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Environmentally Conscious Machining of Difficult-to-Machine Materials with regards to Cutting Fluids

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Abstract

Machining difficult-to-machine materials such as alloys used in aerospace, nuclear and medical industries are usually accompanied with low productivity, poor surface quality and short tool life. Despite the broad use of term difficult-to-machine or hard-to-cut materials, the area of these types of materials and their properties are not clear yet. On the other hand, using cutting fluids is a common technique for improving machinability and has been acknowledged since early 20th. However, the environmental and health hazards associated with the use of conventional cutting fluids together with developing governmental regulations have resulted in increasing machining costs. The aim of this paper is to review and identify the materials known as difficult-to-machine and their properties. In addition, different cutting fluids are reviewed and major health and environmental concerns about their usage in material cutting industries are defined. Finally, advances in reducing and/or eliminating the use of conventional cutting fluids are reviewed and discussed.

Keywords

Cutting fluids; environmentally conscious machining; difficult to machine materials

1 Introduction

Material cutting also known as machining is one of the most used techniques for producing different components. In the machining processes a cutting tool removes material from a workpiece of a less resistant material. The removed material called chip or swarf slides on the tool face and leaves the workpiece material. As a result of this process the cutting tool would be subjected to high normal and shear stresses [1]. Figure 1 shows a schematic view of a typical cutting operation also known as the single shear plane model. Although from the modelling point of view this model is a matter of debate and suffers from a lack of accuracy [2] it provides sufficient information required for this paper. As shown the chip formation is categorised into two zones, namely primary and secondary shear zones. In the primary shear zone, the material is being cut by elasto-plastic deformation. The majority of the energy used for cutting in this section is transformed into heat. At the secondary shear zone the produced chip slides on the rake face of the cutting tool resulting in high frictional force and heat. In addition to these zones, sliding of the tool flank face on the machined surface at the tertiary deformation zone generates friction and heat and could cause flank wear on the flank face [3, 4]. Furthermore friction and heat on the rake face could result in chipping and crater wear leading to tool failure.

Machining advanced engineering materials is usually associated with high machining costs and low productivity. This is due to the excessive generation of heat at the cutting zone and difficulties in heat dissipation due to relatively low heat conductivity of these materials. High material hardness and strength together with high temperatures at the cutting zone could result in excessive tool wear and thus short tool life and poor surface quality. Most components produced from advanced materials such as titanium and nickel based alloys have high buy-to-fly ratio as most of them are made to be used in aerospace, engine and gas turbine industries [5].

2 Difficult to Machine Material

Titanium and nickel based alloys are readily regarded as difficult-to-machine or hard-to-cut materials. Commonly, wider categories of materials defined as difficult-to-machine are super-alloys and refractory metals which are consisted of titanium, nickel, steel, molybdenum, rhenium, tungsten, cobalt, tantalum, niobium, chromium, etc. alloys [6]. However, materials which are hard to machine are not limited to these alloys and also consist of structural ceramics, composites, polymers and magnesium alloys.

Difficult-to-machine materials are referred to the materials which during machining operations produce excessive tool wear, heat and/or cutting forces, difficulties in chip formation and/or poor surface quality. One of the important phenomena in machining difficult-to-machine materials is excessive generation of heat at the cutting zone resulting in very high cutting temperature. In this section hard-to-cut materials are reviewed and their characteristics, which make them difficult to machine are identified.

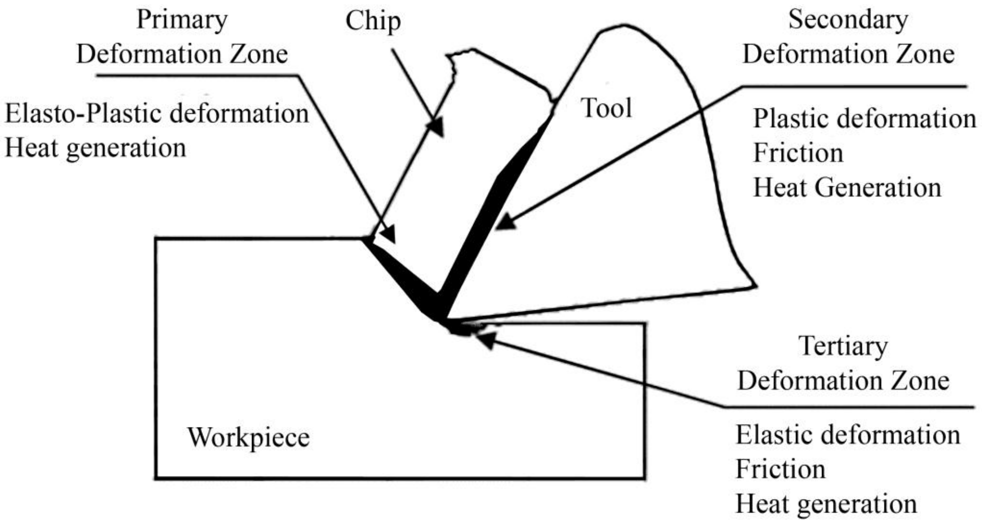

Figure 1, Schematic view of the cutting zone and chip formation [4]

2.1 Titanium Alloys

Titanium is the fourth most abundant structural metal in the earth's crust [7]. While pure titanium is soft and does not have significant mechanical properties, alloyed titanium exhibits mechanical and thermal characteristics close to that of nickel alloys. In addition the density of titanium is half of nickel and closer to that of aluminium with considerable higher fatigue resistance [8].

Titanium and its alloys are attractive materials in many engineering fields such as aerospace, vehicles, engines and gas turbines, nuclear, biomedical, etc. This is mainly due to their superior mechanical and physical properties such as: high strength to weight ratio, high yield stress, very high creep and corrosion resistivity, high toughness, high wear resistance and good biocompatibility [7, 9-11]. In addition titanium alloys are low dense materials which maintain their hardness and strength at very high temperatures. Titanium poses the highest strength to weight ratio between all common metals up to 550˚C [12]. However its application is limited to 400˚C as it can ignite and cause serious problems during operation [8]. These properties in conjunction with high chemical reactivity, low thermal conductivity, high specific heat and high strain hardening (work hardening) have made machining of titanium alloys extremely difficult, which is often associated with low productivity and very short tool life [8, 13]. It has been reported that economical machining of titanium alloys is limited to 30m/min and 60m/min using High Speed Steel (HSS) and tungsten carbide tools respectively due to high tool wear [14, 15]. In machining titanium alloys, due to low thermal conductivity of the material the generated heat during machining cannot be conducted through the workpiece and chips effectively. Hence the generated heat should be dissipated through the cutting tool and cooling media. Conventional coolants fail to penetrate into the cutting zone as they are vaporised before reaching the tool-chip contact area. This could result in very high localised temperature at the cutting zone and thermal stress at the cutting edge [16, 17]. As titanium alloys maintain their strength even at very high temperatures, increases in the cutting temperature is not beneficiary for machining these materials where the cutting tools suffer from heat softening.

Titanium is also chemically reactive to all known cutting tool materials. This reactivity increases at elevated temperatures, resulting in adhesion and diffusion wear accompanied with formation of BUE, smearing, chipping and galling [16, 17]. While cutting forces in machining titanium alloys is comparable with that of steels, very high pressure on the cutting edge is contributed as an inherent characteristic of machining titanium. This is attributed to very small tool-chip contact area close to the cutting edge rather than high cutting forces [7, 18]. This high localised mechanical stress together with thermal stressed induced from rubbing the chips on the chip-tool contact area lead to crater wear on the tool rake face close to the cutting edge. The presence of the crater wear has the potential to weaken the cutting edge and result in catastrophic tool failure.

Titanium machining is characterised by the production of serrated or saw-tooth chips. This is attributed to the localised adiabatic shear bending at the primary shear zone where the material suffers from an intense shear rate. It is due to the high dynamic shear strength of titanium and high chip-tool interface temperature. Formation of serrated chips results in machining instability, force fluctuations and thus chatter which can lead to chipping on the cutting edge [12, 17, 19, 20].

Properties which have made titanium alloys hard to machine could be summarised as follows [7, 8, 19, 21, 22]:

- Low thermal conductivity and high thermal capacity
- High chemical reactivity with all known tool materials
- High strain hardening due to their austenitic matrix
- Low elastic modulus; workpiece deflection due to cutting forces causing chatter and vibration
- Springing and chatter
- Small tool chip contact area
- Tendency to adhesion and forming BUE
- High dynamic shear strength

2.2 Nickel-Based Alloys

The advantages of nickel-based alloys over titanium alloys have made them another attractive material for aerospace, gas turbine and nuclear industries. Nickel based alloys have very broad operational temperature which makes them more attractive than titanium alloys at extreme temperatures. For example nickel alloy Inconel® 718 has high fatigue endurance up to 700˚C [23, 24] while Udimet® 720 nickel-based alloy has a service temperature of up to 982˚C for long exposure times [25]. Nickel exhibits superior hot strength and hardness and is very temperature resistance. It maintains its chemical and mechanical properties at elevated temperatures and is highly resistant to creep and corrosion [26]. Other unique properties of Ni-based alloys can be defined as: high thermal fatigue resistivity, high erosion resistivity, resistance to thermal shock and high melting temperature [9, 19, 27]. It has been reported [28] that 50% of the materials used in aerospace industries are nickel based alloys.

Due to the high strength of nickel alloys, very high temperatures and forces are produced during cutting operations. As nickel has very low heat conductivity, the generated heat cannot be effectively dispersed through the workpiece and chips. Conventional cutting fluids cannot penetrate the chip-tool interface and reach the highest temperature zone especially at high cutting speeds. They tend to evaporate at high temperatures and form a high temperature blanket over the cutting zone which results in further increase in the temperature [5].

Drastic increases in the cutting temperature lead to excessive tool wear and low surface quality of the machined part. In addition, the hardness of the nickel alloys increases with increases in the temperature below 650˚C. This is due to the presence of γ' participates in the material which is also responsible for the material work hardening. For instance, the hardness of Inconel® 718 increases by temperature up to 650˚C as shown in figure 2 [29]. Thus, increases in the cutting temperature under 650˚C do not help to soften the material and improve machinability. Furthermore, nickel is chemically reactive to most cutting tool materials. High temperature at the cutting edge together with increased chemical reactivity at elevated temperatures results in very low tool life. Attrition and crater wear on the rake face and flank wear are the dominant tool failure modes in machining nickel based alloys. Diffusion, adhesion and formation of BUE on the rake face cause attrition (notching), alteration and crater wear while abrasion is dominant on the rake face. Abrasion wear is mainly attributed to the presence of super hard carbide particles such as TiC, CrC, MoC, NbC, FeC, WC, MC, $M_{23}C_6$, etc. in the microstructure of the material [19, 30-33].

As mentioned before, strain hardening is an intrinsic property of nickel based alloys such as Inconel®, Hastelloy®, Nimonic®, Waspaloy®, Udimet®, etc. due to the presence of molybdenum and niobium in the material. This is dominant in the cutting operation as the hardness of the chips is increased after being subjected to deformation at the first shear zone. While the strain hardened chips are very abrasive to the cutting tool, the strained hardened machined surface could notch the tool face [6].

The high temperature produced during machining not only shortens tool life and reduces the surface quality but could also alter the microstructure of the material and induce residual stress, micro cracks and micro-hardness variations through the formation of white layer. These machining induced problems are identified as affecting the service life of the machined component and particularly its fatigue resistivity [34].

