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An Investigation into the Metal Grinding Process under Sub-Zero Temperature Cutting Fluid

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ABSTRACT

The grinding process falls under the category of abrasive machining, which is a material-removal operation that involves abrasive grits interacting with the workpiece at high speeds and shallow penetration depths. In surface grinding, high heat is generated at the contact regions due to friction between the grit-chip and grit-workpiece interactions. This generated heat may damage the machined surface due to a sudden rise in temperature which induces phase transformations on the machined surface. These phase transformations lead to workpiece burns that drastically decreases the fatigue life of the job. Thus, the elimination of these burns is of considerable interest in this study. It is apparent that sub-zero temperature coolants would have the ability to bring about lower grinding temperatures than what is typically achieved under conventional fluids.

In this study, a factorial experimental approach was used to investigate the effects of liquid carbon dioxide (LCO_2) on grinding stainless steel (SS304) material. The LCO_2's performance was benchmarked against grinding under dry and emulsion coolant environments. Based on the experimental results it was found that under specific conditions, LCO_2 proves to be a viable coolant alternative for grinding of temperature sensitive materials. Furthermore, under low depths of cut (0.012 – 0.025 mm) and table speeds (100 mm/s – 258.33 mm/s), LCO_2 restricts the occurrence of grinding burns.

Keywords: *Surface grinding, Stainless steel (SS304), Sub-zero coolant, Liquid carbon dioxide (LCO_2), Grinding burns*

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Introduction

Surface metal grinding is categorized as an abrasive machining process, where the removal of metal is accomplished by the circular movement of an abrasive grinding wheel, comprised of irregular shaped abrasive particles, relative to the linear movement of the workpiece. Most metal cutting operations result in the formation of swarf that requires metal working fluid (MWF) to aid in the removal process. MWFs are used mainly in machining and grinding operations to increase tool life, improve surface finish, and provide the power and the force necessary for the removal of metal [1]. Generally, a large quantity of energy is converted to heat in the cutting process; this heat can lead to distortion of the workpiece. In the metal grinding process, more than 97% of the energy is converted to heat. The remaining energy is split into residual stress (1-2%), to overcome sticking friction (0.67%) as well as sliding friction (0.33%) in the shear zone [2]. MWFs also perform the task of cooling both the work piece and the cutting tool and also assist in the protection of the workpiece from corrosion.

In 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 in its plastic state. The strain energy involved in this deformation is then converted to thermal energy which is sheared between the workpiece and chip [3]. However, it should be noted that most of the strain energy is converted to heat while a small amount goes to the deformation of the lattice structure. The heat produced at the chip-grit interface is as 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 as a result of tool wear, which is apparent by the formation of a smooth shiny tool surface [3]. Malkin and Anderson [4] explained that the total energy in grinding can be separated into three components, which comprises of chip formation, sliding and plowing energy, where plowing is a deformation process that involves no removal of metal. Malkin and Anderson [4] also deduced that most of the plowing and sliding energies were converted to heat within the workpiece. However, only 55% of the chip formation energy is transmitted to the job.

On the other hand, the metal cutting industry has witnessed extreme changes in cutting fluid technology ranging from conventional MWFs to advanced coolants by more direct ways of delivering grinding fluids to the cutting zone and heat affected zones. However, with these technological advances, the looming health and environmental risk involved with grinding fluids are still present. Grinding fluids are not only a nuisance when it comes to recycling but they also pose a severe health threat to workers and surroundings [1], [5]. It has been proven that traditional MWFs are responsible for respiratory illnesses as well as skin infections. Cryogenic coolants have been tried and tested as an alternative to conventional MWF by many researchers and have been proven to have positive effects on addressing grinding defects [6]-[8].

There are many issues associated with cutting fluid selection in abrasive grinding process. Other than heat dissipation and lubrication aspects, chip disposal, health and safety will also influence the selection process. This paper focuses mainly on surface metal grinding, where the main thrust will be on examining the effects of liquid carbon dioxide (LCO_2) on the ground specimen and inspection of workpiece microstructure. Particular attention has been directed towards the effectiveness of LCO_2 to combat grinding burns and microstructure phase change. The rest of the paper is organized as follows: In section 2, a review of literature on MWFs in surface grinding is presented. Research agenda is presented in section 3. This is followed by results and analysis in section 4. Section 5 deals with discussion of results. Finally, section 6 concludes the research work.

A Review of Literature

MWF acts as a lubricant, by reducing the friction caused between the grit and the workpiece; this leads to a drop in the amount of heat generated. In order for the MWF to perform satisfactorily as a lubricant, the fluid must maintain a strong protective film in between the grit and the metal being cut where a hydrodynamic condition can be present [5]. This condition assists the chip in sliding readily over the cutting faces of the grains. Besides reducing heat, the lubricant lowers power requirements and reduces the rate of tool wear and loading [2].

The majority of heat produced at the grinding zone is not as a result of friction. MWFs cannot eliminate the friction between the grit and the workpiece. Therefore, it must act as an effective coolant, in order to remove the remaining heat generated due to other mechanical actions such as shearing, ploughing, and sliding. If the MWF is successful in performing as a lubricant, the problem of heat removal from the grinding zone is minimized, but cooling still remains an important function. To perform this function effectively, the MWF should have a high thermal conductivity, so that maximum heat will be absorbed and removed per unit fluid volume. MWFs may act as an anti-weld agent to counteract the tendency of the swarf to weld onto the work material or get entrapped into the pores of the grinding wheel [2].

Types of MWFs

MWFs used for abrasive machining may be divided into three main groups [2], [5]: emulsion type, chemical type and sub-zero temperature type. These are briefly reviewed and presented in the following sections.

i. Emulsion type

An emulsion is a suspension of oil droplets in water made by blending oil along with emulsifying agents and other materials [2]. Water is an attractive extender of lubricating oils because of its attributes: cheap, high specific heat capacity, high thermal conductivity, high vaporization characteristics and non-flammability [9]. Metal working fluid emulsions are 'oil in water' as opposed to 'water in oil' emulsions, where the water is the continuous phase. The blend of water and oil, provides a good coolant with lubricating properties required by metal removal operations. During the lubrication process by emulsions, water is separated from the loaded contacts and as a result the performance of an emulsion is close to that of a pure mineral oil [9]. One of the major drawbacks with MWFs is the temperature range at which the fluid can operate effectively. They are limited to the temperature phase range that 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.

ii. Chemical type

Chemical or synthetic oils do not contain mineral oil but they do contain some synthetic chemicals as substitutes. Semi-chemical or semi-synthetic fluids contain 5 to 30% of refined petroleum. These semi-type coolants have combined properties of both synthetic coolants and mineral oils. Chemical or synthetic fluids do not contain petroleum; however they are made up of detergent like compounds and other additives that are used to penetrate the surface of the workpiece. Apart from using additives to increase the moisture content of the lubricant, other chemical additives are used to increase the functions of the cutting fluid, such as corrosion inhibitors, anti-misting agents, and emulsifiers [2],[10],[24]. Synthetic coolants are not affected by bacterial growth hence having a long usage life. This is primarily due to the absence of organic compounds in the composition of the fluid.

iii. Health and environmental issues attached to various conventional MWFs

MWF is a complex mixture that may contain petroleum products, vegetable and animal fats, organic and inorganic salts, and a variety of additives. Over the past 8 years, many medical research institutes have studied the health effects associated with MWFs. Many have tried to formulate proper data gathering protocols and standards used in detaining the various chemicals found in various MWFs. Health hazards that have been associated with exposure to MWFs include dermatitis, respiratory health effects, gastrointestinal health effects and increased mortality from a variety of cancers [1]. In MWFs there are numerous additives and biocides that are used as sensitizers, which can aggravate respiratory symptoms [11]. These include lubrication boosters, anti-mist, anti-foaming and anti-corrosion elements along with blending agents and dyes. Biocides are used to suppress growth of micro-organism contamination. In this process bacteria can be introduced to the fluid due to water used in dilution of chemical concentration, exposure to machine parts and surrounding elements of the manufacturing system. Though most bacteria can't survive in MWF, they do promote growth of various species [2].

