EFFECT OF PRE-COOLING LOW CARBON STEEL IN LIQUID NITROGEN ON PRODUCTIVITY

by

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A dissertation submitted in partial fulfilment of the requirements for the degree of Master of Engineering in Production Engineering and Management

University of Zambia

LUSAKA 2019

DECLARATION

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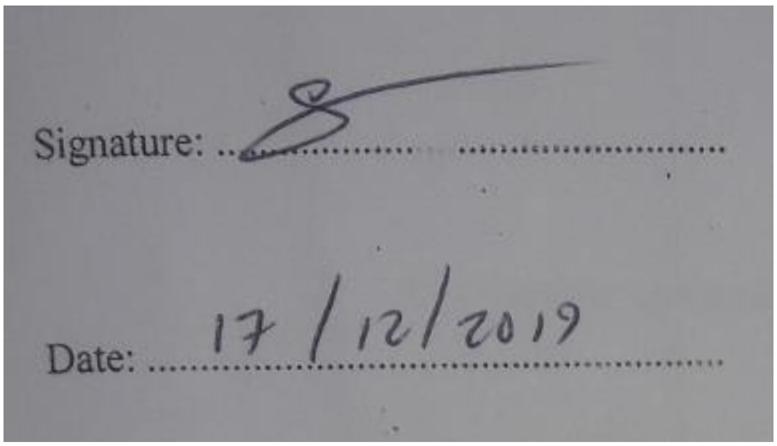

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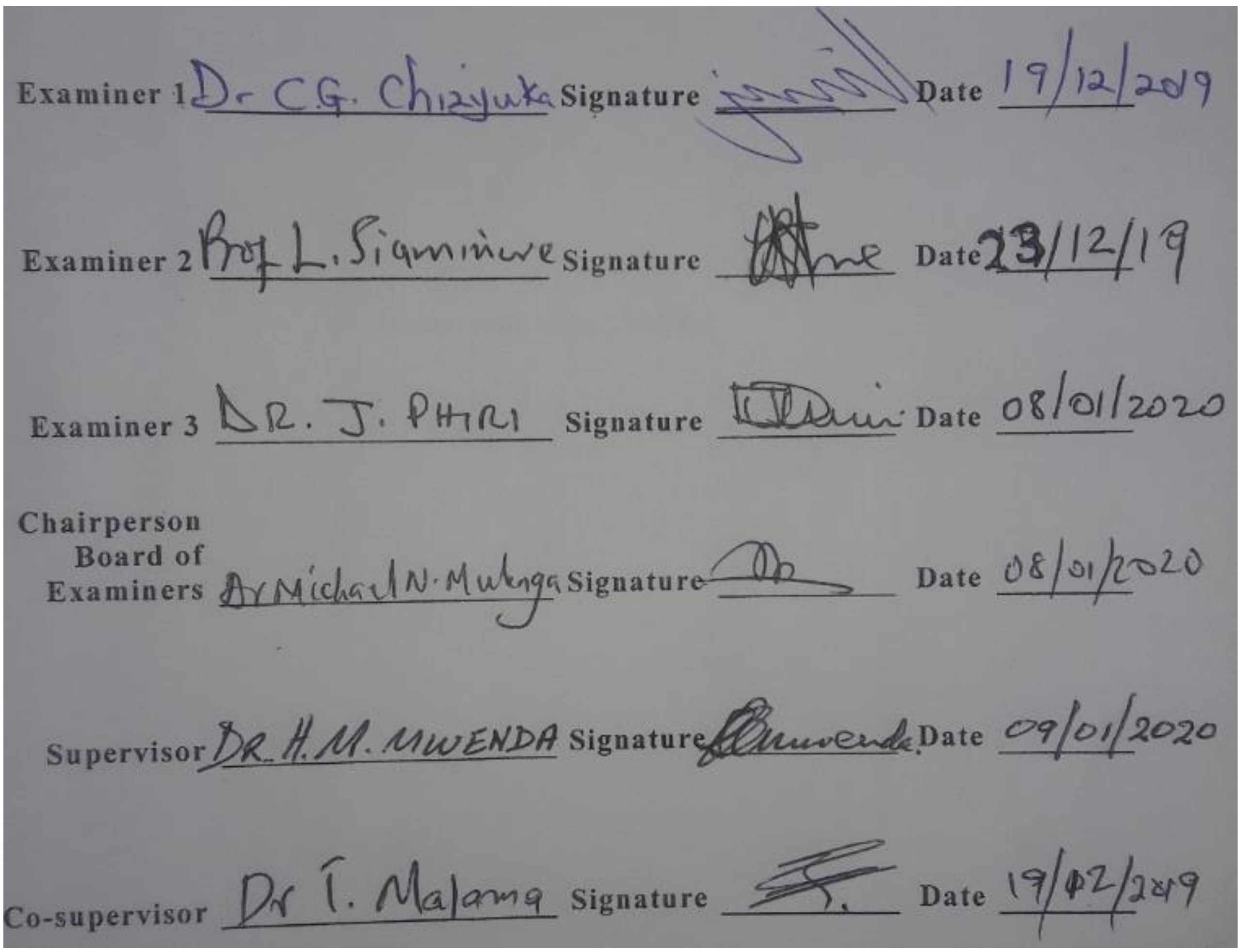

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DEDICATION

To my wife, Leya Gordić

ACKNOWLEDGEMENTS

I thank God for His grace and mercy for theopportunities availed and the resources He has equipped me with to excel in my studies.

