BULETINUL INSTITUTULUI POLITEHNIC DIN IAŞI
Publicat de
Universitatea Tehnică „Gheorghe Asachi” din Iaşi
Volumul 63 (67), Numărul 2, 2017
Secţia
CONSTRUCŢII DE MAŞINI

STUDY REGARDING METALWORKING SUSTAINABILITY WITH REGARDS TO CRYOGENIC COOLING – LUBRICATION METHODS – AN OVERVIEW

BY

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Received: October 19, 2017
Accepted for publication: November 23, 2017

Abstract. This paper presents theoretical considerations regarding the use of cryogenic cooling in metalworking as an alternative to conventional cooling-lubrication methods, aiming the achieving of an environmentally-friendly processing, in terms of cryogenic agents, methods and equipments, materials being cut, tool materials and influences on cutting process parameters.

Keywords: green manufacturing; liquid nitrogen; carbon dioxide; tool life; forces; surface quality.

1. Introduction

Metalworking continues to be the leading industry within the global industry and for over three decades, solutions have been sought in order to increase its sustainability, meaning the achieving of a full correlation of the three dimensions, namely social, ecological and economic, with the purpose to create maximal value and minimal damage.

Research literature in this area (Pusavec *et al*., 2009; Pusavec *et al*., 2010a,b; Kopac and Pusavec, 2009; Gunay and Yucel, 2013; Alvarez Peralta *et*

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al., 2017) suggests some ways to improve the sustainability performance, such as reducing machining processes energy consumption; minimizing waste (generate less waste and increase waste reusage or recycling); using resources efficiently; using recyclable materials or reusing machine-tool components; improving the management of metalworking fluids, swarf, lubricating oils and hydraulic oils and adopting life cycle assessment methods. Therefore, one may say that the cooling methods used during the cutting process have an important contribution in achieving an environmentally-friendly machining within a sustainable metalworking industry.

The importance of using cooling-lubrication fluids during the cutting process is well known and there are operations that cannot be carried out efficiently without cooling, since their main roles are to cool and reduce friction, remove metal particles, increase tool life, dimensional accuracy and surface quality, decrease cutting temperatures, forces and the power consumed in a metal cutting process.

However, the use of cooling-lubrication fluids in industry creates several health and environmental problems, such as 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) menace to operator's health coming in fumes, smoke, physical contact, bacteria and odors with cutting fluid; requirement of extra floor space and additional systems for pumping, storage, filtration, recycling, chilling, etc. (Yildiz and Nalbant, 2008). This is the reason why many alternatives were studied in the last years (Yildiz and Nalbant, 2008; Kopac and Pusavec, 2009; Shokrani *et al*., 2012; Gunay and Yucel, 2013; Lawal *et al*., 2013; Veiga *et al*., 2013; Shokoohi *et al*., 2015; Thakur and Gangopadhyay, 2016; Alvarez Peralta *et al*., 2017; Bordin *et al*., 2017; Benedicto *et al*., 2017; Liew *et al*., 2017; Ramachandran *et al*., 2017; Sivaraman and Prakash, 2017).

Therefore, the opened literature in the field divides the cooling methods in two categories, namely conventional lubrication-cooling and alternatives to conventional lubrication-cooling methods, first one referring to cutting fluids which are mixtures formulated with oil as base and additives to enhance various properties depending on the machining process, and the alternatives referring different options in cooling in order to increase the productivity and reduce the environmental burden (Alvarez Peralta *et al*., 2017). In this regard, a diagram showing the cooling - lubrication methods used in metalworking was drawn (Fig. 1). From the diagram one can see that the field is not completely covered, leaving space for research activity.

