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Applications of cooling and lubrication nozzles in grinding, milling, and turning: A review emphasising nozzle design, location and orientation

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Abstract

Cooling systems in standard machining operations play an essential role in achieving the quality and performance required in operational outcomes. Most machining operations, and especially those dealing with refractory materials such as nickel, cobalt, and titanium-based alloys, cannot be conducted efficiently without the application of cooling. Cooling nozzles are important elements of cooling systems and control the flow rates of coolants as well as their direction. The design of the nozzle may significantly influence the efficiency of cooling systems, where high coolant consumption is one of their main ecological and economic drawbacks and poor nozzle design may result in the dissipation of coolant in an inefficient manner. This paper reviews state-of-the-art cooling systems used for machining, with an emphasis on the designs and applications of cooling nozzles used for grinding, milling, and turning operations. The first part of the paper considers recent publications concerning common types of cooling systems as well as the nozzle designs and applications used, and also summarises the advantages and disadvantages of each system. The second part briefly discusses important research studies of the design, location and orientation of cooling nozzles. Finally, conclusions are drawn that represent the most significant results and findings of this review, the main objective of which is to fill the research gap identified with regard to the development of cooling and lubrication nozzles and their applications during grinding, milling, and turning processes.

Keywords: Cutting fluid; Flood cooling; MQL; Nozzle; Nozzle location and orientation; Coherent nozzle

الملخص

تلعب أنظمة التبريد في مختلف عمليات التصنيع بواسطة التشغيل الميكانيكي (الخراطة، التفريز، التجليخ وغيرها) دوراً أساسياً في جودة أداء هذه العمليات. لا يمكن إجراء عمليات التشغيل الميكانيكي على بعض المواد خصوصاً المواد الهندسية المقاومة

للحرارة مثل سبائك النيكل والكوبالت والتيتانيوم بكفاءة دون استخدام أنظمة وسوائل التبريد. يعتبر نوع وشكل فوهة خرطوم التبريد (Cooling Nozzle) أثناء عمليات التشغيل الميكانيكي عنصرًا مهمًا في أنظمة التبريد، حيث يتحكم في معدلات تدفق سوائل التبريد وكذلك اتجاهاتها. قد يؤثر تصميم فوهة خرطوم التبريد على كفاءة أنظمة التبريد سلبًا أو إيجابيًا. وفي الواقع، يعتبر الاستهلاك المرتفع لسوائل التبريد أحد العوائق البيئية والاقتصادية الرئيسية اثناء عمليات التصنيع في حين أن التصميم السيئ لفوهة خرطوم التبريد سيؤدي بالتأكيد إلى تبديد الكثير من سوائل التبريد بطريقة غير فعالة ومكلفة. تستعرض هذه المقالة العلمية أحدث أنظمة التبريد المستخدمة في مختلف عمليات التشغيل الميكانيكي. كما تلقي الورقة الضوء بشكل خاص على مختلف التصميمات وتطبيقات فوهات خراطيم أنظمة التبريد المستخدمة في أهم عمليات التشغيل الميكانيكي والتي من ضمنها فوهات خراطيم أنظمة التبريد ذات التدفق المتناسق (Coherent Nozzle)، تنقسم الورقة إلى ثلاثة أجزاء رئيسية: الجزء الأول يستعرض أحدث الدراسات المتعلقة بالأنواع الشائعة لأنظمة التبريد بالإضافة إلى تصميمات وتطبيقات فوهات الخراطيم المتعلقة بها. كما تستعرض الورقة سلبيات وإيجابيات ووجهات النظر العلمية المتعلقة بكل نظام. بينما خصص الجزء الثاني من الورقة لتقديم عرض موجز للعديد من أحدث الدراسات البحثية التي تهتم بتصميمات فوهات خراطيم أنظمة التبريد وأماكن توجيهها نحو منطقة القطع. أخيراً، تختتم الورقة بملخص للأهم الاستنتاجات من الدارسات البحثية المنجزة في هذا المجال. إن الهدف الرئيسي والقيمة المضافة لهذه الورقة هو سد الفجوة البحثية الحالية فيما يتعلق بتطوير فوهات خراطيم أنظمة التبريد وتطبيقاتها أثناء مختلف عمليات التشغيل الميكانيكي المذكورة آنفاً.

الكلمات الدالة: سوائل وأنظمة التبريد، عمليات التشغيل الميكانيكي، فوهات خراطيم أنظمة التبريد ومواضعها، فوهات خراطيم أنظمة التبريد ذات التدفق المتناسق.

1. Introduction

In the machining industry, cutting fluid supply systems (cooling systems) are crucial. Without coolants, most difficult-to-cut materials such as hardened steels, and ferrous, nickel, and titanium-based alloys cannot be machined efficiently. These systems have significantly improved machinability, cutting efficiency, and productivity. The use of these systems in manufacturing has enabled various advances such as in heat dissipation, cutting force reduction, lubrication, chip control, improved surface finish, higher metal removal rate, and dust suppression. Regardless of its type and design, a cooling system consists of two main parts: the hardware or the equipment used to deliver the cooling agent, and the cooling fluid (coolant) itself. Coolants have been developed to protect the microstructures of materials being machined from the heat generated during cutting operations. Coolants dissipate heat and help provide a uniform heat temperature field around a tool tip and inside the workpiece, which helps in the production of more accurate products, protects the cutting tool from premature failure, and maintains the microstructure of the machined material. Coolants also prevent

Nomenclature	
MOs	Mineral oils
VOs	Vegetable oils
FCL	Flood cooling and lubrication system
MQL	Minimum quantity lubricant
HPC	High pressure cooling
HPCL	High pressure cooling and lubrication system
OMCCL	Oil mist and cryogenic cooling and lubrication system
MCL	Mist cooling and lubrication system
CCS	Cryogenic cooling systems
ACF	Atomisation-based cooling fluid spray system
CUT-LIST	**C**ontrolled c**ut**ting f**l**uid **i**mpinging **s**upply sys**t**em
CFD	Computational fluid dynamics
CNC	Computer numerical control
CO_2	Carbon dioxide
Ti–6-Al–4V	Titanium Alloy
$MQL+CO_2$	A mixture of minimum quantity lubricant and carbon dioxide
Loc-Line	A type of commercial cooling nozzle used in standard machine tools
Ra	Average surface roughness
V_B	Principal tool flank wear
V_S	Auxiliary tool flank wear
T_L	Tool life

corrosion and contribute to reducing the friction between the cutting tool and workpiece material (by lubrication action at lower cutting speeds) and dissipating heat from the machining zone (by cooling action at higher cutting speeds), resulting in extended tool life and improved machining quality [1]. Coolants are categorised into three main groups of neat cooling oils, water-soluble coolants, and gas-based coolants [2]. Coolants based on mineral oils (MOs) are used widely in the machining industry. However, they are associated with various environmental and health issues throughout their lifecycle [3]. Due to their better tribological qualities and high biodegradability, vegetable oil (VO)-based coolants have recently been proposed as suitable alternatives to conventional coolants [4]. Meanwhile, regardless of which type is used, coolants are delivered to machining zones using different supply methods and corresponding hardware. The nature of a cooling system's hardware depends on whether it employs, for example, conventional flood cooling and lubrication (FCL), high pressure cooling and lubrication (HPC), minimum quality lubrication (MQL), or oil mist and cryogenic cooling and lubrication (OMCCL) [5]. However, any cooling system must have a nozzle which delivers coolants to cutting zones. Indeed, the cooling efficiency of the system is not only influenced by coolant type and volume, but also by the type and design of the nozzle which controls the flow rate and direction of the coolant [6]. The traditional sloped nozzle is the most common type of nozzle, especially when performing common machining operations like turning, milling, and drilling. For various grinding activities such as cylindrical and surface grinding, coherent, tapered, slot, spot jet, or shoe-type nozzles are frequently used [7]. This is because, in comparison to other machining operations, grinding can produce a significant amount of heat due to the high contact area between the grinding wheel and workpiece surface. Many studies have been conducted of coolants and their applications, and the characteristics of coolants during machining processes and their environmental impact have been investigated. However, no substantive review has comprehensively discussed recent developments in the design of nozzles used for cooling and lubrication in turning and milling operations.

