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A Review of Cooling and Lubrication Techniques for Machining Difficult-to-cut Material

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Abstract: **Superalloys have magnificent properties which make them widely applied in various industrial fields. They possess high mechanical properties such as high strength, high rupture resistance, and high resistance to corrosion and oxidation. Since they can maintain these properties even at elevated temperatures, they face some problems during the cutting and machining process. They are classified as difficult-to-cut alloys, which means that high heat is generated in the cutting zone due to their poor thermal conductivity. In addition, high friction takes place between the tool and the chip. To overcome these problems during their machining process, different cooling and lubrication techniques using suitable cutting fluids are highly recommended. In this study, the cooling and lubrication techniques that have been applied in the literature to machine superalloys such as dry machining, flood cooling, high-pressure jet machining, minimum quantity lubrication and cooling, and cryogenic machining are reviewed. The technique of each type followed by its advantages and disadvantages are mentioned.**

Keywords: **Difficult to cut alloys; Minimum quantity lubrication; Dry machining; Flood cooling; Nano cutting fluids.**

I. INTRODUCTION

The machining sector is considered a major consumer of energy. High energy consumption increases the emission of harmful gases like carbon dioxide, and sulfur dioxide [1]. The emission of these gases has a hazardous effect on human beings and the surrounding environment since they are considered greenhouse gases. As shown in Figure 1, which models energy consumption sectors in the USA, 75% of the electricity consumption in the manufacturing field is for the sake of the machining sector [2]. Energy consumed by machining is subdivided into categories as the following: energy required for manufacturing cutting tools, energy for production and preparation of material blank, energy for changing and replacing broken cutting tools, energy for machine tool operations, and finally the energy required for the cutting process [1]. Machinability is an indicator of the degree of easiness of machining a material. The higher the machinability, the lower the cutting power, machining time, and wear of the cutting tool, and the higher surface finishing is obtained [3].

Superalloys are those composed of some elements like nickel, titanium, and cobalt which have very good properties like high mechanical strength and high oxidation resistance. Additionally, they can maintain these properties even at elevated temperatures[4].

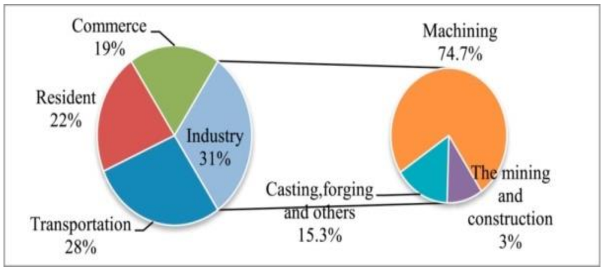

Figure 1. Percentage of electricity consumption in various fields [2].

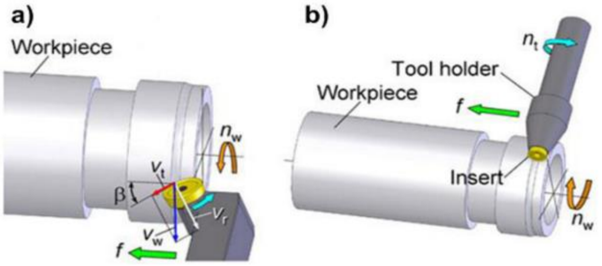

Figure 2. Rotary cutting tools a)self-propelled type and b) actively driven type [14].

Two-thirds of superalloys are applied in the aerospace industry[5]. About half of the overall aerospace alloys are nickel-based alloys [6]. Since the majority of the superalloys could keep their high mechanical properties like high strength and hot hardness, this makes the cutting process more difficult to take place and require high consumption of energy [5]. Mostly they have low machinability. As a result, during their machining, large heat is generated, high cutting forces are generated, large tool wear occurs and high residual stresses on the surface which is machined are then produced [7]. The elevated temperature generated in the machining zone has a very bad influence on the machining process. The hardness of the tool is decreased and it becomes more susceptible to wear [8].

Too much heat generated leads to the occurrence of thermal expansion to the workpiece and hence poor dimensional accuracy is produced [9]. Some of the proposed methodologies in the literature to enhance the cutting process of difficult-to-cut superalloys are: utilizing the rotary cutting tool as in the work of [10]. Rotary tools were mentioned in the literature to have promoted tool life due to the reduction of wear rate [11]. A schematic of the rotary tool is given in Figure 2. In addition, adjusting a suitable positive rake angle for the tool,

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and designing a tool with a large nose radius if not conflicting with other demands of the shape and geometry required for the cutting tool are proposed techniques [5]. In previous works, other recommended techniques were utilized. In [12], textured face-cutting tools were used. In [13] ultrasonic-assisted vibrational machining was applied. A schematic for assisted vibrational machining is shown in Figure 3.

