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Technical, Economic and Environmental Review of the Lubrication/Cooling Systems used in Machining Processes

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Abstract

The use of cutting fluids in machining processes is a serious concern because their cost, and environmental and health effects. In the last decades, efforts have been developed to come up with alternatives to overcome their main drawbacks. The ultimate goal is the complete suppression of cutting fluids. However, because of the demanding requirements of the machining processes, in some cases it is not possible to use dry machining conditions. Reasons can be found in the excessive heat generated in the process, the increase of the friction between the tool and the workpiece or the need to evacuate the chips generated. The pull for sustainable products is also encouraging the developing of new cutting fluid formulations. In the present paper, a comprehensive analysis of the use of cutting fluids and main alternatives in machining is carried out. Particularly, the analysis was done focusing on the economic, environmental and technical points.

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*Keywords:*cost; cryogenic machining; dry machining; environmental impact; machining; MQL system; solid lubricants

1. Introduction

The global lubricant demand was 39.4 million tons in 2015 [1] and it is expected to reach 43.9 million tons in 2022. The industrial lubricant market can be segmented into several categories taking into account their applications. Some of the most used lubricants are gear oils, hydraulic lubricants and engine oils. Cutting fluids represent about

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5% of the global lubricant market, with Asia as the largest consumer [2]. Approximately, 85% of the cutting fluids used are mineral based. However, the estimated values deviate significantly because of the processes diversity [3].

Cutting fluids are widely used in machining processes. The main cutting fluid roles are cooling, reducing friction, removing metal particles, and protecting the workpiece, the tool and the machine tool from corrosion [4]. However, the use of cutting fluids has also associated some disadvantages such as their cost, environmental impact and health hazards to workers (Fig.1) [5]. In machining processes, sustainable manufacturing can be addressed for example, by reducing the consume of electric energy [6], improving the tool life and the surface quality of the workpiece [7].

In the last decades, new alternatives have been developed to overcome the main drawbacks of cutting fluids. The main alternatives include dry machining, minimum quantity lubrication (MQL), solid lubrication, cryogenic cooling, gaseous cooling, sustainable cutting fluids and nanofluids. Some of these alternatives, such as dry machining and minimum quantity lubrication, have been widely evaluated from the technical point of view. However, the study of other alternatives such as gaseous cooling has received less attention. Besides, further efforts in the analysis of these alternatives in both economic and environmental aspects are clearly needed.

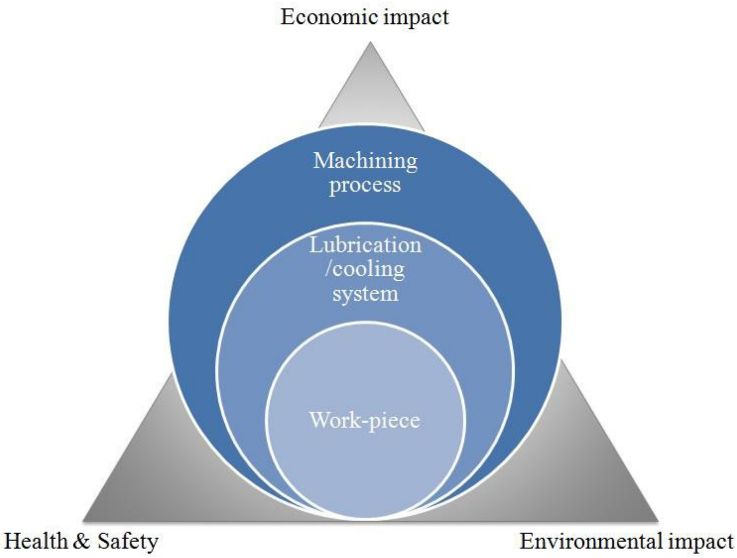

Fig.1. Economic, environmental, and health & safety impacts in sustainable manufacturing.

2. Technical review

2.1. Conventional lubrication/cooling systems

Cutting fluids are mixtures formulated with oil (base) and additives to enhance various properties depending on the machining process. They have been commonly used to enhance productivity and quality in the machining processes. They play an important role in the machining along with machining parameters such as cutting speed, depth of cut and feed rate [8]. The main function of the cutting fluids is to cool and lubricate. So, the use of cutting fluids helps reducing power consumption and protecting from corrosion the machined surface as well as tools and machine tools parts [9]. Moreover, cutting fluids cool down and transport the chips out of the cutting area, carrying away contaminants and debris in liquid instead of being suspended in the air. The ability to evacuate the chips will strongly depend on the viscosity and surface tension [10]. They allow increasing the cutting speed, prolonging the tool life, reducing the workpiece damage, improving the surface quality and meeting with the dimensional specifications. Therefore, cutting fluids increase productivity, improve efficiency by reducing the number of defects, help to ensure the process safety and guarantee and enhance the machining quality [11].

Low speed machining processes benefit more of the lubrication than of the cooling. Cutting fluids minimize friction creating a lubrication film that varies depending on the lubrication regime [12]. When friction is reduced, lower heat is generated and wear is decreased. As the cutting speed increases, the wear by built-up-edge (BUE) decreases and the cutting forces are lower, but the heat generated increases. In these cases, the use of cutting fluids is important to reduce the temperature of the tool the workpiece and the chip [13]. It provides thermal stability to the cutting zone allowing a greater dimensional control. The tool heat release depends on the tool form and its thermal conductivity, the cutting speed and the cooling system used [14]. For example, at a cutting speed of 150 m/min, 75-80% of the heat is conducted by the chips, 10-15% is transferred into the tool and the residual 5-10% is transported by the workpiece [15].