Developments in Sub-Zero Temperature Coolants as an Alternative to Conventional MWFs

In this section, an attempt has been made to accentuate the amount of research conducted over the three decades in the field of sub-zero temperature coolants. Although the overview does not reflect the total body of work, it replicates research that is adequate to draw meaningful inferences. Particular attention was paid on the surface grinding process (refer Table 1).

There have been many publications in the field of grinding under sub-zero coolant as a means of replacing conventional MWFs. The bulk of publications related to the coolants, addressed the various machining problems faced in turning. Sub-zero coolant machining was first investigated around 1953 by E.W. Bartley who used sub-zero cooled CO_2 as the coolant [12]. Many researchers regard metal grinding as an art, which is essentially as a result of the process complexity and stochastic nature of grinding [13].

Chattopadhyay et al. [12]'s study was the first attempt to investigate the effects of liquid nitrogen (LN_2) on the grinding process, where it was noticed 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 other physicochemical reactions at the job surface. In addition, it was found that extreme cooling action had a positive effect on tool life, where the grits of the wheel retained its sharpness under low temperature machining environment. The study concluded that LN_2 grinding increase the depth of cut and in-feed parameters without generating extreme temperatures at the wheel-workpiece interface, as opposed to grinding under the same conditions with water soluble emulsions.

Paul et al. [14] highlighted that cooling under LN_2 environment yield mostly laminar chips when compared with dry and flood machining. However, dry and flood machining produced irregular and hollow chips ranging from long laminar to spherical, but the flood method had fewer spherical chips. This phenomenon was explained by stating that the sharpness retention of the grit for longer periods leads to a decrease in the force and specific energy needed to shear the material. Paul and Chattopadhyay [6] conducted experiments to study grinding forces, specific energy, grinding zone temperature and surface residual stress under cryogenic cooling environment and compares them to the results obtained from dry grinding and grinding with soluble oil. It was found that cryogenic cooling have an edge over other coolants in terms of controlling the temperature, residual stresses and grinding forces. Paul and Chattopadhyay [7-8] reported the effect of cryogenic cooling on grinding zone temperature for five commonly used steels. The study results indicate substantial reduction in the grinding forces under cryogenic cooling over range of infeed and dressing procedure for different commonly used steels.

Table 1: A Selective Summary of Literature in the Field of Machining Under Cryogenic Environment

Authors	Machining process	Dependant Variables	Material	Grinding Fluid/Coolant
Chattopadhyay et al. (1985) [12]	Grinding	G,H	Mild steel, AISI 4340, HSS	Dry machining, soluble oil (1:20), LN_2
Paul et al. (1993) [14]	Grinding	E,G,F,H	AISI 1020, AISI 1080, Cold die, Hot die steel, HSS	Dry machining, Soluble oil (1:20), LN_2
Paul and Chattopadhyay (1995) [6]	Grinding	D,E,F	AISI 1020, AISI 1080, Cold die, Hot die steel, HSS	Dry machining, Soluble oil (1:20), LN_2
Paul and Chattopadhyay (1996) [8]	Grinding	A	AISI 1020, AISI 1080, Cold die, Hot die steel, HSS	Dry machining, Soluble oil (1:20), LN_2
Paul and Chattopadhyay (1995) [15]	Grinding	A,H,K,F	AISI 1020, AISI 1080, Cold die, Hot die steel, HSS	Dry machining, Soluble oil (1:20), LN_2
Paul and Chattopadhyay (1996) [7]	Grinding	A,K	AISI 1020,AISI 1080, Cold die, Hot die steel, HSS	Dry machining, Soluble oil (1:20), LN_2
Hong and Ding (2002) [16]	Turning	I,H	AISI 1018, TI-6Al-4v	Dry machining, LN_2, Emulsion
Paul et al. (1993) [14]	Turning	B,C	AISI 4140	Dry machining, Soluble oil (1:20), LN_2
Ramesh et al. (2003) [17]	Grinding	A,K,E,H,G	S45C, SS304	Chilled air, Water-based coolant
Upadhyaya and Malkin (2004) [22]	Grinding	A,G,K	Nickel alloy	Dry
Hong (2006) [23]	Turning	A,H,J	Carbon steel, Titanium alloy	LN_2

Key

A: Interface temperature, B: Wear, C: Surface roughness, D: Dimensional deviations, E: Chip formation, F: Residual stress, G: Surface investigation, H: Cutting force, I: Coefficient of friction, J: Microstructure, K: Specific energy, L: Micro-hardness, LN_2: Liquid nitrogen

Paul et al. [18] have investigated the role of LN_2 cooling on tool wear and surface finish in plain turning of AISI 1060 steel at industrial speed-feed conditions. The results have been compared with dry and soluble oil machining. The study reports various benefits of cryogenic cooling such as improvement in tool life and surface finish due to reduction in cutting zone temperature. In addition, the study concluded that machining in soluble oil environment failed to provide any significant progress in tool life. Dhar et al. [19] have studied the function of cryogenic cooling under LN_2 environment on chip-tool interface temperature, tool wear, dimensional accuracy and surface finish in turning AISI 4140 steel. The research found that cryogenic based cooling enabled substantial reduction in cutting zone temperature, favourable chip-tool interaction and significant improvement in surface finish and dimensional accuracy. Efforts to determine the coefficient of friction and the lubricating effect of LN_2 machining can be seen in the past [16], where the investigation involved the turning of Ti-6Al-4v and AISI 1018. It was found at low normal loading the micro scale hydrostatic effect can be the predominant mechanism of LN_2 lubrication. Hong, et al. [20] presented a pragmatic approach in order to measure the normal and friction forces in an altered machining setup. The results show that LN_2 cooled condition has a significantly lower coefficient of friction than dry conditions. The experimental data also shows that the friction is lower for Ti-6Al-4v but mixed results obtained for mild steel (AISI 1018) when LN_2 is applied properly as compared to traditional emulsion flooding.