This research presents state-of-the-art knowledge concerning the most common cooling and lubrication systems used for grinding, milling, and turning, focusing on recent publications related to the types and designs of cooling nozzles used. The paper is divided into three main parts. The first part presents a literature review of the most common cooling and lubrication systems used in standard machining operations, and summarises their advantages and disadvantages. The second part then considers recent research studies of cooling nozzle designs and applications, and the results of real-world case studies are discussed. Finally, conclusions are drawn which represent the most significant findings of the review. The main objective of this study is to fill the research gap which has been identified in regard to the development of cooling and lubrication nozzles and their applications and adjustments during grinding, milling and turning processes.

2. The most common cooling and lubrication systems used for machining operations

2.1 Flooding cooling and lubrication (FCL)

This is the most widely used cooling and lubrication system in many standard machining operations. In this system, a high stream of cooling and lubrication fluid (coolant) is pumped directly toward machining zones through conventional, randomly positioned, and sloped nozzles, as illustrated in Figure 1. The coolant is usually delivered under low pressure (10 bar or less), and low flow rate ≤ 220 L/min [8]. The coolant disperses heat from machining zones so as to prevent damage to workpieces and tools, and also clears chips away from as well as lubricating the machining zone, thus reducing friction at the tool-workpiece and tool-chip interfaces. This type of cooling system relies on different types of fluids such as water-soluble oils (emulsion), synthetic and semi-synthetic fluids, and pure oils. However, these systems are not very efficient, since they utilise huge quantities of fluids, most of which are not ecologically friendly. In addition, they have to be replaced and disposed of frequently after specific periods of time, which creates further environmental problems. These cooling systems also fail to control the fluid stream at localised hot zones and exhibit low penetrability, especially at high cutting speeds, due to the formation of a high-temperature vapour blanket that renders the coolant ineffective [9].

Furthermore, when the cutting fluid stream is applied to the rake and flank faces simultaneously, good cooling performance can be attained. This requirement cannot be properly achieved by flood cooling where the fluid is often flooded from the chip side (i.e., the rake face) to the cutting tip, and therefore a substantial thermal load leads to rapid tool wear and shorter tool life [10].

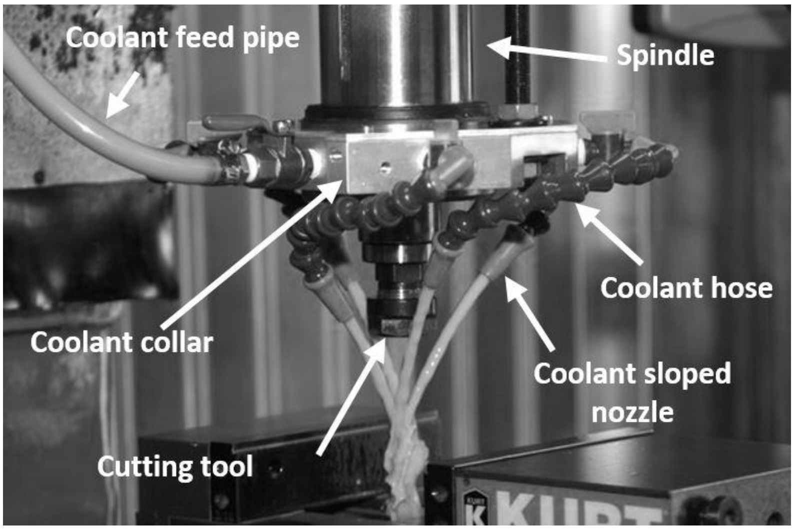

Figure 1. Flooding cooling and lubrication system [11]

2.2 High-pressure cooling and lubrication system (HPCL)

This is an upgraded version of FCL in which the coolant is pressurised and directed onto machining zones to increase the heat dissipation rate, and chips are ejected from the narrow points of the cutting zone. This system was invented to tackle the high temperatures accompanying modern machining processes in which metal removal rates increased substantially and assists to cut hard-to-machine materials. . HPCL applies coolants under high pressure (up to 200 bar) through customised nozzles to provide a powerful jet of fluids into the machining zone [12]. The force of the pressurised coolant in the system promotes superior penetration capabilities into the tool-workpiece and tool-chip interfaces, thus prolonging the tool's life and inhibiting tool wear. Additionally, HPCL helps to create small discontinuous chips, which can easily be hydraulically ejected away from the machining zone and tool rake face. However, the the main limitation of such systems is that up to 75 L/min of coolant are applied utilising very expensive pumping and filtration techniques, and the microparticles (< 20µm) of chips may cause damage to the system [13]. Figure 2. illustrates the HPCL system applied in a high-speed milling operation.

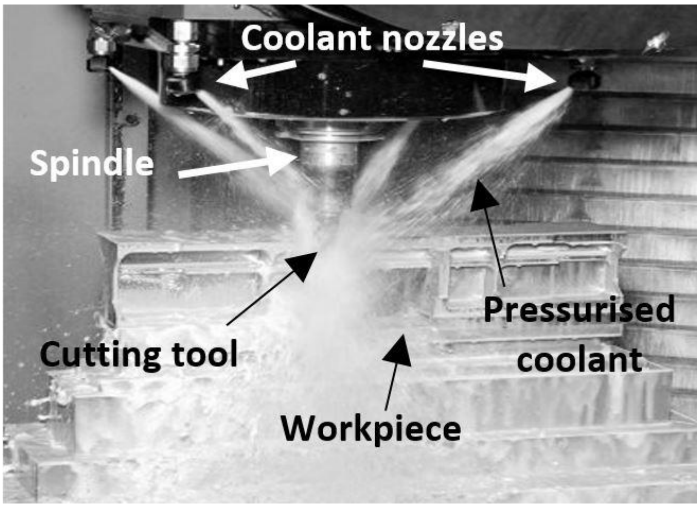

Figure 2. HPCL system applied in a high-speed milling operation [11]

2.3 Mist cooling and lubrication (MCL)

Figure 3. shows an MCL system where external equipment attached to a machine is connected to a special compressor which pressurises the air up to six bars and cools it down to 0˚C. The compressed and cooled air is pumped to a special nozzle connected to a small tank that supplies the coolant. The high-pressurised cold air splits up the coolant particles into a mist (aerosol) of droplets of about 20 µm. The aerosol is sprayed toward the cutting zone in order to cool the hot tool tip and workpiece surfaces and to blow chips away. MCL is characterised by its high cooling and lubrication efficiency. Moreover, the aerosol can reach narrow zones as well as provide good visibility during machining operations [14]. Additionally, unlike FCL and HPCL systems, MCL applies a much smaller volume of coolants all of which is converted into an aerosol, and thus tanks or containers to collect the coolant for reuse or disposal are not required. This characteristic is very important since coolants may be very toxic and hazardous to the environment. Moreover, the equipment used can be adapted for manual, semi-automatic, and automatic operations, and MCL can dramatically improve the quality and productivity of most machining operations. However, neat mineral oil mists, particularly when used in grinding

processes, are more prone to fluid ignition than water-miscible fluids [15]. In addition to its other drawbacks, the use of MCL necessitates an appropriate ventilation system to prevent personnel breathing in harmful airborne fluid particles. Furthermore, high-speed machining with oil mist poses severe health risks because so much mist is produced, making it far riskier than low-speed milling [16].