Cutting fluids are classified according to their chemical formulation in straight oils and water soluble oils [16]. Straight oils or neat oils are non-water-soluble fluids formulated to reduce the friction between the tool and both the chips and workpiece. They can be mineral (petroleum based), vegetable or animal oil [3, 17]. Straight oils have excellent lubrication and corrosion resistance properties but poor cooling capacity and they may create mist, which is harmful to the workers health [16]. They have a specific heat capacity close to 2.10 J/(g·K), around half the water's capacity, and a thermal conductivity approximately one-third of the water. Straight oils are more effective in low cutting speed operations and tend to lose their effectiveness at high speeds. One of the reasons is due to the chip movement at high speeds that prevents the fluid to reach the tool interface. Another reason is that, at high speeds, high cutting temperatures are generated and oils vaporize before they can lubricate [18].

Water soluble oils, contrary to neat oils, are more effective at relatively high cutting speeds, where heat generation and high temperatures are a problem [18]. They are usually supplied as concentrates and the end-user dilutes them in water before use. Water content increases the specific heat and thermal conductivity and allows the coolant to remove heat from the machining process, thus reducing the temperature [3]. However, water content induce corrosion, bacteria growth and evaporation losses [16]. These fluids generally contain emulsifiers which provide good cleaning properties, although they may have foam tendencies, which can inhibit heat transfer. In addition, water soluble oils are non-flammable and its tendency to form aerosols is lower than that of neat oils [19].

Water soluble oils can be classified according to the oil content in [12, 20]: emulsions, semi-synthetic fluids and synthetic fluids (Table 1). Emulsions and microemulsions with oil content greater than 40% provide lubricity and better corrosion protection than fluids with higher water content. They are more effective at high speeds machining. Semi-synthetic fluids are emulsions with less than 40% of oil and additives, emulsified in water. Synthetic fluids are oil free cutting fluids that have the greater cooling effect. Different from emulsions and semi-synthetic, they are not sensitive to water hardness and they are transparent, that allows good visibility during machining.

Table 1. Cutting fluid properties[3, 16]

	Straight oils	**Emulsions**	**Semi-synthetic**	**Synthetic**
Aspect	Oily	Milky	Translucent	Transparent
Lubricity	Excellent	Good	Good	Poor
Cooling	Low	Good	Good	Excellent
Corrosion control	Excellent	Poor	Good	Good
Microbial control	Excellent	Poor	Good	Excellent
Fire	Hazard	Non-flammable	Non-flammable	Non-flammable
Other disadvantages	Limited to low-speed operation Create mist	Evaporation losses Foam tendencies	Hard water influence Foam tendencies	Easily contaminated by other processing fluids

Cutting fluids can be applied by different methods, the most common is by flood. This method provides a continuous cutting fluid flow to the tool and the workpiece. It needs several components in the system, mainly filters, a recirculation system, pipes and nozzles and oil recovery device [19]. Other application methods are by mist, where the fluid is applied by pressurized air stream at high speed mist; and high pressure system, where the fluid is supplied at 5.5 to 35 MPa, which allows increasing heat removal and chip transport [3].

2.2. Alternatives to conventional lubrication/cooling systems

Dry machining

Dry machining eliminates completely the use of cutting fluid. Therefore, the heat removed decreases, resulting in a temperature increase on the tool and workpiece [14]. To implement dry machining it should be considered an adequate selection of the tool material to improve wear resistance [21]. The tool should have high hardness and resistance to pressure and temperature, high toughness, high thermal fatigue limit and chemical stability [22, 23].

Generally, dry machining operations are possible at lower cutting speeds [24] and when the workpiece does not require great dimensional and shape precision, which depends on the temperature. Thus, it is required to take special measures to ensure that hot chips are drawn quickly and efficiently from the cutting area, and that the heat introduced into the elements of the machine-tool is removed [25]. The main advantage of dry machining is that there is no atmosphere and water contamination. Moreover, there are no fluid residues in the workpiece neither in the chips. As a result, there is a cost and energy reduction due to the elimination of the cleaning process and the waste fluid treatment. However, dry machining has several disadvantages like material adhesion on the cutting tool, heat generation, friction increase between the tool and the workpiece, and poor chip removal [9].

In interrupted machining processes such as milling with ceramic tools, dry machining could prolong the tool life compared to conventional lubrication/cooling systems, because of the reduction of thermal shock effects [16, 26, 27]. Another application of dry machining is when machining magnesium to avoid ignition and fire hazards caused by the hydrogen formation due to magnesium and water reaction [28].

Although dry machining has been successfully implemented in numerous machining processes such as the drilling of aluminum [29, 30], nowadays there are still several challenges such as the drilling and turning of titanium that still require the use of cutting fluids [31, 32, 33].

Minimum Quantity Lubrication

Minimum Quantity Lubrication (MQL) uses a mix of compressed air with a reduced amount of oil in form of drops, producing a spray that is pulverized on the cutting zone [34]. The oil flow used is in the range between 0.01 and 2 l/h [10], instead of the 50-1000 l/h in the case of conventional lubrication/cooling systems [3, 35]. Most commonly products for machining with MQL system are fatty alcohols and synthetic esters (vegetable oils chemically modified). However, fatty alcohols are used in machining operations where it is more important the cooling than the lubrication effect [23].

Some MQL advantages against other lubrication/cooling systems are: reduction of cutting fluid consumption, cost and tool wear; improvement of surface roughness, diminution decrease of the environmental and worker health hazards and improve lubrication than that of the of conventional lubrication/cooling system [36, 37, 38, 39]. The cutting fluid is used in such small quantities that it is practically consumed in the process, eliminating the fluid disposal problems. In addition, chips produced are nearly clean from cutting fluid, which are easily recyclable [35].