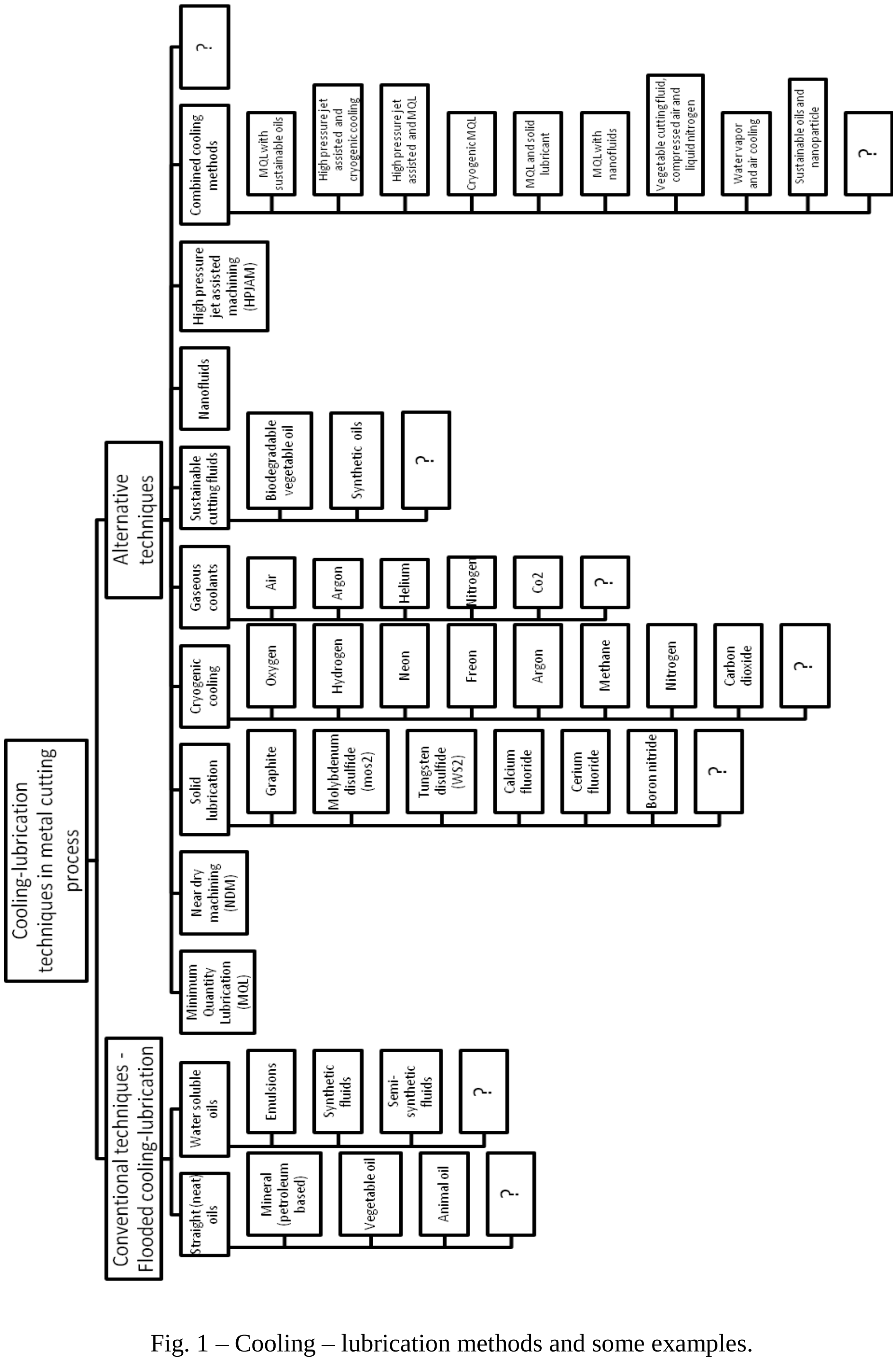

Fig. 1 – Cooling – lubrication methods and some examples.

Analyzing the diagram one may see that one of the alternative to conventional cooling is the cryogenic cooling that many authors have studied and concluded that this is an environmental-friendly solution for metal machining which requires application of cooling and lubrication.