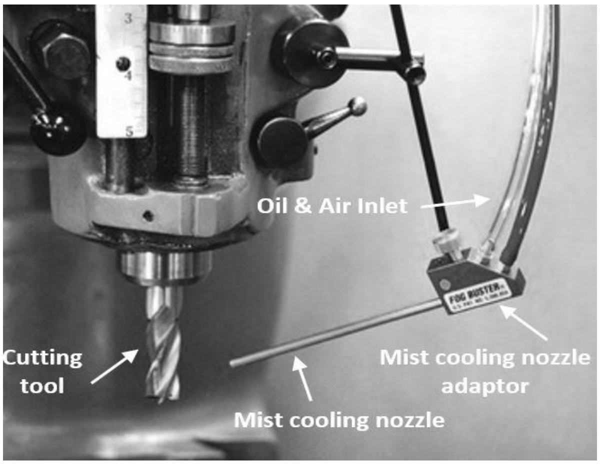

Figure 3. Mist cooling and lubrication system in an end-milling operation [11]

2.4 Minimum quantity lubrication and cooling (MQL)

The MQL system depicted in Figure 4. is also known as ‘micro-lubrication’ or ‘near-dry lubrication’, and this system was presented as a feasible substitute for FCL [17]. Its main principle is that it spreads a fine mist containing a mixture of air and oil to cutting zones where oil and air are mixed inside well-directed and specially designed nozzles. This application uses pressures of up to 6 bar, nozzles with an outlet diameter of around 1 mm, and flow rates of 10 to 450 mL/h. MQL systems depend on very low oil volumes (in mL/h instead of L/min) compared to the previously mentioned systems, and it commonly uses biodegradable lubricants such as vegetable oil-based fluids [18]. The best coolants for MQL are neat vegetable oils and synthetic ester oils because of their better lubrication capabilities and biodegradability. When compared to dry and FCL, MQL has been observed to significantly lower the frictional cutting force by 24 % and 32 % respectively at low cutting speeds [19]. When applied to the tool flank face rather than the rake face, MQL has also demonstrated a considerable reduction in tool wear. However, the use of MQL is restricted to the machining of typically hard and refractory materials like nickel- and titanium-based alloys where heat dissipation is a priority, and many studies view it as a lubrication rather than cooling system [20-22]. In addition to other criticisms, hazardous fluid aerosols are frequently produced in MQL machining due to the mist application spraying mechanism used [23]. Additionally, the utilisation of MQL in the machining of highly ignitable materials like magnesium alloys is particularly risky [24]. Figure 4. illustrates the commercial MQL system applied in an end-milling process.

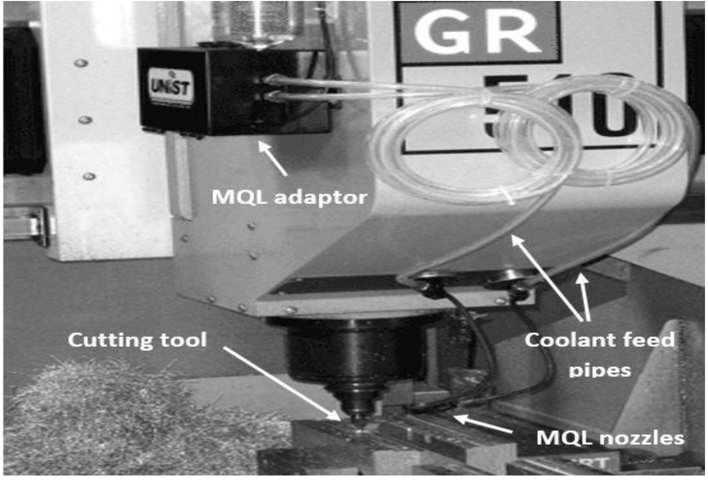

Figure 4. MQL system applied in an end-milling process [11]

2.5 Cryogenic cooling system (CCS)

Cryogenic cooling refers to the application of a high-velocity jet of cryogenic agents such as liquid nitrogen or liquid carbon dioxide which possess very low boiling points (−195°C and −78 °C respectively) to deliver the rapid cooling of machining zones. This system provides a highly efficient cooling effect and maintains cleaner machining environment since no oil or liquid is left. When using this system, the cooling agent is blown toward cutting zones which are too hot. The agent cools both the workpiece and tool and instantly evaporates, and hence this system creates what is termed a pollution-free atmosphere. However, because cryogenic coolants spread into the atmosphere as soon as they leave the nozzle, they perform poorly as lubricants [25].

3. Design of cooling and lubrication nozzles in machining

3.1 Grinding operations

Grinding operations are characterised by relatively large contact areas between tools and workpieces. Consequently, high friction usually arises between abrasive grits and workpiece surfaces. Sometimes coolants experience difficulty reaching deep and narrow zones between the grinding wheel and workpiece and extinguishing the grinding arcs. Thus, there is a high risk of thermal damage to the workpiece surface, as well as grinding wheel wear [26]. Thermo-mechanical processes in contact zones are defined by tribological relationships between the grain cutting edge, grinding wheel bonding, workpiece, and chip, and therefore cooling and lubrication play a decisive role during grinding with respect to heat generation and dissipation. In addition to cutting fluid type, composition and filtration, studies have shown that cutting fluid supply variables including nozzle type, position, and geometry, supplied flow rate, and jet characteristics can influence process productivity, workpiece quality and tool wear [27]. Many nozzles have been designed and fabricated to control thermal damage to surface layer of the workpiece. Figure 5. shows various nozzle designs based on different grinding operations [28]. In comparison to other grinding processes, creep-feed grinding is widely prevalent and characterized by slower workpiece speeds and deeper cuts, resulting in a longer arc length of contact between the grinding wheel and workpiece [29]. One of the more popular upgrades to creep-feed is the use of coherent jet nozzles, as shown in Figure 6.

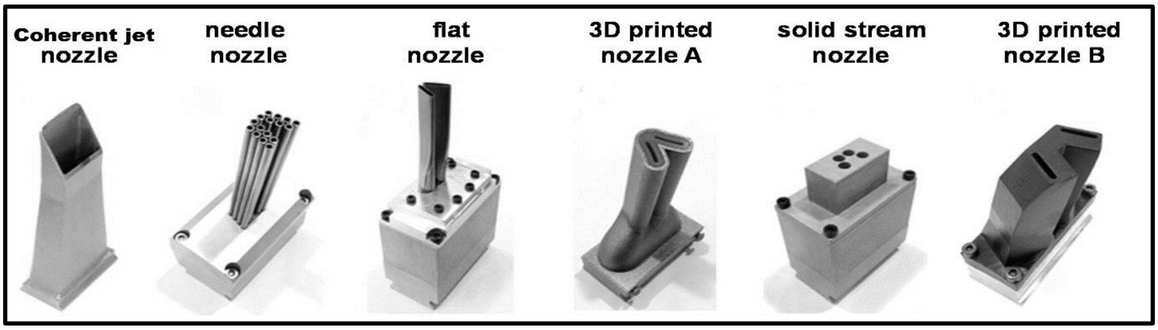

Figure 5. Various designs of cutting fluid supply nozzles in grinding operations [28]