I am very grateful to my supervisors Dr H.M Mwenda and Dr T. Malama for their guidance and support during this research.

To my family, I thank you for your patience, encouragement and love.

ABSTRACT

In machining operations, the effects of high temperatures are i) reduction in tool life, ii) production of hot chips and iii) inaccuracies in workpiece dimensions. Coolant is applied to convey away heat to extend tool life and ensure a good surface finish of the workpiece. While conventional cooling methods make use of soluble oils, cryogens have found applications for difficult to machine materials. Selection of an appropriate treatment plan when using a cryogen during machining of steel workpieces has an impact on shop floor productivity. This research employed time-study techniques to assess the impact that pre-cooling of mild steel had on human and machine productivity on a shop floor. Identical mild steel workpieces were milled using a 3-axis computer numerically controlled (CNC) Vertical Milling Centre (VMC). Each sample was subjected to one of four different conditions of cooling; viz., dry, pre-cooling, pre-cooling and raising to ambient temperature and soluble oil. Pre-cooling was achieved by submerging mild steel workpieces in a 10-litre Dewar of liquid nitrogen for five minutes. This brought the temperature of the workpieces down to -40°C. Results of the pre-cooling treatment plan were compared to the other treatment plans. Through the time studies, it was found that handling times of pre-cooled workpieces was comparatively higher than other treatment plans, especially when it came to mounting them in the vice. Unlike the other treatment plans, where the workpieces were handled at temperatures of 24ºC (ambient temperature), the pre-cooled parts were handled at -40°C. This near cryogenic temperature necessitated the use of leather gloves and tongs which slowed down the machine operator, thus in some respect reducing their productivity. The CNC machine does not have an in-built temperature error compensation feature, so it was unable to automatically adjust its tool position. The result of which was that the rough cut of pre-cooled workpiece was observed to be more of a finish cut, with the cutting tool barely making any contact with the workpiece surface and thus very little material being removed. This low material removal rate is considered to be a reduction in productivity from the machining stand-point. From a tribology perspective, the surface texture measurements revealed that pre-cooled parts did not fare well compared to other treatment plans as with each workpiece being cut in sequence, the surface roughness got progressively worse. However, from the analysis of process flow charts, pre-cooled parts had more value addition processes (or operations), compared to other treatment plans, in its processing cycle. Finally from the environmental point of view, the use of liquid nitrogen proved to be safe and low cost for achieving pre-cooling function for small workpieces, via adapting a dewar commonly used for artificial insemination for this purpose.

Keywords—Cryogenic, productivity, machining, computer numeric controlled (CNC), surface roughness

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ABBREVIATIONS

CNC	Computer Numerical Control
VMC	Vertical Machining Centre
MQL	Minimum Quantity Lubrication
HSS	High SpeedSteel
BUE	Built Up Edge
CLA	Centre-Line Average
MSDS	Material Safety Data Sheet
LN2	Liquid Nitrogen

LIST OF SYMBOLS

ΔT	[°C]	Mean temperature rise at the tool-chip interface
U	[N-m/mm^3]	Specific energy in the operation
V	[m/s]	Cutting speed
t_o	[m]	Chip thickness before the cut
ρC	[J/mm^3-°C]	Volumetric specific heat of the work material
K	[m^2/s]	Thermal diffusivity of the work material
Ø	[°]	Shear angle
α	[°]	Rake angle
β	[°]	Friction angle
σ_τ	[s]	Standard deviation of time data
σ_{CLA}	[μm]	Standard deviation of surface roughness data

Numerical Control ISO Codes

O	Programme number for identification
N	Sequence number for line identification
G	Preparatory functions
X	X axis designation
Y	Y axis designation
Z	Z axis designation
R	Radius designation
F	Feed rate designation
S	Spindle speed designation
H	Tool length designation
D	Tool radius designation
T	Tool designation
M	Miscellaneous function

CHAPTER 1
INTRODUCTION

1.1 Introduction

Conventional machining operations make use of oil-based coolants. Oil-based coolants are beneficial in that they can dissipate heat from the cutting zone, lower the coefficient of friction between the cutting tool and material interface and provide an oil film that prevents corrosion of the material. However, these oil-based coolants are known to be environmentally hazardous due to their composition of hydrocarbons. Disposal of oil-based coolants consists of drying the emulsion and its subsequent combustion (Pušavec and Kopač 2011). There are known health risks for machine operators working in an environment where there is a presence of the emulsion mist (Skerlos et al 2008).

Use of cryogens in machining has become an attractive alternative to using soluble oils for their generally environmentally friendly characteristics and for their positive impact in processing hard to machine materials. One such cryogen of interest is Liquid Nitrogen. Nitrogen makes up 78% (by volume) of the earth's atmosphere and is generally classified as an inert, noncorrosive and nonflammable gas. It is also easy to extract in large quantities using liquefaction process. These stated benefits make liquid nitrogen an attractive cryogen to use in a machining operation. To summarize, liquid nitrogen can be obtained at a comparatively lower cost to soluble oils and when applied to a machining operation, it evaporates into the atmosphere without leaving any harmful residue.

