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Investigations into Grinding under Cryogenic Cooling

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Abstract

The intensive temperature in grinding not only diminishes tool life but also subjects the machined surface to various defects such as inducing tensile stresses, surface burns and discolorations, micro cracks, dimensional irregularities and other thermal damages. This problem becomes magnified when materials with a low grindability index are to be machined. In this situation, the machinist heavily relies on grinding fluids as a way to drastically reduce these defects.

The past decades has witnessed extreme changes in cutting fluid technology raging from advanced formula coolants to more direct ways of delivering grinding fluids to the cutting zone and heat affected zones but with these technological advances, the looming health and environmental risk involved with grinding fluids are still present. Grinding fluids aren't just a nuisance when is comes to recycling but it also poses a serious health threat to workers on the work floor and surroundings.

It's a proven fact that Metal Working Fluids (MWF) such as grinding fluid, are responsible for many upper and lower respiratory illness and diseases as well as various cancers and skin infections. Cryogenics have been tried and tested as a green alternative to conventional MWF by many researchers and have been proven to have positive effects on addressing grinding defects. This paper will provide an overview on the recent developments in cryogenic cooling in metal cutting, especially in metal grinding and propose further investigations into the viability of such a fluid in the machining industry.

Keywords

Grinding, Cryogenics, Metal working fluids (MWF), Grinding fluids, Thermal damages, Grind burns

1. Introduction

Most metal cutting operations, which result in the formation of swarf, require metal working fluids (MWF) to aid in the removal process. MWF are used in machining and grinding operations to increase tool life, improve surface finish, and the power and the force necessary for the removal of metal (Woskie et al., 2003). Generally, a large quantity of work energy is converted to heat in the cutting process; this heat can lead to distortion and warping of the work piece. In the metal cutting process, more than 97% of the work is transformed to heat, 1-3% goes to residual stress, 0.67 and 0.33% goes to over coming the sticking friction in the shear zone and sliding friction at the tool/chip, tool/flank interface respectfully (Springborn, 1967).

Hence, MWF also perform the task of cooling both the work piece and the cutting tool. MWF also help in removing swarf from the cutting zone, lubricating the machine slides and protects the work piece from corrosion.

In the metal cutting as well as the grinding process, heat is generated at three distinct zones; the shear plane, the wear flat and the chip-grit interface. At the shear plane metal is deformed plastically, the strain energy involved in this deformation is converted into thermal energy which is sheared between the workpiece and chip, this view is sheared widely among many researchers (Moneim, 1978). It should be noted that, when the plastic strain energy is large, most of it is converted to heat while a small amount goes into the deformation of the lattice structure. The heat produced at the chip-grit interface is a result of friction between the two bodies and is estimated to be 50% of the total grinding energy. Heat produced at the wear flat is a result of attritious wear of the tool, which is apparent by the formation of a smooth shiny tool surface (Moneim, 1978). (Malkin and Anderson, 1973) explained that the total energy in grinding can be separated into 3 components, which comprises of chip formation, sliding and plowing energy, where plowing is a deformation process involving no metal removal. (Malkin and Anderson, 1973) deduced that almost all of the plowing and sliding energies are converted as heat to the workpiece, whereas only 55 percent of the chip formation energy is conducted to the workpiece.

There are many considerations associated with cutting fluid selection, aside from just heat dissipation and lubrication other factors such as Chip disposal corrosion, health and safety, and cost are also looked into. This article reviews some of the health issues associated with conventional MWF manly grinding, and looks at cryogenic machining as a “green fluid” alternative.

2. Types of Metal cutting fluids

2.1 Emulsion

An emulsion is a suspension of oil droplets in water made by blending the oil with emulsifying agents and other materials (Springborn, 1967). Water is an attractive extender of lubricating oils; cheap, high specific heat, high thermal conductivity, high heat of vaporization characteristics and non-flammability are all useful attributes (Stachowiak and Bachelor, 2001), is one of the most effective media known. Metal working fluid emulsions are “oil in water” (O/W) as oppose to “water in oil” (W/O) emulsions, where the water is the continuous phase. The blend of water and oil, provides both good coolant and lubricating properties required by metal removal operations; where the cooling characteristics is attributed to the presence of water and the lubricating characteristics is a result of the oil . During the lubrication process by emulsions, water is expelled from the loaded contacts and as a result the performance of an emulsion is close to that of a pure mineral oil, (Stachowiak and Bachelor, 2001). Mineral oils are normally used to create water miscible fluids. Paraffinic and Naphthenic mineral oils are the two most commonly used oils, other additives are also present, such as (Springborn, 1967):