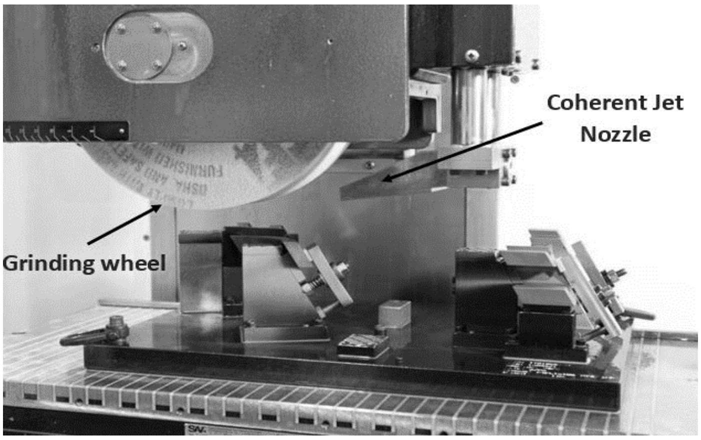

Figure 6. Creep-feeding grinding using coherent jet nozzle [30]

H. Rouse introduced a coherent cooling nozzle for the metalworking industry in 1951 after observing a jet produced by fire hose nozzles. Later, Webster [31] improved nozzle design for use in cooling systems suitable for most grinding operations. Figure 7. illustrates the distinctive interior design of coherent nozzles which inhibits the development of boundary layers, enhances flow coherency, and creates high-quality jet streams with minimal entrained air and low dispersion. The coherent nozzle’s fundamental feature is coherency, which is described as “a dimensionless unit defined by the ratio of jet width at some downstream distance over the jet width at the orifice” [32]. To meet the coherency requirement, the contraction ratio of the inlet to exit diameter must be greater than or equal to 2:1. According to continuity and Bernoulli's theorem [33], the coherent nozzle can enhance dynamic pressure more than fourfold as kinetic energy in the form of a homogenous jet up to 300 mm in length.

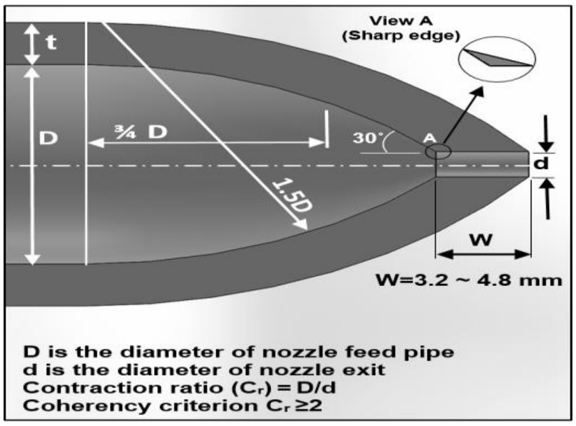

Figure 7. Cross-sectional view of a coherent round nozzle used in grinding operations [34]

It has been shown that a coherent nozzle’s effectiveness depends on a variety of variables, including pressure, flow rate, and the direction of the fluid jet, all of which have an impact on how effectively the fluid cools and lubricates. While pressure controls fluid velocity, flow rate controls the rate of heat transfer into the fluid [35]. It has been noted that a coherent jet of fluid was shown to dramatically decrease cutting temperature and improve heat and mass transfer performance between the fluid and the exposed work part and grinding wheel surfaces during grinding operations [36].

3.2 Turning and milling operations

The majority of CNC turning and milling machines are equipped with two or more conventional sloped nozzles, also known commercially as Loc-line nozzles. They are used where a plentiful volume of cutting fluids is required, as shown inFigure 8, and these nozzles are often made of plastic with conical or spherical connectors that can be manually fixed at a specific orientation during milling and turning processes [31].

Figure 8. A Loc-line cooling and lubrication nozzle used in turning and milling operations [11]

Figure 9. Shows a sectional view of the Loc-line nozzle type. They have a large nozzle aperture diameter and are made to feed cutting fluid at flow rates greater than 4000 L/h (up to 10 mm) [37]. However, '*vena contracta*' phenomenon and eddy formation are the main problems affecting the efficiency of these nozzles. Eddy formation occurs when a sudden change in the tube diameter reduces the coolant's flow direction from a large zone into a smaller one, causing fluid dispersion particularly at higher velocities. Due to the adhesion of fluid to the inner side of the nozzle, the *vena contracta* (a point in a fluid stream where the diameter of the stream is lowest and fluid velocity is highest) can negatively affect the aperture size [32].

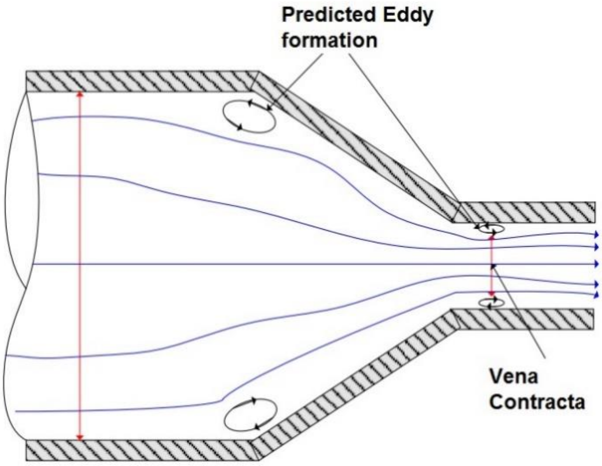

Figure 9. Cross-sectional view of a Loc-line nozzle showing eddy formation and vena contracta [32]

4. Design of MQL cooling and lubrication nozzles

In general, the MQL nozzle mechanism consists of two main parts. The first is the mixing chamber, where the compressed air and oil are mixed; and the second is the nozzle's tip where the pressurised mixture is sprayed out toward cutting zones. MQL mechanisms afford many advantages such as maximising the volume of cooling liquids, controlling the mixing rates of air and oil, and precise spray direction using less mist [38].

Figure 10. depicts an MQL nozzle mechanism in which the liquid mixture is accomplished inside the nozzle.

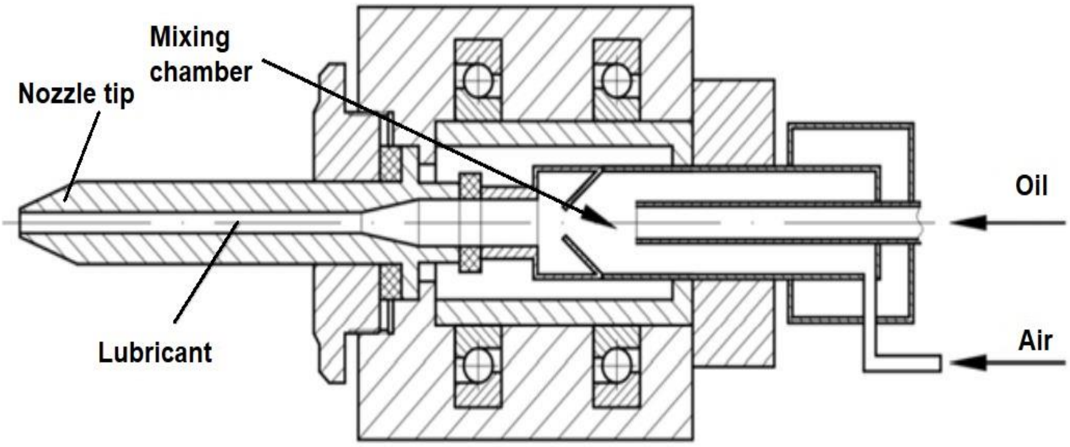

Figure 10. MQL nozzle mechanism [38]

