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Application of coolants during tool-based machining – A review

Khor Zheng Yang [a], A. Pramanik [a], A.K. Basak [b], Y. Dong [a], Chander Prakash [c,*], S. Shankar [d], Saurav Dixit [e,f,*], Kaushal Kumar [g], Nikolai Ivanovich Vatin [e]

[a] School of Civil and Mechanical Engineering, Curtin University, Bentley, WA, Australia
[b] Adelaide Microscopy, University of Adelaide, Adelaide, SA, Australia
[c] School of Mechanical Engineering, Lovely Professional University, Punjab 144411, India
[d] Department of Mechatronics Engineering, Kongu Engineering College, Erode, India
[e] Peter the Great St. Petersburg Polytechnic University, 195251 Saint Petersburg, Russia
[f] Division of Research & Innovation, Uttaranchal University, Uttarakhand, 248007, Dehradun, India
[g] Department of Mechanical Engineering, K. R. Mangalam University Gurgaon, 122103, India

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ABSTRACT

Coolant is a substance that applied in a machining process for the efficient machining of materials. The application of coolants is based on the several factors including the types of machining process, workpiece material, cutting tool and cost. Coolant helps to dissipate the heat that can be generated during the machining operation, induce lubricating effects to decrease the friction caused by the interfaces of two surfaces, flush away chips and offer corrosion protection. With the right type of coolants used, the performance of machining applications and the attributes of workpieces can be remarkably enhanced. The objective of the study to provides a critical review on the mechanism of coolant penetration, functions, variety of coolants, cooling actions, effectiveness, applications, and the additives that alter the ability and properties of coolants. Furthermore, the critical review also addresses the new technology cryogenic machining that uses cryogenic gases as coolants instead of conventional coolants.

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1. Introduction

Machining processes such as drilling, turning, milling and grinding transform bulk workpieces into the desired form, size and shape. The machining operations deform workpiece materials plastically where large thermal stress is experienced by cutting tools and workpieces [1]. Other than that, the chip formation during the machining process inevitably affects its performance and thus the quality of newly generated surfaces. Therefore, coolants of different forms such as solid, liquid or gases are used to decrease the friction and heat generated in the contact zones between cutting tools and workpieces during machining operations [2]. Several methods used to deliver the coolants such as flooding, misting and spraying depend on the requirement of the machining process. The main roles of coolants in machining processes are (i) to decrease the machining temperature, (ii) to induce lubrication for the reduction in friction, (c) to facilitate chip evacuation from machining zone and (d) to deter a corrosion process [3]. Therefore, coolants increase the efficiency of the machining process, provide better surface quality, and extend the life of cutting tools. Coolants generally contribute to a large portion of total machining costs (Shaw & Cookson, 2005). By choosing the right type of coolants, the effectiveness of the machining process and the produced workpiece quality may improve, thereby leading to low total machining costs.

The very first coolant that was used during machining was 'water' because its high specific heat and thermal conductivity [4]. However, water has less lubricating effect due to low viscosity induce corrosion process. In such case, friction caused in the machining process is hardly reduce by water. It has been reported that approximately 320,000 tons of coolants are used by European Union in a given year [5]. Coolants induce a number of negative impacts to the environment such as water and air pollution and the contamination of soil, surface water and groundwater, resulting in blemishing to agricultural products [6]. In addition, coolants

* Corresponding authors.
E-mail addresses: chander.mechengg@gmail.com (C. Prakash), sauravarambol@gmail.com (S. Dixit).

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cause skin diseases and health issues to the person/operator when in close and frequent contact [7,8].

The objective of this paper is to elaborate a critical review for the role of coolants during the tool-based machining. To achieve this, information was structuralized and separated into several sections. The first section of the paper determines the mechanism of coolants, penetrability, and typical effects of coolants into the cutting zone. Secondly, the types of coolants widely utilized by the industries have been discussed. Thirdly, the cooling action of the coolants, consisting of dry application, application with flooding, minimum quantity lubrication (MQL) and cryogenic machining, was holistically reviewed. Furthermore, the characteristics of additives added into the coolants were also evaluated to enhance the ability of cooling and lubricity properties.

2. Machining mechanism and role of coolants

Heat is generated through the friction taking place between two surface parts where relative movement would occur like "rubbing". In such a case, the increase in material deformation rate are associated with several factors such as temperature, stress and characteristic of the material [9]. The plastic deformation and friction contribute to heat generation commonly in three zones of tool-workpiece interface, as shown in Fig. 1. Primary deformation zone is the first affected zone where the chips are formed after being cut off by cutting tool. The second affected zone is where the tool and the chip are contacted to each other, and the third affected zone is the contact zone of tools and workpieces. Therefore, coolants are commonly applied along the paths A, B and C (Fig. 1) [10,11]. However, the penetration of coolants in these paths are questioned by some researchers since coolants may only affect the primary zone but hardly influence the secondary and tertiary zones [12].

Kishawy et al. [13] mentioned that coolants undergo the difficulties to access into the flank face during the machining operation as well as in the seizure zone according to Trent et al [14,15]. Childs and Rowe [16] also agreed that lubricants encountered specific challenges in accessing the seizure zone. Postnikov [17] assumed that the penetrability of lubricants in the interface only affect the sliding zone instead of the seizure zone. Horne et al., [18] used a clear sapphire tool to determine the penetrability of cutting fluids. It was noted that cutting fluids not only could flow against the chip but also flow through the sides of tools and parts. Once the coolants are able to penetrate into the interface, a 'shear resistance layer' (lower than the materials' resistance) was formed, which could avoid the chips to weld on the rake face of cutting tools [18]. The life of cutting tools may shorten due to high thermal energy as the temperature exceeds the allowable level of cutting tools. As such, the tools would be softened, and material adhesion could occur with the workpieces resulting in tool breakage. A different role of coolants will be discussed hereafter.

2.1. Temperature reduction in cutting zones

The coolant must be capable of dissipating heat efficiently in order to reduce the machining temperature. It was reported that coolants only affect the primary zone in which approximately 60 % of the total machining heat could be generated [19]. In high speed machining, coolants hardly penetrate in both secondary and tertiary deformation zones [20]. Sales et al. [21,22] used the infrared sensor to measure the machining temperature while turning at 150 rpm to investigate the role of different coolants, as depicted in Fig. 2. This confirms that cutting fluids do assist in decreasing the temperature of the machining process either by the vaporisation (heat absorption) of coolants or due to fluid wettability. The higher wettability of machining fluids, the less splashing action when applying cutting fluids into the machining process, therefore the higher chance that the heat may go away [21,22]. Additionally, other coolant properties include (i) thermal conductivity (the amount of heat or thermal energy that is conducted or transmitted through a material) [23], (ii) specific heat, (iii) flash point [24] and (v) thermal stability [25].

2.2. Lubrication action of coolants

Coolants also can be performed as a lubricant to reduce the friction in the tool-chip and tool-workpiece interfaces, which in turn reduces the cutting force and the temperature. Moreover, coolants decrease the wear rate of tools, restrain the development of built-up edges (BUE) and enhance the surface quality of workpieces [26].

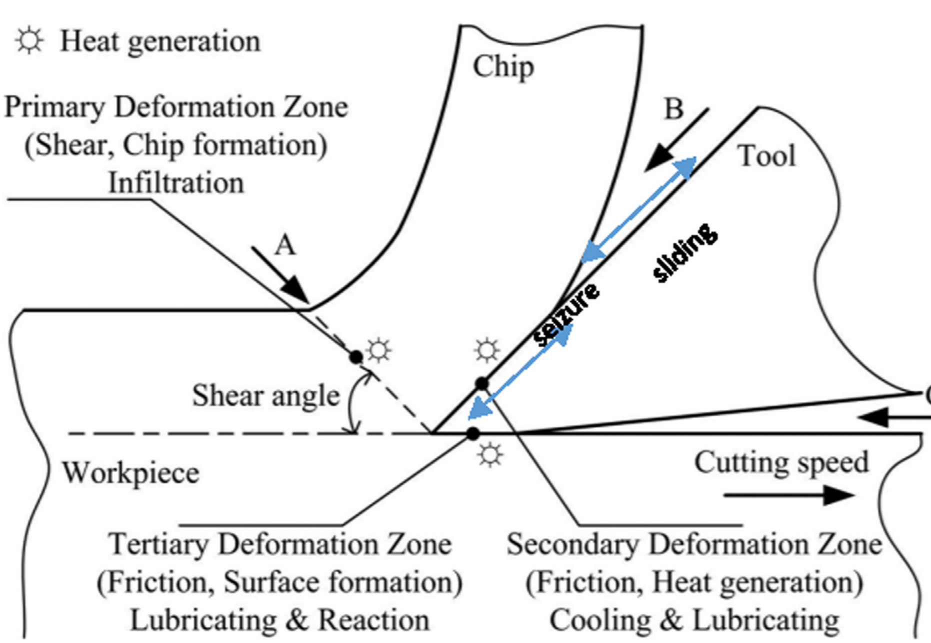

Fig. 1. Affected cutting zone areas generated by coolants.

