D VAM) motion. Figure 9 illustrates idealized 1D VAM [120].

VAM Advantages:

- Improved form accuracy and reduce surface roughness.
- Reduced tool forces
- Extended life of tool
- Suppression of burr formation

VAM has capability to enhance life of tool significantly, as than conventional methods. VAM used diamond tools, CBN and carbide tools to machine brittle materials, ferrous metals and nonferrous 'hard' metals [121, 122]. VAM can achieve surface finishes for hardened steels at economical machining distances in the limits of 10–30 nm RMS [123, 124].

Ultrasonic vibration-assisted (UVA) machining has been effective than conventional process. UVA can minimize tool wear, ability to enhance surface finish and has higher machining stability. UVA has been used in cutting of a diversity of materials together with brittle materials, composite materials and ductile materials. [125–127].

9.1. Laser assisted machining (LAM)

LAM is a technique to machine hard materials. Laser machining has number of advantages as compared to conventional machining processes as no tool wear, breakage of tool, and machine deflection [128]. Laser machining during a cutting operation use laser to heat the piece of work material particularly, i.e., heating only the region of the cutting tool. To improve the efficiency of different forms of surface machining and machinability of materials many LAM methods have been developed. LAM can be classified as either in-process-heat or preheat as shown in figure 10, according to whether the laser irradiates the sub-surface material across the transparent tool or laser pre-heats the material close to the rake face, respectively [129].

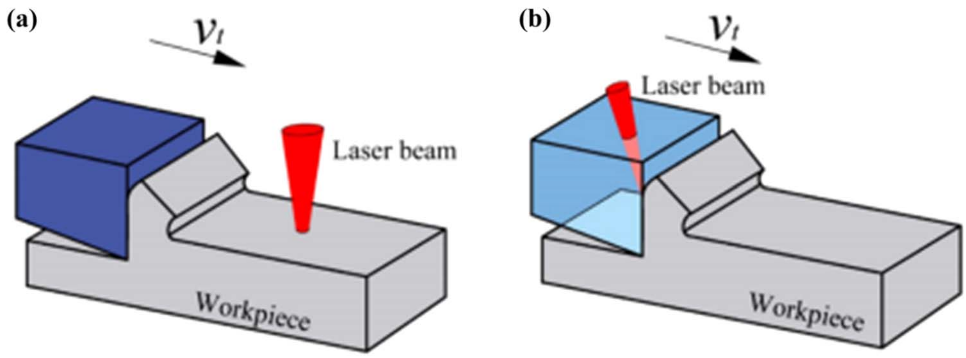

Figure 10. Schematics of the (a) pre-heat LAM and (b) in-process-heat LAM [129].

Table 2. A summary of the applications of dry machining in various machining operations.

Machining operation under Dry cutting	Merits & drawbacks
Turning	Merits Dry turning is environment friendly because there is no coolant around the machining area Dry turning reduces the cost associated with coolant. Dry turning using coated polished CVD diamond tool can increase the life of tool and decrease the formation of airborne particles during turning can cause health hazards in human in the work atmosphere. Demerits No movement of chips from the cutting zone. Increase the temperature at cutting zone Dry turning creates dust formation and debris.
Milling	Merits Dry milling is safe and environment friendly. Decrease the cost of cutting process. Dry trochoidal milling enables longer tool life. Dry milling extends the life of cutting Demerits Increase cutting forces Affect the Surface quality of machined parts. Dry milling results in dust formation
Drilling	Merits Environmental and economic benefits are acquired with elimination of cutting coolants Good for softer materials. Demerits Dry drilling creates dust formation and debris Accelerated tool wear Time consuming

LAM Advantages:

- Reduce cutting forces
- Crack-free machined surface
- Higher material removal rates

Jeong *et al* (2021) studied life of tool employing a heat shield in LAM to Inconel 718. They reported that combination of LAM and heat shield reduced the thermal energy supplied to tool by laser heat source and improved the life of tool [130].

Laser Assisted Drilling (LAD) process combines the benefits of a traditional drilling process and a laser heating process. A heat source is used to heat the workpiece to a softening temperature using a high intensity laser beam. After heating, a conventional drilling bit is used to drill just below the melting temperature. LAD reduced drilling time of materials, produced less tool wear, increased production rate and is suitable for

Table 3. Significant findings under dry machining by different researchers.