Ramesh et al. [17] looked at cryogenic cooling, but they used a sub-cooled jet of air. A decrease in grinding force was found when a jet of air at 0.35°C and 0.3MPA was applied to the grinding zone when compared to water soluble coolants. At the end, the study stated cooled air only functions at a certain threshold value for various dependant variables such as wheel speed and table speed. In order to reduce surface grinding temperatures effectively, an active coolant cooling system was proposed by Gao et al. [21]. The system was based on the use of forced convection of the heat generated during the machining process. During the experimental testing, it was found that the coolant temperature can be reduced to approximately –2°C under no load condition, and to approximately 3°C under loaded condition. Upadhyaya and Malkin [22] have reported on the thermal aspects of grinding with cubic boron nitride (CBN) wheels. It was found that low energy partition values of 3% - 8% were obtained at temperatures below the fluid burnout limit.

Hong [23] has proposed two mechanisms to verify how LN_2 can provide lubrication in the cutting process. It was found that low work zone temperatures can alter the material properties and change the friction coefficient between the specimens. Jaswin and Lal [24] have optimized the deep cryogenic treatment parameters for processing of En 52 valve steel. The factors considered for the optimization are the cooling rate, soaking temperature, soaking period, and tempering temperature. The mechanical properties such as the tensile strength, hardness, and wear resistance were selected as the performance measures. The results show that the tensile strength, hardness, and wear resistance of the deep cryotreated En 52 valve steel samples improved concurrently through the optimal combination of the deep cryogenic treatment parameters obtained from the proposed approach.

Metal cutting industry is heavily relied upon MWFs because of their ability to increase production and reduce both part and tool damage that is caused by intense heat and shock load. These features make it as a quintessential aid for metal cutting processes. Though conventional MWFs are helpful, there are certain consequences associated with their usage. These problems range from impaired performance as a result of restricted characteristics of the chemical constituents of the MWF to health and environmental risks. Below is a summary of the findings of this review, which forms the motivation for this study.

- Coolants and lubricants play an important role in metal cutting; MWFs assist the metal cutting industry by an overall increase in tool life, surface finish, and reduction in the forces and the power necessary for the removal of metal [1], [2] and [19].
- MWFs reduce the high temperatures involved in cutting, but the conventional metal working coolants do not fully control extreme temperatures generated at the cutting zone [6]-[8], [12].
- Ineffective application of conventional fluids can lead to various health problems [1], [11].
- Cryogenic cooling research indicates substantial benefits in terms of improvement in tool life and surface finish due to reduction in cutting zone temperature [18].

Research Agenda and Design of Experiments

Grinding under sub-zero temperature has been explored by many researchers and has been found to be a viable medium in addressing the various thermal issues [2], [14], [17], [25]-[26]. The use of LCO_2 as a coolant in surface grinding process has been investigated but the effectiveness of the coolant in dealing with grinding burns and other surface defects such as re-welds and built-up edges has not been considered sufficiently by the academia [6].

The aim of this study is to investigate the effects of commonly used dry, emulsion and LCO_2 coolants on the mechanics of the surface grinding process, especially on heat sensitive materials such as stainless steel (SS304). Furthermore, this paper will address the effects of LCO_2 on a ground specimen in terms of surface defects such as grinding burns, re-welds and sharpening edges. Based on the review of literature, experimental factors and levels under each factor to investigate the performance of sub-zero temperature coolant in the field of surface grinding are listed in Table 2.

Design of Experiments

A full factorial design of experiments (3 × 3 × 3) was used for the evaluation of the effects of coolant on the grinding mechanics and workpiece integrity. The selected factors for investigation are depth of cut, table speed and coolant type. Each factor consists of three distinct settings, while both depth of cut and table speeds are assigned low, medium and high value. Under the type of coolant, three types of fluids were specified. Experimental factors and conditions used for the investigation are summarized in Table 2.

Table 2: Experimental Factors, Levels, and Conditions

i. Experimental factors and levels:

Factor	Level(s)	Description
Workpiece material	1	Stainless Steel (SS304)
Grinding wheel	1	Aluminium Oxide (AA60-K8-V40W)
Metal working fluid	3	Dry, Emulsion and LCO_2
Depth of cut (mm)	3	Low (0.0127), Medium (0.0254) and High (0.0508)
Table speed (m/s)	3	Low (0.1000), Medium (0.2583) and High (0.4250)

ii. Experimental conditions:

Item	Description
Machine	KENT KGS 510
Wheel speed (rpm)	1800
Wheel dresser	Single point diamond
Dressing depth (mm)	0.002
Number of passes	10

In investigating the impact of using a sub-zero temperature fluid on the surface grinding operation of temperature sensitive stainless steel (SS304), test samples were prepared and ground under various parameters. In order to evaluate the response of various MWFs used, each ground sample underwent both destructive and non-destructive testing. The various phases of the research study are described below:

Phase 1 – Preparation of test samples, determination of the machining parameters and machining: The twenty seven experimental samples (each of 40 × 25.4 × 25.4 mm) were prepared using a horizontal band saw from a raw stock (2000 × 25.4 × 25.4 mm bar) of austenitic stainless steel alloy (SS304). Suitable cutting fluids were used for both the cutting and drilling operation to avoid elevated temperatures within the workpiece. The samples were subsequently cleaned of debris and fluid after performing the pre-machining operations.

Phase 2 – Experimental setup, measurement of grinding burns and other surface defects:

i. The experimental setup

Figure 1(a) shows the experimental setup and Figure 1(b) depicts the LCO_2 delivery system used in the study. The experimental setup includes the following:

- A cooling fluid delivery system: To deliver CO_2 to the grinding zone in the liquid state, a special delivery line has been designed since LCO_2 has to be stored at a very high pressure (1000 psi). In order to maintain this state, a CO_2 fill station adaptor assembly was modified and fitted with a chamber and nozzle. The dip tube tank is a source for LCO_2, which allows saturated CO_2 to flow through the vent valve. In addition, a collar and nozzle arrangement can be seen at the end of the delivery line (refer Figure 1(b)). The collar was specially fabricated from SS304 alloy to restrict any diameter fluctuations between the nozzle and the delivery line. Also, the collar was fitted with two bolted screws, to adjust the SS316 type nozzle to any required angle on the holder.
- A force measuring system: The grinding forces were measured through a piezoelectric force measuring system. In order to mount various test units to the dynamometer, a special holder was designed and fabricated. A Kistler charge amplifier (5019B) was used to convert the charge generated from the dynamometer. The voltage signal from the amplifier was acquired by a data acquisition unit (DAU).