Another machining induced problem in cutting nickel based alloys is subsurface metallurgical damage due to the work hardening tendency of the material as a response to the cutting forces [33]. Hence, machining nickel based alloys traditionally is associated with low cutting speeds, poor surface and subsurface quality, short tool life and thus high machining costs [35]. Krain et al. [32] studied the effects of cutting parameters in end milling Inconel® 718 nickel alloy. They found that adhesion and attrition were the dominant tool wear mechanisms resulting in the formation of BUE and notching. It is attributed to the high temperature and pressure at the cutting zone and chemical affinity of the workpiece material to the WC tool.

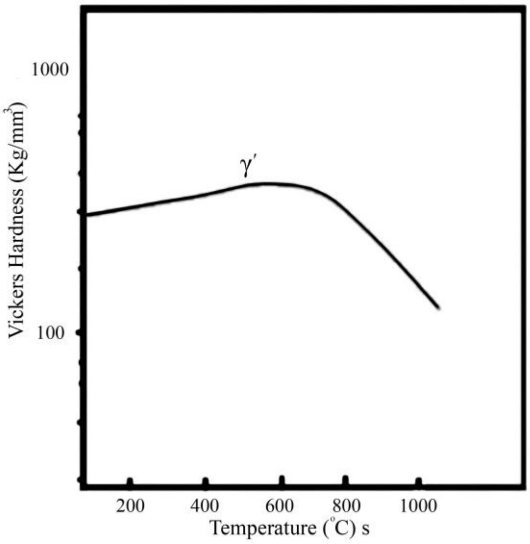

Figure 2, Relation between temperature and Vickers hardness of Inconel® 718 [29]

The properties responsible for making nickel based alloys difficult to machine have been classified by the author and summarised based on a number of references [19, 24, 27, 34, 36] as:

- High shear strength
- High hot strength and hardness
- High strain hardening
- Low thermal conductivity and high heat capacity result in high temperature at cutting zone up to 1200˚C
- High chemical reactivity to most tool materials
- Adhesion and Welding tendency to the cutting tool and formation of BUE
- Very high cutting forces due to the material strength which may result in vibration
- Presence of hard carbide particles in the microstructure which encourage abrasive wear
- Small tool-chip contact area result in high thermal and mechanical stress close to the cutting edge
- Production of long continuous chips which exacerbates the machined surface chip disposal and hinders the machining in unmanned operations.

2.3 Difficult-to-Machine Ferrous Alloys

Iron based difficult-to-machine materials have been classified by the author into three categories, low-carbon ductile steels, stainless steels and hardened steels. While in general the machining of steels is considered easy to moderate, some steel alloys exhibit characteristics which make them difficult to machine.

i) Low-carbon ductile steels: The major problem in machining ductile low carbon steel materials such as AISI 1008 steel is chip formation. Production of long continuous curled chips can scratch the machined surface, jam the automatic machine tool and cause unnecessary machine down time. In addition, low carbon steels tend to adhere and produce BUE on the cutting tool which may affect the cutting forces, tool life and surface finish of the machined part [37]. While conventional cutting fluids are extremely effective in extending tool life and preventing adhesion in machining low-carbon steels, they cannot help chip formation. In addition, cutting fluids are considered as health and environmentally hazardous substances and using them in machining operations should be minimised. In order to improve the chip breakability, employing chip breaker mechanisms and cutting tools with integrated chip breakers is widely accepted. However in machining ductile materials, the effect of chip breakers is limited to the increased plastic deformation at the second shear zone and cannot actually break the chips. As most steel materials are highly temperature dependant, Hong et al. [37] suggested using cryogenic coolant to freeze the chips in machining AISI 1008 low carbon steel. At cryogenic temperatures the material transforms to a brittle state and resulting in enhanced chip breakability.

ii) Stainless steels: Another very difficult to cut material is stainless steel which is widely used in chemical, aerospace, automotive and food processing industries. This is due to high strength, high fracture toughness, high fatigue and corrosion resistivity as compared to plain carbon steels. Low thermal conductivity together with high strength and high heat capacity has made stainless steel a difficult-to-machine material. High material strength requires high cutting energy resulting in high heat generation during machining. Similar to titanium and nickel alloys, in machining stainless steels the generated heat cannot effectively be transferred into the workpiece and chips due to low thermal conductivity of the material. Thus, the generated heat during machining operation is concentrated at the cutting zone and produce high cutting zone temperatures. High temperatures at the cutting zone increase the thermally induced tool wear such as diffusion and chemical reaction between the tool and workpiece materials. In addition, stainless steels tend to adhere to the cutting tools and form BUE. This increases the machining instability and thus chipping on the cutting edge. The work hardening capability of stainless steel together with its mentioned mechanical and thermal properties results in severe tool wear and low surface quality of the machined surface [38-43]. Generally the difficulties in machining stainless steel are attributed to low thermal conductivity, work hardening and poor chip breakability, which characterise the machining of stainless steels together with short tool life and poor surface quality, resulting in low productivity and high machining costs.

iii) Hardened steels: The third category of difficult-to-machine ferrous alloys is hardened steels. The term hard-machining and particularly hard-turning is referred to the machining (typically milling and turning) of steels with hardness beyond 45HRC [44]. This technique is introduced as an alternative to the expensive and low productive grinding operations of heat treated steel components which can contribute up to 90% of the final cost of a machined part. Hard machining eliminates the requirements for grinding and second heat treatment, hence reducing the manufacturing cost. Hard-machining owes its existence to advances in machining operation and cutting tool materials such as ceramics with high hot hardness, toughness and chemical stability which have made machining hardened steels possible [45, 46]. Tool failure modes in hard machining are [47, 48]:

- Superficial plastic deformation of the cutting edge due to high workpiece hardness;
- Dissolution/diffusion between tool and workpiece materials due to high cutting temperatures attributed to high cutting energy requirements;
- Formation of BUE due to high temperatures and chemical welding tendency of ferrous materials
- Non-uniform flank wear result in unpredictable catastrophic tool failure

2.4 Other Materials

In addition to titanium, nickel and ferrous alloys there are some other materials which are classified as difficult-to-machine materials. Structural ceramics, tantalum, elastomeric materials, composites, etc. are also known as difficult-to-machine due to exhibition of one or more following properties:

- High hardness
- High strength
- Ductility
- Toughness
- Low thermal conductivity

These characteristics can result in poor machinability of the material. If any combination of the following characteristics exists in machining a material, it will be considered as a difficult to machine material:

- Short tool life
- Poor surface quality
- Poor geometrical accuracy
- Poor chip formation

Due to the extremely difficult machining of some of these materials and specific application of them, there are very limited studies on the machining of most of these materials. For instance components made of NITINOL® nickel-titanium alloy, Stellite® and Vitallium® Co-Cr alloys, molybdenum alloys and tungsten alloys are usually manufactured by casting and sintering techniques or machined by non-traditional techniques such as electro-discharge machining (EDM), electro-chemical machining (ECM), laser beam machining (LBM) or ion beam machining (IBM), etc. [49].

2.4.1 Composites:

Machining composites is usually different to homogeneous materials due to their inhomogeneous and anisotropic nature. This is attributed to the presence of usually tough and flexible reinforcement fibres in a brittle matrix [50]. It has been reported [51] that cutting mechanisms and chip formation in machining composites consist of a series of material fractures. This cutting condition can result in sever surface quality issues such as delamination, burning, fibre pull-out, uncut fibres, high surface roughness and high dimensional deviation [52].

Difficult-to-machine composites are not limited to the synthetic fibre/matrix materials and also cover metal matrix composites such as 356Al/SiC particulate metal matrix composite [53]. These new engineered materials usually have a metal matrix of aluminium, titanium or magnesium reinforced with silicon carbide or alumina. The presence of hard abrasive particulates such as SiC or Al_2O_3, which are harder than WC tools can cause severe tool wear [54, 55]. It is clear that machining these composites involves problems associated with their matrix material together with other enhanced properties as an advantage of their particulates, such as higher strength, higher abrasion resistance, higher toughness, etc.

2.4.2 Ceramics:

Advanced engineering structural ceramics such as reaction bonded silicon nitride (RBSN) is another attractive engineering material due to its comprehensive properties. It has high hot strength, even at 1400˚C, high thermal shock resistivity, low thermal expansion and is considered as an inert material [56]. High strength together with poor thermal conductivity of the material can result in high temperatures at the cutting zone.

Due to very high hot hardness of the RBSN, the generated heat cannot help soften the material and subsequently cannot improve its machinability. Thus, generated heat at the cutting zone results in tool material softening and plastic deformation of the edge. To machine RBSN the cutting tool should be highly wear resistant, tough and thermally stable. RBSN is more resistant than conventional cutting tool materials such as HSS, tungsten carbide and even ceramics. Thus the only appropriate tool material to machine RBSN is made of diamond or polycrystalline boron nitride (PCBN). However, diamond is not thermally stable and transforms to graphite at elevated temperatures [56]. Thus, Wang et al. [56] suggested that the most appropriate cutting tool material for machining RBSN is PCBN due to its high toughness, hot hardness, wear resistivity and thermal stability.

2.4.3 Elastomers:

Elastomeric materials such as polymers and rubbers are another difficult-to-machine group of materials but are significantly different in nature in terms of machinability compared to previously discussed materials. The elastomeric components are usually produced by injection moulding and not manufactured by cutting processes. They have a very low elastic modulus accompanied with a high percentage of elongation before fracture which results in elastic deformation against the cutting forces, hence preventing the cutting tool from machining the material. Low thermal conductivity results in high temperatures at the cutting edge where the material tends to adhere to the cutting tool. Unlike previously stated materials adhesion in machining elastomers does not affect the tool life but it exacerbates the cutting operation and the surface finish. These properties together with high energy absorption capacity and low stiffness have made these materials hard or even impossible to machine in conventional environmental conditions [57-61]. In addition, traditional machining techniques cannot assure the surface quality and geometrical accuracy of the components and the results are usually not comparable with injection moulded parts.

2.4.4 Magnesium alloys:

Magnesium, cobalt-chromium, titanium, nickel alloys and stainless steels are the most used materials for medical implants. While machinability of stainless steels, titanium and nickel alloys were reviewed in the previous sections, this section is focused on the machinability of the magnesium and cobalt-chromium alloys, although there are very limited studies on the machining of these materials.

Magnesium is known as the lightest structural metal with high strength-to-weight ratio and corrosion resistance [62]. Due to its low density, good ductility, cast-ability, damping behaviour etc. magnesium is very attractive to aerospace and automobile industries [63]. In addition, it has been reported [64-66] that magnesium has the potential to be employed as bio-degradable temporary implants.

Due to low cutting forces, good surface finish, well-formed chips and long tool life, magnesium is considered as one of the easiest structural materials to machine [64, 67]. Magnesium is a highly inflammable material and the risk of ignition increases when temperatures exceed above 450°C, close to the material's melting point (650°C) [68]. Magnesium is able to burn in different atmosphere in such as nitrogen, carbon dioxide and water even in the absence of oxygen. As a result controlling the cutting temperature is extremely crucial during machining in order to prevent ignition.

The presence of inflammable magnesium chips close to the machining zone further increase the fire hazards on the shop floor [68]. Weinert et al. [68] noted that removing the chips from the workspace of the machine tool during the cutting operation is very important. As the chips contain up to 90% of the heat generated at the cutting zone, fast and reliable removal of the chips can significantly reduce the risk of fire and potential damages to the workpiece as well as the machine tool.

Using cutting fluids in order to control the temperature at the cutting zone is limited to neutral mineral oils as magnesium reacts with water-based cutting fluids and produces highly explosive hydrogen gas [64, 69]. Therefore, machining magnesium alloys is usually conducted under dry conditions [69]. This can result in limited productivity as the cutting temperature has to be controlled through precise selection of the cutting parameters e.g. cutting speed and feed rates. Another problem in dry cutting of magnesium alloys is the formation of BUE on the tool which results in an increase in the cutting forces and poor surface finish [67].