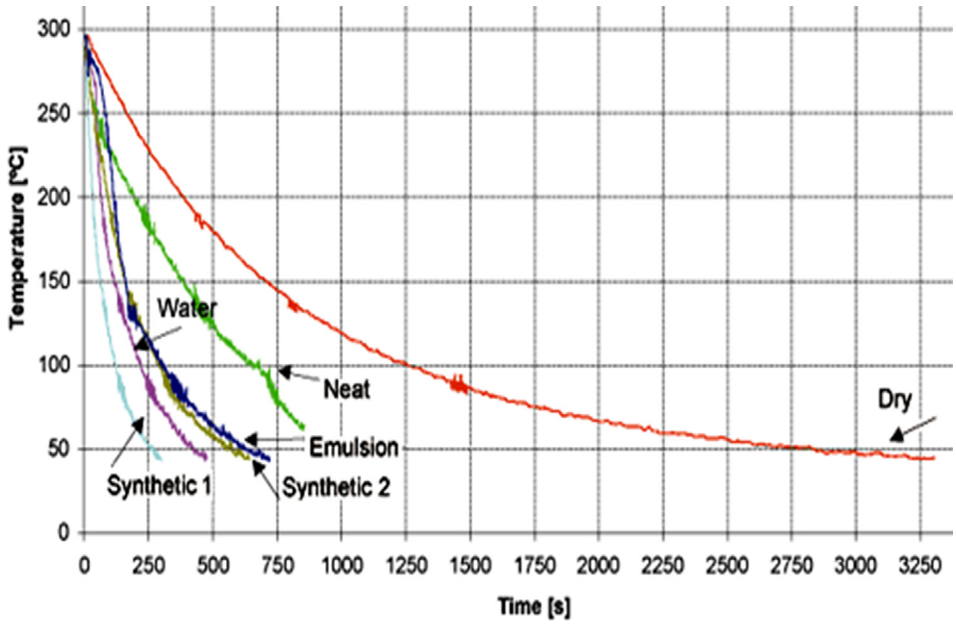

Fig. 2. Cooling ability for all cutting conditions.

However, it is worth noting that the use of coolants may not be always beneficial. For example, Cozzens et al. [27] revealed that the cutting fluid would not affect much on the cutting force, machined surface quality and the BUE formation during the boring process. This is ascribed to the high speed of the process where the lubrication does not occur while coolants may tend to boil or decompose before entering the cutting zone. For instance, when applying neat oil into a high-speed operation, it often forms the smoke as a sign of decomposition and therefore it is not suitable at all. Similarly, Bacci Da Silva [28] reported no lubrication effect against temperature, force and BUE when machining medium 080 M40 carbon steel at a low cutting speed of 22–40 m/min. However, the penetration of coolants to benefit the lubricating effect is doubtful due to high normal stress on the contact zone between the tool and chips [29].

2.3. Coolant role in chips evacuation

Another function of coolant is to facilitate the evacuation of the chips formed during machining operation. Chips can be formed in either continuous or discontinuous ways. Continuous chips are formed in machining operation like turning where the contact zone between chips and cutting tools are extremely tight with high stress. Therefore, the chips form continuously on the surface of the cutting tool and coolants are not able to enter in this zone. On the other hand, discontinuous chips are generated in a machining process like drilling or milling. In this case, as the chips are broken into the pieces, no great surface contact between chips and tools exist and coolants can enter in the interface zone.

When the workpiece is undertaken under high pressure that outpaces the elastic limit of the material, the material tends to release the stress by fracturing and flowing on the top of the tool [30]. During the machining operation, chips are formed in different sizes and shapes leading to poor surface quality of workpieces. This is attributed to capability loss in dimensional control and tool wear [31]. Usually, coolants can be absorbed onto the chips and prevent them from being welded onto the tool. Accordingly, a thin protective layer is generally created in the interface by either physical absorption or chemical reaction with a shearing resistance that is smaller than material resistance. Associated properties like low fluid viscosity may help to flush the chips away efficiently. In some coolants, surface active agents like ethylene oxide and copolymers of propylene oxide are added to enhance physical/chemical interaction [32,33]. The most common method that apply coolant directly to the cutting process is a flooding method for the purpose of flushing away the chips.

2.4. Coolant role in corrosion protection

The last but not the least, coolant also provide corrosion protection to the workpiece. Corrosion can be known as electrochemical oxidation due to the reaction of the metals with an oxidant such as oxygen. Ferrous metal that are freshly cut during machining operation tends to rust easily. To prevent this, corrosion inhibitor additives can be added into coolants, which forms a protective film on the workpiece to avoid any corrosion. There are two types of corrosion protective films available, namely polar films and passivating films. Polar films contain organic compounds like fatty acids and amines. On the other hand, the formation of passivating films comprises inorganic compounds like phosphates, borates and silicates. Both of these films formed a protective coating for the prevention of corrosion [34].

3. Types of coolants

There are various types of coolants that have been used in the industries depending on their own requirements such as machining processes, materials to be cut, lubricity and cooling effect. A proper selection of coolants is essential for it helps us to understand which coolants benefit the machining process and the workpiece along with associated challenges. Nowadays, coolants are formulated from different materials consisting of water, lubricants and other chemical additives to meet the requirement of the machining operation. For example, in some applications, animal fats can be added into coolants to improve the lubricity. However, it does not assist in lowering the temperature caused by machining operation. As such, other additives or substances were added to improve the cooling ability of coolants. A broad classification of coolants used is shown in Fig. 3.

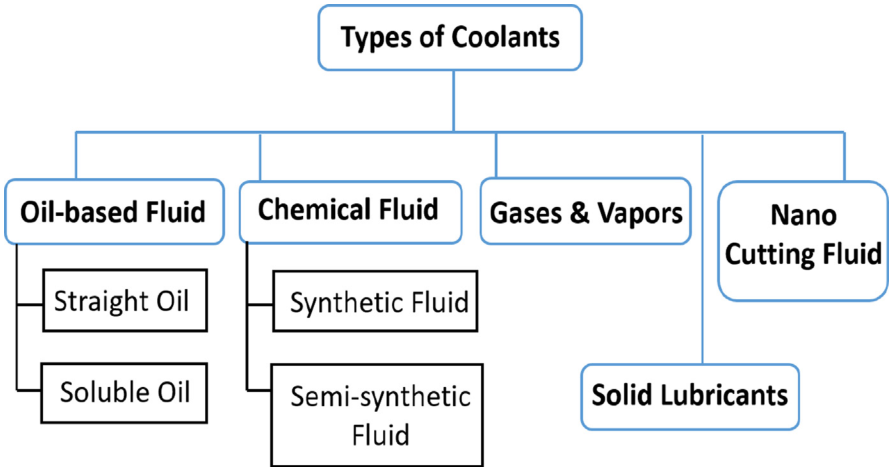

Fig. 3. Various types of coolants.

By selecting the right type of coolant, the cost and the performance of machining operation may be optimized. For example, cooling is not essential in low-speed operation, while lubrication is required to avoid the formation of built-up edges and the friction caused. In such a case, an oil-based cutting fluid is necessary. In contrast with high-speed machining operation, the increasing of cutting speed results in a high temperature, which may decrease the tool life where tool breakage is possible to happen. Accordingly, fluid penetration is nearly impossible for cutting fluids to undergo lubricating effect. Consequently, a water-based cutting fluid is suggested to use for cooling the operation. It is crucial to evaluate the properties for different variety of coolants to obtain the best results and effectiveness to the machining operation mentioned in the forthcoming sections.

3.1. Oil-based fluids

There are two types of oil-based fluids: (i) straight cutting oils and (ii) soluble cutting oils. The difference between these two types of oils is the addition of water. There is no water in straight cutting oils where most of the components are mineral oils with the provision of good lubrication effect in expense of cooling effect. Hence, straight cutting oils are usually applied for low-speed machining operation. On the other hand, soluble oils can be defined as emulsifiable oils or water-soluble oils [35]. The specific heat and thermal conductivity of water are better than those of oil whilst the lubricating effect of oil is better than that of water [36,37]. With the combination of water and oil, the cooling effect for the machining and lubrication can be achieved simultaneously.

3.1.1. Straight cutting oils (Neat oils)

Straight cutting oils can be referred to as neat oils. It is normally formed by 100 % petroleum or mineral oil without any addition of water. Additives are usually utilized to improve the performance of straight cutting oils such as 75–95% petroleum or mineral oils, 5–10% boundary lubricants and 0–20% extreme pressure (EP) additives including sulphur, phosphorus compounds or chlorine [38]. The function of extreme pressure additives is to prevent adhesive wear and yield anti-welding to the workpiece and tools. Additionally, the additives strengthen the lubricity and the wettability of coolants. The advantages of straight cutting oil are that it provides the best lubricity among coolants. Other than that, the tool life is also improved for some machining operations. It is widely used on machining operation with low clearance, low speed, and high demand in surface finish. Also, straight oils are applied in some cutting operation which includes broaching, tapping, grinding and deep-hole drilling. It can be used during the machining of hard metals like super alloys and stainless steel. Besides, straight oils provides decent rust protection and bacterial control [39]. The disadvantages of straight oil are that it may increase the risk of fire due to poor heat transfer or dissipation properties. Mist or smoking may form when applying in some high-speed machining operation with poor ventilation and weak shielding. Hence, straight oil is limited to specific machining operations with low speed and low temperature. Furthermore, the remaining oils that are employed in the machining operations are difficult to clean particularly requiring cleaning agents or solvents [39].