- Emulsifiers: petroleum sulfonates, amine soaps, rosin soaps naphthenic acid
- Coupling agents: complex alcohols and non-ionic wetting agents
- Lubrication enhancers *(present in highly-fatted water miscible fluids)*: sperm oil, lard oil and esters

- Pressure enhancers *(present in extreme pressure emulsifiable oils)*: chlorine, sulphur and phosphorous
- Germicides
- Bactericides

Emulsion fluids generally offer the following advantages (Springborn, 1967 and Woskie et al., 2003):

i. Reduction of heat (due to the presence of water)
ii. Provides cleaner cutting conditions when compared to neat or straight oils
iii. More economical, dilution with water brings the application cost down
iv. Better operation acceptance
v. Improved health and safety, fire hazard is removed, reduction in misting, fuming and fogging

One of the major drawbacks with these MWF is the temperature range at which the fluid can usefully operate. They are limited to the temperature associated with phase changes in water which lies between the melting point and the boiling point of water. This makes the fluid unsuitable for severe cutting operations where high cutting temperatures are generated.

2.2 Chemical and Semi-Chemical

Chemical or synthetic oils do not contain mineral oil; instead they contain some synthetic chemicals as substitutes. Semi-chemical or semi-synthetic fluids contain 5 to 30% of severely refined petroleum oil, this combination combines the advantages of synthetic coolants and mineral oils but at the same time the disadvantages, while chemical or synthetic fluids do not contain petroleum oil, instead, detergent like compounds and other additives are used to help "wet" and penetrate the surface of the workpiece. Besides from additives used to increase the wettability of the lubricant, other additives are used to increase the functions of the fluid, such as (Woskie et al., 2003; Springborn, 1967 and Sheehan, 1999):

- Corrosion inhibitors
- Extreme pressure additives (*chlorinated paraffins, phosphorus derivatives*)
- Anti-misting agents (*polyisobutylene polymer*)
- Emulsifiers
- Alkanolamines
- Biocides (*triazine, oxazolidine compounds*)
- Stabilizers
- Disperants
- Colourants
- Dyes
- Odourants
- Fragrances.

Emulsions are known for their white milky appearance but for chemical and semi-chemical fluids, the appearance varies from clear and transparent to translucent (Springborn, 1967). This is due to the relatively small particle size which is small enough to transmit or allow almost all incident light to pass through making it far much easier for the machinist to inspect the workpiece while being machined.

Synthetic coolants are not affected by bacterial growth hence having a long usage life; this is due to the absence of organic compounds in the composition of the fluid. Some of the major drawbacks with Synthetic coolants are their (Springborn, 1967):

i. Poor lubricating properties

ii. Relatively high pH (around 9.5)
iii. Abrasive interaction with epoxy paints
iv. High detergency property.

3. Health and Environmental issues attached to the various MWF

MWF, or metal working coolants, are complex mixtures that may contain petroleum products, vegetable and animal fats, organic and inorganic salts, and a variety of additives (Woskie et al., 2003). MWF can be broken down into four categories: straight fluids, water-soluble fluids, syntactic fluids and semi-syntactic fluids. Over the past years, many medical research institutes have studied the health effects associated with MWF. Many have tried to formulate proper data gathering protocols and standards used in determining the degree of exposure to the various chemicals found in MWF. The varying data gathering methods displayed by several researchers have impeded the development of an occupational exposure limit (OEL) for MWF. Health effects that have been associated with exposure to MWF’s include dermatitis, respiratory health effects, gastrointestinal health effects and increased mortality from a variety of cancers (Woskie et al., 2003). Apart from the actual MWF there are numerous additives, biocides, and contaminants that are irritants or sensitizers that can cause or aggravate respiratory symptoms (Oudyk et al., 2003). These range from lubrication boosters, anti-mist, anti-foaming, anti-corrosion other additives such as blending agents, surfactants, dyes, or emulsifiers are also used.