Cryogenic cooling is an innovative method of cooling the cutting tool and/or part during machining. More specifically, it relates to delivering a cryogenic fluid, instead of an oil-based fluid, to the cutting region of the cutting 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 (Pusavec *et al*., 2010a, b).

The term “cryogenic” refers to fluids that have boiling point lower than -150°C, including liquefied gases of nitrogen (LN2), carbon dioxide (CO2), oxygen, hydrogen, argon, neon, freon, methane and helium. Cryogenic machining was first investigated around 1953 by Bartley who used liquid CO2 as the coolant. Also, in 1961 W.S. Hollis stated that he could increase the life of carbide tools by using CO2 as a coolant when machining titanium alloys. In 1965, researcher at the Grumman Aircraft Manufacturing reported about increased material removal rates in machining titanium with LN2 and CO2 (Ghosh, 2006; Stefánsson, 2014).

The latest researches (Ghosh *et al*., 2003; Ghosh, 2006; Pusavec *et al*., 2010a; Lu *et al*., 2013; Pusavec and Kopac, 2014) have shown some benefits of cryogenic machining, as follows: **sustainable machining** (a cleaner, safer and environmental-friendly method); **increased material removal rate**; **better chip breaking**; **increased tool life**; **improved** machined **part surface quality/integrity**; **less power consumption**; **improved frictional characteristics** at the tool/chip interfaces; **decreased BUE and burr formation**; **increased machining performance** with offer of machining hard to machine alloys.

The main disadvantage of this technology, besides the additional equipment needed, is relatively high price of the cryogenic fluids, although studies have shown that the increasing research in this field has led to achieving overall costs lower than conventional cooling (Yildiz and Nalbant, 2008; Kopac and Pusavec, 2009, Pusavec *et al*., 2009; Pusavec *et al*., 2010b; Gunay and Yucel, 2013; Benedicto *et al*., 2017; Liew *et al*., 2017).

2. Cryogenic Technology

2.1. Cryogenic Methods

Cryogenic methods consisting in ways that the cryogenic agent could be conducted into the cutting area could be classified into four groups according to applications of the researchers (Yildiz and Nalbant, 2008; Ahmad-Yazid *et al*., 2010):

– **cryogenic pre-cooling the workpiece** by enclosed bath **or cryogenic chip cooling** - the aim is to cool the workpiece or chip and change properties of material from ductile to brittle (Ghosh, 2006; Yildiz and Nalbant, 2008; Kumar *et al*., 2017).

– **indirect cryogenic cooling** or cryogenic tool back cooling or conductive remote cooling - the aim is to cool the cutting point through heat conduction from a cryogenic agent chamber located at the tool face or the tool holder (Ghosh, 2006; Yildiz and Nalbant, 2008).

– **cryogenic jet cooling** by injecting the cryogenic agent to the cutting zone by general flooding or to the cutting tool edges or faces using micro-nozzles - the objective in this method is to cool cutting zone, particularly tool–chip interface with cryogenic agent by using nozzles; cryo-agent 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 (Ghosh *et al*., 2003; Ghosh, 2006; Yildiz and Nalbant, 2008; Khan *et al*., 2010; Pusavec *et al*., 2011; Ravi and Kumar, 2011; Bicek *et al*., 2012; Jerold and Kumar, 2012; Yasa *et al*., 2012; Shokrani *et al*., 2012; Fernández *et al*., 2014; Cordes *et al*., 2014; Sun *et al*., 2015; Bordin *et al*., 2015; Kaushal *et al*., 2016; Boswell and Islam, 2016; Kumar *et al*., 2016; Rahim *et al*., 2016; Tapoglou *et al*., 2017; Balaji *et al.*, 2017; Novella *et al*., 2017).