Sharma *et al.* [40] have presented a review on the MQL system in different machining processes, showing that the MQL system can be a promising alternative to the use of cutting fluids. MQL is used focusing on the lubricant properties rather than coolant properties, heat removal is achieved mainly by the compressed air [41]. Due to its poor cooling capacity, some conditions of the machining process like MQL feed system, cutting parameters, workpiece material, and secondary operations should be studied before reducing the flow of cutting fluid without compromising the workpiece quality [23, 42]. However, some authors have studied minimum quantity lubrication technique in combination with cooled air can improve cooling and lubricating performance during machining steel [43] and difficult-to-machine materials [41].

Solid lubrication

Solid lubricants are materials that are in solid phase, such as graphite and its allotropic structures (fullerene, nanotubes, graphene, diamond), molybdenum disulfide (MoS_2) and tungsten disulfide (WS_2) [44]. They have high heat dissipation and thermal conductivity and are more effective than cutting fluids in machining processes that operate discontinuously under high loads and speeds [45]. Moreover, solid lubricants are able to lubricate at higher temperatures than oil-based lubricants. These materials are highly stable at extreme temperatures and pressures. They can be used up to 350°C in an oxidizing media and even at higher temperatures in a reducing or non-oxidizing media (molybdenum disulfide up to 1100 °C) [46]. The lubricity of these solids is attributed to their layered structure with weak Van der Waals bonds. Their layers are capable of sliding on each other with very small forces, which gives them the properties of low friction [44] and wear resistance [47].

They are mostly used in aerospace and automobile industry, though they are being also used in machining industry [45]. They are required in applications where it is necessary to avoid contaminating the product or environment, to maintain or to lubricate inaccessible or difficult-to access areas or to provide prolonged storage [45].

Solid lubricant can be applied as an additive in lubricating oils but they may have undesirable color [48] or directly applied [49, 50]. The combination of graphite with MQL system is a good alternative to conventional cutting fluids in the grinding [51] and turning [52] processes. With low concentrations of solid lubricants, the cutting temperature can be reduced, which improves the tool-chip interaction and the tool life is increased, allowing higher cutting speed and feed rate [53].

Cryogenic cooling

Cryogenic cooling uses materials like liquid nitrogen (LN_2) at - 196 °C or carbon dioxide (CO_2) at - 78 °C, as support during machining. Liquid nitrogen absorbs the heat and evaporates quickly, forming a gas layer between the chip and the tool face, acting as a lubricant [19]. In the case of LN_2 cryogenic cooling, it is a system that leaves no harmful residues to the environment. LN_2 absorbs the machining process heat, the fluid evaporates as nitrogen gas and becomes part of the air (taking into account that the 79% of the air is nitrogen) [5].

In general, cryogenic cooling is an expensive system. Both the $LN_2$and the CO_2 are basic products, but it is needed special equipments to reach the temperatures of -196 °C and -78 °C for the LN_2 and the CO_2, respectively [19]. However, despite the high cost of the equipment and the challenges to implement this technique in industrial applications, it is an alternative that may be of particular interest in special operations and, particularly, when the tool cost is high. For example, the use of the CO_2 liquid is very effective to reduce the crater wear on the carbide tools in the machining of titanium alloys, austenitic nickel-based superalloys, and other materials difficult-to-machine [12].

Gaseous cooling

Gaseous coolants are substances which are in a gaseous state at room temperature. Air is one of the most commonly used gas, though it has a low cooling capacity that can be increased by its cooling, preserving its gaseous state. Other usual gases are argon, helium and nitrogen used to prevent workpiece and tool oxidation [54]. However, as cryogenic cooling, the high cost of these gases makes them not advisable for common applications [55].

Compressed air in combination with cutting fluids reduces the consumption of fluid and can ameliorate the heat transfer problems in superalloy machining [56]. Moreover, the simultaneous use of the spray mode of a vegetable cutting fluid, compressed air and inserting liquid nitrogen to the cutting zone, not only can reduce the cutting forces and temperature, but also makes possible to achieve high cutting speeds and feed rates [57].

Sustainable cutting fluids

Sustainable cutting fluids are one of the main growth areas for the lubricants market due to restrictions and individual pressures and environmental concerns, which is opening multiple research lines. On the one hand, the market is exploring the use of biodegradable vegetable or synthetic oils to replace petroleum products [58]. The rapid increase in the petroleum products prices, the higher dependence on offshore sources, the declining rate of production and the decreasing rate of finding new reserves are some of the reasons to remove mineral based oils [45]. On the other hand, there is a tendency to eliminate or reduce the use of dangerous substances in the cutting fluids formulation. For example, the removal of sodium nitrite and aromatic compounds, the use of more biodegradable additives and an efficient use of biocides in water based fluids [59].

There is a wide range of base fluids that can be used as alternative to mineral oil based like poly-alkylene glycols, vegetable oil, poly-alphaolefins, dibasic acid esters, polyol esters [60], and polymer based fluids [61]. Table 2 compares the properties of different base fluids: canola oil with a 60% oleic acid, a commonly used polyol ester such as trimethylol propane trioleate (TMPTO), a fully saturated or complex synthetic ester, a polyalkylene glycol and a mineral oil. Several studies show that vegetable oil based cutting fluids can be a good alternative to conventional fluids [8, 62, 63, 64]. Vegetable oils have excellent lubricity, biodegradability, viscosity-temperature properties and low volatility. Their main disadvantage is their low thermal and oxidative stability, but it can be improved by using a combination of chemical additives, olefin and high oleic vegetable oils [62].