A highly recommended methodology for machining is to apply a cutting fluid that acts as a coolant by dissipating heat out of the cutting zone and a lubricant by reducing the friction among chip-tool-workpiece interfaces. A long time ago the utilization of mineral-based oils as cutting fluid takes leadership. But for all the harmful consequences of applying mineral oils in large quantities such as the health problems to operators who are in direct contact with these oils and the environmental hazards and problems related to disposing of the mineral oil after usage, recently the application of vegetable-based cutting fluid becomes more preferable.

Recently nanofluids, which are fluids reinforced with nanomaterial, have been used as cutting fluids. Due to the high cooling ability of nanosized bodies, when embedded in a cutting fluid either mineral-based or vegetable-based, they enhance their performance and characteristics. Nanofluids are considered a highly effective absorber to heat thanks to their high stability over large ranges of temperatures and their high coefficient of absorption [16]. For all these benefits, they are highly recommended to be used as cutting fluids to abstract heat from the machining zones.

In the next section, a brief note is given on the properties of the most widely spread difficult-to-cut alloys. The third section discusses the mechanism and role of the cutting fluids and their types are mentioned. In the fourth section, an explanation of different lubricating and cooling techniques in machining giving focuses on the advantages and disadvantages of each type. In the fifth section, the role of nanofluids in the cutting process is mentioned. In the sixth section, a review of the performance of cooling techniques during machining difficult-to-cut alloys is discussed. Later, a note is given on the gaps concerning the previous work of authors.

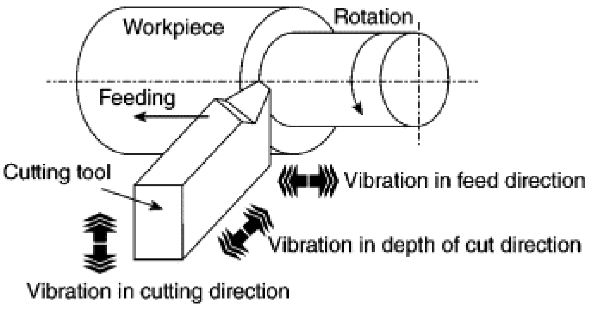

Figure 3. A schematic of ultrasonic-assisted machining [15].

II. DIFFICULT TO CUT ALLOYS

Difficult-to-cut alloys have superior properties which make them applied in various industrial and manufacturing fields. They possess extremely high mechanical properties and high resistivity to both corrosion and oxidation. However, during the cutting and machining process of these alloys, some problems arise. High heat is generated into the zone of machining due to their poor thermal conductivity. In addition, high thermal gradients may arise at the cutting tool tip which may increase the wear of the tool surface. Among the most common superalloys mentioned in the literature are the following:

A. Stainless steel 304

Stainless steel alloys belong to the family of iron-based superalloys. Among the most common stainless steel alloys used in manufacturing is 304 stainless steel. Steel 304 is an austenitic stainless steel alloy. It is commonly used in the petrochemical industry and manufacturing of many important components like gaskets, bolts, screws, and piping systems [17].

Stainless steel 304, faces many problems during the machining process among which is the high ability to form build-up edge because of its high ductility [18]. It also rapidly gets strain hardened when machined. It has a poor thermal conductivity which leads to a low dissipation rate of heat during the cutting process [19].

B. Stainless Steel 316

Stainless steel 316 has high creep resistance and high resistance to elevated temperatures. 316 type has more resistance to corrosion than 304 stainless steel thanks to the addition of molybdenum element in its chemical composition [20]. It is mostly applied in nuclear reactors, and steam plants.

Stainless steel 316 exhibits work hardening during the machining process. Moreover, it has poor thermal conductivity. The elevated temperatures generated at the cutting zone along with highly produced cutting forces will render severe tensile residual stresses [21].

C. Stainless Steel 321

Type 321 stainless steel is an austenitic type that possesses high temperature and high welding properties [22]. Titanium element in the chemical compositions adds to this alloy more strength and resistivity to higher temperatures. It is widely used in heat-exchanging tubes [23].