1.2 Problem Statement

Like most other machine tools used in local industry in Zambia, the 16-tool CNC machine is designed for use of conventional coolants discharge. Bearing in mind the environmental hazards of using soluble oils and the high costs associated with disposal, the large scale at which it is applied means that not only is a significant proportion of Zambia's skilled work-force exposed to the dangers it poses but industrial houses are also having to pay a great cost to use it and to dispose of it. There is a need to seek a paradigm shift in coolant applications in local industry from the use of soluble oils to use of cryogens and cryogenic machining techniques. But while it is imperative to raise awareness and encourage local industry to implement cryogenic machining, it is also cardinal to firmly establish both the benefits and limitations of these techniques. Beginning with a study of the simplest cryogenic machining technique, i.e. pre-cooling a workpiece in a cryogen to lower its temperature prior to machining, it can be established how beneficial and to what extent cryogenic machining can be a suitable alternative to other more conventional coolant application methods.

1.3 Research Objective

This research was aimed at investigating the impact on human and machine productivity on the shop floor, when a steel workpiece has been pre-cooled in a cryogen (Liquid Nitrogen) prior to milling on a 16-tool Computer Numerically Controlled (CNC) Vertical Machining Centre (VMC). The aspects affecting shopfloor productivity, when a workpiece has been pre-cooled in a cryogen, under investigation include:

a.) Handling time,
b.) Quality of machined surface and
c.) Material removal rate

1.4 Specific Research Objectives

Selection of an appropriate treatment plan when using a cryogen during machining of steel workpieces has an impact on shop-floor productivity. With regards to the main research objective above, the research essentially sought to answer the following questions:

i. Did the production cycle time increase or decrease when a workpiece was pre-cooled before machining?

ii. Which elements (or steps) in the production cycle were mostly impacted by the type of the coolant treatment plan?

iii. What difference was there in the surface roughness of workpieces machined using a cryogen compared to those having undergone other coolant treatment methods?

iv. What difference was there in the amount of material removed between pre-cooled workpieces compared to those having undergone other coolant treatment methods?

1.5 Research Justification

While there have been studies to identify the economic benefits of using cryogenic machining techniques regarding the hourly rate of machining system usage, coolant consumption costs and costs associated with waste (Pušavec and Kopač 2011. It remains to be known what impact a basic cryogenic machining technique, in this case pre-cooling of a workpiece, makes on the shopfloor productivity of a machine operator and a machine. This study aimed to provide a clear answer to this unknown.

1.6 Layout of the Dissertation

This dissertation is presented as follows, to elaborate further on this topic of the Effect of Pre-Cooling Low Carbon Steel in Liquid Nitrogen on Productivity:

1. Chapter 2 is a literature review covering coolant applications in machining. Looking at the problems encountered in machining and the function of conventional coolants to address them. This chapter also presents research in this evolving area of cryogenic machining. A general history of cryogenics is stated and a summary of research done in the area of applying cryogenic media in machining. The chapter ends with a review of literature in the area of work study. Under this section, method study and work measurement are the main focus in identifying the aspects of shop floor productivity.

2. Chapter 3 is dedicated to the design of the experiment. The equipment used and the parameters set for the experiment are elaborated to great detail in this chapter. The basic pre-cooling treatment technique is explained and study limitations encountered.
3. Chapter 4 presents the results from the experiments, which are also discussed in great detail. The emphasis is on the work measurement of the machine operator as they process 4 samples of workpieces undergoing 4 different coolant applications. The stages of the machining cycle, or the general activities the machine operator is expected to do, are studied and analysed individually. The objective is to determine which aspect affects the operator's productivity when a particular coolant application technique: cryogenic or non-cryogenic is employed. A brief section looking at the microstructure of the workpieces subjected to different coolant treatment plans, adds another dimension to the study. The objective is to determine any significant effects on the grain structure when a cryogenic machining technique is employed.
4. Chapter 5 gives the conclusion, recommendations and areas of future research.
5. References and Appendices follow the last chapter.

CHAPTER 2
LITERATURE REVIEW

2.1 Coolant Applications in Machining

Problems related to machining operations are caused by heat produced at the tool and workpiece interface. In machining operations, controlling cutting temperatures are important because the effects of high temperatures are: (1) reduction in tool life, (2) production of hot chips which poses a hazard to the machine operator and (3) inaccuracies in work-piece dimensions caused by thermal expansion in the material (Groover 2010). Coolants are therefore necessary to control the cutting temperatures

2.1.1 Heat Generation at Workpiece-Tool Interface

The temperature generated at the cutting tool workpiece interface is related directly to the cutting speed and type of material being cut. An equation to predict the increase in temperature at the interface of the cutting tool and chip is given by Cook (1973):

$$\Delta T = \frac{0.4U}{\rho C}\left(\frac{vt_o}{K}\right)^{0.333}$$ Equation 2.1

where ΔT = mean temperature rise at the tool-chip interface, C; U = specific energy in the operation, N-m/mm^3; v = cutting speed, m/s; t_o = chip thickness before the cut, m; ρC = volumetric specific heat of the work material, J/mm^3-°C; K = thermal diffusivity of the work material, m^2/s.