Biocides are used to suppress growth of micro-organism contamination, bacteria can be introduced to the fluid through: the water used for mixing, machine/workpiece parts, air and, by the operators hands. Though most bacteria can’t survive in MWF, they do promote growth of some species. Some of the more harmful species out of a family of twelve that are found in MWF are (Springborn, 1967):

i. Escherichia coli
ii. Pseudomonas aeruginosa
iii. Klebisella pneumoniae
iv. Pseudomonas Oleovorans
v. Paracolabactrum species
vi. Salmonella Typhosa
vii. Proteus Vulgaris
viii. Staphylococcus aureus

These eight species are facultative aerobic bacteria meaning that they prefer oxygen for growth but can grow in the absence of oxygen. Escherichia coli, commonly known as E. coli is found in the lower intestines of warm-blooded animals. Certain strains of E. coli are toxigenic and can cause food poisoning usually associated with eating contaminated meat. The severity of the illness depends on the nature of the individual; it can be fatal for infants, elderly and the immuno-compromised. For those in good health, a bout of diarrhoea is associated with the infection. Probable introduction of the E. coli bacteria in MWF are through soiled hands and contaminated water. Pseudomonas aeruginosa is an opportunistic human pathogen; it is also a known hydrocarbon utilizing micro-organism which can cause microbial corrosion in metals. This pathogen affects the pulmonary tract, urinary tract, burns and open wounds and also causes other blood infections (Todar, 2006). Pseudomonas aeruginosa is due to poor what quality and management, eradicating a coolant sump of P. aeruginosa very difficult. The Pseudomonas Oleovorans species also shares the same characteristics as P. aeruginosa. Salmonella Typhosa is one of the causes of disease, typhoid. It is excreted by humans in faeces and maybe transmitted by contaminated water and food, or by person to person contact. Staphylococcus aureus is found on the skin and nostrils of a healthy person, it can cause minor skin infections and abscesses, to life-threatening diseases such as pneumonia, meningitis, endocarditis and septicaemia (Chambers, 2003). Staphylococcus aureus is normally transmitted via skin to skin contact or through air spores. If we were to assume that for a given volume of coolant at room temperature, the bacteria count was two and that for every 20 minutes each cell splits, forming a new cell. Further assuming that each cell has a life span of over 12 hours and that none die within that period, at the end of 12 hours the fluid will have well over 6 billion cells present in the coolant, this is highlighted in Figure 1 . These high levels not only pose a threat to the operator but also to the entire work floor and the surroundings, since MWF mist are present in the atmosphere. The evaporation and condensation of MWF from the heat generated during marching was found to be the major contributor to mist formation mechanism, followed by centrifugal force, then impaction (Thornburg, 2000). The latter two modes will not drastically affect the concentration of bacteria since they do not involve heat and are merely mechanical.

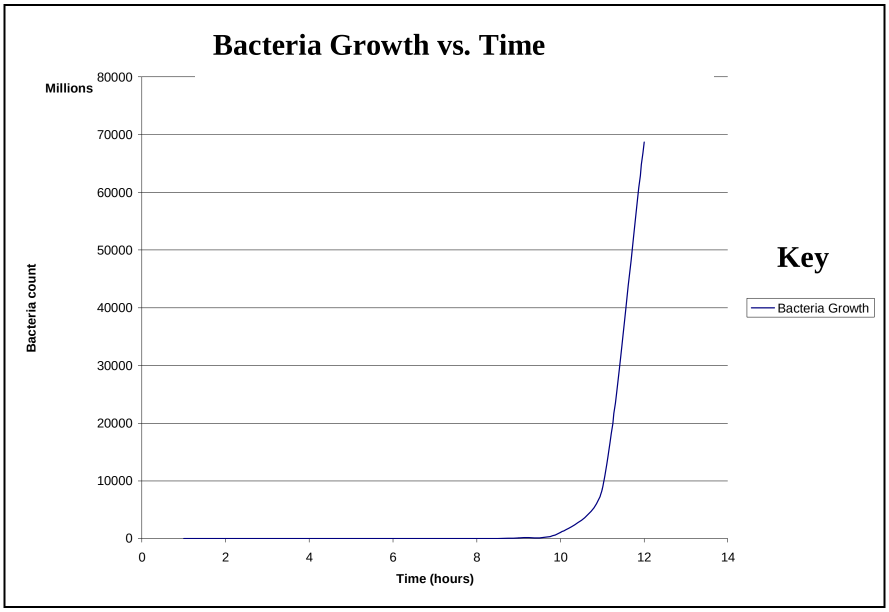

Figure 1 Graph illustrating bacteria growth over 12 hours

Investigations into the carcinogenicity of MWF have been studied as early as 1960’s (Savitz, 2003), the agents and poor hygiene protocol used then have changed throughout the years. Back then, crude methods and negligence in regarding the health consequences in these choices were the norm, as a result data gathered from that era indicated that MWF exposure, elucidate the predominance of cancer cases among operators and job floor workers. Some of the common cancer cases were scrotal and skin cancer, which highlights the synergetic role that the agent found in the fluid and the hygiene practices (Savitz, 2003 and Sheehan, 1999).