5. Evolution of nozzle design for turning and milling operations

Kapoor et al. [39] designed and validated an atomisation-based cooling fluid (ACF) spray system for the end-milling of Ti-6Al-4V. The study has been conducted to compare the machinability of titanium under different cooling fluid application methods, including dry cutting, FCL, ACF, and MCL, based on the five machinability parameters of tool life, tool wear, cutting forces, surface roughness and chip morphology. The ACF spray system they developed is shown in Figure 11., which involves: (i) an ultrasonic-based atomizer; (ii) a cutting fluid reservoir with a delivery tube; (iii) a nozzle unit consisting of a coaxially-assembled outer droplet and inner gas nozzles; and (iv) a high-pressure gas delivery tube for the nozzle-spray unit. The ultrasonic atomizer used was vibrated at a frequency of 130 kHz and atomized droplets were generated with a mean diameter of 11.8 µm. Once the fluid was atomized, the micro-sized droplets moved forward through the outer droplet nozzle. High-velocity gas flowing through the gas nozzle entrains these droplets to produce a focused axisymmetric spray jet that is employed in the cutting zone during machining. The exit diameters of the droplet nozzle and the high-velocity gas nozzle were designed to be 18.8 mm and 1.6 mm respectively, with convergence slopes of 40° and 0.75°, and the gas nozzle was placed inside the droplet nozzle 5 mm from the exit point in order to avoid the divergence of droplets.

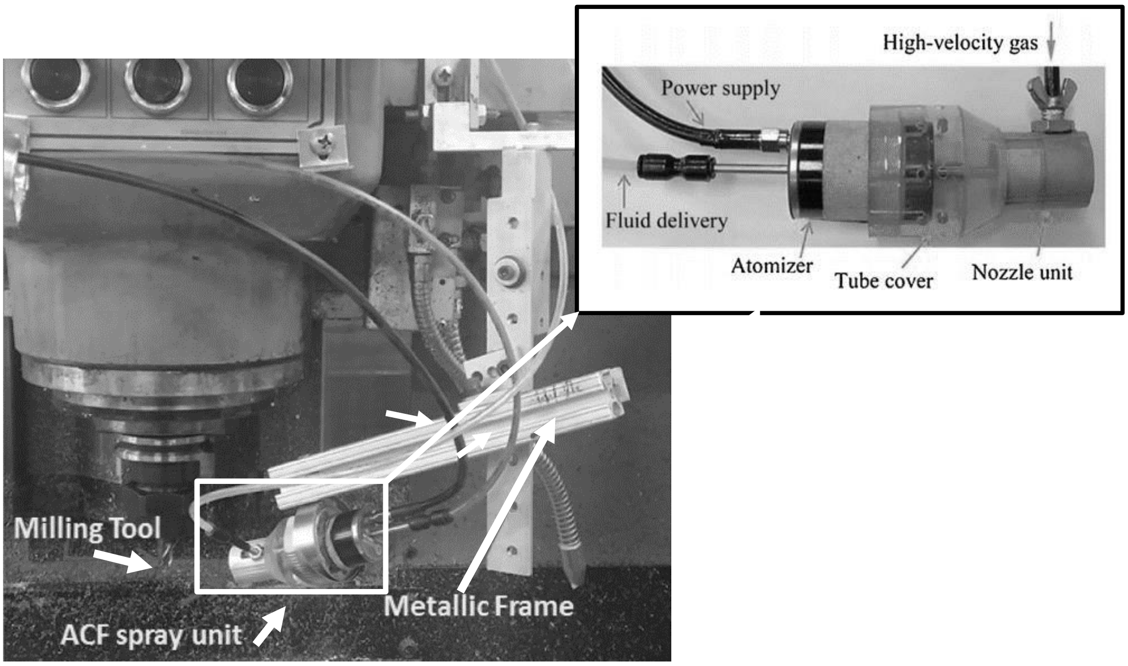

Figure 11. Cutting fluid ACF spray system developed for the milling of Ti–6Al–4V [39]

Experimental results from Kapoor et al.'s study showed that the application of the ACF spray system resulted in uniform tool flank wear, lower cutting forces, better surface finish, and a tool life extended by up to 75% compared to an FCL system. Moreover, chip morphology analysis revealed that using ACF leads to the formation of shorter and thinner chips, as compared to those when FCL is used. Figure 12 and Figure *13* depict the effects of ACF on Ra and tool flank wear respectively.

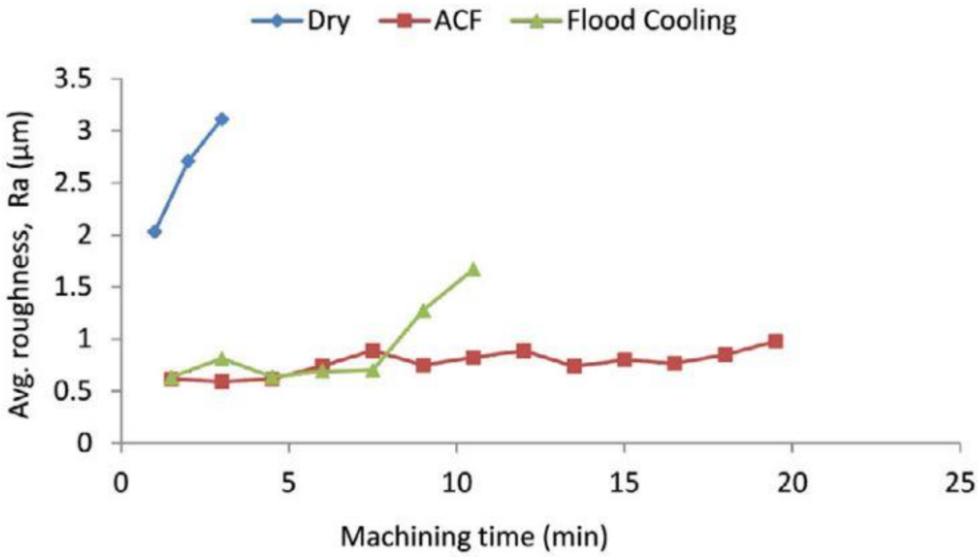

Figure 12. Ra results during end-milling of Ti–6-Al–4V under ACF spray system [39]

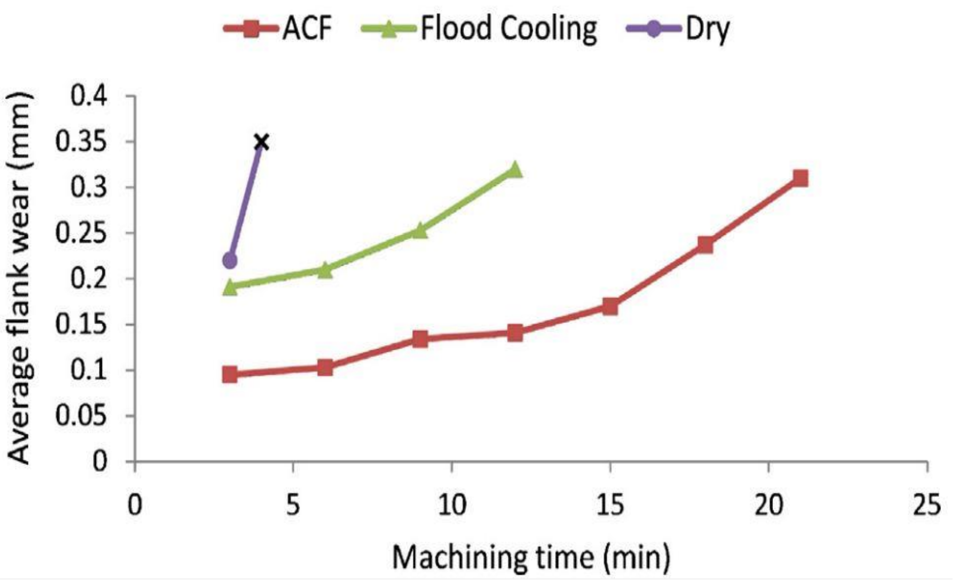

Figure 13. The progress of tool flank wear during end-milling of Ti–6-Al–4V under ACF system [39]