There are two types of straight cutting oils namely, active and inactive oils. These terms are associated with their chemical activities provide by the oil and the capability of their reaction with workpiece surfaces. For example, if a copper strip is submerged in active oil for 3 h at the temperature of 100 °C, the copper will be dark in colour. Whereas with the same condition, if a cooper strip is immersed in an inactive oil, the copper stripe is not darkened. This is attributed to the chemical reaction of sulphur with metals [40]. Active straight cutting oils contain sulphur with weak bonds to the hydrocarbon backbone [40]. Generally speaking, a small amount of sulphur is added into the straight oil to produce an active sulphurised oil. In this case, when heat is generated during the machining operation, sulphur molecules are discharged from the oil and react chemically with workpiece surfaces. In some heavy-duty machining operations, a straight oil with the higher sulphur content can be used. Active straight cutting oils usually comes with dark or colourless feature where dark oils contain a higher content of sulphur when compared with colourless sulfurized oils. Dark oils enable to perform better in heavy-duty jobs as opposed to transparent sulfurized oils. Nowadays, additives are utilized in transparent sulfurized oil to improve the suitability in tough machining operations. Active straight cutting oil provides good lubricating and moderate cooling effect and is recommended for use during the machining of low carbon and chrome-alloy steel. This type of oil is commonly used in thread cutting and grinding operation [41]. In inactive straight cutting oil, sulphur in strongly bonded formation in the hydrocarbon structure and cannot be produced during the machining operation. Thus, no chemical reaction takes place with workpiece surfaces. It offers an excellent lubricating action in expense of lower cooling action. This type of oil is suitable for non-ferrous materials like magnesium, brass and aluminum machining. Such a type of oil is widely used in grinding operations to yield good quality of surface finish with respect to ferrous and non-ferrous materials [41].

3.1.2. Soluble cutting oils

Soluble oils fluids can be known as several names such as emulsifiable oils, water-soluble oils and emulsions. Emulsion is the compound of oil and water or liquid. It can be classified into two types. in the first instance, the oil can be dispersed into water while in the second instance water is dispersed into oil instead. For example, when adding a few drops of oil to the water, the oil will not dissolve but floats on the water. After shaking the mixture, the oil breaks up into small droplets and is dispersed into water. However, the mixture is in unstable form as time goes by, and eventually the oil will slowly separate on the top of water. Therefore, the addition of emulsifier can prevent the mixture from separating. Emulsifier helps to stabilise the mixture and to avoid mixture separation. Emulsifier contains the molecules of both hydrophobic end and hydrophilic end. Hydrophilic end is captivated with the water in contrast with hydrophobic counterpart captivated with the oil. A steady emulsion can be formed by adding an emulsifier into the mixture [42]. Water soluble oil usually appears in diluted form and milky appearance because particles of emulsion can deflect the light. Water soluble oil is usually formed by dispersing the metalworking fluid into water to form a stable emulsion.

The advantages of soluble oil are both cooling and lubrication effect of the emulsion. By applying soluble oil, a protective oil film is formed on the cutting tools to prevent the emulsification of oils and greases. Soluble oil is considered as a general-purpose coolant that is suitable to apply for the light to medium duty operation including ferrous and non-ferrous metals. However, the lubricity of the water soluble is lower compared to straight oil, but the machining applications are wide due to extreme pressure (EP) additives and wetting agents. Some cutting operation such as tapping, trepanning and broaching can be applied by water soluble oil to improve the performance and increase the efficiency of machining processes [39]. The disadvantages for water soluble oil is biological activity and foaming that may occur where the microbial contamination exists [43]. Other than that, rancidity is one of the problems caused by bacterial action thus resulting in unpleasant smell. Moreover, water soluble oil tends to evaporate faster, which may cause misting during the machining application and result in the slippery floor in a working environment. Furthermore, precipitates on machines parts may take place when the application contains water soluble oil and hard water. To control the biological activity in the water soluble, additives are utilized. Additionally, tramp oils (sump oils) are produced after using water soluble oil as the coolant which is a contaminated and unsatisfactory oil formed during the metalworking operation in manufacturing industries [44]. Therefore, the cost to maintain water soluble oil is relatively high. A summary of application ratio and characteristics for water soluble oils are given in Table 1 [45].

Table 1
Application ratios and characteristics for water soluble oils.

Type	Application ratio	Characteristic	Machining operation
General-purpose soluble oil	Dilution at 1:40 and 1:10	Opaque emulsion in milky form	Multipurpose
Clear type soluble oil	Dilution at 1:100 and 1:50	Translucent to clear and high content of emulsifier	Grinding or light-duty
Fatty soluble oil	Dilution at 1:10 and 1:40	Milky emulsion	General-purpose (Nonferrous metals)
EP soluble oil	Dilution at 1:5 and 1:20	Sulfurized or chlorinated EP additives	High performance

3.2. Chemical cutting fluids

Chemical cutting fluids preform stabilized emulsion, contain a very small amount of oil that can mix with water easily. The lubricity and friction reduction are depending on chemical agents in chemical cutting fluids. The use of additives into chemical cutting fluids improves the wettability. Other than that, extreme pressure (EP) additives can also be added to reduce the heat formed during a machining process. Temperature-dependent EP additives react with the metal surfaces when there are the differences with pressure and temperature. General temperature-dependent EP additives used are phosphorus, sulfur, chlorine and boron [46]. Chemical fluids can be subclassified into 2 types, namely (i) synthetic and (ii) semi-synthetic fluids.

3.2.1. Synthetic fluids

Synthetic cutting oils do not contain mineral oils or petroleum. The general composition for this type of oil comprises alkaline organic and inorganic compounds with other additives such as corrosion inhibitors [47]. Synthetic cutting oils are usually supplied as a concentrated substance with the requirement of combining water to form cutting fluid. Synthetic cutting oils are suitable to apply in high speed or high temperature machining operations due to its high capability in cooling. Chemical agents that are utilized in most synthetic fluids are listed in Table 2 to improve their performance during the machining operation.

Based on the report by Center et al [39], synthetic cutting oils can be categorized into simple synthetic, complex synthetic and emulsifiable synthetic oils. Simple synthetic oil in other word is called true solution particularly applicable to light duty machining operation like grinding. Synthetic lubricants can be added in complex synthetic oils, therefore complex synthetic oils can be used from the moderate to heavy applications and machining operations with high feeds and high speeds. Colorless solutions are generated when mixing both simple synthetic and complex synthetic oils in a coolant sump, allow the machine operator to observe the workpiece. For emulsifiable synthetics, additional compounds are added to possess lubricity properties, which is quite similar to soluble oils. This allows the fluids to perform both coolants and lubricants in heavy duty machining operations. Emulsifiable synthetic oils enable to apply in heavy duty machining processes with such materials that are hard to machine or high temperature alloys. Emulsifiable synthetic oils commonly appear to be semi-transparent or non-translucent.

3.2.2. Semi-Synthetic fluids

Semi-synthetic cutting oils are also known as semi-chemical cutting fluids. It is a combination of water-soluble cutting oils and synthetic fluids. Generally, semi-synthetic fluids contain 2–30% mineral oils, emulsifier and water [48]. The additives like corrosion protection, biocide and wetting agents are added into semi-synthetic fluids. Semi-synthetic fluids can be also referred to as the preformed chemical emulsion because their concentrate solution consists of water, oil and emulsifier during the formulation pro-

Table 2
Additives used in synthetic fluids and their functions.

Chemical Agents	Functions
Nitrites and amines	To provide protection against rust
Phosphates and borates	Acts as water softeners
Glycols	Acts as blending agents
Nitrates	To stabilize the added nitrites
Wetting agents and soap	To improve lubricating effect
Extreme pressure (EP) additives	To improve lubricity of the solution
Biocides	To control the bacterial activity.

cess. The appearance of semi-synthetic fluids is commonly in colorless to opaque form depending on the content of the emulsifier. The addition of mineral oils in semi-synthetic fluids enable to enhance the lubricating effect as the oil molecules are capable of spreading around cutting tools [39].

The advantages of semi-synthetic fluids are quite identical to synthetic fluids, which means it can be utilized from moderate to heavy duty machining operations. Semi-synthetic fluids provide both cooling effects and lubricating functions, which can be applied in high-speed machining operations. Furthermore, the maintainability of semi-synthetic fluids is easier compared to that of water-soluble oils. The cleaning process is easier due to lower viscosity compared to that of soluble oils. Semi-synthetic fluids yield a better control in bacterial activity and rancidity. Less smoke and misting of oils are produced as it contains less oil compared to straight cutting oil and water-soluble oil. The disadvantages of semi-synthetic fluid are that hard water scum deposits may be formed due to the water hardness, which affects the solution stability. Moreover, foaming often occur due to the addition of additives for the cleaning purpose. In particular, lubricating effect is slightly lower compared to that of water soluble oil [39]. Table 3 shows the application ratios and the characteristics of semi-synthetic and synthetic fluids [45].