A relationship between the cutting speed and the temperature was given by Trigger (1949):

$$T = Kv^m$$ Equation 2.2

where T = measured tool-chip interface temperature; v = cutting speed, m/s; K and m are parametres depending on the cutting conditions and work-piece material.

Making use of the equation above provided by Trigger (1949) a plot of temperature versus cutting speed was done for different work-piece materials by Loewen and Shaw (1954) as shown in Figure 2.1. Where with increase in cutting speed from 50 ft/min to 1000 ft/min, temperatures could rise up to over 800ºF, 1400ºF and 1600ºF for B1113 Free machining steel, 18-8 Stainless steel and RC-130B Titanium respectively.

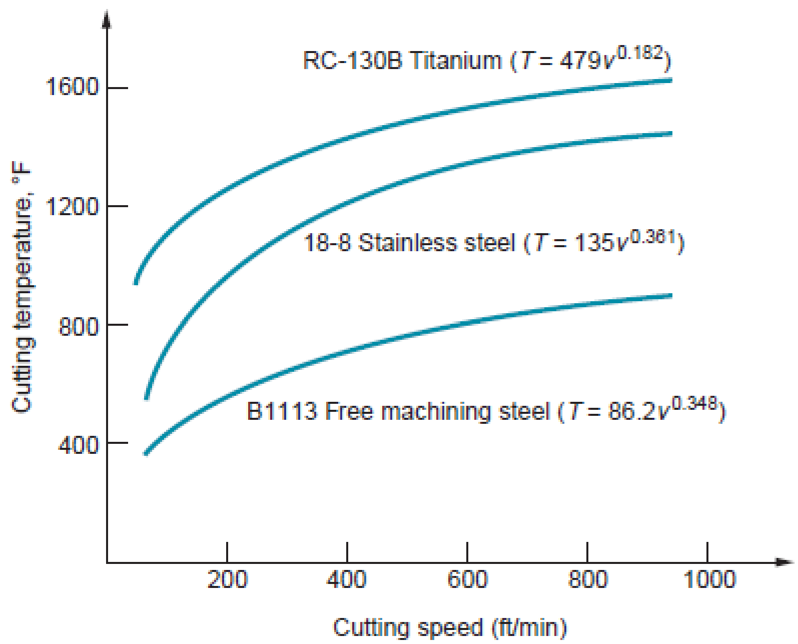


Figure 2.1. Empirical measurements of cutting temperatures against speed (Loewen & Shaw, 1954)

2.1.2 Cutting Fluids

According to Groover (2010), a cutting fluid is any liquid or gas that is applied directly to the machining operation to improve cutting performance.

In machining operations, cutting fluids address two main problems:

1) heat generation and
2) friction.

Other important uses of cutting fluids include washing away chips (important in grinding and milling operations), controlling the temperature of the work-part to levels that allow for easier handling, lowering the magnitude of cutting forces and power requirements, and improving surface finish.

2.1.2.1 Types of Cutting Fluids

On the market there are is a variety of conventional cutting fluids available. It is necessary to first understand them according to their function. It is equally important to classify them according to their chemical composition.

2.1.2.2 Cutting Fluid Functions

The two broad categories of cutting fluids, according to function are coolants and lubricants. (Groover, 2010)

(1.) **Coolants** are primarily designed to reduce the effects of heat generation in the machining operation. While they do not essentially control the amount of heat energy generated in cutting; rather they convey away the heat that is generated. This convective mechanism of heat transfer helps to prolong the life of the cutting tool. The cutting fluid's ability to reduce temperatures in machining depends on its thermal properties. Specific heat and thermal conductivity are the most significant properties that have a bearing on a cutting fluids capacity to convey away heat from the cutting zone. Due to its high specific heat and thermal conductivity relative to other liquids, water is used as the base in coolant-type cutting fluids. Hence, coolant-type cutting fluids are the most appropriate for high cutting speeds applications. They are suited for use on tool materials that are vulnerable to temperature failures.

(2.) **Lubricants** are effective in reducing friction at the tool-chip and tool-workpiece interfaces. This type of cutting fluid operates by a special form of lubrication whereby thin solid salt layers are formed on the hot, clean metal surfaces through a chemical reaction with the lubricant. This is known as ***extreme pressure lubrication***. These surface layers serve the purpose of separating the two metal surfaces (i.e., chip and tool). Lubricant-type cutting fluids are suited for machining at lower cutting speeds. Above 120 m/min they become ineffective as the chip motion, at these speeds, prevents the cutting fluid from reaching the tool-chip interface. Furthermore, high cutting temperatures at these speeds vaporize the oils before they can lubricate.

Although the lubricant's main function is to reduce friction, it can reduce the temperature in the operation through several mechanisms:

i. The specific heat and thermal conductivity of the lubricant ordinarily convey away the heat from the operation, thereby reducing temperatures.
ii. Since friction is reduced, the heat that would be generated from friction is also reduced.
iii. A lower coefficient of friction means a lower friction angle. From Merchant's equation, a lower friction angle increases the shear plane angle, hence reducing the amount of heat energy generated in the shear zone.

$$\emptyset = 45 + \frac{\alpha}{2} + \frac{\beta}{2} \qquad \text{Equation 2.3}$$

Where Ø is the shear angle, α is the rake angle and β is the friction angle. Figure 2.2 shows the cutting force vectors acting on the workpiece and cutting tool.