2.4.5 Cobalt-Chromium Alloys:

Another type of alloy which is considered extremely difficult to machine is Cobalt-Chromium alloys such as Stellite and Vitallium. The main material properties of these alloys are high strength, high hardness, high biocompatibility, high creep resistance and high corrosion and wear resistance superior to that of titanium based alloys [70-72]. These properties have made them appropriate candidates for medical implants, aero-engine, nuclear and gas turbine components [73]. Similar to other refractory metal alloys, machinability of cobalt-chromium alloys suffers from work hardening and poor thermal conductivity of the material, resulting in low tool life and poor surface quality [70]. Due to the poor machinability of the Co-Cr alloys, most components made of these alloys are produced by different casting, sintering or unconventional machining techniques such as EDM, LBM, etc. [49]. This has led to low productivity and high manufacturing costs of the Co-Cr alloy components and especially medical implants such as hip and dental implants.

2.5 Cutting Tool Materials in Machining Difficult-to-Machine Materials

It has been mentioned that the main problems in machining difficult-to-cut materials are very high temperature at the cutting zone, presence of abrasive carbide particles, chemical reactivity between the tool and workpiece materials and high hot strength and hardness of the workpiece materials. Thus the required properties of the desired cutting tool have been recognised by a number of references [14, 21, 34] as:

- High hot hardness
- High strength and toughness
- High chemical and thermal stability
- High wear resistance
- High thermal shock resistance
- High thermal conductivity to reduce the thermal gradient
- High compressive tensile and shear stress

The effect of temperature in machining has been known for several decades. A major portion of the machining energy transforms into heat at the cutting zone [2]. The generated heat at the cutting zone can soften the workpiece materials and result in lower cutting forces and longer tool life. However in machining difficult-to-machine materials the cutting temperature plays a critical role as it is much higher than that of carbon steels. The generated heat in machining difficult-to-cut materials may not only soften the workpiece material but could also reduce the strength and hardness of the cutting tools. It could also increase the chemical reactivity of the materials and cause excessive thermal and chemical tool wear.

It is known that cutting speed has a significant bearing on cutting temperature and thus cutting forces. Hence, increased cutting speed and cutting temperature can result in lower cutting forces and longer tool life [2, 29, 74]. For instance cutting forces in machining Inconel® 718 reduce significantly at cutting temperatures above 750˚C due to significant reduction in its strength and hardness [35]. In order to benefit from workpiece material softening at elevated temperatures, the cutting tool should withstand high thermal and mechanical stresses and be chemically stable at elevated temperatures.

In order to quantify the performance of different cutting tools in machining, their hot hardness and wear resistant could be used. The wear resistance of materials can be calculated from [75]:

$$W_R = K_{IC}^{-0.5} E^{-0.8} H^{1.43}$$

Where W_R is wear resistance, K_{IC} is fracture toughness of the material, E is the Young's modulus and H is the material hardness. The wear resistance of five common tool materials is provided in table 1. In addition to the wear resistance, the hardness of cutting tool materials at different temperatures is presented in figure 3.

Table 1, Wear resistance of different tool materials [56]

Tool material	Wear resistance
White ceramic (Al_2O_3)	0.76
Black ceramic (Al_2O_3-TiC)	0.79
Tungsten carbide	0.92
PCBN	2.01
PCD	2.99

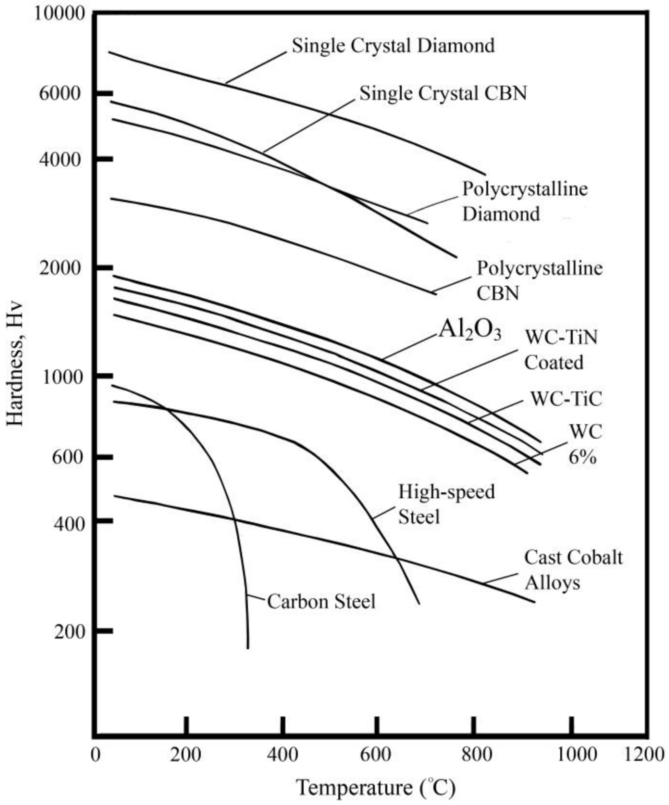

Figure 3, Tool materials hardness at different temperatures [76]

Carbide tools are one of the most used tools in machining difficult-to-cut materials due to their performance and price. It has been reported that 75%-85% of carbide tools used in industry are coated [2, 33]. While the coatings revolutionised the life span of cutting tools, the extent of their effectiveness differ across different manufacturers [2]. Most common tool wear mechanisms in machining difficult-to-machine materials with carbide tools regardless of their coating are, adhesion, diffusion and abrasion.

Different coatings have been introduced in order to improve the cutting tools performance. Figure 4 illustrates the major types of coatings used in industries. While the effect of coatings is still mysterious in machining difficult-to-cut materials, generally coated tool materials perform better than uncoated carbide tools. On the contrary, Hong et al [77] complained the effectiveness of coatings in machining titanium as Al_2O_3 reduces the heat conductivity of the cutting tool and TiC and TiN are reactive to the workpiece material.

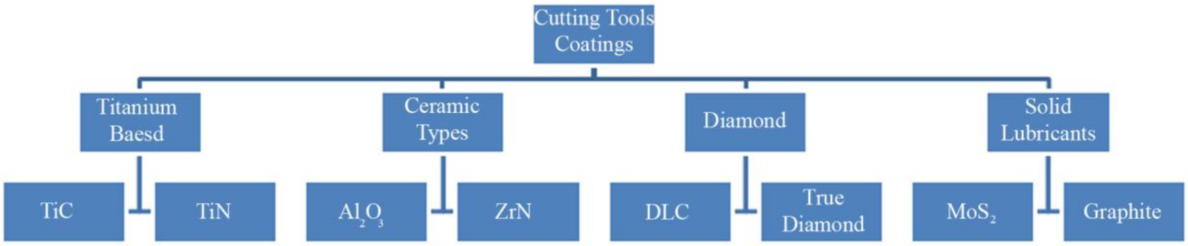

Figure 4, Basic categories of cutting tools coatings and some examples of each category

Excessive research has been conducted to investigate and compare different coatings in machining difficult-to-machine materials [32, 33, 78, 79]. Coatings form a barrier between the cutting tool and workpiece materials preventing the tool material from being exposed. This reduces the diffusion rate and lowers the chemically and thermally induced tool wears such as adhesion and oxidation. Coatings can also enhance the cutting tools performance by altering the friction coefficient, increasing hot hardness, resulting in lower abrasion rate [19]. Krain et al [32] empirically compared the performance of chemical vaporised deposition (CVD) $TiN/Al_2O_3/TiCN$ and physical vaporised deposition (PVD) TiN/TiCN coated WC tools in milling Inconel® 718. The researchers found that the PVD coated tool outperformed the CVD coating in less aggressive (lower cutting speed, feed rate and immersion rate) cutting conditions. Although the CVD coated tool performed better than the PVD coated tools in more aggressive conditions. It has been attributed to the presence of the Al_2O_3 coating layer on the material, which acted as a thermal barrier that preventing carbides from being exposed [32]. López de Lacalle et al. [79] studied different types of coatings in drilling titanium and nickel based alloys and concluded that generally TiAlN coated carbide drills are the most appropriate tools for drilling Ti-6Al-4V and Inconel® 718 alloys.

Ceramic tools are considered as an attractive alternative to carbide tools in machining ferrous alloys [80]. However they are not recommended for machining titanium alloys due to the chemical reactivity between ceramic tools and titanium, low toughness and poor thermal conductivity which causes excessive tool wear at high cutting temperatures [14].

Ceramic tools exhibit high hardness but are very sensitive to mechanical and thermal shocks [21]. The addition of titanium particles and reinforcement with silicon carbide fibres have improved the shock resistance and fracture toughness of the alumina tools which have made them potential alternative for carbide tools in machining nickel based alloys [29].

Machining with ceramic tools is usually conducted under dry condition. It is because ceramic tools are sensitive to thermal shock and have low fracture toughness. The presence of moisture further reduces the fracture toughness of the tool and facilitates crack propagations resulting in excessive notching and catastrophic tool failure [81]. The addition of TiB_2 to the ceramic tool material provides a self-lubricating effect which could lower the forces and improve the tool life in machining carbon steels [82]. At high cutting temperature the TiB_2 grains react with oxygen and form a low friction oxide layer between the cutting tool and chips/workpiece surface. The oxidation process requires high temperature, thus at low cutting speeds oxidation does not take place. The tool wear mechanism at low speed machining of carbon steel material with alumina-titanium boride ceramic tool is reported to be abrasive and adhesive whilst at high speeds it transforms into oxidation [82]. It should be noted that in machining nickel alloys with alumina ceramic tools the tool wear mechanism is notching and attrition while it is diffusion and adhesion in machining titanium [29, 83].

According to table 1 and figure 3 cubic boron nitride (CBN) and diamond based tools demonstrate the highest wear resistance and hot hardness among common tool materials. These properties have made them the most appropriate candidates for machining difficult-to-cut materials. Similar to other tool materials boron nitride particles and carbon particles of CBN and diamond tools respectively are chemically reactive with titanium and nickel which cause serious diffusion wear [29]. CBN tools are conventionally produced from CBN powder in conjunction with a binder material. Thus, the mechanical and thermal properties of CBN tools are highly dependent on the type and quality of the binder material which could be metallic or ceramic [84]. For instance while CBN is not reactive to ferrous materials, cobalt binder of the cutting tool may chemically react with the workpiece and result in diffusion wear [85].

Another type of the CBN tool is binderless CBN (BCBN) which does not have a binder material and so the problems associated with binder materials are eliminated. While the boron nitride component is reactive with titanium and nickel, BCBN tools perform much better than conventional CBN tools in machining titanium alloys [84]. The cutting speed when machining titanium with CBN tools can be as high as 220m/min, which is much higher than that for carbide tools (60m/min) [14].

While diamond tools have the highest wear resistance and hot hardness, they are unstable at temperatures above 700˚C [86]. At high cutting temperature different types of tribochemical and tribothermal mechanisms can affect the diamond tools life. The main tool failure mechanisms in machining with diamond tools are defined by Evans and Bryan [87] as:

- Adhesion and formation of BUE
- Abrasion by micro cleavage, edge chipping and fatigue fracture
- Graphitisation at high temperatures (1800°C in vacuum or inert gas, 1100°C in presence of oxygen and above 1000°C in presence of iron)
- Oxidation at 900°C to 1000°C
- Dissolution and diffusion into the workpiece material
- Catalysed Graphitisation

Despite these problems, polycrystalline diamond (PCD) tools has been reported to be the best candidate for machining titanium alloys credited to their low solubility to titanium, high hot hardness and low tool wear [14, 88].