Though the times and practices have changed the risk is still present, most, not if all, the data used to investigate the carcinogenic nature of MWF steams from both the early years to more present times. Despite the complexity of the MWF, there are a number of additives that warrant consideration, including biocides, surfactants, and corrosion inhibitors. With the use of at least one of the many additives, with the right combination and conditions can generate exposure to a number of compounds that are alleged of causing cancer cells, such as: Poly-nuclear aromatic hydrocarbon, N-nitro compounds, and abrasives such as cobalt grains generated from the tool (Savitz, 2003).

4. Benefits of cryogenics as an alternative to conventional MWF.

There have been many papers published in the field of cryogenic cooling, as a means of replacing conventional MWF. The bulk of the papers relate to the fluid addressing the various machining problems faced in turning as apposed to grinding. Cryogenic machining was first investigated around 1953 by E.W. Bartley who used sub-zero cooled $C0_2$ as the coolant (Chattopadhyay et al., 1985). Many researchers regard metal grinding more of an art than a science, this essentially a result of the process complexity and stochastic nature of grinding (Hou, 2003).

For this section, an attempt has been made to accentuate the quantity of work under gone over the years in the field of cryogenic cooling, though the overview does not reflect the total body of work, it reflects work that are noble enough to draw meaningful inferences from, particular attention will be to the metal grinding process see

Efforts to determine the coefficient of friction and the lubricating effects of LN2 machining by (Hong et al 2002 and Zbigniew et al., 1999), where the investigation involved turning TI-6Al-4v and AISI 1018. Trapped LN2 between the mating surfaces expands, acting as a hydrodynamic boundary layer, which demonstrates a quasi hydrodynamic lubrication mechanism (Hong et al., 2002). The lubrication effect from LN2 can be achieved by a combination of various temperature dependant effects and a micro scale hydrostatic effect. At low normal loading, the micro scale hydrostatic effect can be the predominant mechanism of LN2 lubrication (Hong et al., 2002).

Table 1.

(Chattopadhyay et al., 1985) were one of the first researchers to investigate the effects liquid nitrogen (LN2) had on the grinding process, where they studies found that the surface finish of the ground specimens showed remarkable improvements when compared to specimens ground under soluble oil. They attributed this improvement to the extreme cooling effect and the inert nature of nitrogen, preventing oxidation and any other physico-chemical reactions at the newly ground surface. In addition, it was found that the extreme cooling action had a positive effect on the tool life, where the grits of the wheel retained its sharpness over longer periods under the colder conditions.

A few years later some researchers were able to compare the effects of cryogenic cooling with both dry and flood emulsion cutting, in the work presented in (Paul et al., 1993), it was found that LN2 cooling yielded mostly lamellae chips and few spherical chips when compared with dry and flooding cutting where for the latter two methods produced random orientated chips ranging from long laminar, spherical to irregular and hollow chips, where the flood method had fewer spherical. This phenomenon was explained by saying that the sharpness retention of the grit for a longer period of time leads to a decrease in the force and specific energy needed to shear the material. (Paul et al., 1993) also highlighted that when machining High Speed Steel (HSS) the mode of metal removal is mainly by crushing as opposed to shearing and ploughing when ground under LN2 cooling, this was said to be due to the embrittlement of the specimen's surface as it is being cooled to sub-zero temperatures, causing shorter laminar chips. A reduction in grinding force was also noticed with the introduction of LN2. (Chattopadhyay et al., 1985) also found that LN2 allows the operator to increase the depth of cut and in-feed parameters without generating extreme temperatures at the wheel workpiece interface as oppose to grinding under the same conditions with water soluble emulsions where the temperatures generated are high enough to cause sever thermal damage (Paul and Chattopadyay, 1996a; Paul and Chattopadyay, 1996b; Paul and Chattopadyay, 1995).

(Ramesh et al., 2003) also looked at cryogenic cooling but instead of studying LN2 they used sub cooled jet of air as a means of cheap, ecological cooling. A decrease in grinding force was found to be lower when a jet of air at 0.35^{o}C and 0.3MPA was directed to the grinding zone when compared to water soluble coolants. The same mechanisms used by (Paul et al., 1993) were used to explain such observation. An improved surface was also observed and was ascribed the removal of the ploughing action. The results for residual stress revealed that, within the threshold material removal rate, chilled air imparted more compressive residual stress for S45C and SS304 when compared to water soluble coolant. It should be pointed out that work presented by (Ramesh et al., 2003) showed that, chilled air only works up to a certain threshold value for the various dependant variables.