– **cryogenic treatment of cutting tools** to enhance their performance - 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 their dimensional stability (Ghosh, 2006; Yildiz and Nalbant, 2008; Naveena *et al*., 2017).

As the opened literature shows, the most commonly used cryogenic agent is liquid Nitrogen and some researchers investigated the use of Carbon dioxide (Ghosh, 2006; Jerold and Kumar, 2011; Jerold and Kumar, 2012; Cordes *et al*., 2014; Rahim *et al*., 2016; Tapoglou *et al*., 2017; Balaji *et al.*, 2017).

Liquid Nitrogen (LN2) is the most commonly used element in cryogenic machining. It is industrially produced by fractional distillation of liquid air and is often referred to by the abbreviation, LN2. Nitrogen melts at -210°C and boils at – 198°C, it is the most abundant gas, composing about four-fifths (78.03%) by volume of our atmosphere. It is a colorless, odorless, tasteless and non-toxic gas. These characteristics of liquid nitrogen have made it as a preferred coolant. The liquid nitrogen evaporates quickly under cryogenic machining leaving no wastes to contaminate its surroundings (workpiece, chips, machine tool or operator) thus eliminating disposal costs (Yildiz and Nalbant, 2008; Liew *et al*., 2017).

Liquid Carbon Dioxide (CO2) is a refrigerated liquefied gas. At room temperature it can be held liquid. It can be stored in high pressure gas cylinders.

When it fuses with the ambient air, it becomes a gas and a solid – dry ice – and drops down to -78.5°C due to the phase transformation (Cordes *et al*., 2014; Tapoglou *et al*., 2017). One of the advantages of using CO2 is that unlike simple atmospheric gases like nitrogen and oxygen, CO2 exhibits very strong hydrocarbon solubility which means CO2 gas exhibits more than 600 percent higher solubility in oils as compared to compressed air. Due to this unique physicochemical properties and cohesion energy, CO2 gas modifies lubricant and coolant additive properties to produce mixtures having lower surface tension and lower viscosity, which aids in penetration into chip/tool capillary interfaces (https://www.moldmakingtechnology.com/).

2.2. Cryogenic Equipment

Cryogenic machining by injection of cryogenic agent to the cutting area by general flooding or to the cutting tool edges or faces using micro-nozzles is most widely used cryogenic method and several equipments were developed in order to apply this method, both in terms of laboratory/experimentally set-ups and industrial devices (Ahmad-Yazid *et al*., 2010; Fernández *et al*., 2014; Boswell and Islam, 2016; Rahim *et al*., 2016; Balaji *et al*., 2017; Novella *et al*., 2017; Kumar *et al*., 2017; Natasha *et al*., 2017; www.5me.com). Depending on the cryogenic agent used, there are two generic schemes that were used for conducting the investigations in cryomachining.

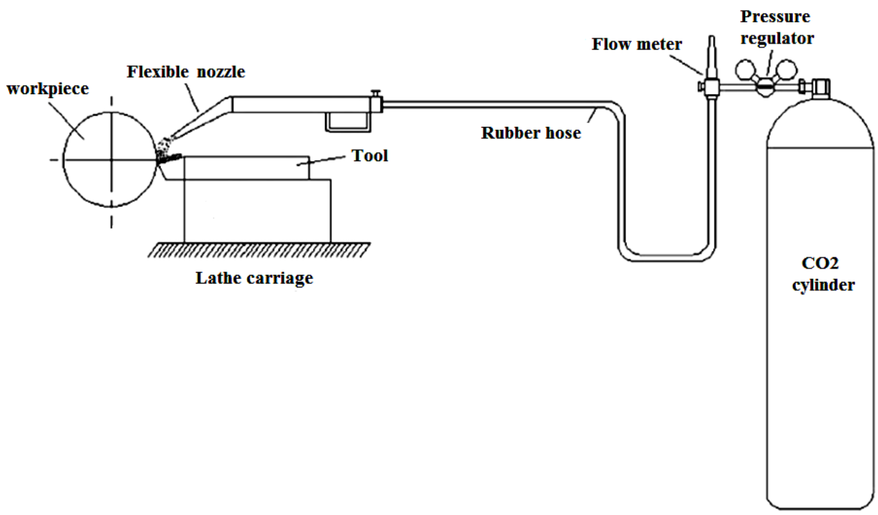

Fig. 2 – Schematic view of cryogenic CO2 machining setup (Jerold and Kumar, 2012).