3 Coolants and Lubricants (CLs)

Shaw [89] defines that one of the main issues that affects machinability is the heat generated during machining. Cutting fluids have been used in machining operations for decades in order to increase the machinability through lubricating the contact areas between rake face and chips, flank face and machined surface and reducing the friction induced heat and removing the generated heat from the cutting zone as a result of severe plastic deformation [1, 2].

Based on the first law of metal cutting developed by Makarow, the highest machinability is achievable at a critical cutting temperature known as optimal cutting temperature (θ_{opt}) which is the temperature that as the highest ratio of the cutting tool hardness over workpiece hardness can be achieved [2]. θ_{opt} is independent of the cutting parameters and machining condition and is based on the material properties of the tool and workpiece materials. Astakhov [2] noted that by increasing the cutting temperature close to θ_{opt}, machinability increases. Although, further increases in cutting temperature beyond θ_{opt} exacerbate the machining condition. Using cutting fluids is one of the most widely adopted techniques to maintain the cutting temperature below the optimal cutting temperature while other techniques such as pre-heating, plasma and ion-beam heating are common to increase the cutting temperature to that of θ_{opt} [2]. The cooling effect of cutting fluids increases tool life by maintaining temperature below the thermal softening temperature of the tool material and decreasing the thermally induced tool wear such as diffusion and adhesion. In addition, the lubrication effect of the cutting fluids could reduce the mechanical wears such as abrasion on the rake face [34]. In contrast, decreases in the workpiece temperature in certain conditions could increase the material hardness therefore increasing cutting forces, power consumption and reducing tool life [90]. Other effects of cutting fluids are flushing chips away and preventing the machined surface and cutting tool from corroding [91]. Maintaining the cutting edge for longer and reducing the heat and friction in machining operations can also lead to improved surface characteristics of the machined parts.

Proper selection of cutting fluids is particularly important as it could affect the tool life, cutting forces, power consumption, machining accuracy, surface integrity etc. For instance cutting fluids with a greater lubrication effect are usually employed in severe machining operations such as low speed machining and machining difficult-to-machine materials. However coolants are more favourable in high speed machining with low cutting forces and high temperatures [91]. Despite the significant effects of cutting fluids in machining, the selection of the type and delivery system of the cutting fluids are usually based on the recommendations of cutting fluid suppliers and machine tool manufacturers which are not necessarily aware of the machining conditions [2].

Substances used in machining for cooling and/or lubrication can be defined as cutting fluids, gas-based coolants/lubricants and solid lubricants [92]. Different approaches have been used in order to classify the cutting fluids due to their wide varying characteristics. One of the widely accepted characteristics of the cutting fluids is their miscibility in water. Thus, it has been used widely in order to categorise the cutting fluids into water-soluble (Water-miscible) cutting fluids and non-water-soluble – also known as oil-based - cutting fluids [90, 91, 93]. In addition, gas-based CLs can also be defined as liquefied gases and gas-form CLs.

3.1 Water Miscible Cutting Fluids

As it was mentioned before, one of the effects of cutting fluids is to remove generated heat at the cutting zone by conduction. Thus, the desired cutting fluid used particularly for cooling should have high thermal conductivity and specific heat [90]. Specifically, water is the most favourable coolant fluid with this characteristics accompanied with low cost. However water is corrosive to ferrous materials specifically used in expensive machine tools [2]. In addition, water has low lubrication effectiveness and tends to wash lubricants used on the sliding and rotating surfaces therefore increasing the machine wear. To overcome these problems and enhance the lubrication properties of water-based cutting fluids, different additives have been added to water [91].

Water miscible cutting fluids are categorised into soluble oil, synthetic and semi-synthetic fluids. Soluble oils consist of a mineral oil accompanied with emulsifiers which allow the oil to be dispersed into the water [93]. The soluble oils have lubrication and corrosion prevention characteristics of mineral oils together with the cooling effect of water. Synthetic fluids are mineral oil free cutting fluids which contains inorganic or organic chemical solutions in order to provide: 1) water softening; 2) corrosion prevention; 3) lubrication; 4) reduction of surface tension and 5) blending.

Synthetic CLs are water-based and contain synthetic water-soluble lubricants, high pressure additives, corrosion inhibitors, biocides, surfactants and defoamer. Synthetic fluids are generally considered as coolants with low lubrication characteristics and are particularly used for low force operations. This poor lubrication characteristic is the major drawback of these CLs which has limited the use of synthetic CLs in industries [2, 90]. Semi-synthetic cutting fluids contain both mineral oils and chemical additives and have both characteristics of soluble oil and synthetic fluids. They are considered of better lubricants when compared to synthetic fluids and are cleaner and more effective in rust prevention than soluble oils.

One of the main problems associated with maintenance of the water miscible fluids is the bacteria and fungi growth in the fluid lowering the fluids service life and increases health hazards. To control the bacteria growth in the cutting fluids, humectants, germicide and bactericide additives may be used [90].

3.2 Oil-Based or Neat-Oil Cutting Fluids

Oil-based fluids are other alternative coolant fluids widely used in most machining operations. They are usually mineral oils which often contains some additives such as other kinds of lubricants and extreme pressure compounds in order to enhance their applications [93]. This type of cutting fluid is used to lubricate the tool-chip interface and thus reduce the friction and friction induced heat at the cutting zone. Reduction in friction can result in lower cutting forces, crater wear on the tool rake face and other types of thermally induced tool wear in certain machining conditions. The application of oil-based fluids also lubricate the moving parts of the machine tool and reduces the corrosion/oxidation on the machined surface and machine tool [90].

The oil-based cutting fluids are classified into two basic categories namely, naphthenic mineral oils and paraffinic mineral oils. The characteristics of these mineral oils are usually enhanced through the addition of fatty lubricants, extreme pressure additives such as chlorine, sulphates and phosphates, friction modifiers, viscosity index modifiers, odorants, thickness modifiers and polar additives [2]. While straight oils provide good lubrication, anti-seizure characteristics and corrosion protection, they cannot maintain their characteristics at higher load and temperatures and make mist and smoke. Thus, the application of straight oils is limited to low duty machining of easy-to-cut metals eg. aluminium, magnesium, brass, low carbon steels, etc. In contrary, compounded mineral oils chemically react with machining surface at high machining pressures and temperatures which makes them favourable for low speed heavy duty machining operations such as threading, broaching, tapping gear hobbing, etc. [2, 90, 91]. This leads to formations of lubricating films between sliding surfaces leading to reductions in friction. It is noteworthy that this chemical reaction should not result in surface degradation. For instance, the presence of chlorine additives in cutting fluids used in machining titanium alloys can cause corrosion on the machined surface and affect the service life of the machined component [22].

3.3 Gas-Based Coolant-Lubricants (CLs)

Gas-based CLs generally refers to the substances that at room temperature are in gas form, however in machining applications they are used in the form of either gas or cooled-pressured fluids. Main gas-based CLs are air, nitrogen, argon, helium or carbon dioxide. The gas-based CLs might be used in conjunction with traditional cutting fluids in the form of mist or droplets to enhance their lubrication capability.

The most broadly known usage of gases as coolants is in dry cutting where air is being used in order to cool the tool and workpiece [90]. However, gases are poor thermal conductors and have low cooling capacity. Different approaches have been used in order to increase the cooling capability of gas-based CLs namely: compressing, cooling and liquefying. Compressed gas-based CLs are especially attractive where traditional cooling techniques fail to penetrate the chip-tool interface, such as heavy duty cutting conditions.

Brandao et al. [94] compared the effect of three different gas-based cooling techniques of dry, compressed air and chilled air on the heat flow through the workpiece during end milling of die steels. The researchers found that the thermal energy transferred to the workpiece reduced by using compressed air and chilled air as compared to dry cutting. In addition, the lowest thermally induced dimensional variations in the workpiece is achieved when using compressed air for cooling.

Gaseous coolants are also beneficial when liquid coolants cannot be applied. In machining medium density fibreboard (MDF) applying chilled air as cutting coolant improves the tool life while not affecting the cutting forces and power consumption. Application of chilled air removes the heat generated at cutting zone effectively and resulted in lower chemical reaction of cobalt binders and tungsten carbide grains of the tool with workpiece material [95].

Hong et al. [77] investigated the effects of different methods of using liquid nitrogen (LN2) as a cutting fluid on tool life when turning Ti-6Al-4V titanium alloy. They found that by applying LN2 on the rake and flank face of the uncoated carbide tool, the tool life could be improved by up to 3.3 times by reducing the thermally induced tool wear and reducing the chemical reactivity of the workpiece material. Other research [96] studied the effect of LN2 on the friction coefficient through the disk-pin sliding test. It has been observed that LN2 can reduce the friction coefficient by changing the material frictional behaviour due to ultra-low temperatures. In addition, it has been proved that LN2 itself is a good lubricant and can reduce the friction coefficient between sliding surfaces. It should be noted that the lowest friction coefficient obtained when freezing the sliding parts together with spraying LN2 between sliding surfaces. This is attributed to formation of a fluid/gas cushion between the tool/workpiece surfaces which results in better lubrication and lower friction coefficient [97].

Adding a small amount of lubricant could reduce the cutting temp and cutting forces. It has been observed that by spraying micro-drops of bio-degradable oil in air the tool flank wear has been reduced by up to 44% in high speed milling of low carbon steels. Application of oil spray into the machining zone also reduces the cutting temperature and forces [98].

Gaseous CLs such as CO2, argon, nitrogen and helium also provide an inert environment which could prevent the cutting tool and machined surface from oxidation at high cutting temperatures.

3.4 Economical, Environmental and Health Issues Associated with Coolants and Lubricants

It is approximated that yearly consumption of cutting fluids in the United States is 100million gallons while it was equal to 71bn Japanese Yen in Japan where 42bn Yen is the disposal cost [99]. In 1994, the cutting fluids consumption in manufacturing industries in Germany was estimated to be 75,491 tons which 28,415 tonnes of it was water-miscible cutting fluids [100]. It is estimated that the costs associated with cutting fluids are about 16% of the total manufacturing costs [101] while in machining difficult-to-machine materials they reach 20%-30% [102]. This is much higher than the tooling costs which are about 2-4% of the total manufacturing cost [100].

The associated costs with cutting fluids is not only limited to their purchase and preparation but also include the maintenance and disposal costs. Disposal costs of the cutting fluids can be up to two or four times their purchase price in the United States and Europe respectively [103]. This is mainly due to the fact that most cutting fluids are not naturally bio-degradable and require expensive treatments prior to disposal [103]. This issue has been supported through the introduction of restricted environmentally conscious regulations such as the Control of Substances Hazardous to Health (COSHH) essentials for machining with metalworking fluids in the UK [104], the technical code of practice for hazardous substances (TRGS) in Germany and the Decree 259/1998 of 29 of September in Spain [98]. It is noteworthy that 155million gallons of used cutting fluids are discharged into the environment yearly only in the United States [105].

Cutting fluids require regular maintenance in order to control their optimum characteristics. They are a rich environment for growth of bacteria and fungi. Presence of bacteria in the cutting fluids could split the emulsion and reduce the lubricity of the fluids. They could also change the PH of the cutting fluid and increase the risk of corrosion on the machine tool and workpiece. In addition, they could be especially dangerous for the workers on the shop floor [105]. To control the bacterial growth in cutting fluids different kinds of bactericides, humectants and germicides are currently in use in industries. Although studies revealed that while PH of cutting fluids exceeds 10, some bacteria known as extremophiles could live and grow in such extreme environments [106]. Even in the presence of bactericides it has been proved that some bacteria such as Pseudomonas could survive [107]. The presence of the bacteria is not limited to the cutting fluids and microbial masses and particularly endotoxin have been evident at the shop floor atmosphere. This increases the importance of controlling the bacterial growth in metal working fluids.