D. Inconel 718

Inconel 718 alloy is a nickel-chromium-based superalloy. It possesses magnificent mechanical properties like high tensile and yield strength even at elevated temperatures [24]. Inconel 718 is widely applied in environments exposed to high temperatures and pressure. It is used in manufacturing nuclear

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reactors, motor shafts, high-pressure vessels, and turbine blades [24]. Some properties of Inconel 718 alloy that hinder their machining are poor thermal conductivity, huge affinity to the cutting tool, tendency to be strain hardened, high toughness, and strong welding tendency [25]. Low thermal conductivity, the most violating property of the machining process, causes high temperatures to be generated at the machining zone. So, higher wear rates of cutting tools are expected [26].

III. MECHANISM OF WORKING OF CUTTING FLUID

A. Role and mechanism of cutting fluid in machining

About 5% of the overall lubricants are utilized as cutting fluids in cutting processes [27]. Cutting fluid has two principal goals in the cutting zone, reduction of temperatures by cooling action and reduction of friction among tool-chip interfaces by the lubrication action [18]. The generated heat in the machining zone is approximately distributed as follows: about 75 % is extracted by the outgoing chips, about 15% is transmitted to the tool and the rest is transferred to the workpiece blank [28]. The cutting fluid is meant to extract as much possible heat out of the machining zone by heat-transferring mechanisms like conduction, convection, evaporation, and radiation [9].

The cutting fluid could have a lubricity role in the cutting zone. At the cutting zone, high pressure and temperatures exist between the tool-chip contacting surfaces. These conditions enthusiast a chemical reaction to occur between the cutting fluid and contacting surfaces forming a thin solid lubricant film [29]. The effectiveness of the cutting fluid is dependent on the time it takes to form this lubrication film, the shorter it takes, the more efficient it is [30]. Cutting fluid has an additional role which is flushing chips away from the surface of the tool. Flushing away of chips maintains less workpiece deformation and prevents the deterioration of the surface that has been machined [31]. It also has a role in the reduction of chemical diffusion between the tool and the surface of the workpiece [32]. It helps to protect the machine tool from corrosion in some cases. Also, the cutting fluid helps to protect the newly machined surface, which is chemically active, by forming a thin film that acts as a barrier on the surface to prevent the occurrence of corrosion [9].

The very good cooling performance of water made it the first coolant to be used as a cutting fluid. However, corrosion and moisture resulted in the workpiece machining obstacles it from becoming dominant in the field of application [33]. Water is not suitable for machining some materials like Magnesium(Mg) due to its high reactivity with (Mg) producing hydrogen in the machining zone which is explosive and may cause fire hazards [34]. Some years later, animal oils and fats were used as lubricants. After that straight mineral oils were principles as cutting fluids for some time [35]. Recently, vegetable oils were utilized as cutting fluids thanks to their good lubricity and environmental friendliness.

It is worth noting that the progress in metal cutting fluids was the cradle to the high-performance machining process that are widely spread in recent days [29].

B. The main types of cutting fluids and lubricants

B.1. Mineral oils

Mineral oils are extracted out of crude oil, one liter of mineral-based cutting fluid consumes about 80 liters of crude oil[1]. The high consumption of mineral oils has many catastrophic consequences on human beings and the surrounding environment when not consumed properly and at considered rates. Environmental pollution certainly occurs when mineral oils are disposed of improperly due to their low biodegradability behavior [36].

Harmful depositions of chlorine and sulfur are left behind when utilizing mineral oils in machining. These depositions if got vaporized over time will cause catastrophic diseases to the human respiratory system [37].

B.2. Vegetable oils

Vegetable oils are primarily extracted from agricultural plants. They later go through stages of refinement and purification [38]. Vegetable oils are triglycerides in their structure. Three long fatty acid chains are connected to a glycerol molecule backbone at hydroxyl groups by ester linkages [39]. The presence of polar fatty acids in their structure gives higher chance for a reaction to take place with the surface of the workpiece [40]. They are capable of maintaining their viscosity over a wide range of temperatures. They are featured by the stability of the boiling temperature. This could be related to the homogeneity of the size of molecules in their structure [40]. They have high flash points which reduce the risks of occurring fire hazards [41]. The higher molecular weight and boiling point of vegetable oils reduce their vaporization process[42]. For all those benefiting features of vegetable oils, many of them are used as cutting fluids in cutting process like kapok oil [43], olive oil [44], and sunflower oil [45].