Reference No	Work material	Operation	Critical parameters	Salient findings
[21]	Cast iron	Turning	cutting speed (m min)$^{-1}$ = 50,100,150, 200,250,300,350,400,450,500,550	An optimum tool life of K060 tool was recorded at 200m min^{-1}. K090 tools gave an overall better performance.
[31]	Al-Si alloy	Turning	Cutting speed = 350 m min^{-1}, cutting depth = 0.4 mm, feed rate = 0.1 mm/rev	The flank wear was observed low for MCD/NCD coating after turning cutting length around 3000nm.
[36]	6061-T6 Al alloy	Turning	Cutting speed = 0–300 m min^{-1}, cutting depth = 0.5 mm, feed rate = 0.1 mm/rev	Dust emission can be minimized by using better lead angle (90°), by machining at high speed or by making chip brittle
[41]	Inconel 718 alloy	Turning	Cutting speed = 60–120 m min^{-1}, depth of cut = 0.10–0.30 mm, feed rate = 0.068–0.120 mm/rev	The surface roughness and cutting force generation are lower when machining with the coated tool.
[49]	Steel alloy	Turning	Cutting speed = 60 m min^{-1}, depth of cut = 0.5 mm, feed rate = 0.098 mm/rev	One of the successful ways of dry machining is the use of cooled compressed air.
[75]	Magnesium alloy	Milling	Cutting speed (V) m min^{-1} = 50, 100, 200, 400 Feed rate (f) mm/rev = 0.4, 0.6, 0.8 Depth of cut mm = 1.5 Width of cut mm = 3	The cutting speed in the range of100–200m min^{-1} could be more beneficial to keep the stability of surface quality.
[77]	Hardened Steel (P20, HRC 45).	Milling	Spindle revolution/(r·min−1) = 10616 Cutting speed, v/(m·min−1) = 200 Feed rate/(mm·s−1) = 0.02 Depth of cut/mm Radial = 0.1; Axial: 2	The flank wear of the uncoated end mill and coated mill 200 μm and 68 μm at cutting length of 10.4 m respectively;
[84]	Titanium alloy	Milling	cutting speed = 100–125 m min^{-1} feed = 0.15–0.20 mm/tooth axial depth of cut = 1.5–2.5 mm radial depth of cut = 8.8 mm	The microstructure at the sub-surface down to 50 mm exhibits a thermal softening, which results in a lower microhardness beneath the machined surface.
[90]	Al2024, Al6061, and Al5083 alloys	Drilling	Spindle speed (rpm) = 1007, 2015, and 3025 Feed (mm/rev) = 0.04, 0.08 and 0.14	A multi-spindle cutter was used to perform multi-hole drilling for reducing time.
[92]	Inconel 718	Drilling	Cutting speeds (m min)$^{-1}$ = 10, 12.5,15 and 17.5 Feed rate (mm/rev) = 0.05, 0.075 and 0.1	The lowest deviation values and highest deviation values from circularity values were obtained at cutting speed 12.5 m min^{-1}. and 17.5m min^{-1} respectively.
[93]	Inconel 718	Drilling	Cutting speed (m min)$^{-1}$ = 15 Feed (mm/rev) = 0.02	LN_2improves the hole quality in terms of lower burr formation than dry and wet conditions

Table 4. Shows comparison of dry machining with MQL and flood coolant.

S.No	Dry Machining	MQL	Flood coolant
1	No corrosion of machine tool due to absence of coolant	MQL causes slow corrosion of machine tools and other accessories.	Flood cooling corrodes the machine and other accessories more quickly.
2	No environmental impact	Partly impact on environment	Negative environmental impact
3	No cutting fluid used	Cutting fluid not reused	Cutting fluid reused
4	Dry machining can increase Tool life under the right conditions.	MQL can increase Tool life under the right conditions.	Thermal shock in carbide tooling can be caused by flood coolant, reducing tool life.
5	Overall machining costs are lower than MQL and flood coolant.	Overall machining costs are lower because less cutting fluid is required for the same task.	The overall cost of machining rises as a result of additional expenses for a large volume of expensive cutting fluid. The cost of filtration is also not insignificant.
6	More suitable to sawing, milling and turning	More suitable to sawing, milling and turning	More suitable for honing and lapping and drilling

machining shaft parts and high hardness materials [131]. Drilling time for stainless steel is approximately 30% shorter with laser assisted drilling than with conventional drilling [132–145].

Table 2 shows A summary of the applications of dry machining in various machining operations. Table 3 Significant findings under dry machining by different researchers. Table 4 shows comparison of dry machining with MQL and flood coolant.

Although, Kondo *et al* (2019) used Taguchi method to assess the influence of cutting parameters during the turning of VAT32 nickel superalloy using coated carbide tools. Only the cutting power is affected by the depth of cut (contribution of 48.80%). When compared to dry turning conditions, the need for surplus availability of lubricating oil has a substantial favorable impact (contribution of 31.03 percent) on cutting-power [146]. Tool life for line textures and dimples has been discovered to be higher. It is stated that ‘textured-tools’ have had the ability to process ‘hard-materials’ like Inconel super alloys while also giving longer tool life. Due to the obvious alleviation in ‘friction’ as well as ‘heat’, the cutting-tool ‘wear-resistance’ has been substantially enhanced with the varied textured layout design arrangements [147]. The ‘cutting-speed’ and work-piece ‘hardness’ was observed to be the most influential factors in tool life. Regardless of the ‘hardness’ of the work-piece, Al-oxide cutting inserts outperform Si_3N_4 cutting-inserts and ‘mixed-oxide’ cutting-inserts in terms of flank wear resistance. Cutting forces were found to be greater for ‘harder’ workpieces and ‘mixed-oxide’ cutting-tools [148]. Thakur *et al* (2016) carried out turning of Incoloy 825 super alloy under dry-environment utilising PVD-process on (‘TiN’/‘TiAlN’) coated-tool. The findings in both rougher and finishing machining methods conclusively substantiated the usage of ‘PVD-coated tools’ in a ‘dry-environment’ as a long-term approach toward attaining sustainable greener-machining [149]. A reduction in ‘cutting-force’ and ‘surface-roughness’ was observed in turning of super alloy Monel K500 using ceramic wiper inert in MQL technique as compared to the dry environment [150]. With an increase in average flank wear, surface roughness tended to decrease first and then increase. Because of the poor surface finish, coated tools should not be used to machine super alloy GH2132 at high cutting speeds [151].