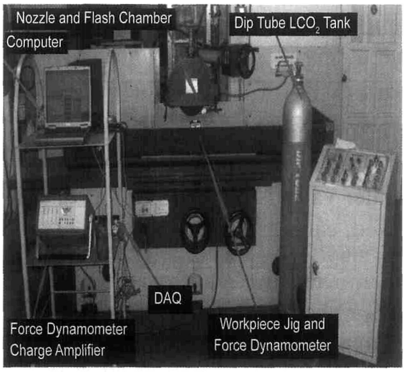


Figure 1(a): The Experimental Setup

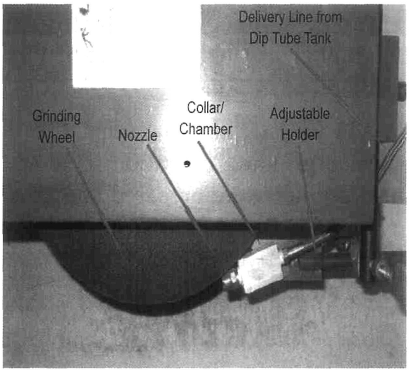


Figure 1(b): The LCO_2 Delivery System

- A temperature measuring system: The temperature of the LCO_2 at the exit of the nozzle was measured through a k-type thermocouple. The thermocouple was located at the centre of the jig and was connected to a DAU.
- A data acquisition unit (DAU): A DAU was responsible for capturing both temperature and force information in real time.

ii. Measurement of grinding burns and other surface defects

a. Grinding burns

In this study, visual inspection method was used to determine the occurrence of grinding burns on the grounded samples where its severity was quantified by measuring the area of discolouration. Measuring the area of discolouration of the workpiece surface was done with a flat bed scanner to acquire a standardized, high resolution photograph (2840 × 2045 pixels) of the machined surface. Actual area measurement was done using cell image analysis software (CellProfiler™).

In order to identify the grinding burn spots, the burnt areas on each workpiece were first highlighted and then scanned. A monotone image was then prepared from the scanned marked image using Adobe Photoshop CS®. The four-step approach to acquire grinding burns data using CellProfiler™ is shown in Figure 2.

b. Microscopic investigation

The microscopic investigation of the ground surfaces was done using a Carl Zeiss ICM 405 inverted microscope. Digital photographs were obtained by using a Dino-Eye AM423 digital microscope eyepiece camera. This method was used to examine the occurrences of surface defects on the ground surface, such as grinding burn spots, re-welds, built-up edges and roughness due to tool chatter.

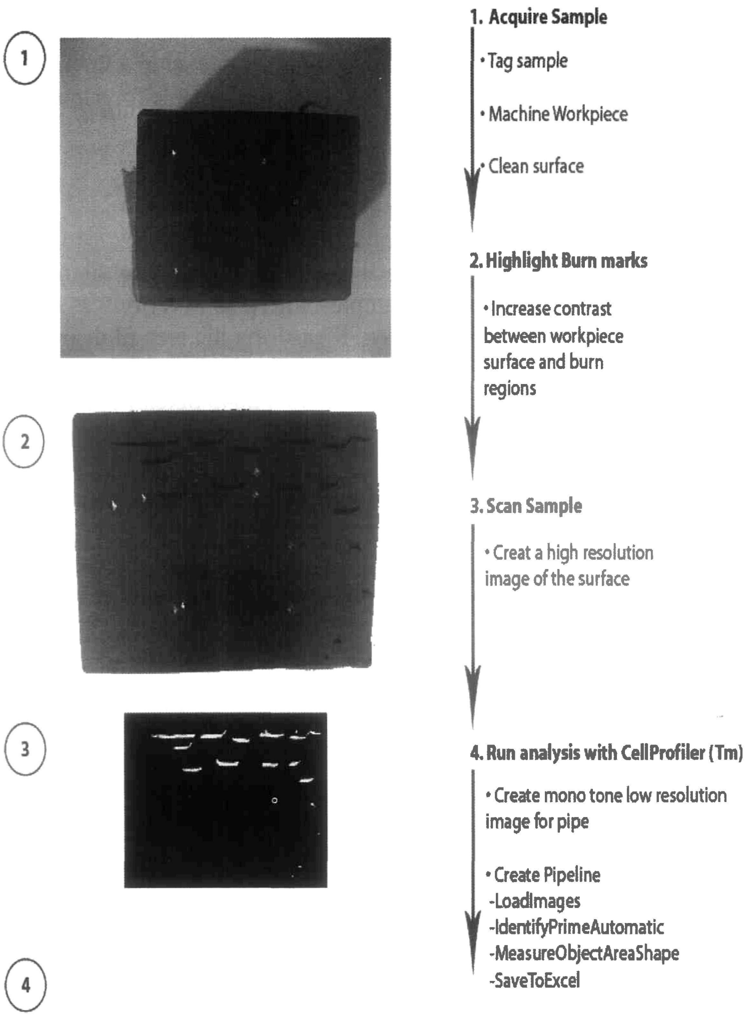
Phase 3 – Evaluation of the samples after being ground and presentation of results.

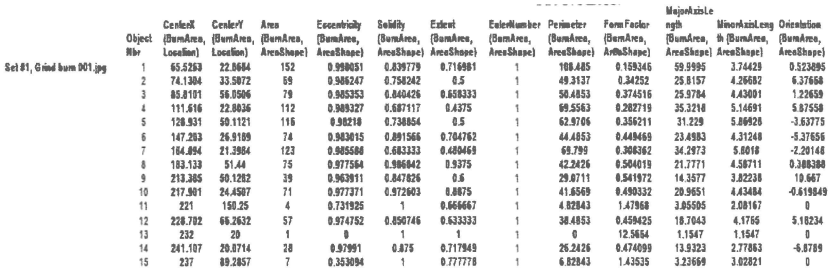
Results and Analysis

i. Analysis of grinding burns

Results of the grinding burn analysis can be seen in Figure 3 and Figure 4. There is a lack of any drastic change in the occurrence of grinding burns when comparing the different coolant usage methods. The emulsion coolant displayed a greater ability to control the accumulation of burns on the workpiece, showing little change in burn area over altering depths of cut and table speeds (see Figure 3).

On the other hand, dry machining shows predictable trends at table speeds of 100 mm/s and 258.33 mm/s where the increase in depth of cut under dry





	Object Nbr	CenterX (BurnArea, Location)	CenterY (BurnArea, Location)	Area (BurnArea, AreaShape)	Eccentricity (BurnArea, AreaShape)	Solidity (BurnArea, AreaShape)	Extent (BurnArea, AreaShape)	EulerNumber (BurnArea, AreaShape)	Perimeter (BurnArea, AreaShape)	FormFactor (BurnArea, AreaShape)	MajorAxisLength (BurnArea, AreaShape)	MinorAxisLength (BurnArea, AreaShape)	Orientation (BurnArea, AreaShape)
Set #1, Grind burn 001.jpg	1	65.5263	22.0684	152	0.998051	0.839779	0.716981	1	108.485	0.159346	59.9995	3.74429	0.523895
	2	74.1304	33.5072	69	0.986247	0.758242	0.5	1	49.3137	0.34252	25.8157	4.26682	6.37668
	3	85.8101	56.0506	79	0.985353	0.840426	0.658333	1	50.4853	0.374516	25.9784	4.43001	1.22659
	4	111.616	22.8036	112	0.989327	0.687117	0.4375	1	69.5563	0.282719	35.3218	5.14691	5.87558
	5	128.931	50.1121	116	0.98218	0.738854	0.5	1	62.9706	0.356211	31.229	5.86928	-3.63775
	6	147.203	26.9189	74	0.983015	0.891566	0.704762	1	44.4853	0.449469	23.4983	4.31248	-5.37656
	7	164.894	21.3984	123	0.985588	0.683333	0.480469	1	69.799	0.306362	34.2973	5.8018	-2.20148
	8	183.133	51.44	75	0.977564	0.986842	0.9375	1	42.2426	0.504019	21.7771	4.58711	0.388388
	9	213.385	50.1282	39	0.963911	0.847826	0.6	1	29.0711	0.541972	14.3577	3.82238	10.667
	10	217.901	24.4507	71	0.977371	0.972603	0.8875	1	41.6569	0.490332	20.9651	4.43484	-0.619849
	11	221	150.25	4	0.731925	1	0.666667	1	4.82843	1.47968	3.05505	2.08167	0
	12	228.702	66.2632	57	0.974752	0.850746	0.633333	1	38.4853	0.459425	18.7043	4.1765	5.18234
	13	232	20	1	0	1	1	1	0	12.5664	1.1547	1.1547	0
	14	241.107	20.0714	28	0.97991	0.875	0.717949	1	26.2426	0.474099	13.9323	2.77863	-6.8789
	15	237	89.2857	7	0.353094	1	0.777778	1	6.82843	1.43535	3.23669	3.02821	0

