A Review of Cryogenic Coolant in Traditional Machining

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ABSTRACT - Cryogenics is an exciting, important and inexpensive technique that already has led to main discoveries and holds much future assurance. Cryogenic processing is the treatment of the materials at very low temperature. This technique has been proven to be efficient in improving the physical and mechanical properties of the materials such as metals, alloys, plastics and composites. The cooling applications in machining operations play a very important role and many operations cannot be carried out efficiently without cooling. Application of a coolant in a cutting process can increase tool life and dimensional accuracy, decrease cutting temperatures, surface roughness and the amount of power consumed in a metal cutting process and thus improve the productivity.234In this review, liquid nitrogen, as a cryogenic coolant, was investigated in detail in terms of application methods in material removal operations and its effects on cutting tool and workpiece material properties, cutting temperature, tool wear/life, surface roughness and dimensional deviation, friction and cutting forces. It improves the wear, abrasion, erosion and corrosion resistivity, durability and stabilizes the strength characteristics of various materials. Cryogenic refines and stabilizes the crystal lattice structure and distribute carbon particles throughout the material resulting a stronger and hence more durable material. Cryogenic treatment has been acknowledged in several researches as a means of extending the tool life of many cutting tools. Cryogenic treatment is an inexpensive supplementary process to conventional heat treatment, which improves the tribological properties of metals. A study has been made on the effect of cryogenic treatment done at different stages of heat treatment. As a result, cryogenic cooling has been determined as one of the most favourable method for material cutting operations due to being capable of considerable improvement in tool life and surface finish through reduction in tool wear through control of machining temperature desirably at the cutting zone.

1. Introduction

Excessive heat and consequently wear formation are the most important factors affecting performance and productivity of metal cutting operations. Different methods, i.e. hot machining [1], high-pressure coolant application [2], application of minimum quantity lubrication (MQL) [3] have been tried by researchers to enhance machining performance. One of these methods is conventional cutting fluid application.

1.1. Cutting fluids (coolants)

Conventional cutting fluids were classified into three groups as seen in Fig. 1 [4]. Water soluble fluids were defined suitable for operations where cutting speeds were very high and pressures on the tool were relatively low. Neat cutting oils are straight mineral oils, or mineral oils with additives. They were preferred when cutting pressures between chip and tool face were very high and where the primary consideration was lubrication. It was determined that cutting fluids cannot penetrate the chip–tool interface at high-cutting speeds [5]. Gaseous lubricants were seen very attractive when the cutting fluid penetration problem was considered but the high cost of gases made them uneconomical for production applications.

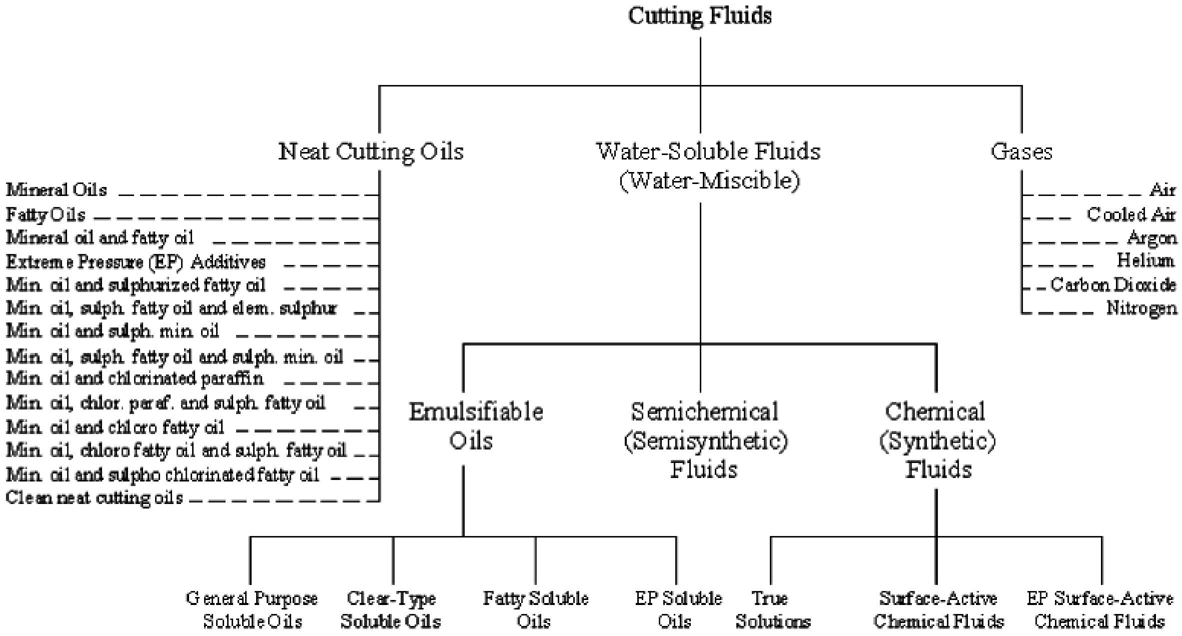

Fig. 1. Classification of cutting fluids.