Table 2. Typical base fluid for sustainable lubricants compared to mineral oil. Based on [45]

Performance	Canola oil (vegetable oil)	TMPTO (polyol ester)	Sat/Complex (synthetic ester)	PAG (petroleum synthesized)	Mineral oil (petroleum)
Biodegradability	Excellent	Very good	Good-Very good	Good	Poor
Toxicity	Low	Low	Low	Low*	High
Lubrication	Excellent	Very good	Very good	Very good	Good
Oxidative stability	Poor	Moderate	Very good	Good	Very good
Thermal stability	Moderate	Good	Very good	Good	Good
Hydrolytic stability	Poor	Moderate	Good	Good	Very good
Viscosity index	Very good	Very good	Very good	Very good	Moderate
Low temperature	Poor	Good	Good	Good	Good
Seal compatibility	Moderate	Moderate	Moderate	Good	Very good
Relative cost**	2	4	6-8	4	1

*Solubility may increase the toxicity of some PAGs

**Cost compared to mineral oil cost (1)

Nanofluids

Nanofluids are fluids obtained by suspending nanoparticles (nanographene or nanoparticles prepared from materials like copper oxide, molybdenum disulphide or titanium) in a base fluid like water, ethylene glycol or oil. Nanofluids physical analysis show that these dispersions can easily penetrate the surface, increase the heat transfer capacity and improve the tribological properties of the fluid [65, 66]. Many lubricants containing nanoparticles are considered advantageous in new technology, as they can provide lubricity over a wide range of temperatures [66].

Water with oxide graphene nanosheets show better friction and wear properties than pure water and water with oxide multiwall nanotubes [47]. Nanoparticles synergism in terms of the lubrication film stability have been found mixing MoS_2 and SiO_2 [67] or alumina and colloidal solution of silver [68].

Recently, an extensive number of studies combine nanofluids with MQL system as alternative to conventional lubrication/cooling systems. For example, nanographene particles in combination with vegetable oil in MQL milling [69], turning [52, 70, 71], and grinding decreases the tool wear and exhibits better performance in terms of surface roughness [72] than MQL. One barrier for the industrial use of the nanofluids is the viscosity. By adding nanoparticles to the base fluid both thermal conductivity and viscosity are increased. Another barrier is the special condition required for nanofluids, such as uniform and stable suspension or low clustering of particles [73].

3. Economic review

3.1. Conventional lubrication/cooling systems

Machining process cost depends strongly on the Material Removal Rate (MRR), but increasing the MRR results in shorter tool life due to the increase of friction and heat generation in the cutting edge [14]. Winter *et al.* [61] have studied grinding process, identifying the influence of the cutting fluid composition on the MRR, the energy consumption and the surface quality reached. Besides, the cutting parameters and workpiece properties, there are three other factors to improve the technological requirements, and the environmental and economic impact, which are: tool, machine tool and cutting fluids [74].

These fluids provide numerous advantages in the manufacturing process, but there are also several disadvantages that suppose a machining cost overrun (Table 3) [75]. In addition to these considerations, environmental legislation is becoming more severe, increasing disposal costs and arising the need to develop new lubrication/cooling systems and new cutting tools.

Table 3. Cutting fluids advantages and disadvantages in machining operations

Advantages	Disadvantages
Increase tool life	Costs related to fluid purchase, storage, maintenance, waste fluid disposal
Lower cutting forces and power required	As time passes it can cause workpiece and machine tool damages due to a bad maintenance
Higher cutting speeds and feed rates	Environmental impact
Reduce post-process heat treatments	Worker health hazards
Better workpiece quality	

Heine (1998) [76] noted that the cost of lubrication/cooling systems represents between 7.5 and 17% of the total manufacturing costs, compared with 4% of the tool costs. Later, Sreejith *et al.* (2000) [77] estimated that the lubrication costs ascend to 16-20% of the manufacturing costs. More recent studies showed that the lubrication/cooling costs in the automotive industry achieves the 16-18% versus the 7-8% of the tool costs [78]. Moreover, in machining of difficult-to-cut materials, the coolant acquisition, use, disposal and the cleaning of the pieces lead to major costs, four times more expensive than that of other machining materials [24]. For the evaluation of the cost of the cutting fluids system should be taken into account the following factors [75]:

- Cutting fluid purchase cost.
- Workpiece cleaning and secondary operations costs to remove the lubricant film from the surface and avoid contamination between different manufacturing process [10].
- Water cost to dilute the concentrated emulsifiable cutting fluids and added to offset losses by evaporation. The water amount may vary between 5 and 20% of the tank volume per day. Moreover, water used for cleaning the workpiece and the system itself should also be considered [79]. This cost can vary greatly depending on the water quality required.
- Energy costs. Recent studies indicate that the use of cutting fluids has a significant influence on up to 50% of the total energy demand. Therefore, it is very important the proper selection of the lubrication/cooling system to improve the energy demand of the manufacturing process [10].
- Costs associated with the fluid replacement due to the drag out of fluid with chips and workpiece. Fluid must be added to reach the concentration and the level required [11].

- Fluid supply system costs like fluid recirculation and filtration.
- Maintenance costs associated with the additives used to prolong the fluids life. Additives, such as bactericides or pH buffers, may be controlled and added when necessary.
- Maintenance tasks costs associated with pumping, cleaning and refilling.
- Costs of treatment and fluid disposal. They can cause air and soil pollution, and surface water and ground contamination [80].