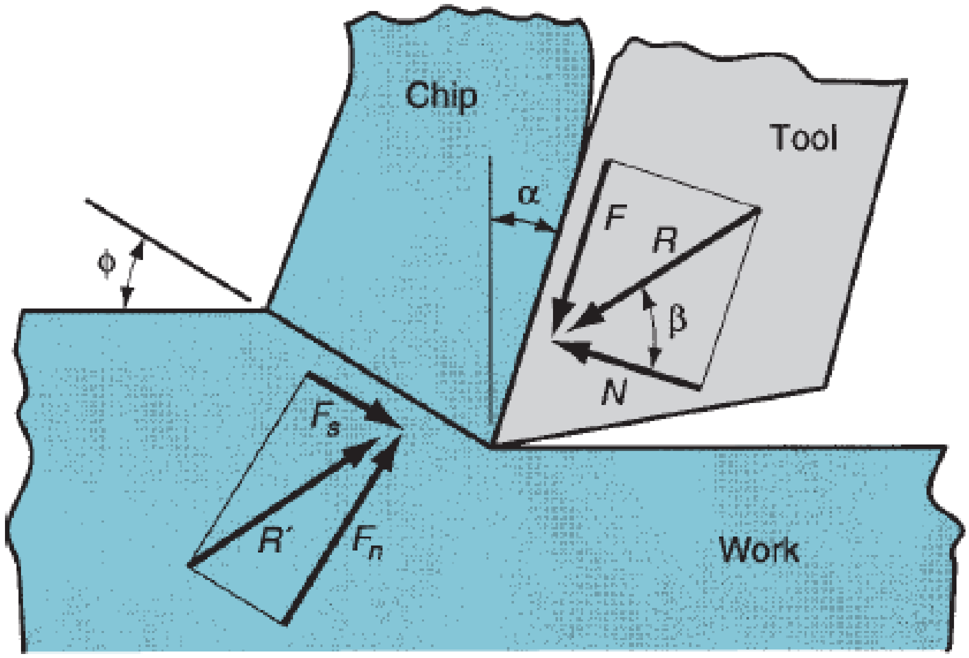


Figure 2.2. Forces Acting on the Chip in Orthogonal Cutting (Groover (2010))

2.1.2.3 Chemical Formulation of Cutting Fluids

Groover (2010) lists four categories of cutting fluids that exist according to chemical formulation:

(1) **Cutting oils** are derived from petroleum, animal, marine, or vegeTables. Mineral oils (petroleum based) are abundant and have generally desirable lubricating characteristics, hence their prominence. Chemical additives may occasionally be mixed with the oils to enhance lubricating qualities.

2) **Emulsified oils** consist of oil droplets suspended in water. They are produced by blending oil (usually mineral oil) in water. An emulsifying agent is used to promote blending and stability of the emulsion. The ratio of water to oil is typically 30:1.

3) **Semi-chemical fluids** contain small quantities of emulsified oil to increase the lubricating characteristics of the cutting fluid. They are essentially a hybrid class between chemical fluids and emulsified oils.

4) **Chemical fluids** are chemicals in a water solution rather than oils in emulsion. They consist of compounds of sulfur, chlorine, and phosphorus as well as wetting agents. The chemicals are necessary for providing a small degree of lubrication to the solution.

2.1.2.4 Cutting Fluids Application in Machining

There are various methods in which cutting fluids are applied to machining operations (Groover, 2010). The most commonly applied method is ***flooding***, also known as flood-cooling since it makes use of coolant-type cutting fluids. The working principle is that a steady stream of fluid is directed at the tool–work or tool-chip interface of the machining operation.

Another method is ***mist*** application. It mostly makes use of water-based cutting fluids. The working principle in this method requires that the fluid is directed at the operation in the form of a high-speed mist carried by a pressurized air stream. This application is not as effective in cooling the tool as in the case of flooding. However, the benefit of the high-velocity air stream enables delivery of the cutting fluid to areas that are generally difficult to access by conventional flooding.

Minimum Quantity Lubrication (MQL) is yet another possible solution. A small quantity of lubricant is atomized in a stream of air supplied at a rate of up to 500ml/hr. This is a near-dry process since a very small percentage (2%) of the cutting fluid actually adheres to the chips. (Nigar, Hasan, 2017).

2.2 Cryogenic Machining

The use of liquid nitrogen in machining operations is known as cryogenic machining. Cryogenics is the science of very low temperatures. Apart from liquid nitrogen, other cryogens include liquid carbon dioxide, liquid oxygen and liquid helium. Typical temperatures in cryogenics are lower than 120°K (Timmerhaus and Reed 2007). Cryogenic technology in its earliest stages was mainly used in oxygen-acetylene welding and oxygen furnaces for steel production (Shokrani et al, 2012).
When introduced into the cutting operation the cryogen acts as a coolant in order to alter the material properties and/or dissipate the heat generated at the cutting zone (Shokrani et al. 2012b).