On the opposite side, some disadvantages of vegetable oils have been stated such as:

- The corrosion resistance of vegetable oil is poor [46].
- No consistent thermal stability or rust control is mentioned for vegetable oils [47].
- They are poorly oxidative resistant and possess high freezing points [48].

B.3. Solid lubricants

The master role of solid lubricants is to cool and lubricate tool-workpiece interfaces by forming a thin lubricating film that acts like a cushion [49]. They could be applied directly to

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the solid surface or either be dispersed in oils and greases for lubrication [50]. Some materials that could successfully be used as solid lubricants are carbon-based materials like graphite and diamond, soft metals like tin and silver, and transition metal dichalcogenide compounds like molybdenum disulfide (MoS_2). The layered structure for solid lubricants as shown in Figure 4 and Figure 5 for graphite and MoS_2, gives them the ability to slide over each other reducing the friction among contacting surfaces [51]. Solid lubricants formulate a lamellar structure lubricating film [52]. The feeding of the solid lubricant in the machining zone requires high pressures of the compressed air which adds up some costs[1].

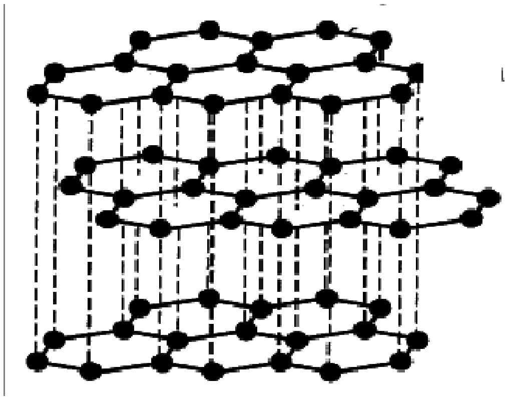

Figure 4. Structure of layered graphite[53].

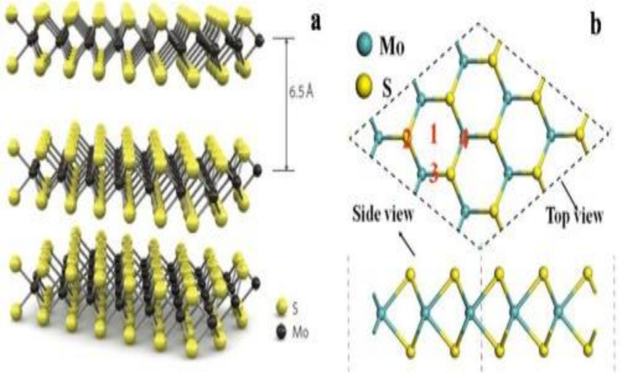

Figure 5. Molybdenum disulfide chemical structure[54].

IV. TECHNIQUES OF LUBRICATION AND COOLING IN MACHINING

A. Dry machining

It is the technique by which machining takes place without the application of any cutting fluid. This eliminates the problems accompanied by using the cutting fluid. However, it in turn prevents benefiting from their advantage as a cooling and lubricating medium [55]. The lubricating mechanism in the absence of lubricating oils in dry machining could be conducted by self-lubricating cutting tools [56].

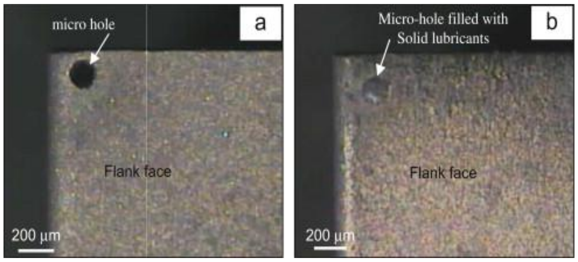

Figure 6: Self-lubricated cutting tool a) without filling the hole with lubricant and b) with the hole filled with lubricant [58].

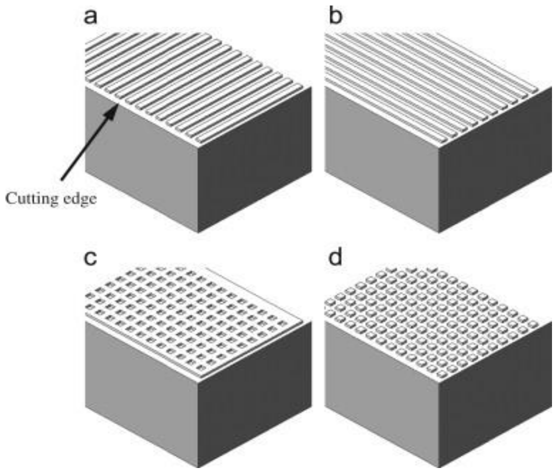

Figure 7. Various surface shapes of textured cutting tools [12].