While chemicals additives are necessary to control the bacterial growth in cutting fluids, they are accounted as hazardous substances for both the environment and workers health. Discharge of cutting fluids containing biocides could affect the natural decomposition process and some municipalities prohibited the disposal of biocides into the sewage systems [105]. It has been argued that antimicrobials and biocides are used to maintain the cutting fluids functionality rather than protect the workers. Many of the available biocides release formaldehyde which is a potential carcinogen. Similarly The International Agency for Research on Cancer reported that mineral oil used in metal workings is carcinogenic and exposure to it could result in occupational skin cancer [108]. On the other hand, non-formaldehyde releasing biocides are very dangerous for health and highly corrosive to the skin [105].

In addition to biocides, there are many other chemicals in the cutting fluids which are considered hazardous to the environment and health. Chlorinated and sulphurised additives in extreme pressure cutting fluids chemically react with metallic surfaces resulting in formation of a low friction protective film between the sliding surfaces. However they are considered as toxic substances for workers health as well as the environment [96]. Chlorinated paraffin in extreme pressure cutting fluids changes by heat and pressure to dioxin which is a toxic substance. The existence of chlorine in cutting fluids also increases the disposal costs by a factor of 7 due to restricted environmental regulations [99].

Cutting fluids in machining operations could be vaporised and atomised due to high pressure and temperature and form cutting fluids mist. As a result the airborne particles of cutting fluids could be easily inhaled by workers causing different kinds of lung diseases ranging from mild respiratory problems to asthma and several types of cancers. The effect of aerosols of the cutting fluids on the workers' health is not limited to the lung disease and could also increase the risk of esophagus, stomach, pancreas, prostate, colon and rectum cancers.

Some manufacturers use cutting fluids in order to reduce the machining solid dust. However it has been found that wet machining could produce 12-80 times more airborne particulate matter than dry cutting [109]. In addition, airborne particles produced at wet machining are much smaller than that of dry cutting. Smaller particles could remain suspended longer in the working area and are easier to inhale. They are also more likely to pass the larynx and penetrate into the conducting airways and bronchial part of the lungs. Skin exposure to the cutting fluids could also cause skin dermatitis. In Finland in 1993, registered cases on occupational dermatoses formed the fourth most common work place disease after musculoskeletal disease, hearing loss and disease caused by asbestos and counted as 16% of all registered occupational diseases [110]. Some types of allergens in the water-miscible oils are coconut diethanolamide, tertiary-butylhy-droquinone, alkanolamine borates, oleyl alcohol, bronopol, etc. cutting fluids induced dermatitis ranges from ugly rashes to malignant cancer [103].

In contrast to the conventional cutting fluids, gaseous CLs are relatively cleaner and more environmentally friendly. However they are generally known to be more expensive alternatives than cutting fluids which require additional equipment which normally are not provided with machine tools [111]. In addition, gas-based CLs cannot circulate in the machine tool and thus they are not reusable in the system as they vaporise after application [112, 113]. This on the other hand eliminates the disposal costs and cost associated with cleaning the parts, machining chips and machine tools [46].

While nitrogen is lighter than air and can be dispersed into the atmosphere, when using CO2 as coolant there is a requirement for ventilation over the machining zone. This is due to the fact that CO2 is heavier than air and accumulates at the shop floor increasing the risk of oxygen depletion [114]. To conclude, while gas-based CLs are considered to be more environmentally friendly solution for machining operations, there is not any gas-based and particularly cryogenic system which is economical and practical enough to replace current conventional techniques [77].

4 Environmentally conscious machining

As mentioned previously using cutting fluids in the cutting operations becomes a major problem due to the associated economical, environmental and health problems. The best approach to eliminate the effects of cutting fluids is to eliminate their usage completely which is known as dry cutting [100]. However dry cutting is not applicable in all machining operations mainly due to excessive tool wear or low surface quality. In order to improve machinability a minimum quantity lubricant (MQL) could be penetrated into the cutting zone. Although MQL reduces the CLs consumption, it still uses them in the form of mist or droplets which increases health hazards for the workers [76]. Another alternative is to use cryogenic coolant in order to dissipate the generated heat at the cutting zone and enhance the machinability through the changes in cutting tool/workpiece material properties. In this section different issues and achievements to eliminate or reduce the consumption of cutting fluids in machining are reviewed through three different methods, namely 1) Dry machining; 2) MQL and 3) Cryogenic Machining.

4.1 Dry Cutting

Dry machining is considered as the best approach to eliminate the use of cutting fluids in manufacturing enterprises and thus reduce the machining costs and ecological hazards [100, 115] Weinert et al. [68] identified the benefits of adopting dry machining which are shown in figure 5. It is known that employing cutting fluids can improve tool life, prevent built up edges (BUE) from forming on the cutting tool and reduce the cutting forces and surface roughness. On the contrary, in dry machining friction and cutting temperature could be more than that of wet machining. These could reduce the tool life, reduce the surface quality and cause thermally induced geometrical deviations in the machined part. However, this is not the case for all materials and machining operations and dry cutting shows positive effects such as lower thermal shock and improved tool life in some cases [76, 100].

Techniques employed by researchers to compensate the effects of the elimination of cutting fluids in machining could be categorised into i) indirect heat dissipation and ii) improving cutting tools properties by introducing better tool materials, coatings or tool geometries. This has led to the introduction of advanced tool materials such as Cubic Boron Nitride (CBN), Polycrystalline Cubic Boron Nitride (PCBN), Polycrystalline Diamond (PCD), cermets, ceramics and different kinds of coatings.

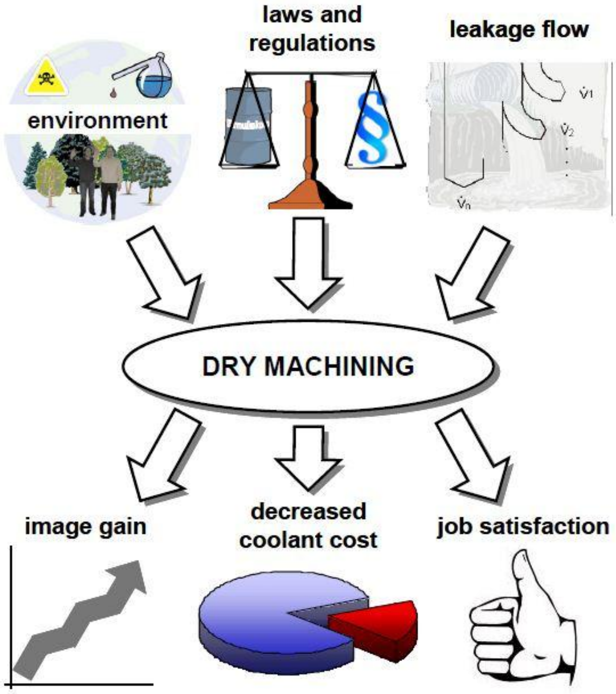

Figure 5, benefits of adopting dry machining [68]

It is known that an increase in cutting speed results in higher cutting temperature. Higher cutting temperatures could reduce the workpiece material strength and thus result in lower cutting forces. Although, high temperatures can also reduce the hardness of the cutting tools and result in excessive tool wear. In addition, higher temperatures at the cutting zone increase the risks of adhesion and diffusion wear due to the higher chemical reactivity of the workpiece and cutting tool materials at higher temperatures. Lenz et al [1976. In: 100] studied the effects of cutting speeds on tool wear of uncoated tungsten carbide tools in machining carbon steels. Investigations revealed that at low cutting speeds the dominant flank wear mechanism is abrasion which changes to adhesion at higher cutting speeds. Further increases in the cutting speed changes the dominant wear mechanism to diffusion. Thus an increase in the cutting speed to a certain point could result in lower flank wear by changing the wear mechanism from abrasion to adhesion.

Tool wear and the failure mechanisms of different tool materials were investigated by Dearnley and Grearson [18] during turning Ti-6Al-4V alloy. Their experimental studies revealed that the main tool failure mechanism was diffusion on the rake face resulting in excessive crater wear. This is attributed to high and localised temperature at the chip-tool contact on the rake face and high chemical reactivity of the workpiece material. CBN tools performed better than other ceramic and carbide tools by showing a lower and smoother tool wear. In addition, studies showed that the straight grade carbide tools with finer grain size pose lower tool wear than that with larger grain size or steel grade.

Ginting and Nouari [20] investigated the applicability of dry end milling of Titanium alloy Ti 6242S with uncoated alloyed carbide tools. They used an uncoated tungsten carbide with cobalt binders alloyed with 20.7 wt% of (Ti/Ta/Nb)C. The investigations were limited to the study of chip formations, tool wear, cutting temperature and surface finish of the machined part. Observation of the worn tools after machining under the scanning electron microscope (SEM) revealed that localised flank wear was the dominant tool failure mode. Brittle fracture of the cutting edge accompanied with localised flank wear was reported to be the second most observed tool failure mode.

In contrary to the observations of Dearnley and Grearson [18] in the study by Ginting and Nouari [20] the tool did not suffer from excessive crater wear. This could be explained by the fact that in continuous machining such as turning, temperature at the cutting zone is much higher than that of intermittent cutting operations. This high temperature facilitates the adhesion of the chip to the rake face of the cutting tool. The adhered material is then torn off by the flow of the chips. In addition, at high temperatures the cutting tool material diffuses into the chips at the tool-chip interface. Thus abrasion and diffusion due to high cutting temperature are responsible for crater wear on the rake face of the cutting tool in turning [20]. The researchers [20] concluded that uncoated alloyed carbide tools with properties as specified before are suitable for dry end milling of titanium alloys with the following machining parameters: cutting speed> 150m/min, feed rate = 0.15 mm/tooth, 2mm of axial depth of cut and 8.8mm radial depth of cut. These machining parameters result in 11.3min tool life and 0.61µm surface roughness. In addition, experimental investigations proved that FEA could effectively model the dry end milling operations.

Krain et al. [32] studied the effects of machining parameters in end milling operation of Inconel® 718 nickel based alloy in order to gain higher productivity through optimising the material removal rate. Generally, adhesion and attrition was found to be the main tool wear mechanism due to high cutting pressure and chemical reactivity of the tool and workpiece materials. Low thermal conductivity of Inconel® 718 leads to high local temperature at the cutting zone which facilitates the wear mechanisms. At high cutting temperatures the workpiece material is adhered to the tool and forms a BUE on the flank face. Experiments revealed that immersion rate (percentage of radial depth of cut) controls the effect of feed rate on the tool life and material removal rate. While higher immersion rate reduces the machining time, it was found that optimum material removal rate was achieved at immersion rates of 25% and 50%.

As mentioned previously one of the requirements to move toward dry cutting is enhanced cutting tools. In this regard tool coating is considered as a technique to apply the characteristics of several materials on the surfaces of the cutting tools. These nanostructured materials may enhance the characteristics of the cutting tool by providing different properties such as higher hardness, higher strength, higher Young's modulus, higher wear resistance, higher fracture toughness, higher chemical stability and reduced frictional behaviour [78]. In addition to machining parameters, Krain et al [32] compared the tool life of two different types of coatings in machining Inconel® 718. Empirical evaluations illustrated that PVD TiN/TiCN coated tungsten carbide tool performed better at less aggressive cutting conditions. At more aggressive cutting conditions CVD TiN/Al_2O_3/TiCN coated carbide tool outperformed the PVD coated tool. This is mainly attributed to the existence of a thermal barrier of Al_2O_3 which prevents the tungsten-carbide particles to be exposed [32].