2.2.1 Effect of Cryogenic Treatment on Tool and Workpiece Materials

The effect of cryogenic treatment on the tool materials was first reported by Gulyaev (1937) where the high-speed steel (HSS) cutting tool was cooled to temperatures in the range of -80°C to -100°C for 30 to 60 minutes. Studies have found that using cryogenic machining methods increases tool life by up to four times (Khan and Mirghani 2008) and improves the machinability of low carbon steels by reducing the ductility and toughness (Hong and Zhao 1999). Their studies showed that soft, low strength, ductile materials such as low carbon steels were usually considered to be difficult-to-machine due to two key factors: their welding tendency and difficulties in chip formation. According to the study, it was found that low carbon steels have a unique ductility to brittleness temperature similar to the glass transition temperature in polymers. When temperatures get to levels lower than this temperature, the effect is that the ductility and toughness of the material reduces significantly. This reduction works in favour of the machinability of the material. It was also found that cryogenic temperatures reduce the welding tendency of the material and lowers the formation of Built Up Edge (BUE). In another study, the surface roughness of materials machined in cryogenic conditions was better than under conventional coolant application (Yildiz and Nalbant 2008). In a similar study, it was posited that the reduction in surface roughness could be due to less adhesion between the tool rake/flank face and the newly generated machined surface under a lower cutting temperature caused by the delivery of liquid nitrogen during cryogenic machining (Sun et al 2016). It has also been shown that the cutting forces used reduces significantly by using cryogenic machining techniques (Yildiz and Nalbant 2011).

2.2.2 Techniques of Applying Cryogenic Media

Different techniques have been adopted in order to apply the cooling effect of cryogenic media into the cutting process. These techniques can be classified into workpiece cooling, cutting zone and/or chip cooling and indirect cutting tool cooling (Yildiz and Nalbant 2008) or the combination of these techniques. Cryogenic cooling of the workpiece material before or during the cutting operation is a widely used cryogenic machining technique. The main thrust of employing this technique is to improve machinability by altering the material properties of the workpiece. Workpiece cooling is achieved by using one of two methods: cryogenic bath and/or cryogenic spray. In the case of the former, the workpiece is usually submerged in a cryogen, while in the latter the cryogen is sprayed onto the workpiece during machining, particularly before the cutting operation.

2.3 Machine and Human Productivity

The definition of productivity is simple and complex at the same time, and this is because it is both a technical and managerial concept (Thomas, 2004). Productivity (Thomas, 2004) is defined as an index that measures the output (goods and services) relative to the input (labour, materials, energy and other resources) used to produce them (Stevenson, 1996). Productivity is usually expressed in terms of a ratio of output to input:

$$Productivity = \frac{Output}{Input} \qquad \text{Equation 2.4}$$

There are a number of factors that affect productivity, such as methods, quality and technology.

2.3.1 Machine Tool Productivity & Quality Control

Machines are tools used by skilled workforce to enhance productivity on the shopfloor. They achieve this by carrying out functions that would be too cumbersome to do by hand. Machines have gone through great advancements such that with the integration of computers, they can do repetitive work accurately. For a machine to be considered highly productive requires:

1. Low energy input for high product output
2. Low probability of deviating from set parametres under normal working conditions
3. High reliability through proper maintenance at the appropriate intervals to minimise downtime
4. Integration of automation and control systems to guarantee high quality products are produced consistently and repetitively.

An expansion of point 4 delves into the cucial realm of quality control. This science employs statistical methods to measue the level of conformance of a process to the intent of design. The statistical tools commonly used are control charts. When considering the appropriate chart to use to effectively control the process it is important to define what is being controlled; whether it is a variable or an attribute. A variable is measurable on a numerical scale, whereas an attribute is a quality characteristic that cannot be measured on a numerical scale. Only those characteristics that can be counted or measured are candidates for control. (Stevenson W. J., 1996). In this scenario, the surface roughness is a measurable quality characteristic (or variable) that can be controlled on the CNC machine.

The 16-tool vertical machining centre used during this research is the Supermax 65A. Its manufacturer is Yeong Chin Machinery Industries of Taiwan. Its construction consists a full-casting design with large sized ball screws and sliding guideways, these provide for digital control and drive for precision (Supermax, 1969). The basic features of the machine include:

i.) Base: Made from cast iron, it provides the link between the spindles and the slides.
ii.) Spindle: Vertical in its orientation, it facilitates for both clockwise and counter-clockwise rotation about the spindle axis.
iii.) Cartesian Axes: these are the X, Y and Z axis. Movement in each axis is achieved with the aid of servo stepper motors. These motors serve the purpose of controlling slide positioning and acceleration.
iv.) Tool changer unit: This feature uses pneumatics to control the selection and storage of tools
v.) Control panel: This feature is where the machine parametres are selected and controlled from.

Like other CNC machines, the Supermax 65A also has features that help to control the quality of the part produced:

i.) Backlash compensation: this is caused by play between the screw and nut. Motion is lost when the slide direction is reversed. Automatic compensation is achieved each time this takes place.
ii.) Tool nose radius compensation: this eliminates positioning errors that may be encountered as a result of the radius of a tool
iii.) Diagnostic features: these check the operation of the CNC system at several levels:
- Real-time diagnostics: power supply voltage and real-time clock are checked
- On-line diagnostics: program diagnostics feature detects errors in the programming, i.e. syntax.