An example of a self-lubricated tool is shown in Figure 6. Figure 7 shows a schematic of a textured type cutting tool. For the sake of good performance, the usage of textured cutting tools was recommended to be utilized in the case of dry cutting [20]. In addition, coated cutting tools are proposed by many authors in the literature to be used in dry machining [57].

Some advantages of dry machining are as follows:

- It facilitates the recycling process of metal scrap since chips are easily collected from the machining zone[59].
- It reduces the probability of occurrence of a thermal shock to the cutting tool especially in interrupted machining unlike in the case of flood cooling where cutting tools are more exposed to thermal shock [60].

Some concerns should be regarded during dry machining concerning the costs of the process and additional requirements for the process. The cutting tool has a huge role in dry machining. Cutting tools should possess some special characteristics. High resistivity to pressure and temperature over a wide range and high toughness are required [52]. In addition, the material selected for the tool should possess high resistivity to heat and has a low coefficient of friction to reduce the heat generated. [61]. Tool coating is a highly proposed technique to increase tool life in dry machining. The high manufacturing costs of such coats would lead to additional

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costs to the process, hence reducing the overall profitability[33]. A machine tool of high rigidity is recommended to be utilized to bear high cutting forces and high temperatures generated during the dry-cutting [24]. There exists an upper limit for the machining parameters during dry machining. If this limit is surpassed, deterioration may occur to the workpiece due to highly generated heat [62].

B. Flood cooling

Flood cooling, which is known as wet machining or conventional machining, is the most applied cooling method in the machining process [61]. The cutting fluid is applied continuously into the tool-workpiece interface [63] at a rate of flow of 3- 10 L/min [64]. Figure 8 shows a machining process via the flood cooling technique. It suits high cutting temperatures processes thanks to its ability to dissipate heat at a high rate. It can overcome sparks associated with some machining operations [65].

Some limitations stated in the literature for flood cooling are the following: in some studied cases, the action of flood cooling in minimizing the heat generated in the cutting zone was not as good enough as was expected. Authors have related this bad performance to the low pressure accompanied by the feeding flood of cutting fluid which was not sufficient enough to reach deeply into the machining spot [67]. The low pressure of flood coolant was unable to penetrate the vapor blanket formed by the highly generated heat of the process [68].

Not much consideration is given to the quantity of cutting fluid that is being consumed in flood cooling supplied to the cutting zone, this might cause too much waste and cost a lot [69]. High power consumption by flood cooling, the energy required for recirculating cutting fluid, and the energy needed for the disposal of chips reduce its opportunity of being a sustainable methodology [1].

C. Minimum quantity lubrication

MQL is considered among the most applied method of cooling and lubrication[70]. MQL is also named near dry machining due to the very low amount of cutting fluid that is remained adhered to the metal chips at the end of machining [71]. Due to the low quantity of fluid used within MQL and the good lubrication action, it is in the intermediate area between dry and flood machining [72]. A cutting fluid with high stability over a long time is required to be used with the MQL cooling since the available fluid quantity during the process is of a very small amount [61].

In the MQL technique, a very low amount of cutting fluid in the range of (0.01- 1 L/h) is delivered to the cutting area with the aid of pressurized air. The pressurized air is the carrier medium for the cutting fluid into the system. Figure 9 shows a schematic for the MQL setup. The delivery system of MQL is composed of an oil pump, air compressor, oil containers, mixing chambers, nozzles, and transferring pipes [73]. The cutting fluid reaches the cutting region in the form of an atomized mist which is sprayed over the machining surface properly [74]. The atomization process that occurs during the MQL would ensure that a large number of oil droplets exist near the cutting tool edge when delivered[75]. Once the fluid is sprayed on the surface, a thin film of lubrication is created over it. when it penetrates tool-chip interfaces, it forms a cushion between chips and cutting tool interfaces[67]. The area of contact between the chip and tool surfaces is reduced, so the friction coefficient is reduced [57].