Additionally, to comply with environmental regulations there are other costs associated to reduce and maintain a low level of workers exposure to cutting fluids [75].

3.2. Alternatives to conventional lubrication/cooling systems

When using dry machining, both cost of the cutting fluid and subsequent waste treatment costs are suppressed. Moreover, not using cutting fluids reduces the workpiece cleaning and maintenance operations. However, in general there is a higher tool wear. It should be noted that a higher tool wear leads to higher costs due to the need of changing tools more often [54]. This system requires specific studies and involves tools and materials technology development, opening new application possibilities.

A growing number of companies are making the transition to the MQL systems to reduce costs, the environmental impact and health hazards, that it is going on in U.S according to Skerlos *et al.* [31]. Although, it should be considered that there is a power consumption to produce compressed air, costs savings are mainly due to a lower infrastructure required and less cutting fluid consume which could be reduced down to 95%. Moreover, MQL system enhance the tool life [81] and the chips are released in a practically dry condition, thus avoiding cutting fluid recycling costs [82]. However, if costs related with the health and the environment are not considered, many manufacturers consider that the costs for changing the technology are too high [31].

Solid lubricant applied directly as lubricant, reduces friction in machining, resulting in better material removal rates without affecting the quality of surface produced and thus increasing product reliability, enhancing productivity, and reducing costs. However due to the high cost and the difficulty to clean and apply the lubricant, it is only found in specific machining applications [83]. Solid lubricants in combination with MQL system reduces the tool wear, improving the tool life and enhancing the productivity [51].

The cryogenic machining equipment cost is much higher than that of conventional lubrication/cooling system [7]. The nitrogen liquid storage needs special pressure tanks. Cryogenic gas transport to the cutting zone is one of the main challenges of these systems. Hong and Broomer [5] and Lu and Jawahir [84, 85] make an economic analysis of cryogenic machining. These studies show that, contrary to the general perception, the cost of liquid nitrogen is competitive against the conventional fluids, due to a lower flow, the high cost of cutting fluids treatment and that liquid nitrogen can be used only when machining. Cryogenic cooling is significantly less expensive than conventional machining when high efficiency and high productivity are required [7].

Gaseous cooling is more environmentally friendly than conventional lubrication/cooling systems. However, they require additional equipment, which normally is not provided with the machine tools, although it is not needed special equipments to achieve cryogenic temperatures. Moreover, the high cost of some of these gases, like helium, usually does not make them profitable for manufacturing processes [86].

Price is a major barrier in the sustainable lubricants development as the vegetable oil prices are not competitive in comparison with the world market prices for many mineral oils [57]. They are between 1 to 8 times more expensive than a mineral based fluid [45]. In addition, the use of sustainable cutting fluids can help improving machining performance and increasing the tool life. Moreover, it may lead to cost decreasing to ensure competitiveness and meet the demands of cleaner production [87].

Nanofluids are transported to the cutting zone through nozzles like the conventional lubrication/cooling system, but the higher manufacturing costs of nanofluids and waste treatment during the machining is a barrier for its use [88]. The cost of nanoparticles and the prevention of the sedimentation are the major challenges for the application of nanofluids in machining processes [73, 89]. Among a variety of nanoparticles, nano-SiO_2 are identified as a material easily acquired on the market in a wide range of sizes at affordable prices [90] compared to nano-MoS_2 [67]. Despite their costs, in the last decade, they have been combined with MQL system to increase the energy savings and reduce costs, gaining interest as an alternative to cutting fluids [55].

In order to evaluate machining costs for conventional lubrication/cooling systems alternatives, all the costs should be included, beginning with the raw material until the final workpiece and disposal costs. Therefore, raw materials costs, fluids consumption, equipment costs, tools costs and disposal costs are included. Moreover, costs for cleaning the final part and chips are also considered because of they are time consuming and so costly [7]. Table 4 shows a comparison for different lubrication/cooling systems of the costs.

Table 4. Qualitative estimation of lubrication/cooling system costs[31, 37, 88]

	Raw material cost	Fluid consumption	Equipment costs	Tool cost	Cleaning costs	Disposal costs
Cutting fluids	**	*****	****	***	*****	*****
Dry machining	*	*	*	*****	*	*
MQL	**	**	***	**	**	**
Solid lubricant	****	***	***	***	***	****
Cryogenic cooling	***	***	*****	***	*	*
Gaseous cooling	***	***	****	****	*	*
Sustainable cutting fluids	***	****	****	**	****	***
Nanofluids	*****	****	****	***	****	*****

(*) Very low; (**) Low; (***) Medium; (****) High; (*****) Very high

4. Environmental review

4.1. Conventional lubrication/cooling systems

Cutting fluids are used worldwide in large quantities. In 2010, the consumption in Europe, including Russia, was approximately 610,000 tones [59], that means a risk for many workers but also a high environmental impact [91]. The environmental impact minimization of manufacturing processes has become an important research topic. Cutting fluids are one of the main causes of environmental pollution during the machining [92].

The selection of the product cannot be based only on its primary properties (cooling, lubrication and chip evacuation), it should also considered secondary properties such as biodegradability and stability [9]. Cutting fluids must meet the governmental regulations for the environmental protection, and voluntary international ISO 14000 standards for environmental management system [78]. Law restrictions not only establish limitations in the manufacturing processes and provoke undesirable costs; they also encourage developing and finding new technological alternatives. Some countries have promulgated an Ecomark, for instance the European Ecolabel [58] or the German “Blue Angel” [17], to give security to the users of environmentally compatible products.

