Considerations regarding the use of cryogenic cooling in metal cutting as an alternative to conventional cooling – brief review

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Abstract. This paper presents a study regarding the latest researches on cryogenic cooling used in metal cutting as an opportunity for achieving green manufacturing, in terms of cryogenic methods, cutting tools, effects on cutting process parameters, industrial solutions and some possible applications in the areas where this cooling method presents deficiencies.

1 Introduction

Of all manufacturing processes available, metal cutting is one of the most common used as it results in products with complex geometric shapes, high surface finish, productivity and acceptable costs, reason why a great deal of research has been dedicated to better understand this process in all its regards. Researches from the last decades were mainly devoted to investigate the metal cutting process from a cleaner, green or environmental - friendly perspective as part of a worldwide increased demanding for a sustainable metalworking industry.

According to available literature in this field [1-3] some ways to improve the sustainability performance would involve reducing energy consumption, minimizing waste, using resources efficiently, using recyclable materials, improving the management of metalworking fluids, swarf, lubricating oils and hydraulic oils and adopting life cycle assessment methods.

Therefore, a viable approach to achieve an environmental-friendly machining takes into account the cooling-lubrication methods used during the cutting process. Although the importance of cooling-lubrication fluids is well known, their use creates several health and environmental problems. This is the reason why many alternatives were studied in the last years [3-10].

The studies in this field divide the cooling methods in two categories, namely conventional and alternatives to conventional cooling-lubrication methods, first one referring to mineral - oil based fluids, and the alternatives including different options in cooling in order to increase the productivity and reduce the environmental burden [3].

One of the alternatives to conventional cooling is the cryogenic cooling that many researchers have studied and concluded that it is an environmental-friendly solution for metal machining.

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Cryogenic cooling relates to delivering of a cryogenic fluid, instead of an oil-based fluid, to the cutting region of the tool which is exposed to the highest temperature during the machining process, or to the part in order to change the material characteristics and improve machining performance [11]. Of all the fluids used in cryogenic cooling, liquid nitrogen LN2 has been the most widely used in machining operations, but there are also studies involving liquid carbon dioxide CO2 [12-16].

The available literature in this area has shown some advantages of using cryogenic cooling, such as performing a cleaner and environmental-friendly machining, better chip breaking, increased tool life and material removal rate, dimensional accuracy, less power consumption, improved frictional characteristics at the tool/chip interfaces, decreased BUE and burr formation, increased machining performance by processing hard-to-cut materials.

On the other hand, some disadvantages could come from the attempts to implement these cooling methods into industry, such as lack of specially designed tools for cryogenic cooling, in terms of geometry, substrate and coating, lack of machine-tool interface designed for cryogenic machining, high initial costs, high complication level of optimizing the flow and pressure, cutting fluid is not reusable as it is in conventional cooling and in some case it may be necessary to pre-cool the workpiece in order to prevent thermal shocks [17].

Continuous research in this field and current industrial applications are attempting to overcome a large part of these disadvantages.

2 Experimental applications of cryogenic cooling

According to researcher applications, cryogenic cooling approaches in metal machining could be classified into four groups, as follows:

- **cryogenic pre-cooling the workpiece** [4, 12, 18];
- **indirect cryogenic cooling** [4, 12];
- **cryogenic jet cooling** [4, 11-16, 19-29];
- **cryogenic treatment of cutting tools** [4, 12, 30, 31].

Of all these methods, most commonly used is the cryogenic jet cooling that consists in injecting the cryogenic agent to the cutting zone by general flooding or to the cutting tool edges or faces using micro-nozzles.

Theoretical and experimental studies have been conducted in various machining operations, using different kinds of part materials, tools and cutting parameters. Within these studies cryogenic machining was compared to other cooling methods in terms of energy consumption, overall costs, productivity and environmental protection, reflected in the measurement and analysis of the temperature and cutting forces, cutting tools wear, dimensional accuracy, surface quality and material removal rate.

Most of the investigations in cryo-machining were conducted in **turning** operations [4, 6, 11, 14, 19, 21-25, 28, 32], but there are also investigations carried-out in **grinding** [12, 33], **drilling** [12, 29] and **milling** [4, 13, 15, 16, 34, 35] using different kinds of tools, mostly carbide coated and uncoated tools [19, 11, 13, 14, 21-29, 33, 34] and also PCBN, PCD and ceramic tools [12].