Also, like most typical CNC machines, the Supermax 65A is able to carry out the following functions:

i.) Controlled axes
ii.) Rapid traverse
iii.) Thread cutting
iv.) Dwell
v.) Reference point return
vi.) Coordinate system setting
vii.) Canned cycles
viii.) Emergency stop

Malama (2006) reported that for production of a collimator, the Supermax 65A is able to produce a satisfactory surface finish with a mean centre-line average (CLA) of 1.22 microns. Figure 2.3 and the formulae below (Equation 2.5) below shows the statistical technique used to obtain this value. Using this method of 'control charts for individual measurements', the sample size for process control is set to n=1 (Montgomery, 1994). In the same study, Malama reported that critical dimensions were within tolerances.

$$\left.\begin{aligned} UCL &= \bar{x} + 3\frac{\overline{mr}}{d_2} \\ CL &= \bar{x} \\ LCL &= \bar{x} - 3\frac{\overline{mr}}{d_2} \end{aligned}\right\} \quad \text{Equation 2.5}$$

where,

$\overline{mr}$ is the mean of the moving range

$\bar{x}$ is the mean of the CLA

d_2 is a factor obtained from Tables for constructing variables control charts

Figure 2.3 was the control chart generated for individual CLAs.

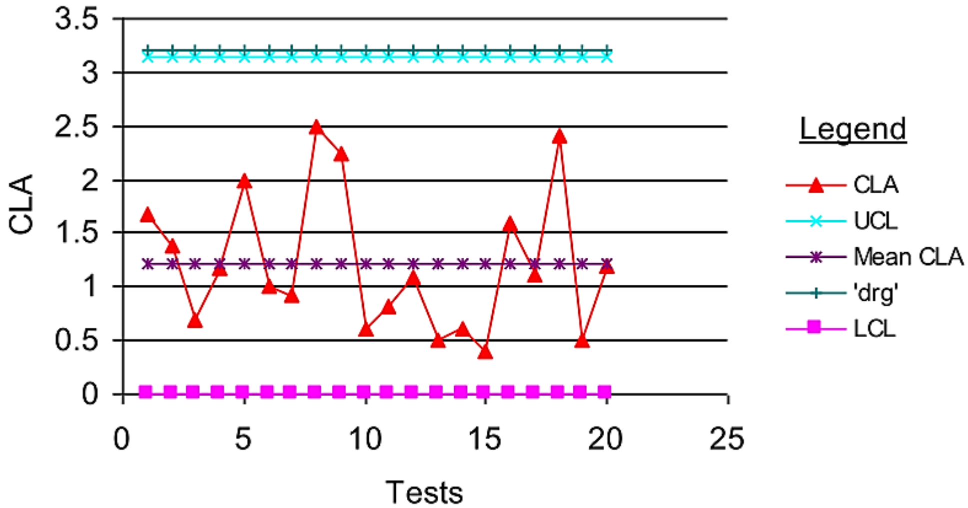


Figure 2.3. Control Chart for Individual CLAs (Source: Malama, 2006)

In another study, it was proved that the Supermax 65A can be adapted to carry out turning operations (Mwanza, 2001). This was achieved by mounting a workpiece in the spindle and fixing the cutting tool to the machine Table so that the workpiece is moved against the stationary tool, as shown in Figure 2.4. The turning operation was able to obtain dimensional results with high accuracy. From measurements taken on turned workpieces, as presented in Tables 2.1 and 2.2 below, Mwanza concluded that within a given design, product and process tolerances, the simulated turning fixture is able to give higher dimensional accuracy and surface finish on turned workpieces.

Table 2.1. Dimensions on Aluminium Piece (Source: Mwanza, 2001)

Diameter	Drawing	Machined	Difference
1	38.45	38.45	0
2	35.45	35.45	0
3	32.45	32.45	0

Table 2.2. Dimensions of Prowax Piece (Source: Mwanza, 2001)

Diameter	Drawing	Machined	Difference
1	64.70	64.70	0
2	34.80	34.80	0
3	27.30	27.30	0