At the end of its useful life, cutting fluids are considered dangerous and, therefore, non-environmentally friendly fluids. Four major environmental problems related to cutting fluids can be distinguished in the machining process: cutting fluid disposal, fluid drag in workpiece and chips, the use of hazardous substances and mist.

Cutting fluid disposal

It is considered a waste cutting fluid when it is degraded and cannot meet the required functions. The fluid is recirculated; so throughout its use, it suffers chemical, physical and biological changes that affect its composition. Wasted cutting fluid residues depend on the physicochemical nature of the product, which will determine the fluid life as well as the waste treatment type. The deterioration of water-based cutting fluids is the result of several causes [4, 93]:

- Oil and water incompatibility, from the accumulation of oils, hydraulic fluids and other external to the cutting fluid lubricants.
- Metal particles and chips, dirt and debris accumulation.
- Susceptibility to microbial growth.
- Water evaporation and additives depletion.
- Hard water ions capacity to destabilize the emulsion and losing the capacity of lubrication and cooling
- Surfactants susceptibility to generate foam when they are agitated mechanically.

Some of the problems associated with the bad condition of the fluid are corrosion or oxidation of the tool or workpieces, tool failure due to the loss of functionality, rancid smell due to microbial growth and fluid properties changes, for example in pH.

Fluids must periodically be replaced. The replacement period can vary from weeks to months depending on the process requirements and the cutting fluid maintenance. Life can be enlarged by increasing the resistance to micro-organisms growth and to fluctuations in the concentration of active ingredients that are consumed during the process. It should be also taken into account the cutting fluid robustness to contaminants such as oil drip and the accumulation of ions and metal particles generated from the machined parts [31]. Cutting fluids replacement involves a high volume of waste to treat. In order to recycle the water, first the water is separated from the oil. Then, the water goes to a waste fluid treatment and oil can be send to energy recovery [11].

Fluid drag in workpiece and chips

A relevant amount of cutting fluid is lost due to drag-out via workpiece and chips. This loss depends mainly on the workpiece' shape and cavities [94]. Resulting pieces should be cleaned to remove all fluid traces and it is necessary to clean the chips before managing them as a solid residue. Cutting fluids drag causes a high cutting fluid consumption and a reduction of the cleaner bath efficiency due to an excessive accumulation of fluid in the workpiece [31].

Hazardous substances

There is a wide variety of chemical substances on the market, some of them with risk to human health or environment. Cutting fluids substances with major concern are: secondary amines, sodium nitrite, phenols, chlorinated paraffin, boric compounds, polycyclic aromatic hydrocarbons (PAHs) and biocide products [95].

One of the main problems of cutting fluids that has recently been decreased is the amount of nitrosamines, which are carcinogenic; produced by the reaction of nitrite with secondary amines (such as the diethanolamine) [96]. On the one hand, sodium nitrite is a compound used as a corrosion inhibitor, very toxic to aquatic life and harmful to the workers. On the other hand, secondary amines are used to neutralize the acids from the cutting fluids and provide corrosion protection. Currently, these amines are replaced by other primary and tertiary amines, as monoethanolamine and triethanolamine, respectively [96].

The use of chlorine additives, such as chlorinated paraffin which had been used as extreme pressure additives, poses threat to ecology and the workers health. In addition, chlorinated additives are not suitable for the titanium machining because they can cause corrosion on the workpiece surface [54]. Treatment of cutting fluids disposal with chlorinated content is classified as hazardous waste and it is expensive [11].

Boric compounds, such as boric acid, are substances that provide multiple functions including corrosion protection, pH buffer capacity and bacterial growth inhibition [64]. However, boric acid is classified as substance that may cause problems for reproduction and is included as a candidate on the list of substances of very high concern from the ECHA (European Chemicals Agency) [97]. Other compounds that have been banned or restricted because of their toxicity are PAHs. PAHs are present in the mildly refined base oils and as a product of thermal degradation at very high temperatures. These compounds are carcinogens, mutagens and teratogens. The exposure risk has decreased and currently, the formation during the machining is very low [96].

Bacteria and fungi may grow in water miscible cutting fluids, the most common *Comamonas* and *Pseudomonas testosteronei* [98]. These organisms feed on corrosion inhibitors, emulsifiers and contaminants from the system. The uncontrolled microorganisms growth can cause the premature loss of fluid functional characteristics [11] and adverse economic charges. Biocides can be used to control the microbial and bacterial activity and increase the fluid lifetime. Some of the most commonly used biocides are triazine, the oxazoline, the dicyclohexylamine or phenoxyethanol.

However, maintaining the optimum concentration of biocides in the cutting fluid can be difficult due to the fluid evaporation. On the one hand, high concentrations of biocides can affect the workers health and cause dermatitis through cutting fluids contact. On the other hand, an insufficient concentration of biocides does not inhibit the bacteria growth and may even promote the formation of biofilms. When there is microorganisms growth and biofilm, even if there are biocides, only a thorough cleaning and a disinfection process prior to the system filling, are effective for inhibiting the microorganism regrowth [98].

Many of the biocides used in the lubricants industry, as the HTHT (hexahydro-1, 3, 5-tris(2-hidroxietil)-triazine) are formaldehyde releasers [99]. Formaldehyde is a highly volatile and extremely flammable chemical compound that has been classified by the International Agency for Research on Cancer (IARC) in Group I, carcinogenic to humans. The use of biocides is literally forbidden by some manufacturers, regardless of whether they are legally certified or that there is a demonstrated microbiological need. There is no consensus of the bactericide or fungicide level, each lubricant manufacturer may make a recommendation to the user to determine the best prophylactic level [11]. Pasteurization and UV irradiation have been proposed as biocide alternative; however their use is not extended due to economic reasons [59].