The suitability of synthetic fluids and semi-synthetic fluids for machining operations and metal compatibility are listed in Table 4.

A general comparison of oil-based and chemical cutting fluids in terms of their respective applications are exhibited in Table 5.

3.3. Gases and vapors

There are many ways to deliver cutting fluids into machining operation. In some machining applications, coolants are delivered in gaseous form to achieve the function of coolants in machining processes. The gases or vapors commonly used are compressed inert air such as carbon dioxide, freon, argon, helium and nitrogen [45]. Gaseous coolants can be delivered by spraying, minimum quantity lubrication (MQL) and misting. For instance, compressed air can be delivered by using vortex tube or a pure jet mixing with other fluids targeting the region of cutting zones [50]. To achieve better results, the compressed air should be directed to the interface or against the chips [2]. Due to the lack of lubricity in compressed air, they are generally used for cleaning and cooling purpose. However, Kishawy et al [45] reported that the penetrability into the sources of heat was better than those coolants in a liquid or solid form. This is because the constituent and size of molecules are finer compared to other coolants. Additionally, the usage of compressed air can avoid the disadvantages of using water-based liquids. For instance, the contamination of reactive workpiece materials such as zirconium may occur when using liquid-based coolants. There are specific means to improve the cooling ability of gaseous coolants by using high compressed and low temperature air. Sometimes, a small amount of water-soluble cutting oil was added into the high compressed air to improve the lubricating effect, which is known as air-oil mists or aerosols. The advantages of using gaseous coolants lie in better penetrability into cutting zones. Moreover, the cost and usage of coolants are lower when compared to flood applications. The disadvantages of gaseous coolants are that the inhalation of these gases may lead to a significant threat to the health of operators.

3.4. Solid lubricants

Solid lubricants can be defined as those solid materials that decrease the friction and wear between the contacts of two surfaces. It offers the protection to avoid the damage during relative motion. Solid lubricants can be presented in forms of dispersed particles or coated films on the surfaces. Generally, solid lubricants are applied on the exterior of workpieces or cutting tool to make sure that the coolants can reach a maximum penetrability between the cutting zones. Common solid lubricants are inorganic compounds such as molybdenum disulphide, polymer materials (e.g., polytetrafluoroethylene) and graphite. The common terms to describe the application of solid lubricants are referred to as solid-film lubrication, dry-film lubrication or dry lubrication [51].

The advantages of solid lubricants rely on the ability to apply in specific applications in high stress or load. Moreover, it has high thermal stability to keep its form at high temperature. It can be applied in diverse applications including tapping and grinding [52]. There are also a few disadvantages of solid lubricant such as their lower ability for heat dissipation when compared with fluids. Secondly, relative to hydrodynamic media like cutting fluids, the friction coefficient and the rate of wear appear to be higher. Furthermore, the stability of coated films on the surfaces becomes low due to high stress. In addition, the chips formed from the cutting zone may stick with solid lubricants. Therefore, solid lubricants are required to supply repeatedly, to clean or to filter and cool, resulting in less convenience to the machining operation [52].

3.4.1. Polymer lubricants

Polymer solid lubricants are commonly applied in light load applications. They have low thermal conductivity to allow for the dissipation of a limited amount of heat. There are three commonly used polymer solid lubricants, namely polytetrafluoroethylene (PTFE), synthetic polymers and nylon [53]. PTFE is also referred to as Teflon. It is a particular polymer formed from ethylene by substituting hydrogen atoms into fluorine atoms. PTFE is not suitable to apply in high temperature machining condition. As PTFE is non-toxic, it can be used in industrial applications like pharmaceuticals and food [53]. Synthetic polymer is a modification of PTFE to overcome the disadvantages caused by PTFE. It is formed by mixing glass-based fillers and carbon-based fillers with PTFE. In some

Table 3
Application ratio and characteristic of synthetic and semi-synthetic fluids.

Classification	Type	Application ratio	Characteristic	Machining operation
Synthetic Fluids	True solution	Dilution at 1:50 and 1:100	Consist of rust inhibitors	Grinding (Iron and Steel)
	Surface-active chemical fluids	Dilution at 1:10 and 1:40	Consist of water-soluble form of surface-active load-carrying additives and rust inhibitors	Grinding (Ferrous metals and Nonferrous metals)
	EP Surface-active chemical fluids	Dilution at 1:5 and 1:30	Consists of EP additives	High performance (Ferrous Metals)
Semi-synthetic fluids	–	–	Translucent Stable emulsion Solution of chemical fluids and water-soluble oil	Grinding or moderate to heavy-duty machining

Table 4
Suitability of synthetic and semi-synthetic fluids for machining operations and metal compatibility [49].

Machining Operations					Metal compatibility
Synthetic fluids	**Light duty**	**Light-moderate duty**	**Moderate duty**	**Heavy duty**	
	• General Purpose	• General Purpose Facing Milling Sawing	• Turning Grooving Milling Tapping Drilling	• Broaching Deep Boring Drilling Reaming Roll Threading Tapping	• Ferrous Non-Ferrous Specialty Metals
Semi-synthetic fluids	• Band saw application	• General Purpose Grinding Sawing Drilling Facing	• General Purpose Facing Milling Sawing Turning	• Boring Facing Reaming Tapping Gun Drilling Roll Forming Broaching	• Ferrous Non-Ferrous Specialty Metals

Table 5
Comparison of oil-based and chemical cutting fluids in terms of their respective applications.

	Oil-based fluids		Chemical fluids	
	Soluble oil	**Straight oil**	**Synthetic**	**Semi-synthetic**
General aspects				
Lubricity	G	E	P	G
Cooling	P to G	P	E	G
Wetting	P to G	G	P	G
Residue	E	E	U	G
Foam	P to G	U to P	G to E	U to G
Chip removal	G	G	G	G
Corrosion protection	G	G	G	G
Corrosion inhibition				
Ferrous metal	G	G to E	G	G
Non-Ferrous metal	E	G	P to G	G
Cast iron	P	G to E	P to G	G
Others				
Tram oil rejection	P to G	G	E	G
Disposability	E	P	P	P
Recyclability	P to G	E	G	G
Maintenance	U	E	G	G
Environmentally friendly	G	U	E	G
Cost	G	P	E	G
Wheel life	G	E	U	G

Unacceptable- U, Poor-P, Good- G, Excellent- E.

applications, metal structures like lead or bronze are specifically impregnated into PTFE.

3.4.2. Metal-solid lubricants

Metal-solid lubricants consist of lamellar solids subjected to a film transfer process to obtain a low friction coefficient. The most generally used type of metal-solid lubricants is molybdenum disulphide (MoS_2). Metal-solid lubricants can be used in space industries as it can perform well in a vacuum environment up to 1000 °C [53].

3.4.3. Carbon and graphite

Solid lubricants made up of carbon and graphite have specific desirable properties with some downside effects, as shown in Table 6. The incidence of corrosion may increase when applying in working temperature above 500 °C [53].

3.4.4. Ceramic and cermet

Ceramic and cermet are used as coated films. They are utilized when a lower rate of wear is required provided that the condition with a low coefficient of friction is optional. These coatings can withstand a much higher temperature up to 1000 °C. The delivery method for these coatings is spraying such as using detonation gun and plasma spraying. Additionally, electrolytic deposition is another delivery method by using an electrolyte based on ceramic particles [53].

3.5. Semi-solid lubricants

Semi-solid lubricants are a combination of solids and fluids. This type of lubricants can be adapted in a wide range of applications with various conditions of different speeds, temperatures, and load capacities. Furthermore, semi-solid lubricants can be applied in such a moisture-like or dry and dusty condition, as well as even in a corrosive environment. The most common semi-solid lubricants used is grease [53]. Grease is formed by base oils, additives, and thickeners. Grease is manufactured by synthetic oils and petroleum. The performance of grease can be affected by the oil used in manufacturing. For instance, grease can perform well in a working environment at the low temperature if it is produced from light oils with the low viscosity. On the other hand, those oils with the high viscosity and heavy base can produce the grease that can work in a high temperature condition. Chemical additives are incorporated into grease to improve the performances depending on the specific requirements such as environmental impact, colour, compatibility, sustainability, and performance. A comparative

Table 6
Advantages and disadvantages of different solid lubricants.

Solid lubricant type	Advantages	Disadvantages
Polymer	• Low coefficient of friction Good chemical stability Low surface energy Good chemical inertness Non-toxic	• High wear rate High thermal expansion Low thermal conductivity Low load capacity
Metal-solid	• High load capacity Good performance in high temperature environment Low coefficient of friction Can be used in vacuum environment	• Sub-optimal performance in moisture working condition High film thickness Prone to wear and tear
Carbon and graphite	• Good stability in high temperature High oxidation stability Moderate loads applications Good lubrication at high temperature	• Does not perform well in vacuum environment Weak corrosive resistance
Grease	• Good binding force with surface Good water resistance Good vibration and noise control	• Poor dissipation of heat Poor dust resistance Hard to filter out Contaminants from grease

advantages and disadvantages of different solid lubricants are listed in Table 6 [53].