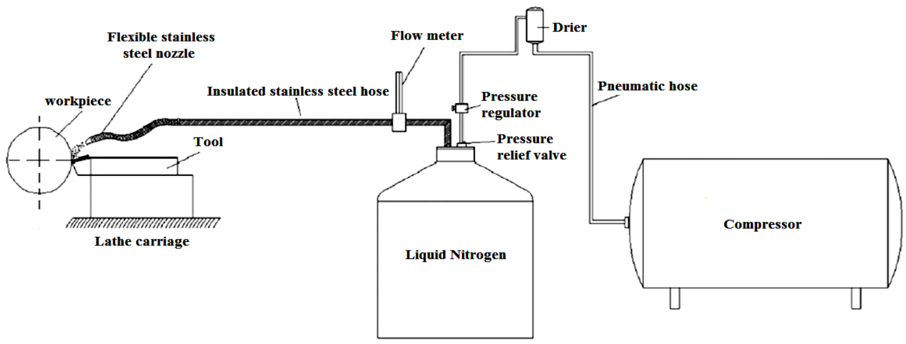

Fig. 3 – Schematic view of cryogenic LN2 machining setup (Jerold and Kumar, 2012).

3. Application of Cryogenic Cooling – Findings from Experiments

3.1. Workpiece Materials

Investigations on tool wear, surface quality, cutting temperature and forces in cryogenic machining have been conducted when processing different types of materials of the workpiece, as follows:

• low/medium carbon steels (Ghosh, 2006; Jerold and Kumar, 2012; Kaushal *et al*., 2016; Rahim *et al*., 2016);

• high carbon/high alloy steels (Ghosh *et al*., 2003; Ghosh, 2006; Ahmad-Yazid *et al*., 2010; Ravi and Kumar, 2011; Bicek *et al*., 2012; Kumar *et al*., 2016; Balaji *et al*., 2017; Natasha *et al*., 2017);

• stainless steels (Ghosh, 2006; Khan *et al*., 2010; Cordes *et al*., 2014; Naveena *et al*., 2017);

• nickel based alloys - Inconel 718 (Ghosh, 2006; Pusavec *et al*, 2009; Pusavec *et al*., 2011; Shokrani *et al*., 2012; Fernández *et al*., 2014; Pusavec *et al*., 2016; Hribersek *et al*., 2017);

• cobalt based alloys (Ghosh, 2006; Pusavec *et al*., 2009);

• iron based alloys (*e.g.* high chromium stainless steel) (Pusavec *et al*., 2009);

• titanium alloys (Ghosh, 2006; Yasa *et al*., 2012; Rui *et al*., 2014; Rotella *et al*., 2014; Sun *et al*., 2015; Bordin *et al*., 2015; Boswell and Islam, 2016; Ahmed *et al*., 2016; Bordin *et al*., 2017; Tapoglou *et al*., 2017; Novella *et al*., 2017; Kumar *et al*., 2017);

• tungsten (Pusavec *et al*., 2009);

• ceramics (Ghosh, 2006);

• tantalum based alloys (Ghosh, 2006; Wang *et al*., 2002);

• non-ferrous materials (Aluminum alloy, cooper, silicon, reinforced plastic fiber) (Ghosh, 2006; Kaushal *et al*., 2016).

Experimental researches have shown that in most situations the cryogenic cooling is efficient by improving the tool 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 as they have high-temperature properties and the ability to retain a high strength-to-weight ratio.