The investigations were carried-out using different types of materials being cut, from ductile to hard and brittles, and the results have shown that in most situations, the cryogenic cooling is efficient by prolonging the tool's life as the cutting area temperature decreases, especially for the high-tech materials, such as nickel, cobalt, titanium based alloys and tungsten which are difficult-to-cut materials.

Investigations on tool wear, surface quality, cutting temperature and forces in cryogenic machining have been conducted in order to test the efficiency of using cryogenic compared to other cooling methods, such as conventional, minimum quantity of liquid (MQL) or dry machining and some results of the latest researches are shown in Table 1.

Table 1. Findings from experiments – literature review

Cryogenic method	**Cryogenic agent (gas)**	**Part material**	**Opera-tion**	**Tool**	**Force**	**Surface quality**	**Cutting temp.**	**Tool life**	**Author - paper**
Cryogenic jet cooling	Cryogenic air	TI–6AL–4V alloy	Turning	Carbide	↑		↓	↑	Sun S. *et al.*, 2015 [24]
Cryogenic jet cooling	LN2	TI6AL4V alloy	Turning	Carbide		↑	↓	↑	Bordin A. *et al.*, 2015 [23]
Cryogenic jet cooling	LN2	Aluminum alloy 6061-T89	Turning	Carbide	↔		↓		Kaushal A. *et al.*, 2016 [25]
		AISI 1040	Turning	Carbide	↑		↓		
Cryogenic jet cooling	LN2	TI-6AI-4V alloy	Turning	Carbide	↑	↓	↓	↑	Boswell B. and Islam M. N., 2016 [26]
Cryogenic jet cooling	LN2	EN 31 steel	Turning	Carbide				↑	Kumar S. *et al.,* 2016 [27]
Cryogenic jet cooling	LN2	TI-6AI-4V alloy	Drilling	Carbide	↓	↑	↓	↑	Kumar P. and Ahmed L. S., 2016 [37]
Cryogenic jet cooling	LN2	Titanium ASTM B265	Drilling	Carbide	↑	↓	↓		Ahmed L. S. *et al.,* 2016 [39]
Cryogenic jet cooling	Super critical CO2	AISI 1045	Turning	Carbide	↓		↓		Rahim E. A. *et al.*, 2016 [14]
Cryogenic jet cooling	LN2	TI-6AI-4V	Turning	Carbide		↑	↓	↑	Bordin A. *et al.*, 2017 [6]
Cryogenic jet cooling	CO2	TI-6AI-4V alloy	Milling	Carbide				↑	Tapoglou N. *et al.,* 2017 [15]
Cryogenic jet cooling	CO2	AISI P20	Milling	Carbide	↓	↑	↓	↑	Balaji V. *et al.*, 2017 [16]
Cryogenic jet cooling	LN2	AISI 4340	Turning	Carbide		↑			Natasha A. R. *et al.,* 2017 [32]
Cryogenic treatment of cutting tools	LN2	AISI 304	Drilling	Carbide		↑		↑	Naveena B. *et al.,* 2017 [31]
Cryogenic treatment of cutting tools	LN2	Nimonic 90 alloy	Turning	Carbide	↓			↑	Chetan *et al.*, 2017 [30]
Cryogenic jet cooling	LN2	TI-6AL-4V alloy	Turning	Carbide	↓	↑			Mia M. *et al*, 2017 [40]
Cryogenic jet cooling	LN2	TI-6AL-4V alloy	Milling	Carbide	↑			↓	Park K.H. *et al,* 2017 [40]
Internal cryogenic cooling	LN2	Hardened steel EN 24	Milling	HSS	↓	↑		↑	AKM Islam K. *et al.*, 2017 [41]
Cryogenic jet cooling	LN2	Inconel 718	Drilling	Carbide	↑	↓	↓	↓	Ucak N. and Cicek A., 2018 [29]
Legend	↑ increase	↓ decrease	↔ equal						

3 Industrial application of cryogenic cooling

As it was described above, the cryogenic jet cooling is most widely used cryogenic method and in order to apply it, several equipment were developed, both in terms of laboratory/experimentally set-ups [13, 19, 21, 22, 23, 26, 28, 29, 41] and industrial devices or systems [42-45]. Depending on the type of cryogenic agent, there are two generic schemes that were used in order to create the cryogenic equipment [8, 20].