Recently, Gariani et al. [34] developed a new controlled cutting fluid impinging supply system named ‘CUT-LIST’ to deliver an accurate quantity of cooling fluid into machining zones through precisely-oriented round coherent nozzles, as shown in Figure 14. Unlike conventional sloped nozzles, CUT-LIST nozzles were designed based on the Webster jet nozzle model. The new system can simultaneously target cooling fluids towards and backwards from the feed direction at three different angles of 15º, 45º and 60º and with various stand-off distances. The performance of the CUT-LIST system equipped with a conventional sloped nozzle when milling Ti-6Al-4V alloy using a soluble vegetable oil-based coolant was compared with that of an FCL system, and the effects of cutting conditions on cutting force, workpiece temperature, tool flank wear, burr formation, and average surface roughness (Ra) were investigated. Additionally, the effects of CUT-LIST on chip formation, microstructure, and micro-hardness of the machined surface have been assessed. According to the study’s findings, the proposed system significantly reduces the amount of cooling fluid used by up to 42%, while also significantly reducing the cutting force, tool flank wear, and burr height by 16%, 47%, and 60% respectively.

Also, it was observed that Ra improved when applying the CUT-LIST supply system, as illustrated in Figure 15. Considering the effects of CUT-LIST machining parameters particularly feed rates, it was found that feed rate has decreased the cutting force by 47.46%, and improved burr formation and surface roughness by 38.69% and 39.10%, respectively compared to a conventional flood cooling system. Likewise, the micro-hardness, microstructure, and chip formation of the machined surface were all assessed. It was revealed that there is no significant disparity between the two cooling (CUTLIST and conventional) systems in terms of microstructural damage. In addition, SEM analysis showed that the formation of discontinuous serrated chips is the main characteristic of the milling of Ti-6Al-4V with both cooling systems. Both cooling systems achieved acceptable micro-hardness variations (always ranging between 386.3 – 419 HV_{100}). In terms of nozzle orientation effects, stand-off distance was found to have a stronger influence on the key process variables than nozzle angle position. This is due to the strong correlation between stand-off distance and fluid penetrability. However, as shown in Figure 16., the positioning of the nozzles, in particular at acute angles (≤ 15˚) in the feed direction, greatly aids in enhancing coolant access to the machining zones and reducing workpiece temperature. The preferred position for chip evacuation and the appropriate cooling of the tool at the tool exit point, however, might be nozzles angled at 45 degrees backwards in the feed direction.

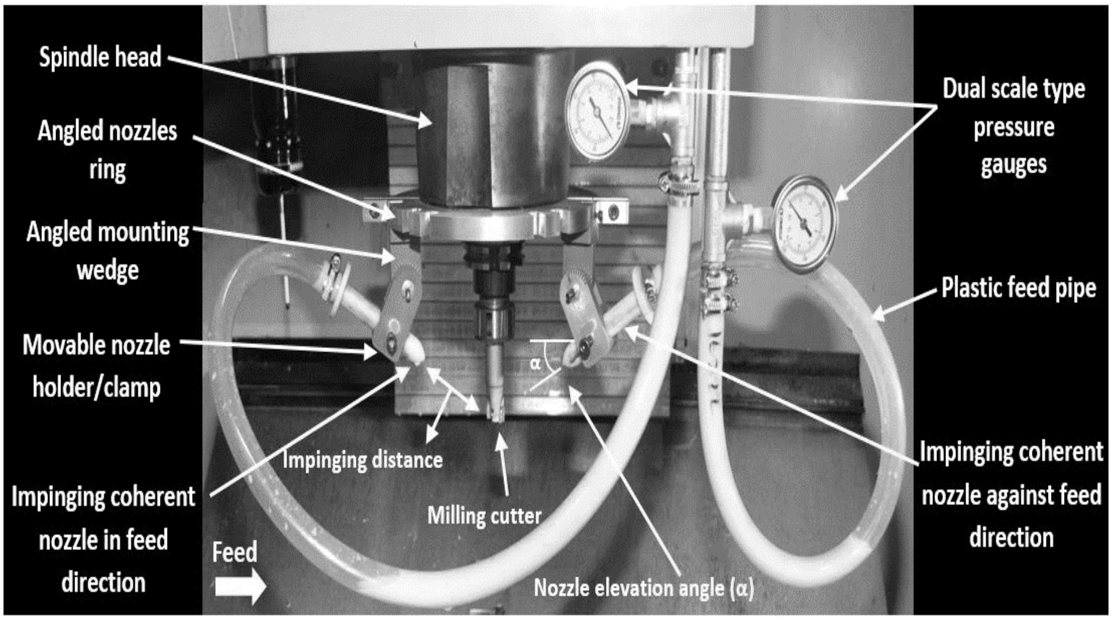

Figure 14. CUT-LIST fluid supply system with round coherent nozzle involved in end-milling of Ti-6Al-4V [34]

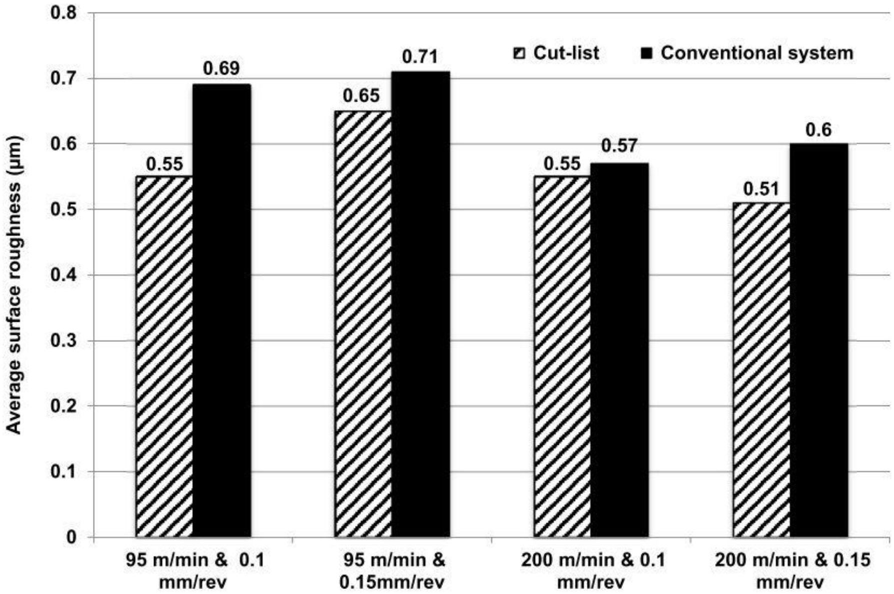

Figure 15. Ra results versus cutting conditions [34]