Generally, coated tools perform better than uncoated tools in dry machining through the three mechanisms of i) increasing the tool hardness; ii) preventing the tool material to be exposed; iii) reducing the friction coefficient. In another experiment [78] the effect of multi-layer solid lubricant (MoS_2/Mo) coated high speed steel (HSS) drill tools was compared with an uncoated drill in machining Ti64 workpiece material. The uncoated drill was tangled into the workpiece as a result of constant increase in torque during machining. On the other hand, 33% reduction in the cutting torque was observed when using the coated drill with no evidence of catastrophic fracture or seizure.

It has been studied [88] that PCD (SYNDITE) tools outperform PCBN (AMBORITE) and CVD TiN/TiCN/TiC triple coated carbide tools in dry turning of Ti48 titanium alloy. This is mainly attributed to the chemical reaction between carbon substrates of the tool material and titanium and formation of a TiC layer. This TiC layer protects the cutting tool from abrasion and reduces the diffusion rate increasing tool life. It could be concluded that chemical reactions between tool and workpiece materials could increase the tool life by the formation of a protective layer.

Liu et al [85] investigated the effect of adding aluminium to pearlitic cast iron on its machinability with CBN tools. They found that addition of Al could result in the formation of a harder protective layer of aluminium oxide on the tool surface. This layer protects the cutting tool from abrasive wear and makes it possible to increase the cutting speed up to 4500 m/min. In most cases the lower tool wear also reduces the cutting forces and surface roughness as the cutting edge remains sharp for a longer period. It is noteworthy to mention that in machining titanium alloys, generally the dominant tool wear mechanism is adhesion and diffusion on the rake face and adhesion and abrasion on the flank face [13, 88]. Excessive crater and flank wear could weaken the cutting edge resulting in plastic deformation and even premature tool failure. Another characteristic associated with machining titanium alloys is that crater wear is usually narrow and formed closely to the cutting edge, which is due to a small contact area between tool and chip [13].

It is known that an increase in the cutting temperature can soften the workpiece material and ease the cutting operation. Studies [29, 84] show that higher cutting speed results in higher cutting temperature which could lower the cutting forces and increase the tool life. However in machining high chemically active materials such as titanium and nickel based alloys high temperatures at the cutting zone is critical. High cutting temperatures increase the chemical reactivity of the tool/workpiece material resulting in excessive tool wear, due to adhesion, diffusion and attrition. Also, while these materials maintain their hardness even at high temperatures, the tools may fail by material softening. Specifically the hardness of Inconel® 718 increases with increase in temperature up to 650˚C. In other words, an increase in the cutting speed when the cutting zone temperature is lower than 650˚C, increases the material hardness and results in more difficult machining condition [29]. Further increases in the cutting speed and thus cutting temperatures above 650˚C lead to lower material hardness and cutting forces resulting in chips changing from segmented to continuous. However cutting temperatures higher than 1100˚C would lead the cutting tool to suffer from heat softening. For instance in end milling Inconel® 718 with a K10 grade of carbide tool it has been observed that increasing the cutting speed up to 113.1 m/min resulted in lower cutting forces and tool wear. Further increase in the cutting speed has led to the welding of chips to the cutting tool retarding the chip flow and increasing the cutting forces [29].

One of the problems in machining with CBN tools is the chemical reaction between binder and workpiece material which reduces the tool strength. It is more obvious in machining ferrous alloys where boron nitride particles are not chemically active with ferrous particles. Studies [85]on the CBN tools with different binder materials in machining ferrous alloys show that CBN tools with TiC or Cobalt binders perform better than their counterparts with TiN and TiCN binders. On the other hand, in machining titanium alloys CBN particles are highly reactive with the workpiece material at high cutting temperatures.

Experiments [84] in machining Ti64 with binderless CBN (BCBN) tools revealed that the highest material removal rate and tool life could be achieved through combining high cutting speed and low feed rate and depth of cut. High cutting speed increases the cutting temperature and reduces the workpiece material strength where BCBN could maintain its hardness. Dominant tool wear in this condition is adhesion and diffusion of the workpiece material into the flank face resulting in non-uniform flank wear. Unlike what was reported [13, 88] about the tool wear when using CBN or carbide tools, the crater is not significant on the BCBN tool and does not affect tool life [84].

Another technique in enhancing the properties of conventional cutting tools is cryogenic treatment [116-119]. The hardness and wear resistance of the metals which contain retained austenite could be improved by this technique [120]. As cryogenic treatment affects the whole material properties, unlike coating it preserves its properties after re-sharpening or regrinding [121]. Sreeramareddy et al [120] reported that cryogenic treatments increased the thermal conductivity and reduced the tool wear of multilayer coated carbide tool as compared to non-treated tools. Increased thermal conductivity resulted in lower temperature and better heat dissipation capability of the tool. This reduces the thermally induced tool wears such as adhesion and diffusion. It should be noted that while cryogenic treatment reduced the hardness of the material at the room temperature, it increased the hot hardness of the tool material [120].

In machining operations the major portion of energy used transforms into heat. In the absence of cutting fluids in dry machining the generated heat should be dissipated by conduction through the chips, workpiece and cutting tool. An alternative to enhancing the heat conduction is indirect cooling of the cutting tool and/or workpiece by using heat pipes [122, 123], coolant through tools [123, 124], cooling the workpiece [125-127], etc.

Jen et al [123] investigated the feasibility of manufacturing and using heat pipes with coolant fluid through the heat pipe for HSS drills. FEM analysis and experimental investigations illustrated that this method has the potential to reduce the cutting temperature up to 50%. However the application of this method is limited due to geometrical restrictions of cutting tools and manufacturing difficulties. Empirical studies [122] also revealed that using a brass heat pipe integrated tool holder in turning engine crank pins with CBN tool can reduce the cutting temperature by 25˚C. This is equal to a 5% reduction in the cutting zone temperature which resulted in up to 9% reduction in the tool flank wear.

4.2 Minimum Quantity Lubricant (MQL)

Minimum Quantity Lubricant (MQL) or near dry machining is another alternative to conventional flood coolant. It also provides an alternative for machining operations which dry machining is not applicable especially where machining efficiency and/or high surface quality are of more interest [128]. Based on the recommendations by Klocke et al [129] table 2 provides a comparative application of MQL and dry machining for some materials in different machining operations. MQL is referred to as the application of a small amount of cutting fluid (10 to 100ml/h) mixed with compressed air to form an aerosol [130]. This mixture is then penetrated to the cutting zone in order to lubricate the chip-tool contact area and reduce the temperature. Boundary lubrication on the contact surfaces results in a lower friction coefficient whilst heat transformation is mainly in the form vaporisation at the cutting zone and conduction through the flow of the air. Evaporation of the CL at the cutting zone eliminates the requirements for maintenance, circulation and disposal of the cutting fluid and the associated costs [130, 131].

Today, there are many companies involved in the production of sophisticated MQL systems for machining operations. UNIST Inc. claimed that its first MQL system named uni-MIST® was designed and patented in 1957 at Grand Rapids, Michigan based on the concept of low volume and low pressure lubrication [132]. Further developments of the system have resulted in the current cutting edge MQL facilities of through-the-tool cooling systems, MQL flow control systems, atomisers, etc. Other major companies in the area of MQL are Accu-Lube, Bielomatik GmbH, MAG, Menzel Metallchemie GmbH.

Most of the commercial products available in the market consist of five main parts namely, air compressor, CL container, tubings, flow control system and spray nozzles. Generally, in all MQL systems, the coolant and pressured air are mixed together and a controlled flow of the mixture is delivered through the tubings and nozzle into the cutting point. The nozzle could be external or internal which is also known as a through-the-tool cooling/lubricating system. Figure 6 provides a schematic view of a typical MQL system developed for turning operations while figure 7 demonstrates a through the tool MQL cooling system for face-milling operations.

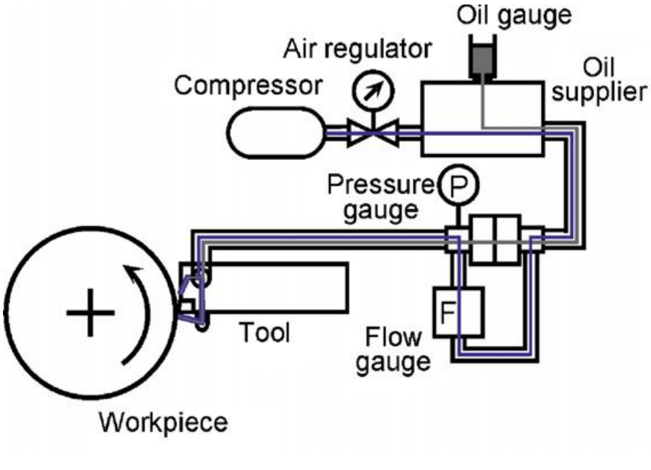

Figure 6, schematic view of the components of a MQL system developed by Kamata and Obikawa [133]

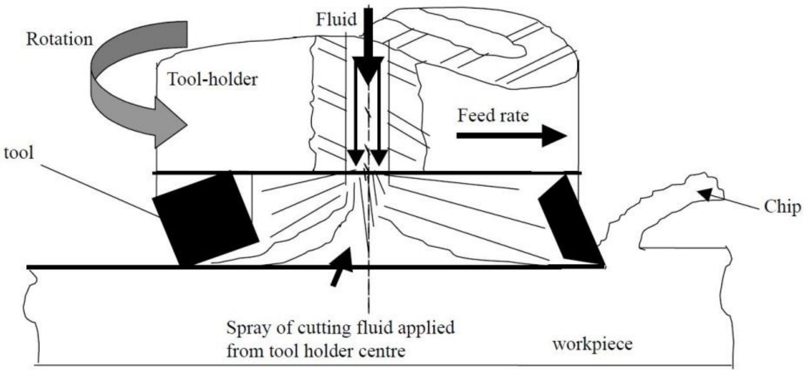

Figure 7, schematic view of a through-the-tool MQL cooling system designed by Sales et al. [131] for face-milling

As mentioned previously, MQL is introduced where dry cutting is not applicable and flood cooling is not desirable. Machining ductile materials is one of these cases where high cutting temperature increases the tendency of adhesion between the cutting tool and workpiece materials. The high cutting temperature in the case of ductile materials is mainly due to large plastic deformation at the primary cutting zone and high friction coefficient at the second shear zone between the chips and rake face. This high temperature increases the adhesion of the chip material to the cutting tool resulting in the formation of BUE. The presence of BUE on the cutting tool in most cases not only reduces the tool life but also worsens the machined surface quality [98]. For instance dry machining of aluminium alloy parts is specifically critical. Heat generated during machining transforms into the workpiece due to its high thermal conductivity. Changes in the workpiece temperature during machining could cause thermal deformation and/or geometrical deviations. Aluminium alloys also tend to adhere to the cutting tool and form BUE. This affects the surface finish of the machined part as well as tool life, cutting forces and power consumption [115]. Studies on the application of MQL in drilling aluminium alloys showed that it could drastically increase the tool life up to 8 times [100].

In high speed milling of A380 wrought aluminium, applying a very small amount (0.06ml/hr) of biodegradable oil in the form of micro droplets in the flow of compressed air can reduce the tool wear and eliminate the BUE. Experiments [98] showed that 0.04ml/hr to 0.06ml/hr of lubricant if sprayed in a suitable area could reduce the tool wear by up to 40% as compared to conventional emulsion cooling. This amount of lubricant is much lower than stated in most other studies [128, 130] and as the difference between tool life at 0.04ml/hr and 0.06ml/hr MQL is not significant 0.04ml/hr is more desirable as lower amounts of lubricant are used. The technique described by López de Lacalle et al. [98] not only enhanced the tool life but also reduced the consumption of cutting fluids by 95%.