Researches have shown the efficiency of cryogenic methods, both in terms of clean processing and productivity, energy and tools consumption, but these methods have to be accepted and sustained by the industry. This means that cryogenic cooling must be applied at small prices and with results that support the initial investment and maintenance costs. Practice has shown that cryomachining is efficient especially for machining metals that are difficult-to-cut under conventional conditions, materials that are mainly used in aerospace, automotive, chemical, petroleum industries and medicine.

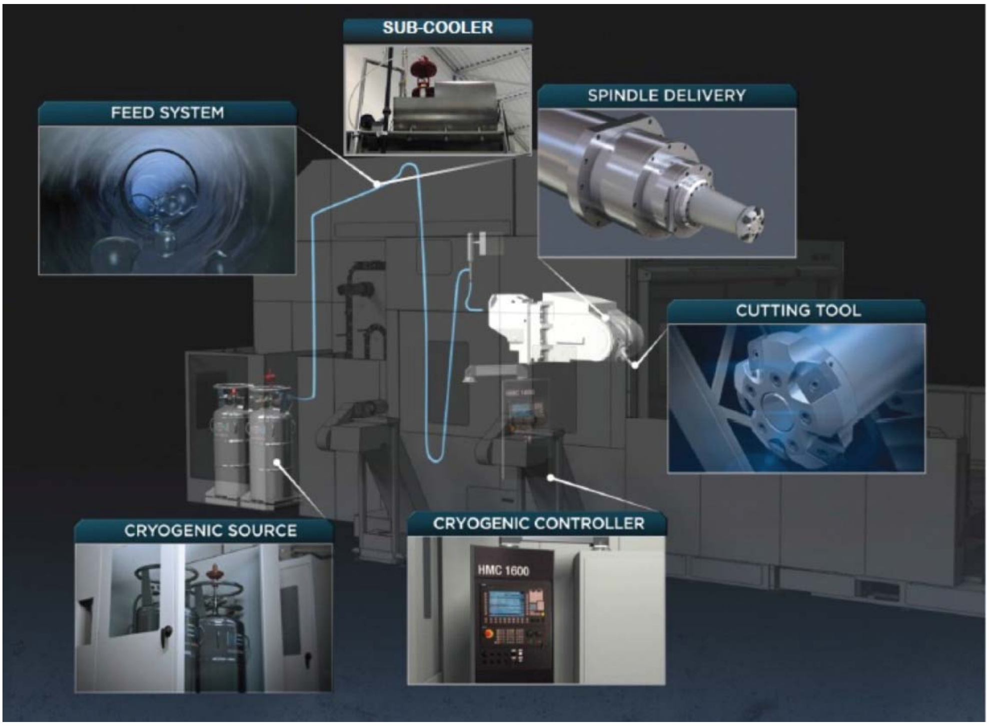

Fig. 1. Example of cryogenic system from 5ME Company [43]

In metalworking industry there are companies that are able to develop and implement cryogenic cooling methods, companies that offer either complete solutions for cryogenic cooling like systems that can be adapted to any machine-tool, software and cutting tools [42-45], either components of a cryogenic cooling system, such as suppliers of adapted / modified tools [43, 44, 46, 47], cryogenic accessories [42-45, 48, 49] or cryogenic agents (gases) [42, 50].

4 Conclusions

This paper presents a brief review on the latest investigations performed in cryogenic machining and the following conclusions could be drawn:
- Most of turning and grinding operations resulted in decrease of cutting temperature and forces and increase of tool life and part surface quality.

- Not all investigations returned results significantly better in terms of forces, surface quality or tool life showing that cryogenic cooling is not more efficient than conventional, MQL or dry machining.
- When performing milling or drilling operations, depending on the other process parameters, results have shown a decrease of tool life in milling and increase of cutting forces and decrease of tool life in metal drilling.
- An important role is played by the type of cooling agent used, as there are situations when CO2 or even cryogenic air have a much better influence on the cutting process parameters than LN2, although in practice LN2 is used more often.
- The literature review has shown that this field is not completely covered as there are workpiece materials, cutting operations and cryogenic methods that require additional investigations.

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