Figure 2: The Steps in Acquiring Grinding Burn Data

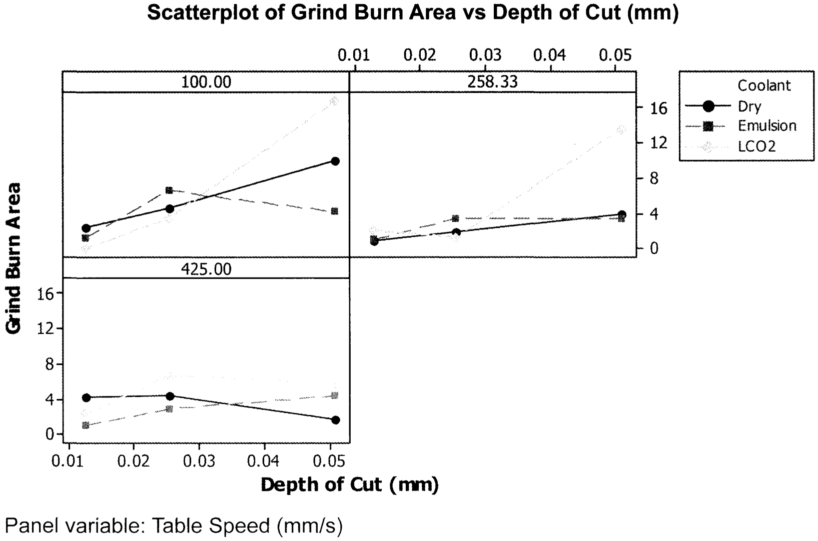


Figure 3: Grinding Burns vs. Depth of Cut for Various Table Speeds

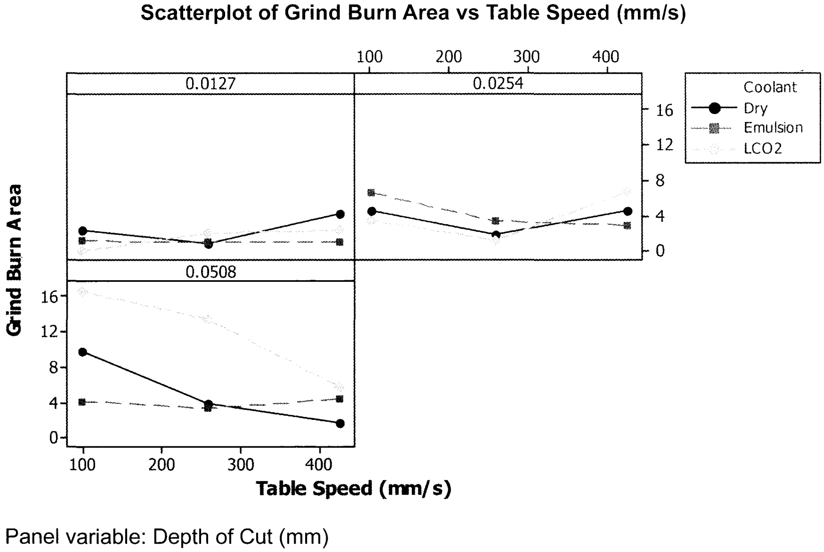


Figure 4: Grinding Burns vs. Table Speed for Various Depths of Cut

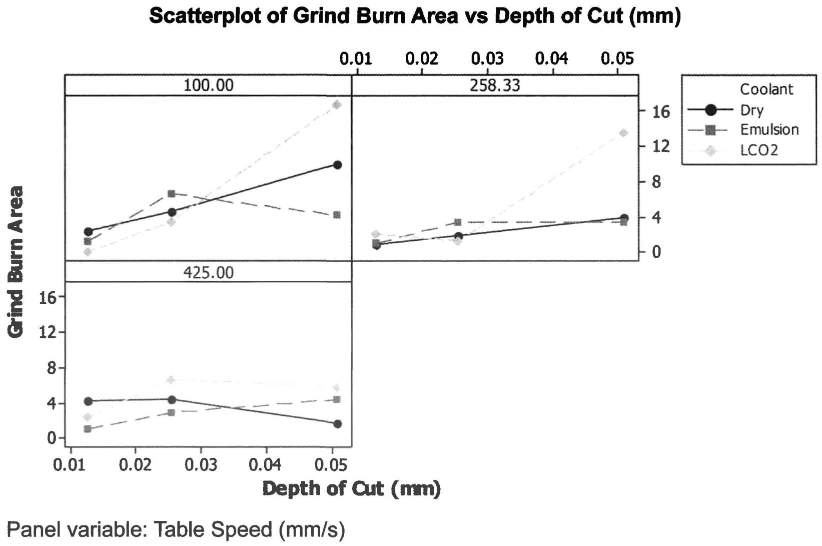


Figure 3: Grinding Burns vs. Depth of Cut for Various Table Speeds

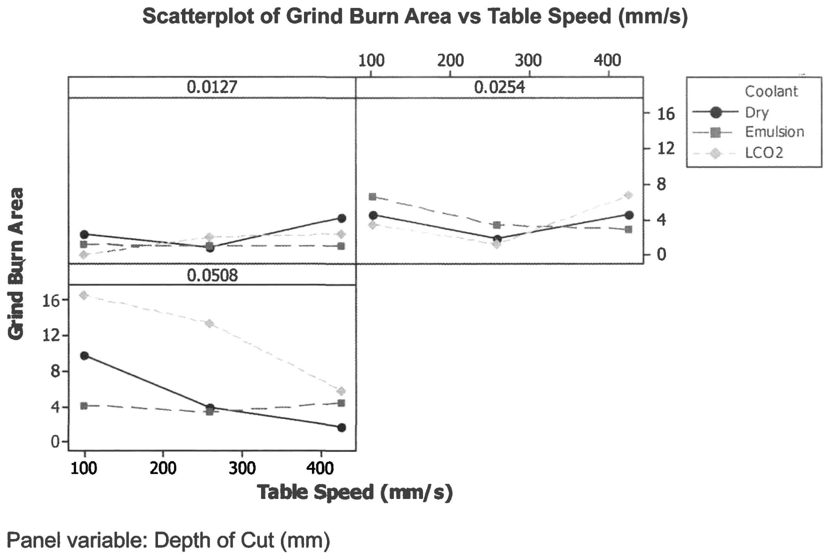


Figure 4: Grinding Burns vs. Table Speed for Various Depths of Cut

machining results in a steady increase in the occurrence of grinding burns. Moreover, LCO_2 machining exhibits erratic responses in the occurrence of grinding burns with changes in depths of cut and table speeds. In addition, at table speeds of 100 mm/s and 258.33 mm/s; and depths of cut of 0.012 mm and 0.025 mm, LCO_2 grinding provided the lowest occurrences of grinding burns (see Figure 4). However, in some instances LCO_2 machining displayed the reverse trend. These cases of grinding burns can be typically seen at the higher depth of cut (0.050 mm) and same table speeds (100 mm/s and 258.33 mm/s).