In the literature, there are two techniques mentioned for minimum quantity application of the cutting fluid in machining. The first one is minimum quantity lubrication, where oils are used as cutting fluids and the lubrication effect possesses dominance. The second one is minimum quantity cooling, where emulsions are used and the cooling effect is the dominant one [77]. The positions of feeding the nozzle onto the surface of the tool together with its inclination angle and the distance between it and the tooltip are among the parameters controlling the efficiency of the process.

Figure 8. Flood cooling technique [66].

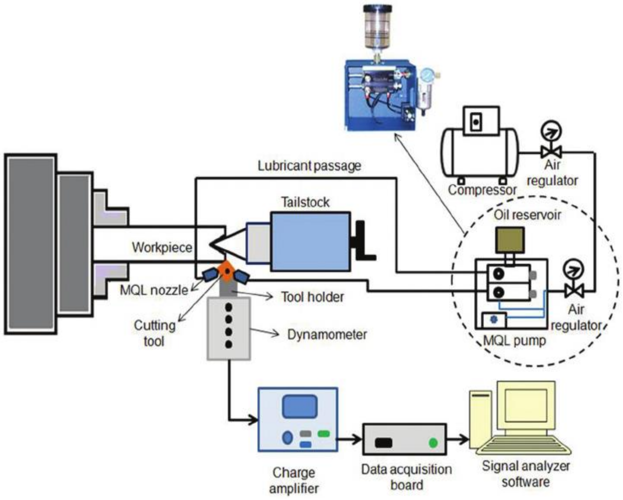

Figure 9. MQL setup [76].

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In addition, the flow rate of the cutting fluid, and the pressure of compressed air of the sprayed mist are affecting parameters [73]. The small-size droplets of cooling fluid in the MQL technique possess higher cooling ability compared to normal-sized droplets in flood cooling. The tiny size of mist particles enables them to easily penetrate the machining spot between the contacting surfaces[67].

Some limitations have been recorded during the application of MQL in the cutting process. Sometimes the cutting tool suffers from thermal gradient during MQL. When the oil mist is evaporated, heat is released from the cutting tool surface within these evaporated droplets causing a sudden thermal gradient for the cutting tool. The thermal gradience accelerates the wear action of the tool [67]. Higher tool wear is also expected to occur due to the low quantity of lubricating fluid which is fed by the MQL setup[78]. In addition, a fluid with high thermal properties is necessary to be utilized to compensate for the low quantity of oil supplied by the nozzle to the machining zone, this adds some extra costs[62].

Moreover, there are some health hazards recorded for MQL since oil mist is evaporated at the end of the process by the effect of heat. The mist generation is considered a health hazard issue in this technique because it could be inhaled by humans [32]. In addition, the emitted carbon dioxide gas due to energy consumed by air compressors in the MQL system is relatively high in comparison to the flood lubricating system, which increases the environmental hazards[79].

D. Cryogenic machining

Cryogenic-assisted machining is carried out by applying liquefied supercooled gases like nitrogen and carbon dioxide at the cutting region [80]. There are many techniques for cryogenic machining. The workpiece could be cooled before the machining process, this is a precooling cryogenic. Another one is by spraying cryogenic fluid directly into the machining spot during the process this is known as cutting zone cryogenic cooling [81]. The high difference in temperature between the hot surface and supercooled cryogenic enthusiasts a faster rate of transfer of heat thus lowering the temperature at a high rate [82].

Among the limitations of cryogenic machining are:

- Large cooling of the work-piece due to cryogenic action during the machining process sometimes leads to the embrittlement of the work-piece [61],
- The over-cooling of the workpiece by the effect of cryogenic requires more cutting forces, so the rate of flow together with the pressure of the cryogenic liquid are important affecting factors in the process and must be adjusted properly to control the cooling and the required forces [83].
- Materials react differently under cryogenic effects and this makes it a non-defined approach in machining [84].

E. High-pressure jet cooling

High-pressure jet machining is similar to the flood cooling technique but with the difference of the high applied pressure of the pumped fluid into the machining spot via special types of nozzles. The pressure of the fluid is between 5 and 35 MPa [60]. The high pressure of the jet can easily break the chips during machining [38]. Segmented chips are more likely to be produced when cooling with this technique. The area of contact between the tool-chip interfaces is reduced in case of segmentation and friction is lowered in the machining zone [68]. In [85], the high-pressure jet is stated to have superior cooling action during the machining process. Among the disadvantages of this technique is the high oil consumption in the high-pressure technique which doesn’t candidate it as a sustainable lubrication technique [67]. Special high-cost equipment is required for applying this technique during the machining [38].