Yuan et al [134] studied the effect of air temperature in MQL milling of Ti64 titanium alloy. They used 20ml/hr of synthetic ester oil in the flow of air at different temperatures of 0˚C, -15˚C, -30˚C and -45˚C compared to MQL at the room temperature, dry and flood cooling. Formation of BUE was observed under dry, wet, MQL at room temperature and MQL at 0˚C. They noticed that the workpiece material became harder at very low air temperatures of -30°C and -45°C which resulted in higher cutting forces as compared to that of dry machining. The longest tool life and lowest surface roughness were achieved under a MQL environment with an air temperature of -15˚C. Application of MQL at -15˚C increased the tool life by the factor of three by eliminating the formation of BUE on the cutting tool while not affecting the workpiece material hardness.

Modifying cutting tools and tool holders is a method widely used to deliver cutting fluids to the desired point of cutting e.g. tool tip, rake face and/or flank face [130, 133, 135, 136]. Specifically in MQL turning operations these modification is used to focus the flow of the air on the rake and/or flank face of the cutting tools. Sharma et al [130] reported that MQL flank face cooling has resulted in longer tool life and lower surface roughness in comparison with dry and MQL rake face. It is because the cutting fluid cannot reach the tool-chip interface when it is sprayed on the rake face [130].

In machining AISI 1045 steel, it was found [135] that application of MQL does not have a significant effect on the cutting zone temperature. It is because the coolant is penetrated between the flank and machine interface which is far away from the highest temperature zone at the cutting edge. Study of the cutting forces [136] showed that spraying the coolant on the flank wear reduced the cutting forces significantly. It illustrated that in machining AISI 1045 steel with uncoated carbide tools the effect of penetrating a small amount of cutting fluid with compressed air is more lubricating rather than cooling. On the contrary, Kamata and Obikawa [133] pointed that in machining Inconel® 718 the cooling effect is more significant than lubrication. It has been found that changing the lubricant carrier gas from air to argon reduces the tool life to that of dry cutting or even lower. This is attributed to the lower heat conductivity, specific heat and lubricating capability of argon in comparison with air. Kamata and Obikawa [133] investigated the effect of MQL in turning Inconel® 718 with carbide tools with different coatings. It was found that while the longest tool life was achieved by TiCN/Al2O3/TiN coated tool, the lowest surface roughness was produced by the TiN/AlN coated tool. This could be explained by uniform wear and an increase in the radius of curvature of the worn edge of TiN/AlN coated tool.

As mentioned before, the MQL method is considered as a lubricating method rather than cooling. This poor cooling capability limits the effectiveness of MQL in machining difficult-to-machine materials such as titanium and nickel based alloys where excessive heat generation is the main problem [137].

Table 2, application areas of dry and MQL for some types of materials [129]

Material	Aluminium		Steel		Cast Iron
Process	Cast alloys	Wrought alloy	High alloyed bearing steel	Free cutting, quenched and tempered steel	GG20 to GG70
Drilling	MQL	MQL	MQL	MQL/DRY	MQL/DRY
Reaming	MQL	MQL	MQL	MQL	MQL
Tapping	MQL	MQL	MQL	MQL	MQL
Thread forming	MQL	MQL	MQL	MQL	MQL
Deep hole drilling	MQL	MQL	■	MQL	MQL
Milling	MQL/DRY	MQL	DRY	DRY	DRY
Turning	MQL/DRY	MQL/DRY	DRY	DRY	DRY
Gear milling	■	■	DRY	DRY	DRY
Sawing	MQL	MQL	MQL	MQL	MQL
Broaching	■	■	MQL	DRY	DRY

4.3 Cryogenic Machining

Cryogenic machining is a term referred to machining operations conducted at very low temperatures typically lower than 120˚K [138]. Although there are some references where the cryogenic term is used for higher temperatures [134, 139]. In cryogenic machining a super cold medium, usually liquefied gases, is directed into the cutting zone in order to reduce the cutting zone temperature and cool down the tool and/or workpiece. The cryogen medium absorbs the heat from the cutting zone and evaporates into the atmosphere. As most cryogenic coolants used in machining operations such as liquid nitrogen and liquid helium are made from air, they are not considered as pollutants for the atmosphere. Nitrogen in particular is an inert gas which forms 78% of the atmosphere and is lighter than air. As a result it is dispersed into the atmosphere and does not harm the workers on the shop floor. On the contrary carbon dioxide is considered as an air pollutant, however it has been suggested [140] that liquid carbon dioxide could be produced from the exhaust gases of power plants thus not forcing additional contamination to the atmosphere. It is noteworthy that carbon dioxide is heavier than air and could cause CO_2 accumulation and oxygen deficiency problems on the shop floor [114].

Cryogenic machining is usually accompanied with changes in the properties of the workpiece and/or cutting tool materials, as a result of lowering the temperature. Ultra-low temperatures could increase the strength and hardness, and lower the elongation percentage and fracture toughness of materials. Cryogenic cooling could be beneficial for machining materials which at room temperature have large elongation to fracture percentage, low elastic modulus and are very ductile such as elastomers [57, 59, 60]. In addition, increases in the hardness of the cutting tool materials could enhance their wear resistance and improve the tool life [103, 141]. The cooling effect of the cryogens are particularly interesting in machining difficult-to-machine materials that suffer from excessive tool wear mainly due to high cutting temperatures such as titanium and nickel based alloys . Common cryogenic coolants used in machining operations are liquid nitrogen (LN2), liquid carbon dioxide (LCO2), solid carbon dioxide (dry ice), liquid helium and air (usually temperatures above -50˚C).

Spraying cryogenic coolant at the cutting zone could reduce the chip-tool interface temperature and thus reduce the chemical reaction between the cutting tool and chips [142, 143]. This reduces the adhesion and diffusion wear of the cutting tool hence increase the tool life [144]. Elimination of BUE as a result of lower temperature could also increase the surface finish of the machined part [86, 113, 142]. Lower chemical reactivity also makes it possible to machine materials with cutting tools which are highly reactive at high temperatures. For instance machining ferrous materials with diamond tools usually results in high tool wear due to chemical reaction between steel and carbon particles of diamond tools and graphitisation. Machining at -196˚C using LN2 reduces both chemically and thermally induced tool wear in machining stainless steel components and significantly increases the tool life [87]. Similarly spraying LN2 at the cutting zone reduces the chemical reactivity and thermally induced tool wear between a titanium alloy workpiece and carbide tools [114, 145, 146]. For instance, as shown in figure 8, Venugopal et al. [147] reported that applying LN2 as a coolant in turning Ti-6Al-4V alloy resulted in 77% and 66% reduction in crater and flank wear respectively as compared to dry machining. Cryogenic cutting environment could also increase the strength and hardness of the workpiece material hence increasing the cutting forces [103]. Higher cutting forces could reduce the tool life, increase vibration and chatter and thus surface roughness. This flourishes the importance of the cooling strategy for machining different workpiece/tool material pairs as they might react differently to the low temperatures [141].

Application of cryogenic coolants specifically LN2 could drastically increase the tool life and allow higher speeds [86, 102, 143, 148]. It has been proved [96] that some cryogenic coolants such as LN2 do not only act as a coolant but has good lubrication characteristics. LN2 could be penetrated between the tool-chip interface and produce a gas/liquid cushion which reduces the friction at second shear zone [97, 149]. Very low temperature also increases the surface hardness of the sliding materials which could alter the coefficient of friction and friction forces resulting in enhanced machining condition [96, 113].

Air Products Inc. and MAG IAS LLC are two pioneering companies in the area of cryogenic machining. ICEFLY® is the first commercial equipment developed by Air Products for cryogenic turning which delivers liquid nitrogen into the cutting zone. The MAG cryogenic milling system delivers liquid nitrogen through the CNC milling machine tool's spindle to the cutting zone. The latter has been recently approved by the US government to be used in the production line of the Lockheed Martin's F-35 Lightning II stealth fighter [150].

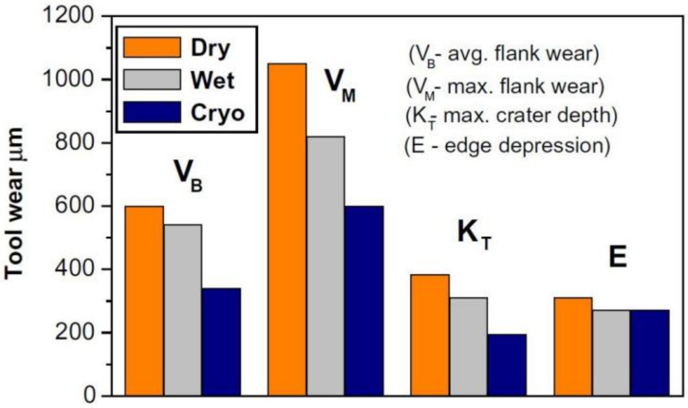

Figure 8, comparison of tool wear in turning Ti-6Al-4V alloy with carbide tools under different machining environments [147]

4.4 Air Cooling

Employing chilled and compressed air for cooling in machining operations is a relatively new technique which has attracted many researchers [5, 94, 95, 112, 139, 151, 152]. As in this technique the cooling media is air, it could be defined as the cleanest and most environmentally friendly method of cooling in cutting operations. Most studies [5, 137, 139] indicated that using chilled air as coolant in machining resulted in longer tool life. The effect of chilled air on the surface finish is highly dependent on the machining parameters. In general it could be claimed that air cooling produces lower surface roughness than dry cutting. However, the produced surface roughness is higher than that made by MQL or emulsion coolant [134, 137, 153].

Liu and Kevinchou [151] studied the effects of chilled air produced by a vortex tube in turning A390 aluminium with an uncoated WC tool. Studies showed that at the cutting speed of 5m/sec and feed rate of 0.055 mm/rev chilled air reduced the flank wear by 20%. In addition the cooling system was found to be effective in reducing the tool-chip contact temperature up to 7%. Furthermore, employing chilled air as a coolant reduced the cutting forces during the operation mainly due to reductions in adhesion and BUE at the cutting edge. However, it should be noted that the effectiveness of the system on the tool life is highly dependent on the process parameters. It could be explained by the fact that in machining A390 aluminium the main tool wear mechanism is abrasion by hard and abrasive silicon particles in the material structure which is not a thermally controlled parameter. Rahman et al [153] reported that in end milling AISI P-20 steel with uncoated WC tool machining at -30°C produced lower surface roughness than flood cooling only at higher feed rates. Whilst at the feed rate of 0.01mm/tooth chilled air cooling produced the highest surface finish, increase in the feed rate reduced the surface finish where at the feed rate of 0.02mm/tooth chilled air resulted in the lowest surface roughness irrespective of the cutting speed.

Kim et al. [112] declared that while using chilled air increased the tool up to 3.5 in machining hardened steel with TiAlN coated WC, no significant changes has been observed in machining Inconel® 718 at high cutting speeds. Although at low cutting speeds the tool machined 2.2m of the workpiece material using chilled air compared to 1.4m in dry machining. This could be explained by poor thermal conductivity of air where at high cutting speeds the generated heat surpasses the cooling effect of the chilled air. A similar effect was observed by Sun et al [5] where they used cryogenically cooled air and compressed air in turning Ti64. They also found that while chilled air cooling increased the cutting forces, the average cutting forces reduced in comparison with dry machining due to reduction in the tool wear. They reported that in dry machining cutting forces along the x, y and z axes increased by 54%, 41%, 23% respectively, while it was 30%, 16% and 6% for compressed air and 17%, 7%, 4% for cryogenically cooled air. However, studies revealed that this is not the case in milling operations.