ii. Analysis of grinding burn spots

Grinding burns were observed in all test specimens and were easily identified without any optical assistance. The grinding burns were tubular in shape and lay along the direction of grinding. Intermittent streaks are seen on specimens displaying severe burns (taken to be greater than 9% burn area). These streaks are collinear in the direction of grinding and parallel to each other (see Figure 2). Figure 5 highlights workpiece burns originated under LCO_2 grinding conditions, where photographs '**a**' and '**c**' show regions of grinding burns with their respective magnified views '**b**' and '**d**'. As pointed out earlier, the burns are located along the direction of grinding. The darker region or the regions

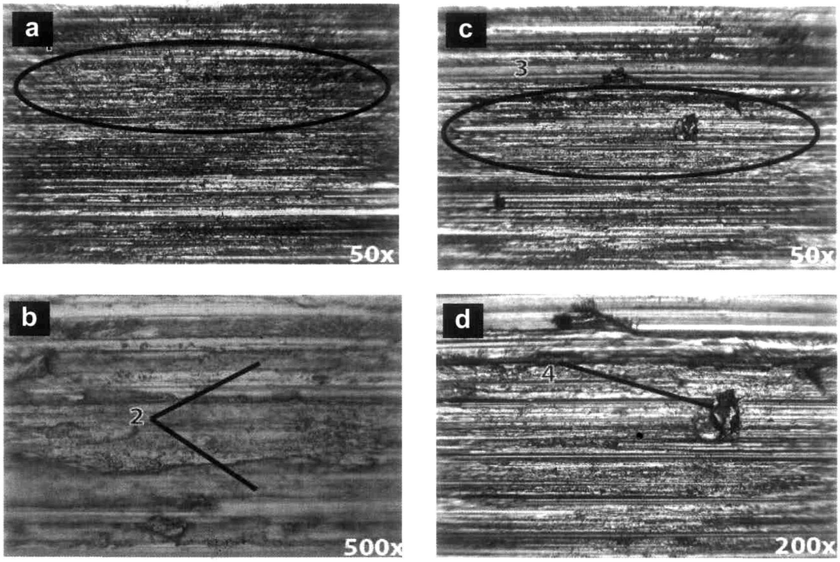


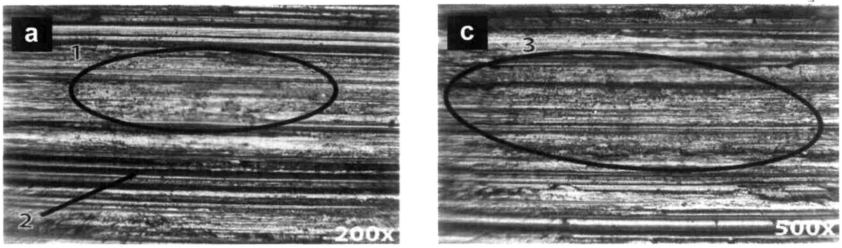
Figure 5: Microscope Photograph of a Specimen Machined under LCO_2 Coolant
(Depth of cut = 0.0127 mm; Table speed = 425 mm/s)
Note: All displaying signs of grinding burns and re-welds

of grater oxidation are found in the troughs of the surface profile, this can be seen in '**b**'.

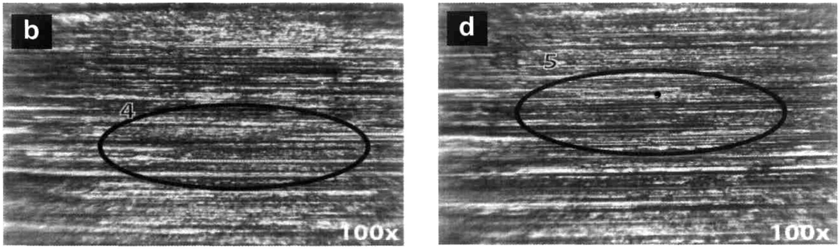
As presented in Figure 6, grinding under dry conditions yielded darker and more pronounced grinding burns when compared with LCO_2 and emulsion grinding. Deep-seated channels are present in the areas of grinding burn; this is evident in photographs '**a**' and '**b**' of Figure 6. The darkness of these regions is as a result of shadow formation rather than oxidation due to high temperature levels. Burns found under emulsion conditions (refer Figure 7) appeared to have lighter colour intensity than those found under both dry and LCO_2 grinding. For dry grinding conditions, the surrounding areas of the grind burns showed rough finishes.

iii. Analysis of re-welds and built-up edges

Figure 8 shows re-welds and built-up edges found when grinding under LCO_2 application. Photograph '**a**' shows the occurrence of a built-up edge located in the groove created by a single abrasive grain, whereas in '**d**', the built-up edge is located on the crest of the surface profile. Photographs '**c**' and '**d**' display the occurrence of re-welds on the machined surface. The size of the re-weld can be easily differentiated in comparison to the groves created by the individual abrasive grains. Re-welds are caused by the implantations of swarf, which is primarily due to the MWFs inability to successfully clear the debris away from the grinding zone.

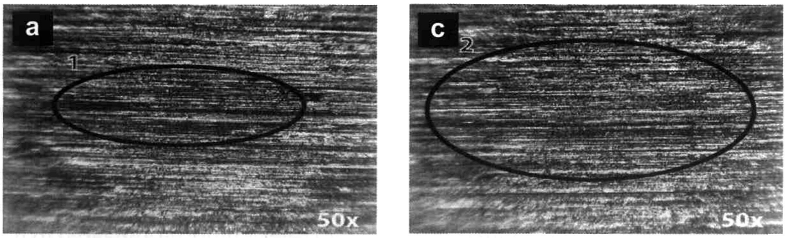


Dry @ 0.0254 mm, 424 mm/s   Dry @ 0.0508 mm, 424 mm/s



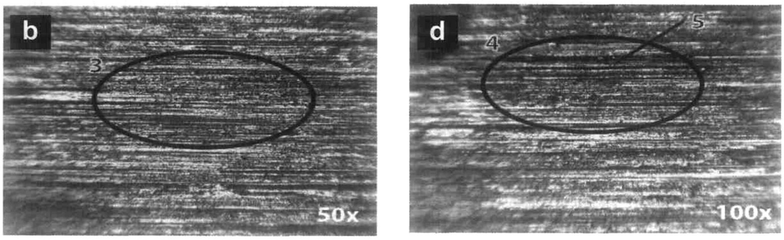
Dry @ 0.0508 mm, 100 mm/s   Dry @ 0.0254 mm, 258.33 mm/s