3.6. Nano cutting fluids

With the development of advanced technologies, the faster rate of cooling to a machining process becomes one of the major challenges encountered by several industries such as manufacturing, automobiles and electronics. The conventional methods to improve the cooling ability has reached their limits. As such, nanofluids have been utilized to overcome this challenge [54,55]. Nano cutting fluids can be defined as the mixture of conventional cutting fluids and nanoparticles. It is contrived by splitting nanometer-sized materials such as nanoparticles, nanofibers, nanorods, nanosheets, nanotubes and droplets in base fluids [56,57]. Nano cutting fluids can be classified into two categories: (i) non-metallic nanofluids and (ii) metallic nanofluids. Non-metallic nanofluids consist of non-metallic nanoparticles such as copper oxide (CuO), aluminum oxide (Al_2O_3) and silicon carbide (SiC). Conversely, metallic nanofluids contain metallic nanoparticles like Ag, Al, Au, Cu, Si, Ni, Ti, Zn and Fe [58]. Nanofluids possess high thermal conductivity to dissipate heat faster, which is particularly important during hard-to-machine materials like nickel-based alloys or titanium. Li et al [59] suggested that nanofluids improved 60 % convective heat transfer coefficient with the addition of 2 wt% Cu nanoparticles as compared to conventional cutting fluids. Khandeker et at [54] reported 150 % increase in thermal conductivity with the addition of Cu nanoparticles into ethylene glycol. Bakalova et al [60] concluded that the addition of particles into conventional fluids enabled to increase the penetrability of fluids into the friction surface, thus resulting in the elasto-hydrodynamic effect of lubrication along with the reduction of friction coefficient, good stabilization and prevention of bacteria growth [61]. The better performance of nanofluids in terms of cutting force and surface roughness (Fig. 4b) over dry machining and conventional cutting fluids was manifested by Khandekar et al [54] as shown in Fig. 4a and 4b, respectively. The formulation of nanofluids for this study was formed by elmulsion-type cutting fluids with the addition of 1 wt% Al_2O_3 nanoparticle. The test data for surface roughness and cutting force are shown in Fig. 4.

At the beginning of machining time (Fig. 4a), cutting force is less required as the cutting tool is sharp. However, the cutting force increases gradually with machining time due to the wear of tools. In the process of dry machining, the wear rate of cutting tools increase leading to the enhancement of cutting force over time. However, in the case of coolant applications, nanofluids are more favourable compared to conventional cutting fluids owing to better wettability and lubricating properties in order to penetrate into cutting zones and accelerate heat dissipation along with better surface finish (lower surface roughness). Manoj et al [62] proposed to use sunflower oils as the base fluids to produce nanofluids by considering its capability to improve thermal conductivity and anti-friction characteristics together with less environmental impacts. Nanofluid offers a potential solution to lowering cutting temperature, tool wear, cutting force, and high surface quality, but there are some disadvantages worth mentioning such as high cost of nanoparticles, tendency to clusters and sediments.

3.7. Alternative coolants used by industries

3.7.1. Mineral oils

Mineral oils are odourless and transparent without the inclusion of additives. It is a by-product derived from the distillation of petroleum in order to manufacture gasoline [63]. It has lower cost despite lower lubricity effect compared to compounds fluids. Mineral oils are commonly used for light-duty machining operation for metals like magnesium, aluminium and brass. It is mainly employed for a machining process when the requirement of cooling and lubricating effects becomes not severe at all. This type of oils is non-corrosive and quite stable. Other than that, mineral oils considered as sustainable as they can be reusable by filtering out the chips after machining operations [64].

3.7.2. Fatty oils

The common fatty oils that are used in machining operations are lard oils. Lard oils are formed by pressing the crystallized or grained lard at the temperature of 7 °C. Additives, like antioxidants can be added into the oils for the protection against rancidity. It can be used as lubricants and cutting oils [65]. By comparing fatty oils and modern cutting fluids with additives, the effectiveness of fatty oils in machining operations becomes lesser. Fatty oils have great oiliness for good lubricating effects due to anti-friction characteristic in spite of poor anti-welding properties. Other than that, fatty oils tend to oxidize rapidly which may cause unpleasant smell and tend to fume [66].

3.7.3. Vegetable oils

The main disadvantages of petroleum based oils can be associated with inappropriate usage and disposal leading to environmental pollution [67]. Furthermore, if highly exposure or close contact with petroleum based oils, it may cause harmful effects to the health of operators such as respirator problems and skin disease [43]. Therefore, vegetable oils have been utilized to replace petroleum-based oils. There are some appealing properties that

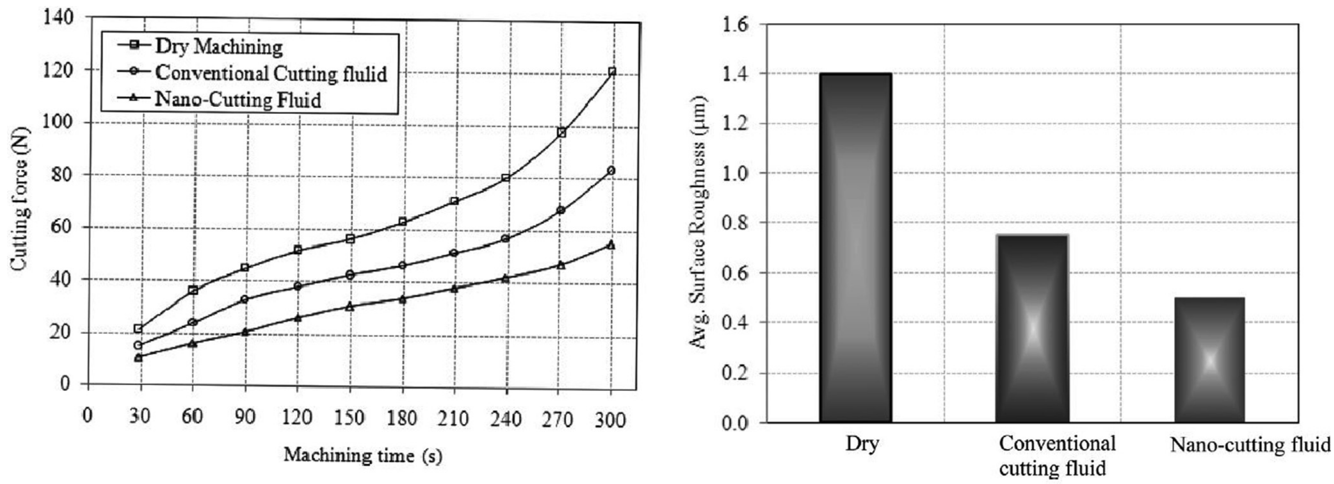

Fig. 4. Performance of nanofluids over dry machining and conventional cutting fluids in relation to (a) cutting force and (f) surface roughness [54].

vegetable oils acquired such as high viscosity index, good lubricating effect, non-toxicity and high biodegradability [68]. However, vegetable oils are suitable for a modest temperature range due to their low temperature and oxidative stability. Therefore, the improvement regarding temperature and oxidative stability of vegetables can be achieved with chemical modification [69]. According to Saleem et al [70], vegetable oils have good cooling and lubricating effects similar to conventional cutting fluids.

3.7.4. Sulphurized mineral oils

Sulphurized oils are generated by dissolving sulphur into cutting oils via a heating process [64]. Due to weak bonding, sulphur molecules tend to break easily, which chemically react with another high reactive substance or metal surface to form metal sulphide. This type of sulphur is known as active sulphur. While "inactive" refers to sulphur that do not form metal sulphides with the metal surface during the contact [71], as exemplified by sulphates. Sulphate is formed by the oxidation of sulphur, and therefore becomes less reactive with metals. The properties of sulphurized mineral oils can be enhanced by the addition of extreme pressure (EP) additives to improve overall lubrication properties.

3.7.5. Compound fluids

Compound fluids are formulated from either mineral oil, use of additives, sulphurization or mixture with one or more oils together, which depends on the severe conditions or requirements. The use of oils and additives improves several properties of the coolants, such as enhanced cooling ability of the fluids [72]. The compounds fluids that are employed by the industries are shown in Fig. 5.

4. Coolant applications during machining

The selection of coolants is essential as it avoids unnecessary cost and prevent bad machining outcomes. The factors that may affect the selection of coolants and their delivery methods comprise (i) machining process and (ii) cutting tool in used, [64,73–75], which will be mentioned in the forthcoming sections.