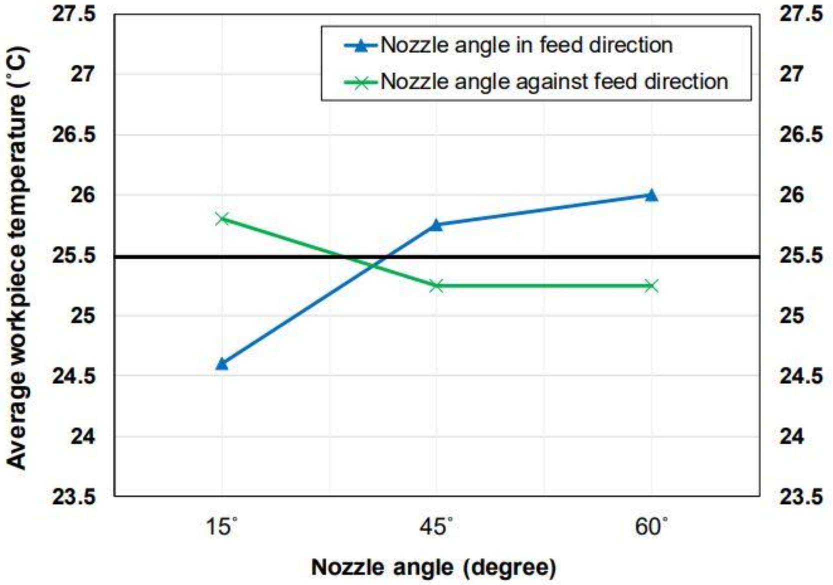

Figure 16. Mean effect plot of nozzle orientation against workpiece temperature for CUT-LIST [40]

Pereira et al. [41] developed plug and play nozzles based on the Laval nozzle model which are directly applicable to commercial MQL systems, as shown in Figure 17. Image of the developed (MQL + CO2) supply system when milling Inconel 718 [41]

. The behaviour of developed nozzle adapters were simulated using computational fluid dynamics (CFD) and the optimal nozzle adapter was tested in the milling of Inconel 718. In these milling tests, tool life was measured using different prominent cooling-lubrication techniques of dry, wet using FCL, CO_2 stand-alone, MQL stand-alone and CO_2+MQL; the latter being the proposed alternative.

In this study, compressible fluid dynamics were taken into account with the aim to achieve that liquid CO_2 speed exceeds sound speed. To accomplish this, the CO_2 channels were modified with convergent-divergent outlets (Laval nozzles). The results showed that tool life in dry machining was 46.7% shorter compared to that when wet machining using FCL. CO_2 cryogenic machining improved the values obtained with dry machining, reaching 67.7%. With an oil flow rate of 100 ml/h in machining with MQL, tool life increased by 84.2%. Finally, when connecting the CO_2 nozzle adapter (CO_2+MQL), the increase rises to 93.5% compared with wet machining as shown in Figure 18.

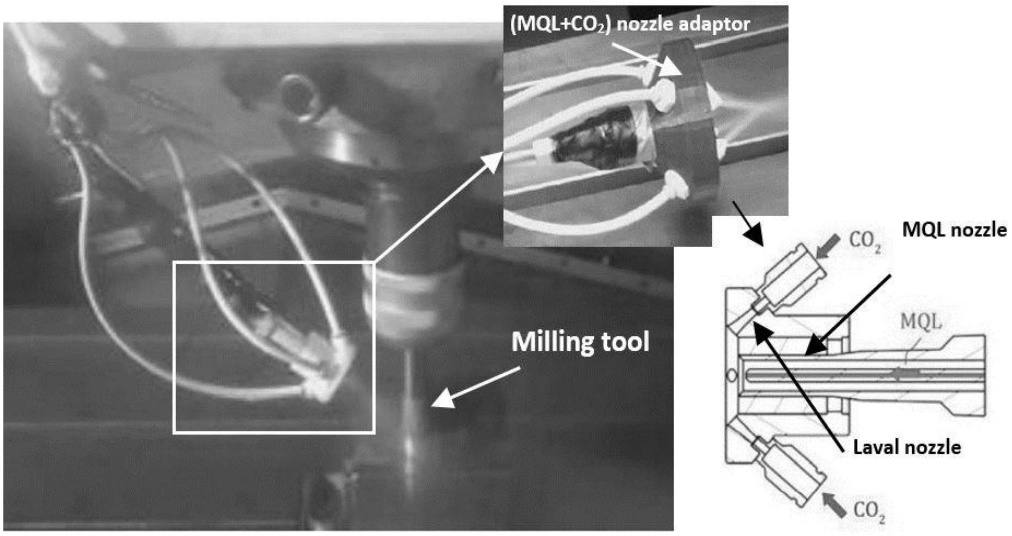

Figure 17. Image of the developed (MQL + CO2) supply system when milling Inconel 718 [41]

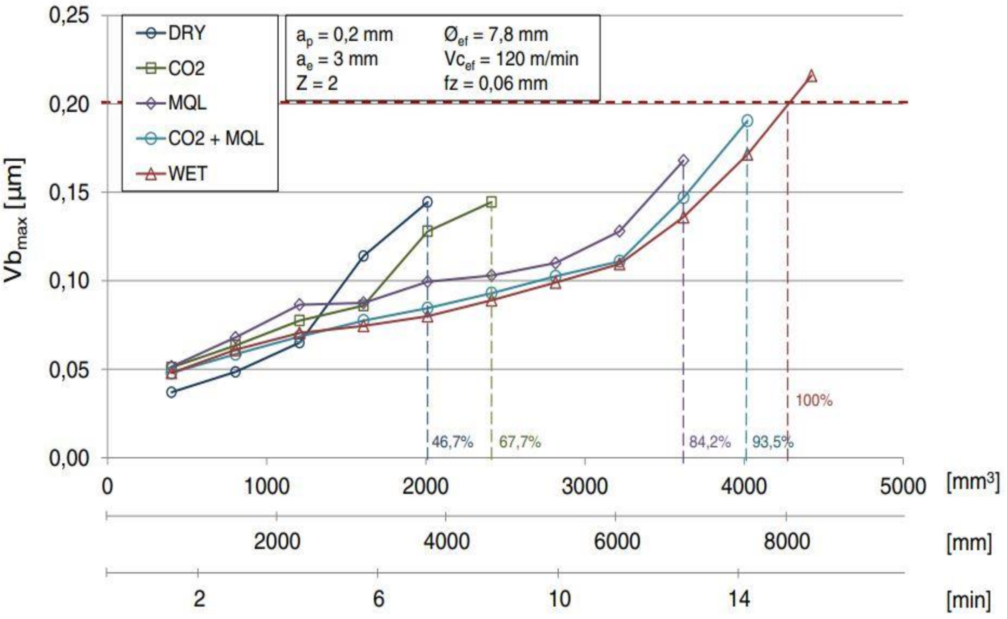

Figure 18. Tool life results of the tested cooling systems when cutting Inconel 718 [41]

Zaman et al. [42] investigated the performance of their new double-jet micro nozzle connected to an oil/air mixing chamber in the turning of medium carbon steel in comparison to dry and external single-jet MQL machining, as shown in Figure *19*. MQL supply parameters were air pressure (13, 16, 19 bar), flow rate (60, 80, 100 ml/hr), nozzle diameter (0.75, 1.00 mm), and primary and secondary nozzle angle (10, 15, 20° each). It was found that the double-jet MQL micro nozzle machining was most effective among other machining conditions regarding cutting temperature, surface roughness, chip reduction coefficient, main cutting force, and tool wear. Their analysis also demonstrated that the most influential factor in providing an optimum response was nozzle diameter followed by air pressure, secondary nozzle angle, oil flow rate, and primary nozzle angle, the optimum values of which were 1 mm, 19 bar, 15°, 80 ml/h and 20° respectively. Figure 20. shows the progress of average principal flank wear (V_B) and auxiliary flank wear (VS) against machining time under different cooling conditions when turning medium carbon steel.