The purpose of the application of the cutting fluids in metal cutting was stated as reducing cutting temperature by cooling and friction between the tool, chip and workpiece by lubrication [6]. Chip formation and curl, which affects the size of the crater wear and the strength of the cutting tool edge, is also affected when coolant is carried out during machining. Generally, a reduction in temperature results in a decrease in wear rate and an increase in tool life. However, a reduction in the temperature of the workpiece can increase its shear stress, so that the cutting force may be increased and this can lead to a decrease in tool life [7]. For instance, Seah et al. examined water-soluble lubricating on tool wear in turning of AISI 4340 and AISI 1045 steel with an uncoated tungsten carbide insert. They found that there was no significant difference between the cases where coolant was used and that of dry cutting. In fact, they showed that it aggravated flank and crater wear in some of the cutting conditions [8]. It was also proved that the conventional cooling action worsened the surface roughness when compared with dry cutting [9].

On the other hand, applications of conventional cutting fluids in industry create several health and environmental problems [10,11]. Environmental pollution due to chemical dissociation/breakdown of the cutting fluid at high-cutting temperature; water pollution and soil contamination during their ultimate disposal; biological (dermatological) ailments to operator's health coming in fumes, smoke, physical contact, bacteria and odours with cutting fluid; requirement of extra floor space and additional systems for pumping, storage, filtration, recycling, chilling, etc. According to the statistical data of 2002, total environmental expenditure of Turkey was $402,947,766. There were 272,482 firms in manufacturing industry for the same year [12]. If each of these firms had one machine (lathe or mill) and if each of these machines held 100 L of cutting fluid, tons of waste cutting fluid must have released to environment.

So, it is absolutely necessary to use an environmentally acceptable coolant in manufacturing industry. For this purpose, liquid nitrogen as a cryogenic coolant has been explored since the 1950s in metal cutting industry. However, it was not examined entirely at the beginning due to the high costs associated with early cryogenic technology. Uehara and Kumagai's studies [13,14] have pioneered to today's cryo-machining works. Their experimental findings were considerable in terms of machining performance. The subject has been still studied in different views and gaining interest due to its remarkable success on machinability. From the machining tests and cost analysis in a study [15], the following advantages of cryogenic cooling over conventional emulsion cooling were determined such as longer tool life, better chip breaking and chip handling, higher productivity, lower productivity cost, better work surface finish, environmentally safer, healthier for the worker. For instance, when compared with conventional emulsion cooling, cryogenic machining had productivity gains of up to 21.36% in machining of AISI 304 stainless steel for different speeds as seen in Fig. 2