Figure 6: Microscope Photograph of Specimens Machined under Dry Conditions with Varying Depths of Cut and Table Speeds
Note: All displaying signs of grinding burn



Emulsion @ 0.0127 mm, 100 mm/s

Emulsion @ 0.025 mm, 100 mm/s

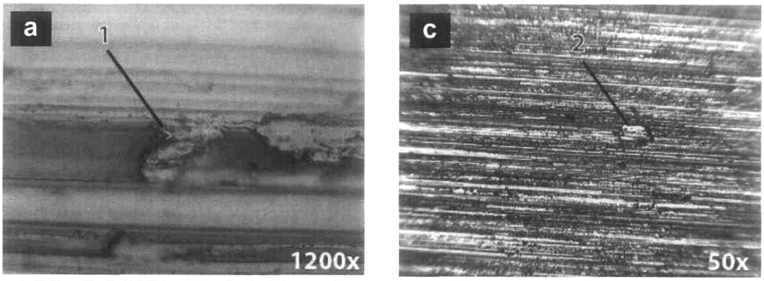


Emulsion @ 0.0508 mm, 100 mm/s

Emulsion @ 0.0508 mm, 425 mm/s

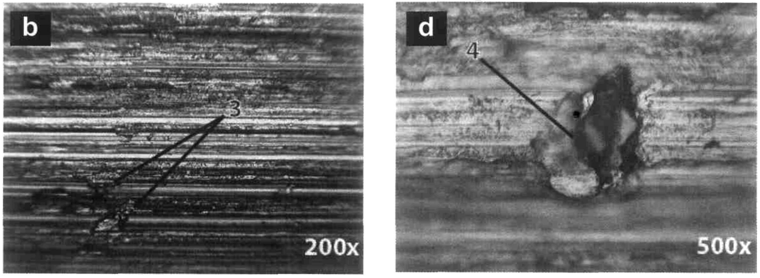
Figure 7: Microscope Photography of Specimens Machined under Emulsion Coolant with Varying Depths of Cut and Table Speeds

Note: All displaying signs of grinding burn



LCO_2 @ 0.0254 mm, 258.33 mm/s

LCO_2 @ 0.0508 mm, 425 mm/s



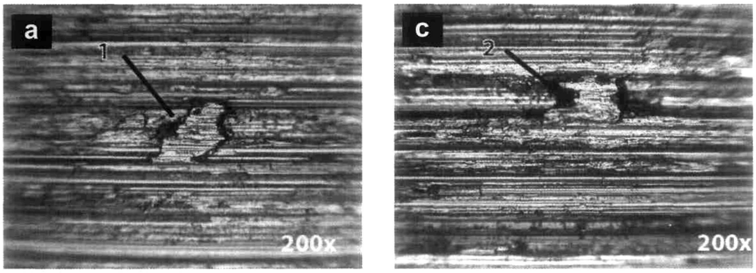
LCO_2 @ 0.0508 mm, 100 mm/s

LCO_2 @ 0.0254 mm, 258.33 mm/s

Figure 8: Microscope Photography of SS304 Specimens Machined under LCO_2 Coolant with Varying Depths of Cut and Table Speeds

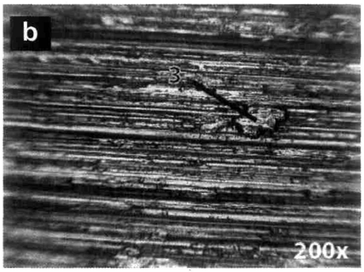
Note: All displaying signs of re-welds and built-up edges

In Figure 9, all three photographs highlight re-welds found on the ground surface under dry conditions. In photographs '**a**' and '**b**' the re-weld is impeded along the grooves left by the grains, suggesting that the wheel was loaded at that point in time. While in photograph '**c**', the re-weld is small enough to fit in a single groove. A sample of re-welds and built-up edges occurring under emulsion conditions is shown in Figure 10. Photographs '**a**', '**b**' and '**c**' show instances of re-welds, whereas '**d**' shows the incidence of a built-up edge. However it should be noted that the occurrences of these surface defects are in regions of rough profiles, hence, causing poor surface finish.



Dry @ 0.0127 mm, 100 mm/s

Dry @ 0.0127 mm, 425 mm/s



Dry @ 0.0127 mm, 258.33 mm/s

Figure 9: Microscope Photography of SS304 Specimens Machined under Dry Conditions with Varying Depths of Cut and Table Speeds
Note: All displaying signs of re-welds

iv. Analysis of rough profiles

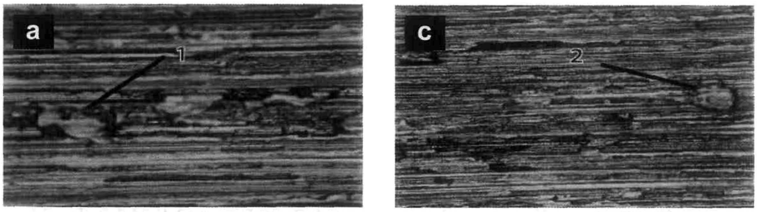
In Figure 11, poor finishes can be seen under dry and LCO_2 conditions. These profiles contain irregular ground patterns. Profiles with intermittent groove depths are depicted in photograph '**c**', drastic changes in both the depth and width of the grooves can be found in photograph '**b**'. Photograph '**a**' represents an irregularly machined pattern, which is encompassed by an "x" region. The region is made up of varying groove heights.

Discussion

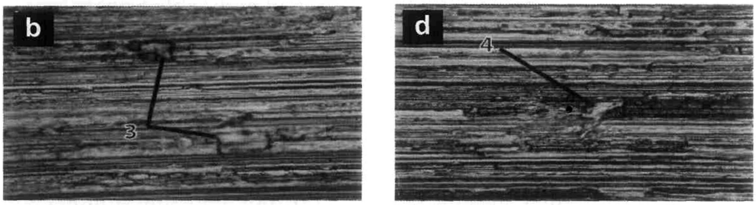
i. Grinding burns

From the analysis, it is clear that grinding under LCO_2 conditions provided mixed results over the occurrence of grinding burns on the workpiece. In fact, LCO_2 conditions showed larger areas of burns than that of grinding under dry and emulsion conditions (refer Figure 12). It is further noticed that LCO_2 was successful in reducing the workpiece temperature when compared to dry conditions (see Figure 13). However, LCO_2 proves to be a viable coolant alternative in surface grinding at table speeds of 100 mm/s and 258.33 mm/s; and depths of cut of 0.012 mm and 0.025 mm which provided the least grinding burns (refer Figure 4).

From Figure 13 it is clear that the grinding burn area increased with an overall increase in the maximum temperature, power and tangential grinding force, regardless of type of MWF used. Even though each MWF showed the same general trend, the increase in area of grinding burn is more sensitive to these responses under LCO_2 conditions. Glazing of the wheel can be used to explain the LCO_2 results, where the high pressure LCO_2 jet inhibited the natural formation of sharper abrasive grains resulting in premature removal and the exposure of duller grains.