4.1. Machining processes

4.1.1. Drilling

Drilling is considered as a high-speed machining operation where lubrication is hard to operate. The coolant applications for drilling process are mainly associated with cooling and chip evacuation [76]. In a drilling process, the geometry of chips is slightly different. In such a case, coolants should be faced directed to the contact zone between tools and workpieces. Flood application is recommended because a large amount of coolants help to dissipate the heat and flush away the chips. It is suggested that the operator should withdraw cutting tools occasionally for the coolants to remove the chips in the holes. Furthermore, it is suggested to use specific tools through holes where coolants can be fed through the tools directly to the cutting edges to aid chip evacuation. The common coolants used for drilling are emulsion oils and oils with EP additives [41,64,75]. Fig. 6 shows a particular drilling application with coolants through tools [77].

4.1.2. Milling

Milling is a process being used to construct various features consisting of holes, cavities, threads and surfaces to be drilled or tapped [78]. Milling operations is deemed as a non-steady process as the temperature caused in the cutting edge can be cold or up to 1000 °C. Due to the temperature variation, thermal shock and cyclic stress often occur with the application of coolants in the cutting edge leading to tool breakage or short tool life. In some conditions, coolants are not necessary to apply in machining processes. For example, in finishing operations like rough milling operations, cutting fluids do not help to reduce the heat generation, therefore no improvement on tool life is manifested. Hence, rough milling operations are mainly suitable with dry machining applications [79]. However, there are some benefits obtained by milling operations with the usage of coolants according to Table 7. It is recommended to use two nozzles in milling machining operations, where one of the nozzle is directed in front of the cutter while another one is located at the back of the cutter to yield good performance of cooling and chip evacuation [41]. Water based coolants are commonly used for milling machining operations [64,75].

4.1.3. Grinding

Grinding is a machining process that used grinding wheels as the cutting tool. The heat generation in grinding is significant high as there are a lot of small cutting edges on the grinding wheel. Each of them produces the friction when in contact with the workpiece. It is recommended to use flood coolants for such an application. There are various ways to achieve good machining outcomes with the application of coolants in grinding machining operations. For example, the use of two nozzles where one located at the left of the grinding wheel and the other on right side. The nozzles should be directed to the cutting zone as close as possible. Another recommendation that could be offered is the use of dummy block on the

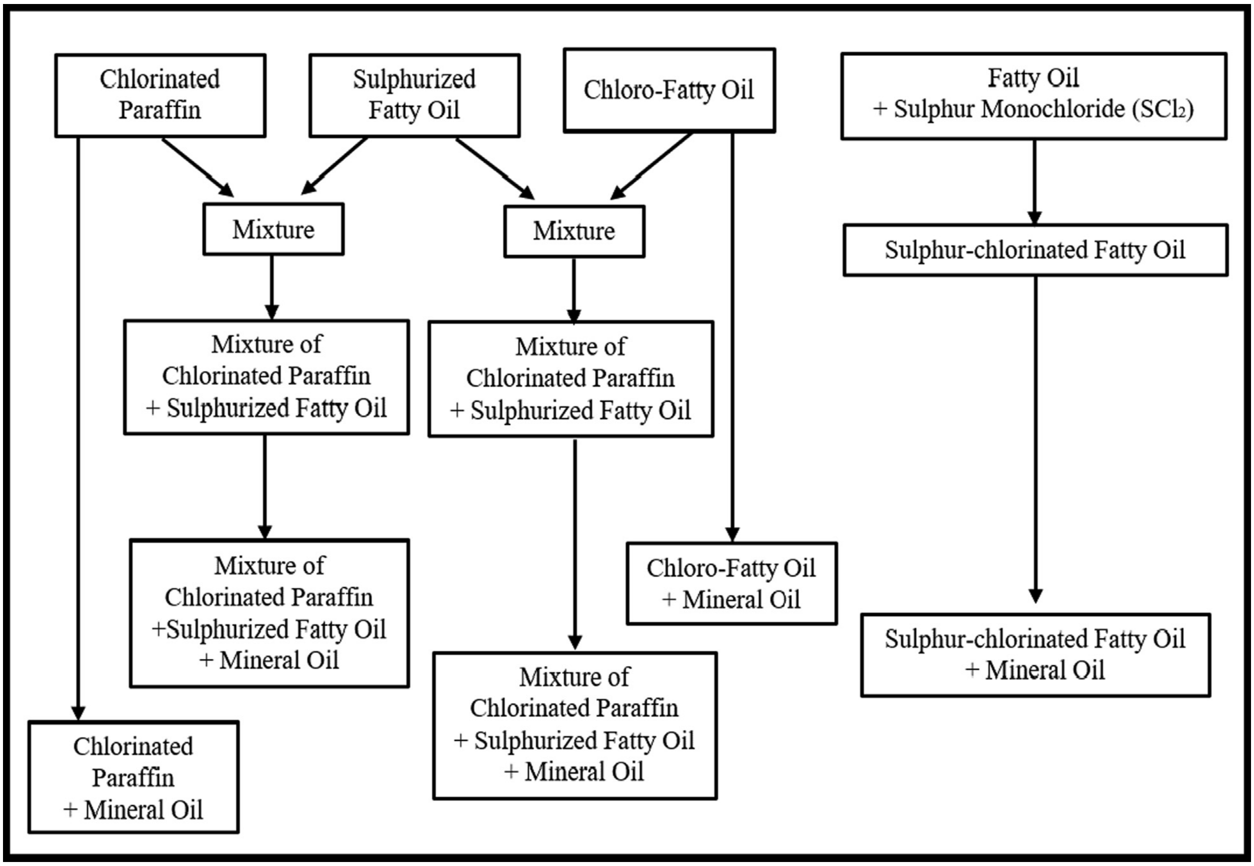

Fig. 5. Compound fluid formulation used by industries.

Fig. 6. Drilling with coolants through tools and schematic diagram of the coolant path with the drill-bit as an insert.

side of workpiece as illustrated in Fig. 7. As such, an adequate amount of coolant can be delivered to the cutting zones between workpieces and the wheel at the beginning of grinding operations [41,75].

The typical application of coolants for grinding operations are water-based oils, chemical fluids and emulsion with a concentration of 1:25 and 1:60 mix with water to form a mixture. If a higher concentration of 2.5–10% cutting fluids is applied, the material removal rate can be higher, and accordingly less power is required with better workpiece surface finish [64,75]. There are different

Table 7
The benefits of cutting fluids usage in different types of milling operations.

Types of Milling Operations	Benefits
Milling with aluminum and stainless steel	Avoid metal particles or chip coating on the workpiece surface
Milling with alloys with heat resistant in low-speed machining operations	Provide both cooling effects and lubricating effects to the machining operations
Milling with cast iron	Provide rust protection
Milling with thin-walled components	Avoid distortion of geometry or low dimensional accuracy
Milling with micro-lubrication systems	Compressed air is mixed with a small amount of unique oil which helps to flush away the chips in the cavities.

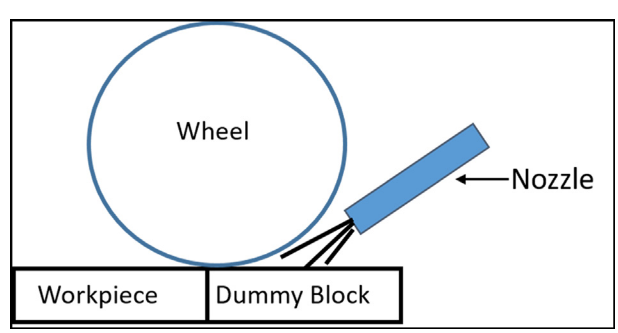

Fig. 7. Use of dummy block in a grinding process.

Table 8
Coolant delivery methods for different types of grinding operations.

Types of grinding	Coolant delivery methods
Cylindrical grinding	Use a fan-shaped nozzle that is wider than the grinding wheel so that the whole grinding surface is flooded
Internal grinding	Use a large wheel with ¾ of the diameter of hole so that an adequate amount of coolant is supplied to the bore
Thread grinding [64]	Oil based fluids, cutting oils with EP additives and emulsion can be used in this application [64]

coolant delivery methods for grinding operations as listed in Table 8.

4.2. Cutting tool material

4.2.1. Tungsten carbide tools

Tungsten carbide is a material that is typically used as a cutting tool due to its outstanding characteristic like high strength, strong resistance to deformation, good impact resistance and oxidation resistance [80]. However, because of high temperature caused by the friction, rapid tool wear results in short tool life and further deteriorates surface quality of workpieces. As a result, coolants with good cooling effect should be utilized for this particular application [73–75].

4.2.2. Boron nitrate and polycrystalline diamond tools

Cubic boron nitride as a cutting tool provides superior hardness, good resistance against thermal shock and good toughness that can be used in high speed machining applications [81]. Cubic boron nitride is manufactured by high temperature and high stress of hexagonal boron nitrate. Both cubic boron nitrate and polycrystalline diamonds possess a similar characteristic to be used in machining applications of iron and low carbon alloys without any issue. Other than that, cubic boron nitride tools can be applied with grey cast iron in a roughing machining process with the high speed like turning and milling [81]. Cubic boron nitride has similar structures and properties as diamond, which is suitable as the material to manufacture for cutting tools [82]. Polycrystalline diamond is a composite comprising diamond particles, which are formed by sintering together with a metallic binder. This type of material has good resistance against wear but does not perform well in high temperature and becomes prone to chemical instability. Furthermore, polycrystalline diamond cutting tool is restricted to use with non-ferrous materials like metal matrix composites, high-silicon aluminium and carbon fibre reinforced plastics. For super-finishing operation regarding titanium, this type of tools can be used with flood coolants [81]. As this type of tool is strong enough to withstand the stress and high temperature, the use of coolants would be unnecessary [73–75]. However, these types of cutting tools generally very costly.