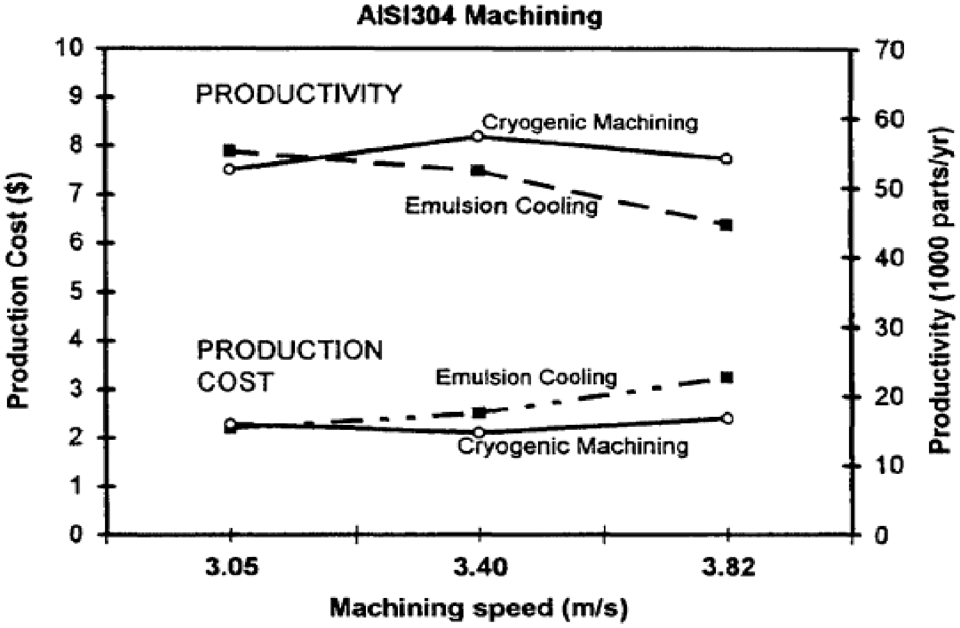

Fig. 2. Comparison of production cost and productivity of cryogenic machining with emulsion cooling [50].

In this study, cryogenic cooling application methods and their effects on production in machining operations have been reviewed in detail. Most of cryogenic cooling applications in machining studies have been examined in turning operations even though there were its applications in other machining operations such as grinding [16–19], drilling [20] and milling [21–23]. Contrary to turning operations, cryogenic cooling has been investigated less by the researchers in milling operations due to possibility of thermal cracks on cutting tool in intermittent cutting operations and difficulties in practice. However, exceptional improvements over dry cutting and emulsion cooling were achieved with cryogenic cooling by Hong et al. in milling processes [24,25]. For example, in milling of A390 with high-speed steel cutting tools, the tool life ratio over dry cutting was found bigger than 1000% by cryogenic cooling.

2. Heat generation in machining process

In any machining process, heat is generated as a result of the plastic deformation of the layer being cut and overcoming friction on the tool–chip and tool–work interfaces. This heat is dissipated by the four systems in processing the material such as the cutting tool, the workpiece, the chip formed and the cutting fluid. The greater part of the heat passes into the chip, while a proportion is conducted into the work material. This proportion may be higher for low rates of metal removal and small shear zone angles, but the proportion is small for high rates of metal removal [29]. O'Sullivan and Cotterell measured machined surface temperature using thermocouples in turning of aluminium alloy 6082-T6 with carbide inserts and their test results indicated that an increase in cutting speed resulted in a decrease in machined surface temperatures. This reduction was attributed to the higher metal removal rate which resulted in more heat being carried away by the chip and thus less heat being conducted into the workpiece [30].

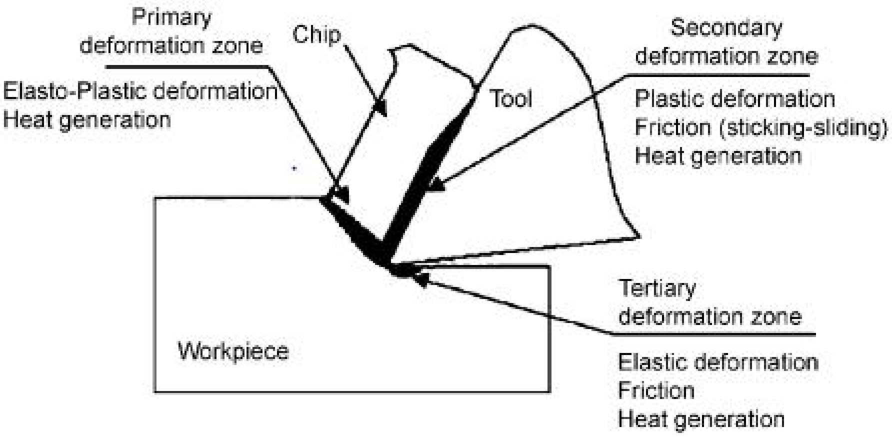

Fig. 3. Heat generation zones in orthogonal cutting [31].

The main regions where heat is generated during the orthogonal cutting process are shown in Fig. 3 [31]. Majumdar et al. developed a finite element-based computational model to determine the temperature distribution in a metal cutting process. Same temperature distribution wasproved by their model and they indicated the maximum temperature generation at the tool–chip interface [32]. Aspinwall and co-workers employed infrared pyrometer and FE model as direct and indirect techniques to measure cutting temperatures in turning of hardened hot work die steel and AISI H13 with PCBN (polycrystalline cubic boron nitride) tool. They obtained good correlation between two techniques and their model also predicted the highest temperatures at the tool–chip interface [33].