3.2. Cutting Tools

Cutting tools used in cryogenic cooling are of many kinds but most of researches regarding cryogenic cooling have been performed with **carbide tools**, both **coated** (Khan *et al*., 2010; Pusavec *et al*., 2011; Ravi and Kumar, 2011; Bicek *et al*., 2012; Jerold and Kumar, 2012; Yasa *et al*., 2012; Shokrani *et al*., 2012; Fernández *et al*., 2014; Rotella *et al*., 2014; Sun *et al*., 2015; Bordin *et al*., 2015; Novella *et al*., 2017; Natasha *et al*., 2017) and **uncoated** (Ghosh, 2006; Cordes *et al*., 2014; Kaushal *et al*., 2016; Boswell and Islam, 2016; Rahim *et al*., 2016; Ahmed *et al*., 2016).

Tests have also been carried out with **polycrystalline cubic boron nitride** (PCBN) tools (Ghosh *et al*., 2003; Bicek *et al*., 2012), **polycrystalline diamond** (PCD) tools (Ghosh *et al*., 2003) and **oxide - ceramic** tools (Ghosh *et al*., 2003).

Investigations on tool life when using cryogenic cooling with different types of tool materials have revealed that using CO2 as cooling agent have led to reduction of wear when machining with HSS, tungsten carbide and CBN tools (https://www.moldmakingtechnology.com/), and when using LN2 as cooling agent, Al_2O_3, PCBN and PCD tools have also shown significant improvements in tool life (Ghosh *et al*., 2003).

3.3. Machining Operations

The use of cryogenic cooling in various fields of machining has been studied for different types of materials being cut and tool materials. Most of cryogenic cooling applications in machining are considering **turning** operations (Ghosh *et al*., 2003; Khan *et al*., 2010; Pusavec *et al*., 2011; Bicek *et al*., 2012; Jerold and Kumar, 2012; Yasa *et al*., 2012; Fernández *et al*., 2014; Rotella *et al*., 2014; Sun *et al*., 2015; Bordin *et al*., 2015; Kaushal *et al.*, 2016; Rahim *et al*., 2016; Bordin *et al*., 2017; Novella *et al*., 2017; Natasha *et al*., 2017), but there were investigations carried out in other machining operations such as **grinding** (Ghosh, 2006, Fredj *et al*., 2006; Manimaran *et al*., 2014), **drilling** (Ghosh *et al*., 2003; Ghosh, 2006; Kumar and Ahmed, 2016; Ahmed *et al*., 2016; Naveena *et al*., 2017) and **milling** (Ghosh *et al*., 2003; Yildiz and Nalbant, 2008; Ravi and Kumar, 2011; Shokrani *et al*., 2012; Cordes *et al*., 2014; Tapoglou *et al*., 2017; Balaji *et al*., 2017).

While most of turning and grinding operations, using cryogenic cooling compared to other cooling methods, such as conventional, MQL or dry machining, resulted in decrease of cutting temperature and forces and increase of tool life and workpiece surface quality, when performing milling or drilling operations, depending on the other process parameters, results have shown a decrease of temperature and cutting forces and improvement of surface quality but also decrease of tool life in milling, and increase of cutting forces and decrease of tool life in metal drilling.

3.4. Influence of Cryogenic Cooling on Cutting Process Parameters

The efficiency of using cryogenic cooling in metalworking has been investigated for various machining operations, workpiece materials, tool materials and cutting parameters, compared to other cooling methods in terms of energy consumption, overall costs, productivity and process ecology, elements that materialize in the measurement and analysis of the temperature and cutting forces, cutting tools wear, dimensional accuracy, surface quality and the material removal rate.

Regarding the cutting temperature, no matter the type of machining, all investigations have showed a large decrease during processing when using the cryogenic cooling.