4.2.3. Ceramic and diamond tools

Ceramic is a hard but brittle material that is manufactured through the burning of non-metallic minerals under a high temperature and pressure condition [83]. Ceramic cutting tools provides excellent resistance against wear in high-speed machining operations. However, there are some limitations of ceramic tools such as fracture toughness and resistance against thermal shock. Ceramic cutting tools can be used in a wide scope of applications like turning, milling and grooving. There are a variety of ceramic tools for diverse applications as listed in Table 9 [81]. Furthermore, gas coolant applications can be used with ceramic cutting tools, while water-based coolants are conversely used with diamond based cutting tools in finishing applications [73–75].

Table 9
Ceramic grade cutting tools.

Ceramic grades	Description
Oxide ceramic	• Aluminium oxide with the addition of zirconia for crack inhibition Good chemical stability but prone to thermal shock
Mixed ceramic	Reinforced particles with addition of cubic carbides or carbonatites Enhanced toughness and thermal conductivity
Whisker-reinforced ceramic	• Addition of silicon carbide whiskers to enhance toughness Good for machining nickel-based alloys
Silicon nitride ceramic	• Elongated crystals form with high toughness value Does not perform well in chemical stability Perform well in grey cast iron machining operation
Sialon	• Combination of silicon nitride network Improved chemical stability Perform well in the machining operation of heat resistant super alloys

4.2.4. Cermet cutting tools

Cermet is a composite material with ceramic and metals (WikiDiff). Cermet cutting tool has better resistance against wear and less smearing tendency compared to cemented carbide tools [84,85]. However, cermet tools have less resistance against thermal shock and low compressive strength. Cermet tools are generally applied in finishing operations due to its good tool life, good dimensional accuracy, and tight tolerances leading to good surface finish. On the other hand, cermet tools can also be used in finishing operations for materials like cast irons, stainless steel, low carbon steel and ferritic and ferrous materials. It is recommended to operate in the low depth of cut and feed rate without the application of coolants to prevent thermal fractures and cracks. A summary of the suitability of coolants to apply in various machining operations for different typical materials are demonstrated in Table 10 [41,86–88].

5. Cooling action

5.1. Dry machining

As a result of the advances in coating deposition technology, it is possible to coat cutting tool tip, which helps to reduce the friction caused in flank wear and make dry machining possible [90]. For some machining operation, the use of coolants is unnecessary. For instance, during the machining process of aluminum and carbon steels, the chips can dissipate the heat away. Whereas dry application is incompatible to the high depth of cut as it may leads to short tool life. According to previous studies, the representative machining parameters for ISO P15 are feed rate of 0.4 mm/rev, cutting speed of 290 m/min with depth of cut of maximum 1 mm [91,92].

5.2. Flood applications

Flooding is one of the common types of cooling system that is used in the industry, as shown in Fig. 8. In this system, the coolants can be delivered through a nozzle from a coolant storage system in machine and splash towards the cutting zone. The heat produced from the machining operation can be dissipated easily, and flush away the chips at the same time. Flood coolant system offers the best performance in machining operation such as milling, grinding and drilling. In some applications, high pressure jets (above 1000

Table 10
Selection of coolant with different materials for turning, drilling and reaming.

Material	Turning	Drilling	Reaming	Threading	Milling	Tapping	Sawing	Grinding
Aluminium	• Soluble Oil Mineral Oil Mineral + Lard Oil Paraffin/ Kerosene	• Soluble Oil Mineral Oil Mineral + Lard Oil Paraffin/ Kerosene	• Soluble Oil Mineral Oil Mineral + Lard Oil Paraffin/ Kerosene	• Soluble Oil Mineral Oil Lard Oil Mineral + Lard Oil Paraffin/ Kerosene	• Dry Soluble Oil Mineral Oil Lard Oil Mineral + Lard Oil	• Soluble Oil Mineral Oil Sulfurized-based Mineral Oil	• Dry Soluble Oil Mineral Oil	• Soluble Oil
Bronze	• Soluble Oil Mineral Oil Mineral + Lard Oil	• Dry Soluble Oil Lard Oil Mineral Oil Mineral + Lard Oil	• Dry Soluble Oil Mineral Oil Mineral + Lard Oil	• Soluble Oil Mineral Oil Lard Oil	• Dry Soluble Oil Mineral Oil Mineral + Lard Oil	• Dry Soluble Oil Lard Oil Mineral + Lard Oil	• Dry Soluble Oil Mineral Oil Mineral + Lard Oil	• Soluble Oil Mineral Oil
Brass	• Soluble Oil Mineral Oil Mineral + Lard Oil	• Dry Soluble Oil Mineral Oil Mineral + Lard Oil	• Dry Soluble Oil Mineral Oil Mineral + Lard Oil	• Soluble Oil Lard Oil Mineral Oil Mineral + Lard Oil	• Dry Soluble Oil Mineral oil Mineral + Lard Oil	• Dry Soluble Oil Lard Oil Mineral + Lard Oil	• Dry Soluble Oil Mineral Oil Mineral + Lard Oil	• Soluble Oil Mineral Oil
Cast Iron	• Dry Soluble Oil Mineral Oil Lard Oil	• Dry Air Jet Soluble	• Dry Soluble Oil Mineral Oil Lard Oil Mineral + Lard	• Dry Sulfurized Oil Soluble Oil Mineral + Lard Oil	• Dry Soluble Oil	• Dry Mineral Oil Lard Oil Mineral + Lard Oil	• Dry Soluble Oil	• Dry Soluble Oil Mineral Oil
Malleable iron	• Soluble Oil	• Dry Soluble Oil	• Dry	• Lard Oil	• Dry Soluble Oil	• Soluble Oil		
Magnesium	• Dry Mineral Oil	• Dry Mineral Oil	• Dry Mineral Oil	• Dry Mineral Oil	• Dry Mineral Oil	• Dry pl Mineral Oil	• Dry Mineral Oil	• Dry Mineral Oil
Alloy steel	• Soluble Oil Sulfurized-based Mineral Oil	• Soluble Oil Sulfurized Oil Lard Oil Mineral Oil	• Soluble Oil Mineral Oil Lard Oil Mineral + Lard Oil Sulfurized Oil	• Lard Oil Sulfurized Oil	• Soluble Oil Mineral Oil Lard Oil Mineral + Lard Oil	• Mineral Oil Mineral + Lard Oil Sulfurized Oil		
Tool Steel	• Soluble Oil Mineral + Lard Oil Synthetic Fluids	• Soluble Oil Mineral + Lard Oil Synthetic Fluids	• Soluble Oil Mineral + Lard Oil Synthetic Fluids	• Soluble Oil Lard Oil Mineral + Lard Oil Sulfurized Oil Synthetic Fluids	• Soluble Oil Lard Oil Mineral + Lard Oil Synthetic Fluids	• Mineral Oil Lard Oil Sulfurized Oil	• Soluble Oil Mineral Oil Mineral + Lard Oil	• Soluble Oil
Wrought iron and stainless steel	• Soluble Oil Synthetic Fluids Mineral + Lard Oil	• Soluble Oil Synthetic Fluids Mineral + Lard Oil	• Mineral + Lard Oil Synthetic Fluids	• Soluble Oil Mineral + Lard Oil Synthetic Fluids	• Soluble Oil Mineral Oil Lard Oil Synthetic Fluids	• Solid Paste [89]	• Soluble Oil Mineral oil Mineral + Lard Oil	• Soluble Oil
Monel metal (Nickel alloys)	• Soluble Oil	• Lard Oil Soluble Oil	• Lard Oil Soluble Oil	• Lard Oil	• Soluble Oil	• Mineral Oil Lard Oil Sulfurized Oil		
Carbon	• Soluble Oil Mineral + Lard Oil Synthetic Fluids	• Soluble Oil Mineral + Lard Oil Synthetic Fluids	• Soluble Oil Mineral + Lard Oil Synthetic Fluids	• Soluble Oil Mineral Oil Lard Oil	• Soluble Oil Mineral Oil Lard Oil	• Soluble Oil Lard Oil	• Soluble Oil Mineral Oil Mineral + Lard Oil	• Soluble Oil
Copper	• Soluble Oil Mineral Oil Mineral + Lard Oil	• Dry Soluble Oil Mineral Oil Paraffin/ Kero-sene Lard Oil Mineral + Lard Oil	• Dry Soluble Oil Lard Oil Mineral Oil Mineral + Lard Oil	• Soluble Oil Lard Oil Mineral Oil Mineral + Lard Oil	• Dry Soluble Oil Mineral Oil Mineral + Lard Oil	• Soluble Oil Mineral Oil Lard Oil	• Dry Soluble Oil Mineral Oil Mineral + Lard Oil	• Soluble Oil Mineral Oil

Fig. 8. Flooding with three nozzles.

psi) may be used to deliver the coolants [93 94]. This application is a better option to evacuate the chips generated from a machining process. However, both applications are not environmentally friendly as most of the coolants are wasted with the difficulty in disposal. Furthermore, the running cost of coolant pumps and the maintenance of the coolant system are very high [95].