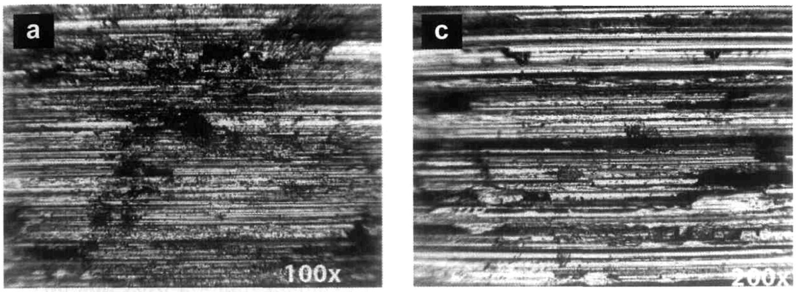
Emulsion @ 0.0127 mm, 258.33 mm/s   Emulsion @ 0.0254 mm, 100 mm/s



Emulsion @ 0.0254 mm, 258.33 mm/s   Emulsion @ 0.00508 mm, 258.33 mm/s

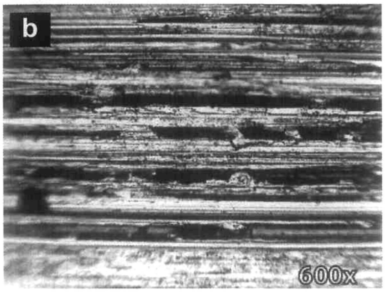
Figure 10: Microscope Photography of SS304 Specimens Machined under Emulsion Coolant with Varying Depths of Cut and Table Speeds

Note: All displaying signs of re-welds



LCO_2 @ 0.0254 mm, 100 mm/s

Dry @ 0.0127 mm, 258.33 mm/s



Dry @ 0.0254 mm, 425 mm/s

Figure 11: Microscope Photography of Specimens Showing Poor Finishes Found under LCO_2 and Dry Conditions

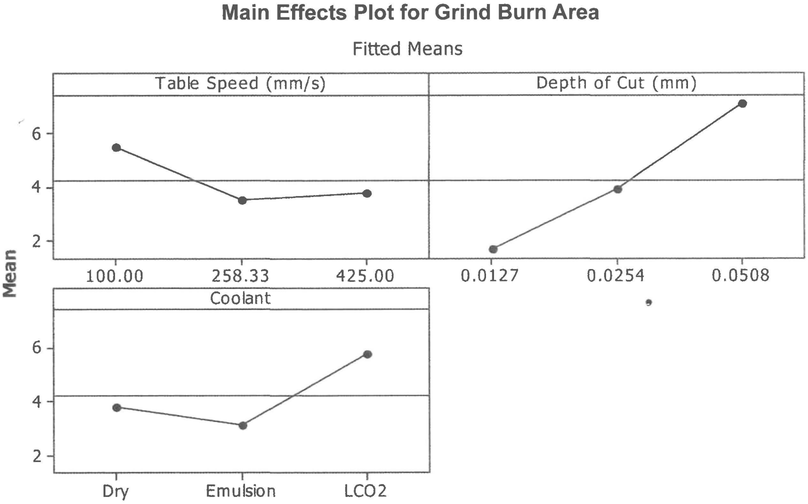


Figure 12: Main Effects Plot for Grinding Burns under Dry, Emulsion and LCO_2 at Various Depths of Cut and Table Speeds

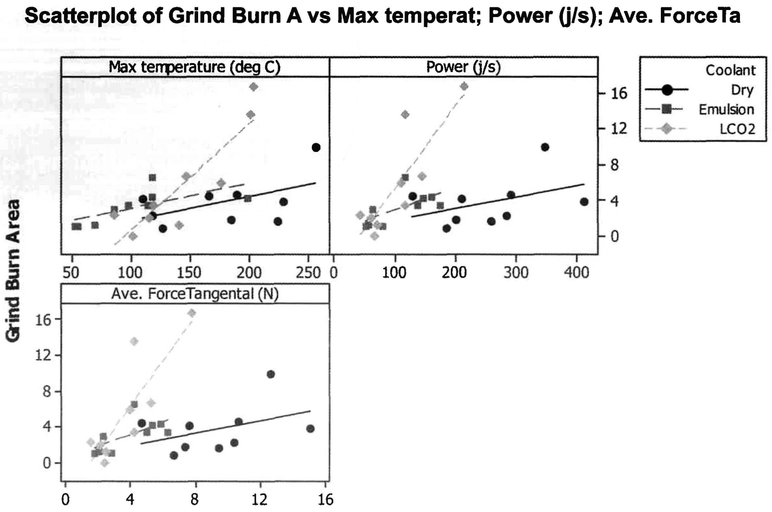


Figure 13: Grinding Burn Area versus Maximum Temperature; Power; Tangential Force for the Various Coolants

ii. Surface Roughness

In this study, grinding under LCO_2 conditions provided no improvements in the roughness of the machined surface when compared to both dry and emulsion conditions. These results are not compatible with the findings of Chattopadhyay et al. [12] where the use of LN_2 conditions produced smoother surfaces than dry and soluble oil cooling environment when grinding of mild steel and high speed steel was performed. The roughness found under LCO_2 conditions can be a result of rapid expansion of the LCO_2 to vapour on contact with the hot surfaces, hence, providing an irregular lubrication layer between the abrasive grit and the workpiece [16]. This irregular layer can give rise to intermittent patterns along the lay of the surface. Also, another cause could be the case where debris such as removed grains and swarf are re-entered into the grinding zone, leaving an imprint or becoming welded on the ground surface [5],[27].

Conclusion and Future Research

Conclusion

A full factorial experimental approach was used to investigate the effects of three different MWFs on surface grinding process. The three types of conditions investigated were dry, emulsion and LCO_2 with depths of cut of 0.012 mm, 0.025 mm and 0.050 mm and table speeds of 100 mm/s, 258.33 mm/s and 425.00

mm/s. The areas of grinding burns and other surface defects such as re-welds and built-up edges were examined. On examining twenty seven test samples, the following inferences can be drawn:

- The sub-zero coolant can reduce the incidence of grinding burns. Under low depths of cut and table speeds (0.012 – 0.025 mm and 100 mm/s – 258.33 mm/s), LCO_2 limits the occurrence of grinding burns. It is understood that at higher speed and depth of cut, LCO_2 has difficulty entering the grinding zone mainly due to the large dynamic air boundary and heavy depths of cut.
- The sub-zero coolant displays lubrication properties since the tangential grinding force under conventional and sub-zero coolant are the same. In certain cases the tangential force is lower under LCO_2 conditions. One such case in which this condition may occur is with a table speed of 425 mm/s and depth of cut of 0.012 mm.
- Surface defects are seen under dry, emulsion and LCO_2 grinding conditions.

Future Research

Further research on grinding of different steels under LCO_2 coolant is necessary so that their responses can be categorized. Steels such as mild steel, high speed steel, titanium alloy steels and martensitic stainless steels should be considered. In addition, any attempt in the following areas may yield significant research findings in the future:

- Development of a feasible LCO_2 delivery system, that delivers a stable supply of fluid at the grinding zone.
- The study of the effects of LCO_2 grinding on residual stresses.

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