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Table 1 List of reviewed authors in the feild of cryogenic grinding

Authors	Machining process	Dependant Variables	Material
Dhar et al., (2002)	Turning	**A,B,C,D**	AISI 4140
Hong, et al., (2001)	Turning	**H,A,J E**	TI-6Al-4v
Hong, et al., (2002)	Turning	**I,H**	AISI 1018,TI-6Al-4v
Paul et al., (1993)	Grinding	**E,G,F,H**	AISI 1020,AISI 1080,Cold die, Hot die steel, HSS
Paul and Chattopadhyay (1996a)	Grinding	**A,K**	AISI 1020,AISI 1080,Cold die, Hot die steel, HSS
Paul and Chattopadhyay (1996b)	Grinding	**A**	AISI 1020,AISI 1080,Cold die, Hot die steel, HSS
Paul and Chattopadhyay (1995a)	Grinding	**D,E,F,**	AISI 1020,AISI 1080,Cold die, Hot die steel, HSS
Wang and Rajurkar (1997)	Turning	**B**	RBSN
Wang et al., (2003)	Turning	**B,C,H**	Inconel 718
Zurecki et al., (1999)	Turning	**A,B**	H10a,1015, TI-6Al-4v
Murthy et al., (2000)	Grinding	**G,H,K,L,C**	Micro-alloyed, Low alloy, Hadifield manganese steel
Paul and Chattopadhyay (1995b)	Grinding	**A,H,K,F**	AISI 1020,AISI 1080,Cold die, Hot die steel, HSS
Hong and Woo-cheol (2001)	Turning	**B**	TI-6Al-4v
Ramesh et al., (2003)	Grinding	**A,K,E,H,G**	S45C, SS304
Hong and Ding (2001)	Turning	**A**	TI-6Al-4v
Paul et al., (2001)	Turning	**B,C**	AISI 4140
Chattopadhyay et al., (1985)	Grinding	**G,H**	Mild steel, AISI 4340,HSS

Key

A: Interface temperature
B: Wear
C: Surface roughness
D: Dimensional deviations
E: Chip formation
F: Residual stress
G: Surface investigations
H: Cutting force
I: Coefficient of friction
J: Microstructure
K: Specific energy
L: Micro-hardness

4.1 Research agenda

At present, work is being undertaken at the Department of the Mechanical and Manufacturing engineering at the University of the West Indies to address the gaps in cryogenic machining. The focus is placed on surface grinding tribology, where the effects of LN2 on surface finish, tool life, thermal distribution, sub-surface microstructure and other aspects that affect the grinding mechanism. Particular attention directed towards the effectiveness of LN2 to combat grinding burns and microstructure phase change. Based on the review of literature, test variables to investigate the performance of cryogenics in the field of surface grinding are listed in Figure 2.

Figure 2 Test variables for investigating LN2 performance

Independent Variables	Dependant Variables	Intervening or Extraneous Variables
• Coolant: • Dry (air) • LN_2 (liquid) • N_2 (gas) • Water Soluble emulsion	Micro Hardness Residual Stress Density of Grinding Burn Surface Roughness Martensitic Depth Temperature at the grinding zone Cutting Forces Density of Micro-Cracks	Depth of Cut Feed Rate Table Feed Number of Cuts Type of Cutting Wheel Coolant Pressure

5. Conclusions

MWF are heavily relied more on the practises of the metal cutting industry, its ability to increase production and reduce both part and tool damage. This is caused by intense heat and shock load, makes it a quintessential aid for any metal cutting processes. Though conventional MWF are helpful, there are certain consequences associated with their usage. It ranges from impaired performance as a result of restricted characteristics of the chemical composition of the MWF to health and environmental risk. Below is a summary of the findings from the study:

i. Coolants and lubricants play an important role in metal cutting, MWF aid by increase tool life, improve surface finish, and reduce the power and the force necessary for the removal of metal.
ii. MWF also reduce the high temperatures involved in cutting, but the conventional metal working liquid do not fully control extreme temperatures generated at the cutting zone.
iii. Poor use of conventional fluids can lead to various health problems, from harbouring hazardous bacteria to contain certain agents that are known to be carcinogenic such as Poly-nuclear aromatic hydrocarbon and N-nitro compounds.
iv. LN2 cooling provides substantial reduction in cutting zone temperatures and favourable chip-tool interactions.
v. LN2 inert nature allows the fluid to provide lubrication with out chemically altering the surface of the ground surface.

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