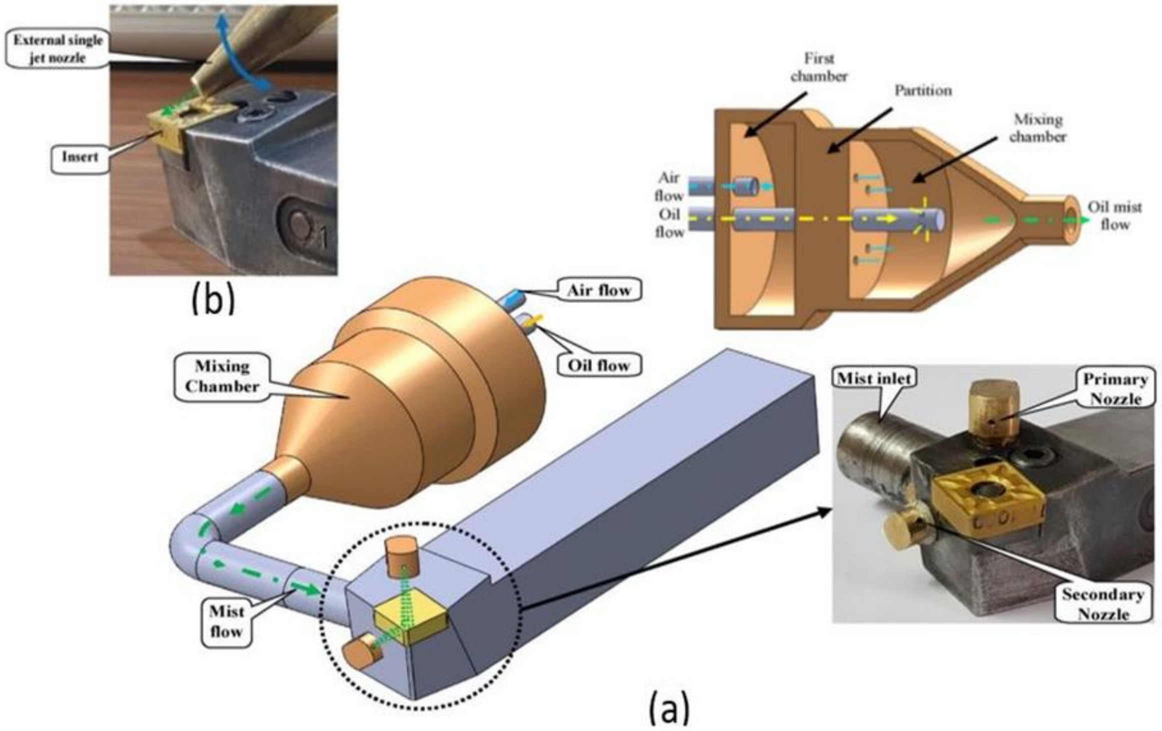

Figure 19. (a) 3D design of double-jet micro nozzle connected to the mixing chamber; and (b) image of external single-jet nozzle set-up used in the experiments [42]

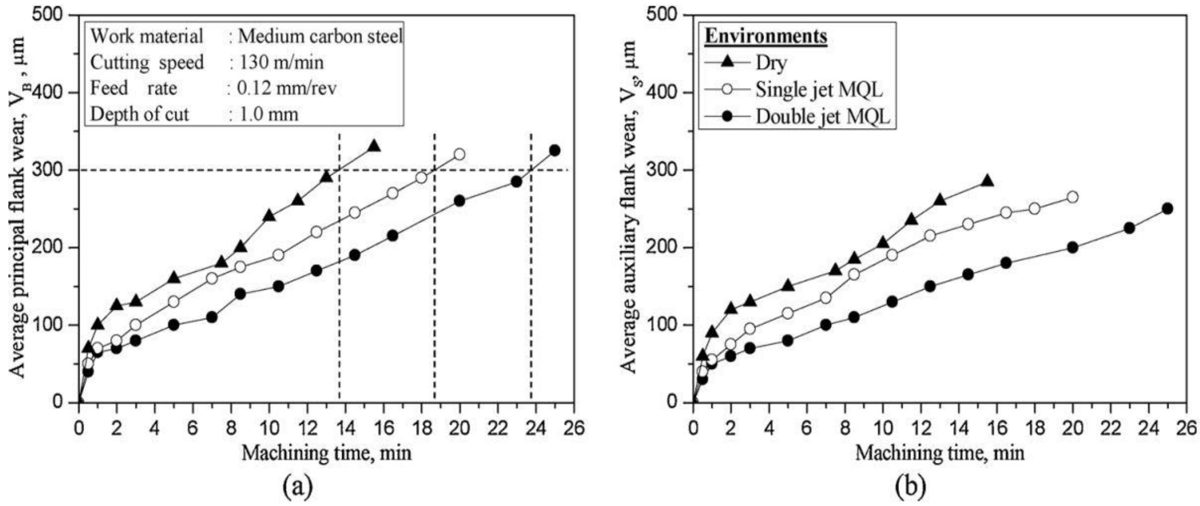

Figure 20. Progress of average: (a) principal flank wear (V_B); and (b) auxiliary flank wear (V_S) against machining time under different cooling conditions when turning medium carbon steel [42]

6. Conclusion

This review has presented the state-of-the-art of the most common cooling and lubrication systems applied in standard machining operations, which are flooding cooling and lubrication (FCL), high-pressure cooling and lubrication (HPCL), and mist cooling and lubrication (MCL). Minimum quantity lubrication and cooling (MQL) and cryogenic cooling systems (CCSs) have also been briefly presented along with the advantages and disadvantages of all of the systems described. Cooling nozzles are very essential elements in cooling systems and for this reason, they have been focused on in this study. In particular, this study has concentrated on the coherent and traditional sloped nozzles used for turning, milling, and grinding, and the findings of several relevant case studies and research endeavours have been presented and discussed. The literature suggests that the coherent nozzle, which is widely used in grinding operations, is a promising alternative to the traditional sloped nozzle used in most flood cooling supply systems. A round coherent nozzle has a unique internal geometry that affords a homogeneous jet stream, reduced coolant consumption and improved machining efficiency. The studies described show that the coherent nozzle orientation in terms of angle, position and stand-off distance plays also a vital role in minimising average surface roughness and workpiece temperature when milling refractory materials such as titanium alloys. These features extend the range of applications for round coherent nozzles, particularly in milling operations. The use of an MQL+CO_2 nozzle adaptor based on the Laval nozzle model elongated tool life by up to 93.5% compared to conventional flood cooling during milling of Inconel 718 in an atomisation-based cooling spray system. The developed double-jet MQL micro nozzle outperformed dry cutting and the traditional external single-jet nozzle in terms of cutting temperature, surface roughness, chip reduction coefficient, main cutting force and tool wear when turning medium carbon steel. In summary, the round coherent and MQL nozzles, along with the other hybrid nozzle adaptors such as MQL + CO_2, are believed to be promising alternatives to traditional flood cooling-based nozzles that could reduce the consumption of cutting fluid with better cutting and cooling performance when turning and milling different engineering materials.

7. Future work

Future research should give more attention to the use of round coherent nozzles in turning and milling operations. Similarly, further attention is warranted to the application of MQL nozzles and MQL+ cryogenic nozzle adaptors, particularly when cutting refractory materials.

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