Heat generation and temperatures in the primary and secondary zones are dependent on a combination of the physical and chemical properties of the workpiece material and cutting tool material, highly cutting conditions, the cutting speed, the feed rate, the depth of cut, and less the cutting tool geometry and the cutting fluid [31]. When low alloy engineering steel was machined with cemented carbide tool, it was seen that cutting temperature increased with increasing of cutting speed and feed rate. In addition, the effect of air and water as a coolant decreased while the cutting speed increased [34]. The other factor affecting the cutting tool temperature is the contact length between the chip and the tool, and it was determined that the temperature was increased with the contact length for the orthogonal cutting of aluminium [29].

3. Cryogenic cooling

Cryogenics express study and use of materials at very low temperatures, below _150 1C. However, normal boiling points of permanent gases such as helium, hydrogen, neon, nitrogen, oxygen, normal air as cryogens lie below _180 1C. Cryogenic gases have a wide variety of applications in industry such as health, electronics, manufacturing, automotive and aerospace industry particularly for cooling purposes. Liquid nitrogen is the most commonly used element in cryogenics. It is produced industrially by fractional distillation of liquid air and is often referred to by the abbreviation, LN2. Nitrogen melts at _210.01 1C and boils at _198.79 1C, it is the most abundant gas, composes about four-fifths (78.03%) by volume of the atmosphere. It is a colourless, odourless, tasteless and non-toxic gas [26,27]. These characteristics of liquid nitrogen have made it as a preferred coolant [15]. The main functions of cryogenic cooling in metal cutting were defined by Hong and Zhao [28] as removing heat effectively from the cutting zone, hence lowering cutting temperatures, modifying the frictional characteristics at the tool/chip interfaces, changing the properties of the workpiece and the tool material. So, it will be useful to summarise heat generation and temperature distribution in a machining process for better evaluation of the subject.

3.1Cryogenic pre-cooling the workpiece

In cryogenic pre-cooling, the workpiece and chipcooling method, the aim is to cool workpiece or chip to change properties of material from ductile to brittle because, the ductile chip material can become brittle when the chip temperature is lowered [36]. Chip formation and its effect on productivity in metal cutting have been proved by Jawahir [37] and control and breaking of chips during cutting will increase performance of machining. This method was also attempted to freeze the workpiece by cryogenic enclosed bath or general flooding. A sample study was made by Bhattacharyya et al. [38] and they tested two methods; in first method, they dipped the test rod in liquid nitrogen and in second method, they poured the liquid nitrogen by continually onto the testpiece. Another sample practice was also experimented by Ding and Hong [39]. Their test setup was illustrated in Fig. 4. They gained significant improvement in chip breaking with pre-cooling of the AISI 1008 low carbon steel. Hong et al. [36,40] also developed a cryogen delivery system as seen in Fig. 5. In his system, LN2 was supplied to chip faces to improve the chip breakability. In this design, the size, shape and position of the nozzle were selected so that the LN2 jet covered the chip arc, and liquid flow was oriented parallel to the axial line of the curved chip faces. They proved in FE analysis that their method provided embrittlement temperature of chips, below -55 ^{0}C, for the AISI 1008. In a design of Ahmed et al. [41], the gas flow was directed towards the tool cutting edge to cool the newly generated chips and enhance their brittleness. However, these methods may be impractical in the production line and negatively increase the cutting force and the abrasion, in addition, they can cause dimensional change of the workpiece and, particularly high liquid nitrogen consumption can be required uneconomically [42].

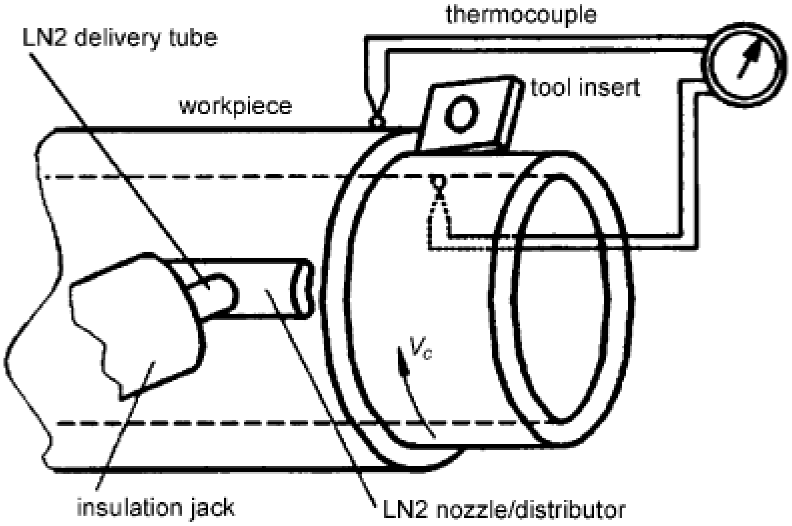

Fig. 4. Cryogenic workpiece pre-cooling [53].