5.3. Minimum quantity lubrication (MQL)

The aim of using minimum quantity lubrication (MQL) is to reduce thermal stress at the tool point, tool wear, the volume of coolants required, and the protection to the environment and operator health [96]. In MQL, no more than 50 ml lubricants per processing hour are used [97]. The selection of coolants for MQL is based on several factors such as oxidation stability, storage stability and biodegradability. Vegetable oils have been commonly used in MQL operations due to their advantageous biodegradable characteristics, while polyol esters and synthetic fluids have started to be taken into consideration in these recent years [98]. In some other MQL applications, compressed air is mixed with a small amount of cutting oils to form air-fluid mixture that is suppled through a 1 mm diameter jet with a pressure of 699 kPa at a rate of 1 – 100 CC/hr. Coolants with good lubricity and high thermal rating provides the best performance of MQL in metal machining. The most typical coolants used for MQL in the industries are synthetic esters and fatty alcohols due to their favourable vaporization behavior and a high flash point [99–106]. As reported by Varadaran et al, [100], MQL has a higher cutting ratio, which is due the better lubricating effect and better penetrability of MQL when compared to dry and flood cooling. Additionally, good surface roughness and lower cutting temperature along the feed rate and cutting speed can be achieved by MQL. In misting applications, the cutting fluid is mixed with the air to produce a mixture called aerosol. It is applied between workpieces and cutting tool through atomizer. The atomizer is an ejector to atomize the cutting fluids with compressed air. On the other hand, spraying lubrication is achieved by spraying a cold liquid that shifts the heat formed in machining operations. The heat energy from the cutting process is transferred by either warming the cold liquid or evaporating the liquid to a gaseous state [107–111].

5.4. Cryogenic machining

Cryogenic machining is a comparatively new technology that uses cryogenic gases as coolants instead of conventional coolants. Cryogenic gas can be defined as the use of materials at a low temperature (e.g., −150 °C). Mostly, cryogenic gases are tasteless, odorless, colorless and non-toxic gas [102], which are widely used in different industries like electronics, automobiles, aerospace and medical services [112–125]. Cryogenic gases can be hydrogen, neon, oxygen, helium, and nitrogen with a temperature below −180 °C. The most used cryogenic gas for machining purpose is liquid nitrogen. Cryogenic machining requires specially designed cutting tools and liquid nitrogen supply by jacketed tubes fitted in the machine [126]. It is an alternative coolant application that can be used to machine hard-to-cut materials [127]. In the past, cryogenic machining is hard to achieve and expensive. There are some difficulties at the time when using cryogenic machining including the methods to spray the liquid nitrogen to cutting tools or to submerge the entire workpiece with nitrogen. Commonly, a high flow rate of liquid nitrogen is supplied, where in such a case, most of the nitrogen evaporates before reaching the cutting surface with lower cooling effect. However, currently there is a new technology for cryogenic machining called 5ME patented by Cryogenic Machining Technology [128]. In this technology, a small flow rate of liquid nitrogen is delivered from the vacuum jacketed feed lines. The gas is then directed to the machine spindle and lastly to the cutting tool. The main function of cryogenic machining is to remove the heat effectively, improve tool life, modifying frictional traits of cutting tools and to shift the material properties of workpiece and cutting tools [107]. Additionally, it is environmentally friendly. Cryogenic machining can be performed in these three ways: (i) cryogenic cooling of the workpiece or cutting tools, (ii) attaching of a cold chamber under the cutting tool tip for heat conduction and (iii) spraying of cryogenic gas on the tip of cutting tools. The first method is immersing the workpiece or cutting tools in the liquid nitrogen before starting the machining process. Nonetheless, not all materials are applicable to this method due to structural transformation at a low temperature, which may result in thermal cracking on both workpiece and tool surface. This method is considered to be inefficient because the time is taken to immerse the workpiece or cutting tools and short machining application time is used to obtain good results [92]. Fig. 9 shows a method to attach a chamber filled with liquid nitrogen under the cutting tool tip. This method provides good cooling effect as the heat enables to dissipate through the tool insert in contact with liquid nitrogen. This method is suitable for cutting tools that possess suitable tool insert thickness and materials with high thermal conductivity [92].

The last method is by spraying liquid nitrogen on the cutting tool tip. However, challenges encountered with the application of this method come from the amount of liquid nitrogen enabling to reach or entering the cutting zone before evaporation. Moreover,

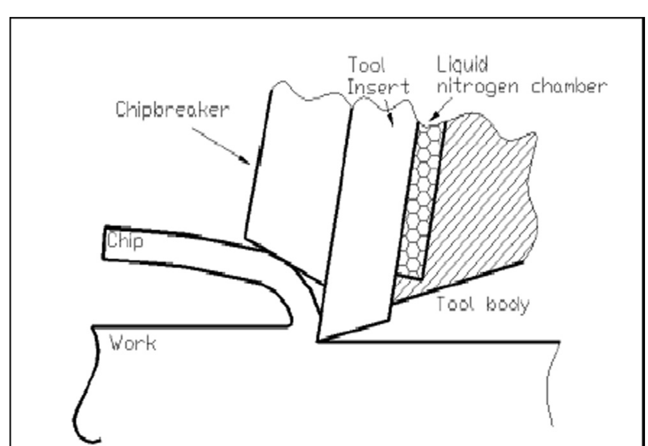

Fig. 9. Nitrogen chamber attached under cutting tool tip.

thermal cracking may occur on the tool surfaces [92]. Apart from the use of liquid nitrogen, CO_2 has been acknowledged a potential coolant for machining [129–138].

Based on the above-mentioned discussion, it can be found that the major challenge is to select suitable coolants for a specific application by taking the consideration of prospective outcomes and to ensure that the coolants reach the desired work zones. In addition to that, environmental issue caused by coolants and proper disposal technique for each type of coolants are of a great concern as well. Other than that, a detail study regarding the additive effect can be conducted for a better understanding of how the additives can change the properties of coolants.

6. Summary and future work direction

The main functions of coolants are to lower down the temperature of the cutting zone, provide lubricating effects to the machining operation, flushing away chips along with corrosion protection. It can be concluded that in high-speed machining operations, coolants cannot penetrate both secondary and tertiary deformation zones to achieve lubricating effects due to high stress and friction. However, coolants enable to dissipate the generated heat in primary deformation zone and account for approximately 60 % of total heat generation in a machining process. Heat also dissipates through generated chips. Therefore, delivering the coolants onto the chips or flushing the chips helps to reduce the temperature of cutting zones. The lubricating effects are only possible for low-speed machining applications to reduce the friction, restrain the development of BUE and provides good surface finish of the workpiece. The delivery methods and cooling actions on how the coolants can be supplied into the machining operations play a leading role in an efficient and better machining process. The selection of appropriate coolants by taking the consideration of machining processes, materials of workpiece and cutting tools is always a great challenge together with the proper disposal of used coolants..

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Declaration of Competing Interest

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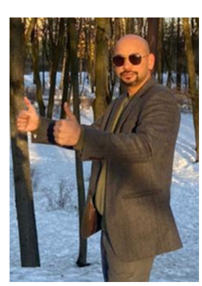
A. Pramanik School of Civil and Mechanical Engineering, Curtin University, Bentley, WA, Australia

A. K. Basak Adelaide Microscopy, University of Adelaide, Adelaide, SA, Australia

S. Shankar Department of Mechatronics Engineering, Kongu Engineering College, Erode, India

Khor Zheng Yang School of Civil and Mechanical Engineering, Curtin University, Bentley, WA, Australia

Chander Prakash, PhD Professor in School of Mechanical Engineering School of Mechanical Engineering, Lovely Professional University, Phagwara 144411, Punjab, India. His research area is Bio-manufacturing, Fabrication of porous Bio-material, Surface Modification of Biomaterial & Finite element analysis of surface texture for medical application.



Saurav Dixit, PhD Senior Researcher, Peter the Great St. Petersburg Polytechnic University, 195251 Saint Petersburg, Russia. Saurav is a creative person with a passion for research and technology up-gradation and works dedicatedly to achieve his goals, led to a good number of publications in peer-reviewed Scopus indexed journals. He is having an excellent publication record (41 publications and 550 number of citations on the Scopus database, with an H-index of 10). He is also contributing to the knowledge of research by serving as for several scientific journals on their editorial/reviewer boards.

Kaushal Kumar, PhD K. R. Mangalam University Gurgaon, India.

Nikolai Vatin, PhD, Dr.Sci.Eng. Professor/Senior staff scientist and Chief of the research lab, World-class Research Center for Advanced Digital Technologies, Peter the Great St. Petersburg Polytechnic University, 195251 Saint Petersburg, Russia.

Y. Dong.