In order to improve the cooling effect of MQL some researchers [134, 137, 152] have integrated chilled air and MQL. Yuan et al. [134] stated that by using chilled MQL the tool life increased by a factor of three in machining Ti64 using uncoated WC cutting tool. In addition, they noted that the best results in terms of tool life and surface roughness was achieved by using MQL at the temperature of -15°C compared to dry, wet, MQL at 0°C, -30°C and -45°C. Su et al [137] declared that chilled MQL produced lower surface roughness as compared to chilled air and dry conditions in machining Inconel® 718 using TiAlN coated WC tool. They found that the dominant tool wear mode regardless of cutting environment was nose wear. Thus the enhancement in the surface roughness was attributed to the increase in the tool wear resistance by using chilled MQL. They reported that respectively 78% and 124% increase in the tool life has been achieved by using chilled air and chilled MQL in comparison with dry cutting. Yalcin et al [139] stated that dry machining of ductile materials is not favourable as it does not provide acceptable tool life and surface finish. They recommended chilled air as an environmentally friendly and cheap alternative to conventional flood cooling.

5 Critique and Research Gaps

In this section the findings of the review of difficult-to-machine materials and their properties together with coolants commonly used in material cutting operations are critiqued. In addition, the problems associated with the use of conventional coolants and different techniques to reduce or eliminate the use of conventional cutting fluids in material cutting are discussed. Furthermore, the areas which require more study and investigation are identified.

5.1 Difficult-to-Machine Materials:

Review of the literature on the machining of hard-to-cut materials revealed that there is no standardised format to categorise difficult-to-machine materials and their definition is still vague. Based on findings in the literature the author has classified the difficult-to-machine materials into three categories namely: hard materials, ductile materials and non-homogeneous materials. This classification and its sub-categories are demonstrated in figure 9. While advances in the metallurgy of engineering alloys have led to an improved service life of the components, they have resulted in difficulties in their machinability. The main properties to consider these materials as hard to machine, are high hardness and strength together with poor thermal conductivity which can result in short tool life, low productivity and poor surface quality [8, 13, 19]. On the other hand another category of materials such as polymers and low carbon steels which are considered to be difficult-to-machine exhibit high ductility and elongation percentage. The main problems in machining these materials are the chip formation, geometrical accuracy and surface quality of the machined components [37, 60, 154]. Composites are also known as difficult-to-machine materials due to short tool life and/or poor surface quality. This is mainly attributed to the fact that composites are made of a combination of different materials with different properties which are neither homogenous nor chemically combined. Thus defining the cutting parameters to deal with the characteristics of all materials, individually within a composite material and the whole composite together is very difficult.

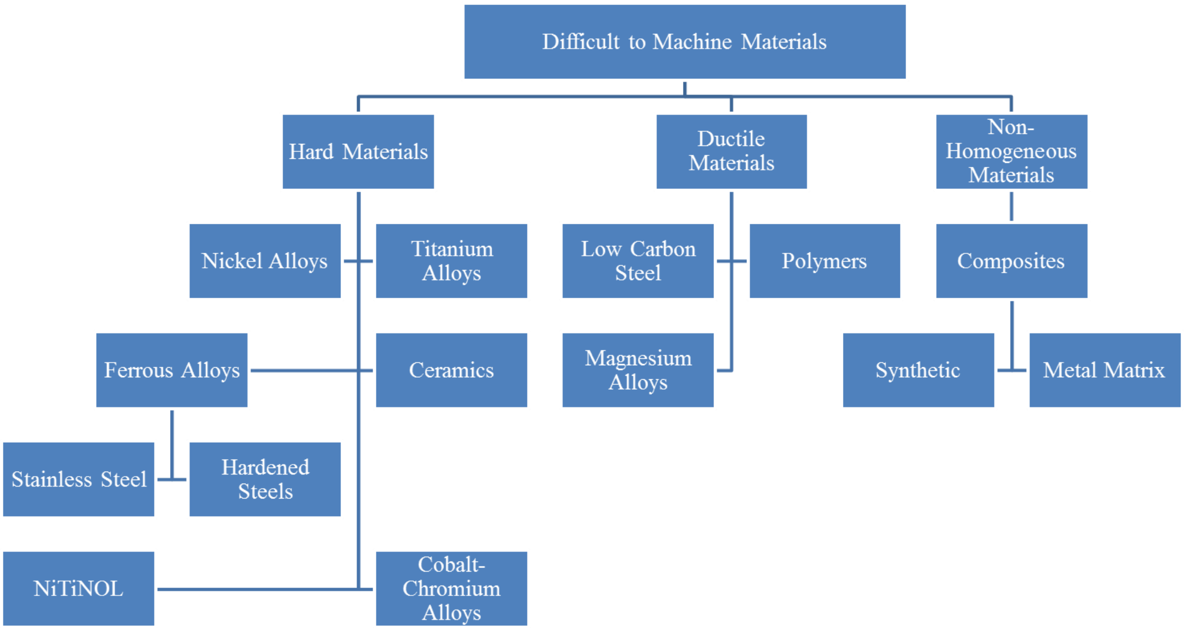

Figure 9, Classification of the difficult-to-machine materials

5.2 Coolants and Environmentally Conscious Machining:

Using cutting fluids is a traditional approach for reducing the temperature and friction at the cutting zone [1]. Astakhov [2] identified that a systematic method is required to quantify and compare the performance of different cutting fluids in machining. Despite the wide usage of cutting fluids in industry to the best of the author's knowledge there is not any standard format to classify the cutting fluids and their usage. Due to the presence of dangerous constituents such as chlorine and microbial growth in the cutting fluids, they are considered as hazardous substances for the workers' health and environment. In addition extending governmental and environmental regulations have limited the usage and increased the costs associated with cutting fluids [98-100, 105]. Another approach to improve the tool life and surface quality of the machined surface is to control the cutting parameters and specifically the cutting speed. However this method fails to satisfy the today competitive manufacturing market requirements for higher productivity at higher quality and lower prices.

The best approach to reduce the usage and costs of using cutting fluids is to not use them at all [76, 100]. However dry cutting fails to produce desired tool life and surface finish in some cases. Due to the excessive generation of heat at the cutting zone and direct relation between the cutting speed and cutting temperature, dry cutting has a limited available cutting speed based on the cutting tool and workpiece materials. In order to realise the dry machining, improved cutting tool materials and further studies on the cutting parameters is inevitable. However most advanced cutting tools are very expensive which can result in higher machining costs.

MQL is introduced to reduce the heat generation at the cutting zone by lubricating the cutting zone by delivering lubricants just at the required point[128, 130]. While MQL is an effective way to lubricate the cutting zone, reduce the heat generation, extend the cutting speed limits and reduce the usage of the cutting fluids, it is not an effective cooling method [136, 137]. This is the case especially in machining engineering alloys where the temperature at the cutting zone could reach the melting point of the workpiece materials [137]. In addition the main environmental problem in MQL is the fact that cutting fluids are still in use. Using air as coolant has been studied for several years. However it is known that air has poor thermal conductivity and cooling capability. Thus some researchers used chilled air to cool the cutting zone although the effect of the chilled air on the machinability is not consistent and is highly dependent on the cutting parameters and tool-material pairing [112, 151, 153].

Using liquefied gases and specially LN2 is also suggested as an approach to eliminate the use of cutting fluids in the machining operations while improving the general machinability. Using cryogenic LN2 is acknowledged as an effective technique to improve the tool life [143]. However the literature has revealed that the effects of cryogenic cooling are not consistent for all tool-workpiece material pairs and cryogenic cooling techniques. The main reason behind this is that cryogenic temperatures change the properties of the tool and workpiece materials but to a different extent. Thus different workpiece-tool material pairs should be studied individually and the appropriate cryogenic cooling technique should be defined for them. Figure 10 illustrates different environmentally conscious machining techniques which have successfully reduced or eliminated the use of conventional cutting fluids in material cutting operations.

It has been found that none of the above mentioned techniques could be mentioned as a general method to be used for all tool-piece material pair. Indeed at the current stage each of the techniques has benefits and disadvantages.

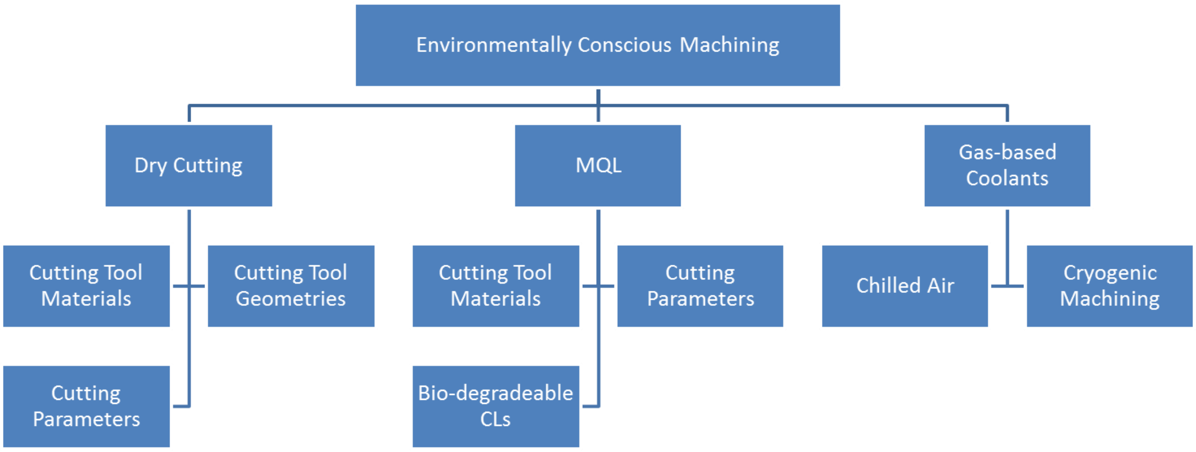

Figure 10, Classification of different environmentally conscious machining techniques

6 Conclusions:

In this paper materials which are generally known as difficult to machine have been reviewed and classified into three major categories namely, hard materials, ductile materials and non-homogeneous materials. Furthermore the material properties which make these types of materials difficult to machine have also been identified. In general, the materials which have one or more of the machining characteristics bulleted below, could be defined as difficult-to-machine, however these criterion need to be quantified.

- High cutting temperature.
- Short tool life.
- Poor surface quality.
- Poor geometrical accuracy.
- Poor chip formation.

Though, as a result of this review it has been found that the area of difficult-to-machine materials is still vague and requires further research.

Different types of coolant/lubricants currently in use in machining industries were reviewed and the drawbacks of using conventional cutting fluids were defined. The major drawbacks are the environmental and health impacts with the costs associated with their use, maintenance and disposal. It has been found that no standard exist to classify the cutting fluids and their usage criteria.

Different machining techniques used to reduce or eliminate the use of conventional cutting fluids in material cutting have also been reviewed in this paper. The most common machining techniques to reduce or eliminate the use of conventional cutting fluids were identified as

- dry machining,
- minimum quantity lubricant (MQL),
- chilled air, and
- cryogenic machining.

Due to the difficulties in machining difficult-to-machine materials, none of the above techniques have been found to be a complete alternative for cutting fluids. As a result, further research on cooling techniques, cutting tool materials, cutting parameters and tool geometries has been identified as essential and has potential to provide significant advantages.

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