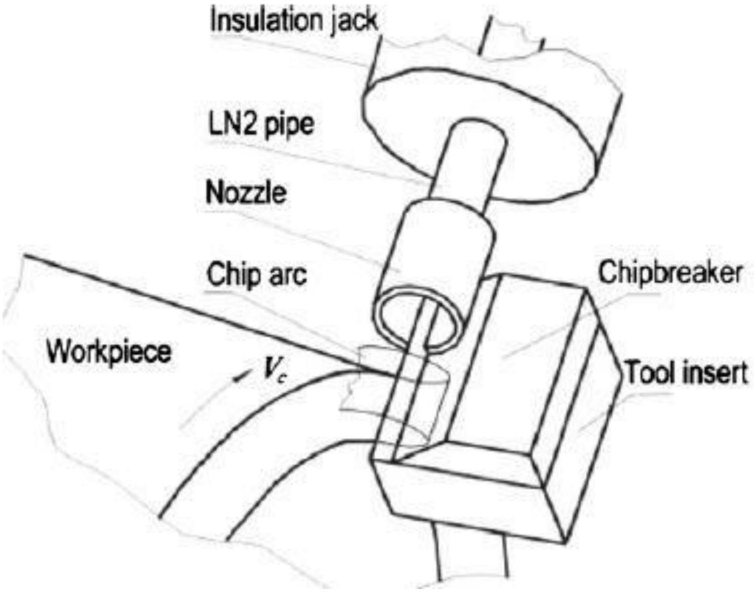

Fig. 5. LN2 delivery system for chipbreaking tests [50].

3.2. Indirect cryogenic cooling

This method was also called as cryogenic tool back cooling and conductive remote cooling. In this distinctive cryogenic cooling approach, the aim is to cool the cutting point through heat conduction from a LN2 chamber located at the tool face or the tool holder. In other words, LN2 is not repulsed to the tool or workpiece. An example was described by Evans [34]; he cooled the tools by immersing the tool shank in reservoir of liquid nitrogen. But his system was not suitable for a practical machining process Similarly, Wang and Rajurkar [44–46] designed a liquid nitrogen circulation system on the tool for conductive cooling of the cutting edge. Ahmed et al. [41] modified a tool holder with two designs for cryogenic machining. In one of their design, the discharging gas was directed away from the workpiece for maintaining ductility of materials. Piling up of nitrogen below the insert and thus keeping the tool insert at low temperatures were targeted without evaporating. So, the design is suitable for conductive remote cooling of the cutting edge.

The machining performance could be improved by indirect cryogenic cooling method because the cooling is restricted only to the cutting insert, LN2 does not contact with the workpiece and it does not cause significant change in properties of the workpiece, in addition, cooling effect is stable [45,46]. However, the effect of this approach is highly dependent on thermal conductivity of the cutting tool material, the distance from the LN2 source to the highest temperature point at the cutting edge and insert thickness. It can be more effective if a larger area of the tool insert is in contact with LN2 [43].

3.3. Cryogenic spraying and jet cooling

The objective in this method is to cool cutting zone, particularly tool–chip interface with liquid nitrogen by using nozzles. LN2 consumption and thus production cost could be high by general flooding or spraying of the coolant to the general cutting area in a machining operation. Fig. 6 illustrates such a cryogenic supply system developed by Zurecki et al. [47]. In such an application, coolant can also lead to cooling unwanted areas and increasing of the cutting forces [48]. Alternatively in a cryogenic jet cooling method, LN2 is applied with micro-nozzles to the tool rake and/or the tool flank, where the material is cut and maximum temperature is formed [15]. In such an LN2 delivery nozzle system, a flat cutting insert is used with an additional chipbreaker and LN2 is sprayed through a nozzle between the chipbreaker and the rake face of the tool insert. The chipbreaker helps to lift up the chips and so that LN2 can reach the tool–chip interface. In another design of Hong and Broomer, LN2 was injected with three nozzles to the cutting zone; in a -Z direction, parallel to the spindle axis, or in -X direction, perpendicular to the spindle axis, on the tool rake face and flank face, similarly [50].