V. NANO CUTTING FLUIDS

Nanofluid is nanometric metallic, nonmetallic, oxidic, carbide, carbonic, or ceramic particulates that are suspended in a base fluid [86]. The nanoparticles act as a medium for transferring and dissipating the heat out of the cutting region [87]. Nanoparticles are featured with their high surface area-to-volume ratio. A large number of atoms exist on its surface, more than that in the core. This gives rise to higher conductivity since heat transfer occurs mainly on the surface[88]. Once nanoparticles are in contact with the hot machined surface, they act as cooling fins that help in cooling the region[8]

Nanofluid has superior properties when applied as a cutting fluid. Less pumping power is required for applying it [89]. No negative drop in pressure occurs as in some cases of microfluidics [62]. The reason for the superiority of nanofluids was discussed previously in the literature. Many authors have proved in their work that Brownian motion contributes to enhancing the thermal conductivity of the nano-fluid [90] [91] [92]. In addition, the effect of the shape of the nanoparticle was mentioned in [93] to have a major role in the thermal conductivity behavior. Within spherical particles, the Brownian effect is more likely to dominate. Particle aggregation was mentioned as a probable reason to enhance the thermal conduction of the nano-fluid [94].

The variation of the volume fraction of particles could enhance the properties of cutting fluid if it is properly adjusted. This gives rise to the high adaptability of the nano-cutting fluid over base fluid [72]. Some mechanisms mentioned for describing the lubricating behavior of nanoparticles embedded in nanofluids are the rolling mechanism, polishing mechanism, mending mechanism, and protective tribo film mechanism [95], and they are shown in Figure 10.

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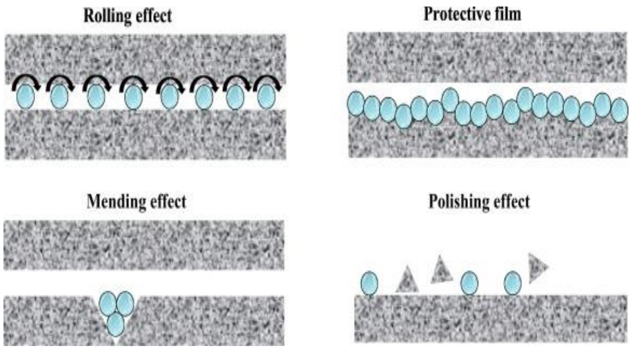

Figure 10: Lubricating behavior mechanisms of nanoparticles in nanofluids [97].

There are some parameters of the nano-additives that control which of the abovementioned lubricating mechanisms are likely to appear. Among them are the shape, the dimension, and the material type. According to shape, the higher the sphericity of the particles the more rolling effect would appear [96]. Also, high symmetricity within the shape would give more opportunity for the rolling mechanism to dominate [72].

In case of small-sized nanoparticles, the mending effect is more probable to dominate. This is attributed to their ability to enter the tiny holes existing on the surface and refill them producing a smooth surface [72]. Also, the type of the material and its mechanical properties can determine the mechanism. Particles possessing high strength and hardness are more likely to show a strong polishing effect in the machining zone [96].

On the other hand, there are some challenges and limitations to the application of nanofluids:

- A wide variety of experimental data and results recorded states that it is difficult to understand the real behavior of nanofluids due to their complexity [98].
- The thermal conductivity behavior of nanofluids is non-linear and couldn't be predicted easily [99]. Moreover, the models which previously were used to describe the behavior of micro-fluids fail to work well in describing nanofluids [89].
- It is mentioned that nanoparticles are metastable regimes that exist at very high energy levels. They tend to transform to lower state energy regimes as soon as possible[93]
- If the nano additives increased more than a considerable limit, the abrasive action of these particles could badly affect the tool wear rate of the cutting tool [38]. The abundance existence of nano additives will collide with the asperities of the workpiece surface increasing the cutting forces[60]. So it is necessary to adjust the additive weight percent.

VI. EFFECT OF CUTTING FLUIDS DURING MACHINING PROCESS

Regarding the literature, we could see many attributions of the authors that demonstrate the effect of the cooling technique during the machining process. At the most severe conditions of machining at a speed of 50 m/min and feed 0.3 mm/rev in the experiments done by Ezugwu et al, [26] they found an enhancement in the tool life of the cutting tool by 740 % in high-pressure machining than in conventional flood machining. This could be attributed to the high pressure of the supplied coolant, which has higher accessibility to the cutting zone. In the conducted experiments by Pal et al, MQL lubrication via sunflower oil reinforced with 1.5 wt. % Mos2 nanoparticles showed very good results in drilling stainless steel 321 in comparison to flood drilling under emulsion cutting fluid.