Cutting forces were measured during turning (Kaushal *et al*., 2016; Boswell and Islam, 2016; Rahim *et al*., 2016), milling (Balaji *et al.*, 2017), grinding (Manimaran *et al*., 2014) and drilling (Kumar and Ahmed, 2016; Ahmed *et al*., 2016). Most of researches revealed a decrease of forces when using cryogenic cooling, compared to conventional, MQL or dry machining, but there are also investigations that have shown an increase of forces (Boswell and Islam, 2016; Kaushal *et al*., 2016; Ahmed *et al*., 2016).

Most of the studies investigated tool wear using different methods of cryomachining compared to other cooling methods used in metalworking, and the results have shown an important increase in tool life. On the other hand, there are investigations showing there are no differences between conventional and cryogenic cooling that prove the effectiveness of using cryomachining (Yasa *et al*., 2012).

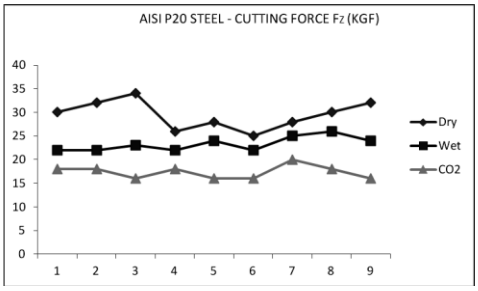

Fig. 4 – Cutting force with different machining condition when milling of AISI P20 Steel (Balaji *et al.*, 2017).

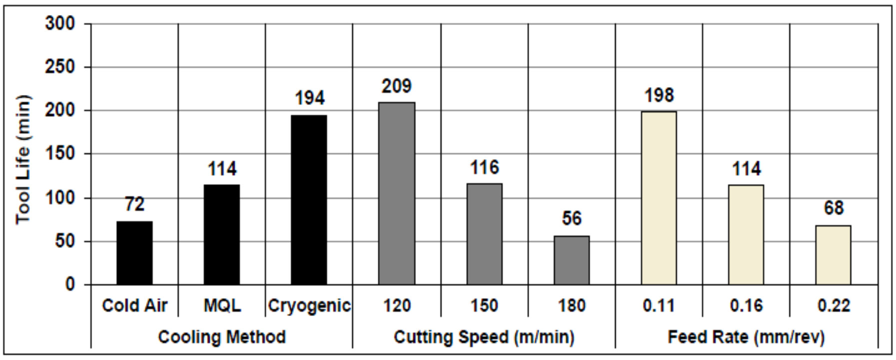

Fig. 5 – Effect of cutting parameters on tool life when turning TI-6AI-4V alloy using tungsten carbide tool (Boswell and Islam, 2016).

Regarding the workpiece surface quality, the experimental results presented in the opened literature show that cryomachining provides lower surface roughness compared to other cooling methods in turning, grinding and milling (Manimaran *et al*., 2014; Cordes *et al*., 2014; Bordin *et al*., 2017; Balaji *et al*., 2017; Natasha *et al*., 2017) and an increase of roughness in drilling (Boswell and Islam, 2016; Ahmed *et al*., 2016), but this also depends on the other parameters of the cutting process.

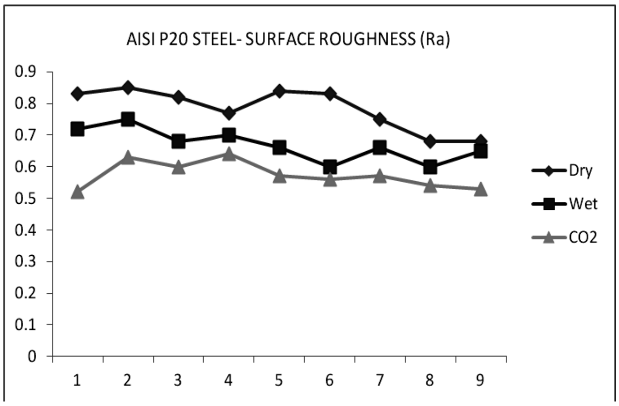

Fig. 6 – Surface roughness with different machining condition when milling of AISI P20 Steel (Balaji *et al*., 2017).