Mist

Mist is one of the environmental concerns with greater impact in the workers' health. The typical particle size of an aerosol is 0.1 to 10 µm, with 75% of particles (mass concentration) size enough to be inhaled by the human body. In the one hand, high cutting speeds results in smaller particle sizes of oil mist, therefore the oil mist concentration is higher. In the other hand, higher cutting fluid flow contributes larger diameter of oil mist and higher concentration [100]. The main mechanisms through which the cutting fluid produces mist in the environment are [59]:

- Evaporation due to the high temperature of the cutting zone. The compounds more volatile vaporize and then are condensed forming small particles of size less than 1 µm, with a composition different from cutting fluid and tend to migrate throughout the environment.
- Atomization occurs by mechanical movement due to the fluid impact against the tool or workpiece, forming particles of a size from 1 to 10 µm, with the same composition as the cutting fluid and do not migrate far from the cutting zone.
- Splash caused by the cutting fluid under pressure against tool, workpiece or machine-tool.
- Fluid aeration, either by its foam tendency or due to an excessive agitation.

Mist inhalation risk is due to the exposure of three agents: fluid process, microbial contaminants and other chemical contaminants accumulated in the cutting fluids during the process as, toxic elements (mineral oils, alkanolamines, nitrosamines, volatile organic compounds) or metal workpiece allergens (such as Cr, Pb, Ni, Cd) [22]. Mist can cause serious problems in the workers' health: eye, nose and throat complaints, irritation of the respiratory tract, pulmonary dysfunction, bronchitis and asthma, and also in less frequent circumstances pneumonitis, lipoid pneumonia and fibrosis [96].

4.2. Alternatives to conventional lubrication/cooling systems

Dry machining reduces the environmental impact and the workers' health risks. Moreover there is no fluid residue in the workpiece or chips, which reduces the costs and energy in the cleaning process.

MQL systems reduces drastically the use of cutting fluids [37]. The amounts used are so low that the cutting fluid is consumed almost completely in the process, eliminating the problems of fluid disposal. In addition, chips produced during machining are almost clean of fluids, which are easily recyclable [35]. Although, the environmental effects that should be considered in the MQL systems are related to the power consumption of the gas compressor and the pressure required for the supply, it can be an intermediate strategy for reducing direct electrical energy requirements and global warming potential compared to conventional machining [81]. However, the main disadvantage of using MQL is mist generation, which is harmful to workers [101]. An excess of MQL fluid flow can produce aerosols, although at a level much lower than cutting fluids, even at levels below the detection limits [31].

Cryogenic cooling with liquid nitrogen is a system that leaves no harmful residue to the environment. Liquid nitrogen absorbs the heat generated during the manufacturing process and evaporates quickly becoming part of the air [19]. In the cryogenic cooling with carbon dioxide, the fluid also evaporates and although the amount of carbon dioxide evaporated is low, it is a greenhouse gas. Workpieces and chips resulting from machining are clean of cutting fluid residues; so further treatment costs are reduced. Moreover, the used substances are not harmful and do not produce mist [86]. Besides, gaseous cooling has the same advantages as cryogenic cooling, being both techniques considered as some of the most eco-friendly cleanest methods for machining of various engineering alloys, after dry machining [102].

Another alternative is the use of sustainable cutting fluids. On the one hand, they eliminate those additives considered dangerous substances, as sodium nitrite or biocides. On the other hand, they replace the mineral oil base by vegetable or synthetic oil, such as rapeseed oil and palm oil. These oils are organic, renewable, less toxic and more easily biodegradable than those of the conventional fluids [64].

The biodegradability is the main measure to determine the environmental compatibility. The plant oils, also used in MQL applications, are highly biodegradable, and the synthetic esters possess a broad range of biodegradability [23]. Currently, there are five major groups of biodegradable products applied as base fluids [60]:

- High oleic vegetable oils, mainly triglycerides.
- Low viscosity olefin.
- Polyalkylene glycols.
- Dibasic acid esters.
- Polyol esters.

Besides the biodegradability, in a sustainable cutting fluid, it must be taken into account the additives. Many of them such as biocides, can be potentially toxic and hazardous to the environment and health [103].

While nanomaterials are a topic of research due to their potential in advanced technologies, little is known about their environmental impact and their effects on human health [104]. Handling the nanoparticles themselves without mixing with fluid is dangerous to human's health. They can be toxic because they would become as airborne nanoparticle in the air and represent a potential source of environmental damage. By mixing them with lubricant oil is hardly to become as airborne nanoparticle in the air [105]. However, limited investigations have been conducted on environmental, safety and health aspects of application of nanofluids in machining processes. Further research should be emphasized in mist generation of the nanofluids, as the fluids have metallic inclusions, the mist might hazards to the workers' health [106].

Table 5 presents a qualitative estimation of the environmental impact of various lubrication/cooling systems used in the machining, taking into account the above considerations.

Table 5. Qualitative estimation of lubrication/cooling environmental impact

	Residue	Fluid drag out	Dangerous substances	Mist and emissions	Workers health hazards
Cutting fluid	*****	*****	****	*****	*****
Dry machining	*	*	*	*	*
MQL	**	**	**	***	***
Solid lubricant	*****	*****	***	****	****
Cryogenic cooling	*	*	*	**(1)	*
Gaseous cooling	*	*	*	*	*
Sustainable cutting fluids	****	*****	***	****	***
Nanofluids	****	*****	Unknown	****	Unknown

(*) Very low; (**) Low; (***) Medium; (****) High; (*****) Very high
(1)Very low for liquid nitrogen.