10. Conclusions

In depth scrutiny of the published work on dry machining of materials highlights that the dry machining approach has widely been used by manufacturing industries taking into account manufacturing costs and health regulations. The utilization of dry system put an end to the concealment of cutting fluid which results in high cost, disposal and environment impact. A relative study of turning, milling and drilling experiments under dry system shows promising results. The materials used in the studies were categorized as Inconel, steel, aluminium, cast iron, magnesium and advanced materials. Dry machining shows promising results in machining of cast iron. Ceramic tools (mixed oxide) show promising results in turning grey cast iron. The geometry of insert, cutting edge preparation, nose radius has major effect on surface roughness and residual stresses. For an appropriate surface integrity and adequate tool life a coating is essential. The scope of dry machining has been increased by employing coating and tool geometries. This leads to beginning of many highly developed tool materials as such as CBN, PCBN, PCD, ceramics and distinct kinds of coatings (TiN, TiCN, TiAlN). TiN and TiC tools (coated) have high resistance to crater wear and flank wear respectively. TiAlN coated micro-tools can show better performance concerning burr formation and tool life than uncoated ones. Polished CVD diamond coated insert contribute green factor by reducing airborne particles during machining. The PVD (TiAlN) coating is beneficial in dry machining as it displays high hot hardness, resistance to oxidation, high temperature and chemical stability. PVD with 0.25wt% with Hexagonal Boron Nitride (HBN) has potential to cut hard materials and an environment friendly option [110]. The tools designed for CVD coatings are not appropriate for PVD coating technology. In dry machining dust emission can be minimized by using better lead angle, by high speed machining. Carbide tools (coated cemented) are usually acceptable in machining Ti-6Al-4V ELI and surface generated freed of damage such as cracks and tears. The WC/C (tungsten carbide/carbon) coating and diamond can be recommended for dry milling of aluminium alloys. Surface texturing can extend life of tool and improves surface finish. The CrTiAlN coating due to excellent mechanical properties can be favorable for carbide tools for HSM. Dry Trochoidal milling can be an effective for machining titanium alloy. For machining titanium alloy straight grade cemented carbides (WC-Co) are beneficial. Commercially eco-friendly coatings of solid lubricants can be developed for industrial applications. VAM has been investigated by researchers without the use of cutting coolants. When compared to traditional machining methods, laser-assisted machining has increased productivity as well as the efficiency of hard to cut materials. Sustainable lubrication methods are required to replace flood lubrication in machining processes in order to improve machinability and make the process more environmentally friendly. Cryogenic lubrication, MQL, and LAM techniques have been studied with a focus on turning, milling, and drilling processes. MQL has been used effectively in numerous metal cutting firms where handling of fluids is not possible. About use of advanced MQL setup along with arrangement of vortex tube can also be explored under industrial applications. The update of research studies let recognise how the dry system is environment friendly and improve the results in turning milling and drilling processes. Though, as it becomes recognised, in certain instances, the utilization of the dry method does not execute good results than those procured with other systems. Therefore, for each unique process the utilization of the dry system must be handily evaluated.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Future viewpoint

i. In coming days dry machining would be carried out in many operations due to economic and ecological advantages. Dry machining would be adopted as environment friendly and would be choice for future machining.

ii. A large work has been reported by various researchers on different materials by employing highly developed tool materials and different kinds of coatings, keeping in mind machining performance and environmental concerns. It is essential to evaluate available developed tool materials and coatings and simultaneously to develop new tool materials and coatings.

iii. Productivity is very low with conventional methods because of excessive tool wear and high cutting forces. Laser assisted machining can be used to overcome the problem. Machining efficiency and Process efficiency can be achieved by using Laser assisted machining.

iv. Solid lubricants are appealing to the manufacturers as they are promoting dry machining an environmentally friendly process. To provide solid lubricants in the cutting zone is still challenging so more attention is required for carrier medium those who do not have effect on friction.

v. To develop textured tools through powder metallurgy commercially can be explored for enhanced machining performance.

vi. To develop an advanced MQL system along with vortex can be explored.

vii. Use of nano based solid lubricants coatings can be explored.

Conflicts of interest

The authors declare no conflict of interest.

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