Conducted experiment at drilling the 30th hole showed about 68% reduction in thrust force in case of nanofluid lubrication than in flood lubrication. A 56 % enhancement in surface roughness was also recorded. Unsatisfying results of flood machining were attributed to the failure of the cutting fluid to penetrate the machining zone so the high temperature generated caused the adhesion of chips to the machined surface [100]. Iturbe et al showed that the conventional turning of Inconel 718 has tripled tool life as much as tool life with nitrogen cryogenic + MQL under the same cutting conditions. Since surface roughness is much correlated to tool wear, the homogenous wear that occurred in conventional machining gave rise to better surface roughness. [101].

During the turning of Inconel 718 by Çakıroğlu et al, the MQL cooling technique outperformed dry machining and gas cooling via vortex tube. It showed the lowest temperatures in the machining zone. For the cutting force components, the lowest was recorded in the MQL case. Best surface roughness was obtained in MQL lubrication followed by the vortex tube cooling technique. It was stated that because of the protective lubricate layer created by the oil mist in MQL on the tool-workpiece interface, it reduced the friction hence better surface roughness resulted [102].

Some authors are concerned with studying the effects of applying vegetable-based cutting fluids during the machining process. In the drilling of stainless steel 321 by Pal et al, sunflower oil outperformed the other five tested lubricating oils castor, coconut, canola, palm, and soybean, all under MQL lubricating conditions. About a 21 % reduction in thrust force was recorded for MQL lubricating over in flood cooling. About a 30% reduction in surface roughness in comparison to flood drilling was also recorded for the same technique [103]. In the work of Xavior et al, coconut oil outperformed both straight-cutting oil and soluble oil in turning austenitic steel 304. Lower wear of the carbide cutting tool was noticed at lower cutting speeds. This could be attributed to the suitability of viscosity of coconut oil which enables it to easily penetrate

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the cutting zone and abstract heat that is generated. Lower surface roughness values of the machined surface at various feed rates were recorded in the coconut case in comparison to the other tested oils [18].

VII.A REVIEW OF GAPS IN THE LITERATURE ON THE APPLICATION OF COOLING AND LUBRICATION OF DIFFICULT-TO-CUT MATERIAL

Regarding the literature, there is a lack of research on some issues concerning the cooling and lubrication of difficult-to-cut alloys. No sufficient studies were conducted for testing the efficiency of cooling and lubrication techniques that are based on minimizing the consumption of the cutting fluid like minimum quantity cooling during the machining process of stainless steel alloys like stainless steel 304, stainless steel 316, and stainless steel 321 alloys. Concerning the additives of nanoparticles in the cutting fluids, most previous works studied metallic and metallic oxide nanoparticle additives in cutting fluids. No focus is given to the effectiveness of utilizing solid lubricant nanoparticles like boric acid and MoS_2 as additives in cutting fluids.

VIII. CONCLUSION

- Regarding the previous work of authors, there is no definite cooling and lubrication technique that could be stated to be the most suitable one or the one which ensures the best results within the machining process.
- Regarding the health operator aspect and the obligatory need to minimize the usage of cutting fluid as much as possible to protect him from the hazardous risks following the long exposure and contact with these cutting fluids, more concern is given to near-dry machining techniques like minimum quantity cooling and lubrication technique.
- It is obvious from the literature that the minimum quantity cooling technique is showing comparative results to the conventional flood cooling technique and could be used instead.
- The sustainability aspect gives rise to minimizing the consumption of mineral-based cutting fluids ones that are extracted from fossil fuels and are less biodegradable and causes environmental pollution when disposed of improperly after usage, so much more concern is given to applying vegetable-based cutting fluids instead of mineral-based oils.
- The emergence of the nanomaterial field and their wide accessibility in various fields give rise to their usage as reinforcements in cutting fluid which enhances their properties and makes them more effective, so nanofluids have been recently applied as cutting fluids.
- Regarding the previous work, there is a lack of research concerning the application of nano-vegetable-based cutting fluids via minimum quantity lubrication technique within machining difficult-to-cut material.

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