In all investigations, 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 (Jerold and Kumar, 2012; Cordes *et al*., 2014; Boswell and Islam, 2016; Tapoglou *et al*., 2017).

4. Conclusions

This paper presents an overview of latest published experimental investigation on metal machining in cryogenic cooling conditions, contributing to better understand of this field. The following conclusion can be drawn from the literature:

• Almost all type of materials, from ductile to hard and brittles have been studied in cryomachining using different cutting tools, but while different kinds of steels were widely used in tests, non-ferrous metals, nonmetallic and composite materials should be examined more.

• Most of the studies have included turning operations, while other machining operations such as milling and drilling could be attempted more with cryogenic cooling.

• In order to test its efficiency, cryogenic cooling is usually compared to conventional cooling, dry machining or MQL and in most of cases, depending on the material being cut, tool material and other cutting parameters, the cryomachining had shown better results in regards of tool life, cutting forces and surface quality.

• In all investigations, an important role is played by the type of cooling agent used, as there are situations when CO2 or even cryogenic air have revealed a much better influence on the cutting process parameters than LN2, although in practice LN2 is used more often.

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STUDIU PRIVIND SUSTENABILITATEA PRELUCRĂRII METALELOR CU PRIVIRE LA METODELE CRIOGENICE DE RĂCIRE-UNGERE – PREZENTARE GENERALĂ

(Rezumat)

Prelucrarea prin aşchiere a materialelor metalice continuă să fie lider în cadrul industriei globale şi de peste trei decenii se caută soluţii pentru creşterea sustenabilităţii acesteia, ceea ce înseamnă realizarea unei corelaţii totale între cele trei dimensiuni - socială, ecologică şi economic - pentru a crea valoare maximă şi daune minime. Literatura din acest domeniu sugerează câteva modalităţi de creştere a sustenabilităţii proceselor de prelucrare a metalelor, cum ar fi reducerea consumului de energie; minimizarea deşeurilor (reducerea deşeurilor şi creşterea cantităţii de deseuri reutilizabile sau reciclarea deşeurilor); utilizarea eficientă a resurselor folosind materiale reciclabile sau reutilizarea componentelor maşinii-unelte; îmbunătăţirea gestionării fluidelor de răcire-ungere utilizate la prelucrare şi a uleiurilor hidraulice. Prin urmare, se poate spune că metodele de răcire utilizate în timpul procesului de tăiere au o contribuţie importantă la realizarea unei prelucrări ecologice în cadrul unei industrii durabile de prelucrare a metalelor.

Una dintre alternativele la utilizarea lichidelor convenţionale de răcire-ungere este răcirea criogenică pe care mulţi autori au studiat-o şi au concluzionat că aceasta este o soluţie ecologică pentru prelucrarea metalelor. Răcirea criogenică este o metodă

inovatoare de răcire a sculei așchietoare şi/sau a piesei în timpul prelucrării. Mai precis, se referă la aducerea unui fluid criogenic, în locul unui fluid pe bază de ulei, în zona de așchiere a sculei care este expusă la cea mai înaltă temperatură în timpul procesului de prelucrare. Cercetările experimentale au arătat eficiența utilizării metodelor criogenice de răcire-ungere atât prin creșterea duratei de viață a sculelor așchietoare, scăderea temperaturii din zona de așchiere, scăderea forțelor de așchiere, îmbunătățirea calității suprafețelor prelucrate, creșterea volumului de așchii îndepărtat deci creșterea productivității, cât și prin faptul că reprezintă o soluție viabilă de prelucrare ecologică având în vedere că prelucrarea are loc în condiții nepoluante și fără obținerea de reziduuri în sculă, piesă sau mediul înconjurător.