5. Discussion

Fig.2 shows a comparison among eight different lubrication/cooling systems used in machining processes. In the one hand, cost and sustainability values are represented taking into account the qualitative estimation of Table 4 and Table 5, respectively. In the other hand, the diameter considers the industrial potential use according to the technical feasibility.

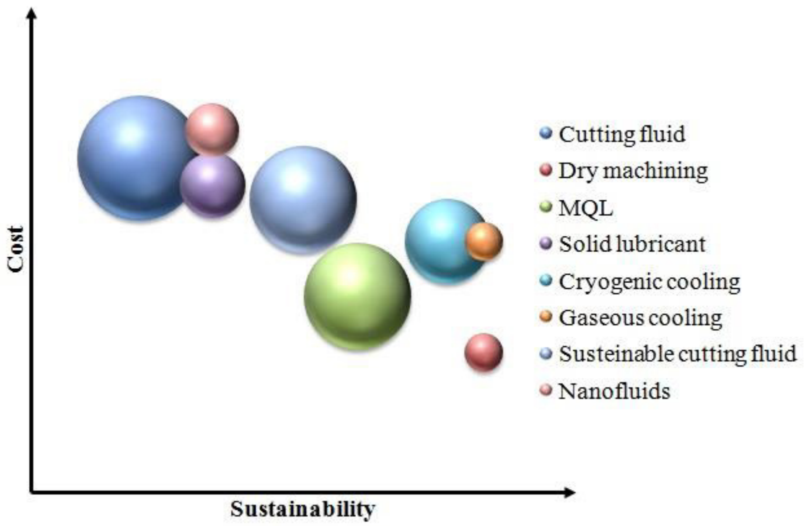

Fig.2. Cost of lubrication/cooling systems in machining as a function of sustainability.

This comparison is based on the type of lubricant/coolant system and the appropriate method of application. However, this is not the only possible classification. It could also be grouped according to the type of lubricant or the type of system separately [10, 107]. Table 6 shows the relationship between the type of application system (i.e. dry machining, flood) and the lubricant type (i.e. neat cutting oil, water soluble fluid, gases).

Table 6. Relation between the type of lubricant and the strategy application methods [10, 107].

	Dry machining	Flood	Cooling	Cryogenic	High pressure	MQL
Neat cutting oil	None	Common	Not common	None	Not common	Mixed with gas
Water soluble fluid	None	Common	Not common	None	Not common	Mixed with gas
Solid lubricant	None	Mixed with fluid	None	None	None	Mixed with fluid
Gases	None	None	Common	Common	Common	Mixed with fluid

While this classification or combination of possible strategies is theoretically possible, some of the resulting combinations are not use in practice. The focus of the work is expected to be eminently practical and applicative. Consequently, even in a qualitative way, efforts have been made in the combinations used in the machining industry, intended to be of assistance to all those persons related to this type of processes, both researchers and manufacturers.

6. Conclusions

Cutting fluids play an important role during machining but they use have some drawbacks such as their negative effects over the environment and workers health as by costs associated such as the equipment, fluids purchase and waste fluid treatment. All of these plus governmental regulations are encouraging companies to implement lubrication/cooling systems more efficient and sustainable. The alternative techniques such as dry machining, MQL, solid lubricants, cryogenic and gaseous cooling have been implemented in some machining processes, even may become more efficient than conventional lubrication/cooling. However, there are still applications where cutting fluids cannot be removed.

- The best environmental alternative is dry machining since completely removes the cutting fluid and ensures a clean atmosphere and workers safety, though it has many application limitations. To implement this alternative is necessary to have an exhaustive control of the cutting parameters and a suitable tool selection.
- MQL system reduces the fluids use and is a more viable alternative taking into account not only the economic and environmental impact, but also the performance.
- Solid lubricants are mostly used in aerospace industry although, for machining process mixed with a base fluid and in combination with MQL, can increase the lubrication performance.
- Cryogenic cooling can lengthen the tool life, especially in difficult-to-machine materials. Its environmental impact is lower than cutting fluids, but the initial cost is high.
- Gaseous cooling are systems with very low environmental impact, but they have limitations in their cooling and lubrication performance.
- Sustainable lubricants are potential substitutes for mineral based cutting fluids. Vegetable base oils are readily biodegradable, environmentally friendly and may have the same or even superior tribological properties. In general terms, their cost is frequently higher than the mineral-oil-based products. Although its use is growing, is proceeding more slowly than expected and currently represents a small part of the overall lubricants market.

7. Future research

Further investigation is needed to overcome the drawbacks of lubrication/cooling conventional systems:

- Research on dry machining with other metal alloys different from aluminum in drilling process.
- Investigate on MQL with materials as aluminum and magnesium to reduce the material adhesion over tool surface and with difficult-to-machine materials.
- Explore further solid particles as additives able to improve lubricity properties.
- Research and development of cryogenic cooling equipments to improve industrial application implementation.

- Research and development of sustainable cutting fluids in applications for non ferrous materials (titanium, aluminum, magnesium, copper, brass) and superalloys (nickel, cobalt).
- Enhance vegetable based fluids characteristics to overcome their disadvantages, such as its low thermal and oxidative stability, without impairing their tribological and environmentally properties.
- Replace dangerous and non-renewable cutting fluids components such as boric acid or secondary amines, conventionally employed due to their low cost as pH-buffers and corrosion inhibitors, with ingredients that are renewable and biodegradable.
- Research and development of the environmental impact and health hazard of nanofluids, which are growing as alternative lubrication/cooling systems.

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