In design of Dhar et al. [51–53], LN2 jets were targeted along the rake and flank surfaces, parallel to the main and auxiliary cutting edges too. In another design, Venugopal et al. [54] used LN2 jets through a nozzle on the face and flank of the cutting tool. There are distinct advantages of the cryogenic jet cooling. The cooling power is not wasted on any unnecessary areas and thus, workpiece will constant temperature and not subject to dimensional inaccuracy and geometrical distortion; this localised cryogenic cooling reduces the tool face temperature, enhances its hardness, and so reduces its wear rate; this approach also embrittles the chip by cold temperature and bend the chip with the chipbreaker. This cryogenic machining approach eliminates the BUE problem on tools because the cold temperature reduces the possibility of chips welding to the tool and the high pressure cryogenic jet also helps to remove possible BUE formation, therefore it will produce better surface quality [15]. In addition, LN2 cannot be circulated inside the machine tool like the conventional cooling fluids, as LN2 is released into normal atmospheric pressure and absorbs heat during the cutting process; it quickly evaporates [43]. In this method, the nitrogen consumption can be so small, for instance, volumetric LN2 flow rate was measured as 0.625 L/min for rake nozzle, 0.53 L/min for flank nozzle and 0.814 L/min for both rake and flank nozzles [55]. So, this process can improve the productivity and reduce the production cost significantly [56].

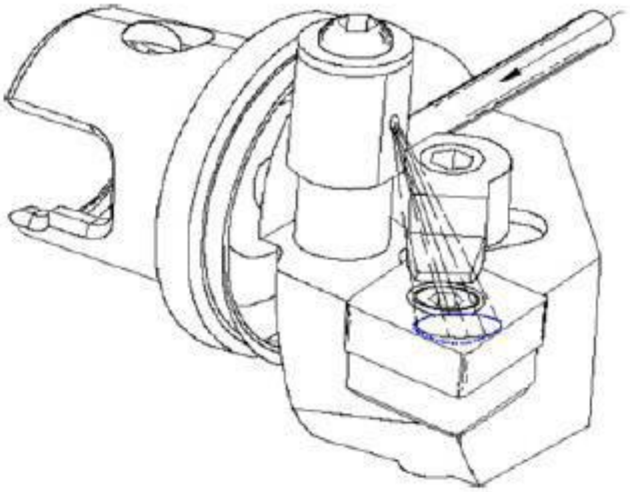

Fig. 6. A sample of cryogenic spraying method.

3.4. Cryogenic treatment

Cryogenic treatment is a process similar to heat treatment. In this method, samples are cooled down to cryogenic temperature and maintained at this temperature for a long time and then heated back to room temperature to improve wear resistance and dimensional stability of them [57,58]. For example, Yong et al. [59] performed a treatment method of tools cryogenically as follows: inserts are placed in a chamber; temperature is gradually lowered over a period of 6 h from room temperature to about -184 1C; temperature is then held steady for about 18 h; temperature is gradually raised over a period of 6 h to room temperature and inserts are tempered. Steps followed by Silva et al. [60] for the cryogenic treatment were: tools were conventionally quenched and tempered lasting a total of 43 h; cooling to -196 1C (20 h); heating to +196 1C (8 h); hot stabilisation at +196 1C (2 h); cooling to room temperature (1 h); stabilisation at room temperature (2 h); heating to +196 1C (1 h). These steps were repeated three times.

There are a lot of applications of cryogenic treatment or processing to enhance wear resistance and strength of tool materials from end mills to guillotine knives in industry [61]. However, the effect of the cryogenic treatment on cutting performance is not stable for all machining applications and cutting conditions, and there was not seen a comparison between cryogenic treatment and other cryogenic cooling approaches.

4.Conclusions

The aim of this study is to analyse and point out the effect of cryogenic liquid nitrogen cooling on cutting performance in material removal operations and its application methods. Other conventional coolants, heat generation and temperature distribution in a cutting process have been also discussed. Following consequences can be drawn from this review.

Cryogenic cooling in metal cutting has been studied nearly for six decades, however, many of the studies and most remarkable of them particularly in terms of application methods have been done in last decade and striking results have been achieved. Cryogenic cooling is still attractive and has been examined in material cutting field.

Almost all type of materials from ductile to hard and brittles have been machined in cryogenic cooling studies by many miscellaneous cutting tools. However, different kinds of steels were used widely in tests; non-ferrous metals, non-metallic and composite materials should be examined more.

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