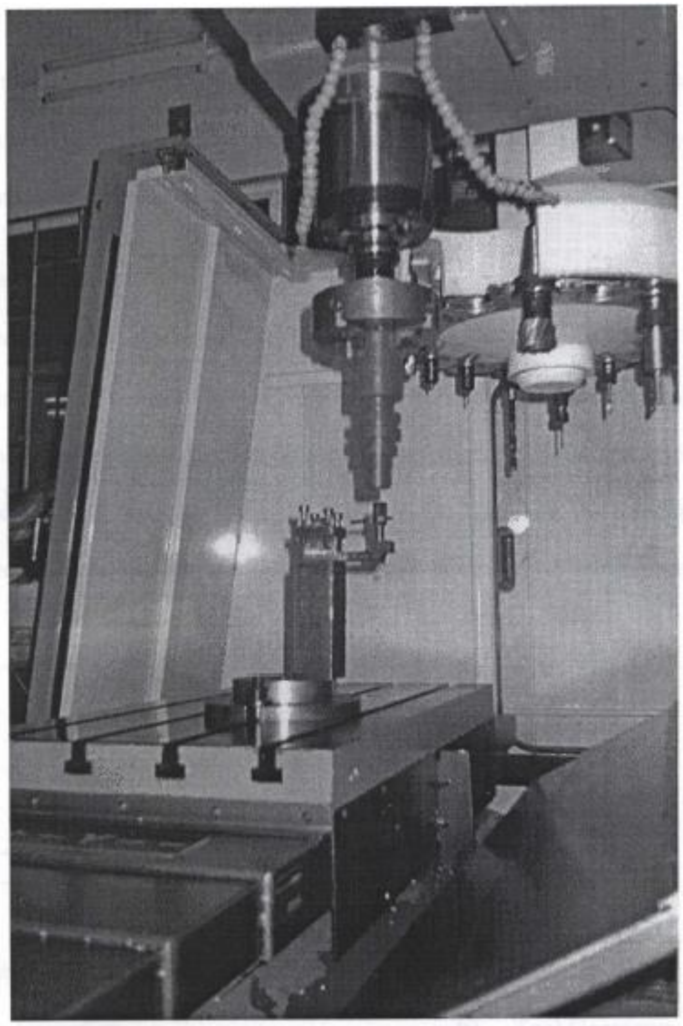


Figure 2.4. Workpiece and Tool Holder Fixtures in Position (Source: Mwanza, 2001)

2.3.2 Human Productivity

In a production process where manual handling processes are required, there are certain part features that affect manual handling time significantly. Boothroyd (2005) lists the following part features:

i. Size
ii. Thickness
iii. Weight
iv. Nesting

v. Tangling
vi. Fragility
vii. Slipperiness
viii. Stickiness
ix. Necessity for using two hands
x. Necessity for using grasping tools
xi. Necessity for optical magnification
xii. Necessity for mechanical assistance

A classification system for manual handling processes is established by a two-digit coding system. The first digit is divided in four main groups:

i. Digit 0-3: parts of nominal size and weight can be grasped and handled without the aid of tools, using one hand
ii. Digit 4-7: parts require the use of grasping tools due to their small size
iii. Digit 8: these parts have a tendency to nest or tangle
iv. Digit 9: parts require two hands, multiple persons or even mechanical assistance.

The second digit of the coding system can also be divided into four group divisions:

i. Digit 0-3: size and thickness of the work part
ii. Digit 4-7: type of tool required for handling part and use of optical magnification
iii. Digit 8: symmetry of part
iv. Digit 9: weight and interlocking characteristics of parts in bulk

Using this classification system, time standards have been developed as shown in Figure 2.5 below.

MANUAL HANDLING–ESTIMATED TIMES (seconds)

Key: ONE HAND

		Parts are easy to grasp and manipulate					Parts present handling difficulties (1)				
		Thickness >2 mm			Thickness ≤2 mm		Thickness >2 mm			Thickness ≤2 mm	
		Size >15 mm	6 mm ≤ size >15 mm	Size <6 mm	Size >6 mm	Size ≤6 mm	Size >15 mm	6 mm ≤ size ≤15 mm	Size <6 mm	Size >6 mm	Size ≤6 mm
		0	1	2	3	4	5	6	7	8	9
Parts can be grasped and manipulated by one hand without the aid of grasping tools	(α + β) < 360°	0	1.13	1.43	1.88	1.69	2.18	1.84	2.17	2.65	2.45	2.98
	360° ≤ (α + β) < 540°	1	1.5	1.8	2.25	2.06	2.55	2.25	2.57	3.06	3	3.38
	540° ≤ (α + β) < 720°	2	1.8	2.1	2.55	2.36	2.85	2.57	2.9	3.38	3.18	3.7
	(α + β) = 720°	3	1.95	2.25	2.7	2.51	3	2.73	3.06	3.55	3.34	4

ONE HAND with GRASPING AIDS

				Parts need tweezers for grasping and manipulation								Parts need standard tools other than tweezers	Parts need special tools for grasping and manipulation
				Parts can be manipulated without optical magnification				Parts require optical magnification for manipulation					
				Parts are easy to grasp and manipulate		Parts present handling difficulties (1)		Parts are easy to grasp and manipulate		Parts present handling difficulties (1)			
				Thickness >0.25 mm	Thickness ≤0.25 mm	Thickness >0.25 mm	Thickness ≤0.25 mm	Thickness >0.25 mm	Thickness ≤0.25 mm	Thickness >0.25 mm	Thickness ≤0.25 mm		
				0	1	2	3	4	5	6	7	8	9
Parts can be grasped and manipulated by one hand but only with the use of grasping tools	α ≤ 180°	0 ≤ β ≤ 180°	4	3.6	6.85	4.35	7.6	5.6	8.35	6.35	8.6	7	7
		β = 360°	5	4	7.25	4.75	8	6	8.75	6.75	9	8	8
	α = 360°	α ≤ β ≤ 180°	6	4.8	8.05	5.55	8.8	6.8	9.55	7.55	9.8	8	9
		β = 360°	7	5.1	8.35	5.85	9.1	7.1	9.55	7.85	10.1	9	10

TWO HANDS for MANIPULATION

		Parts present no additional handling difficulties					Parts present additional handling difficulties (e.g. sticky, delicate, slippery, etc.) (1)				
		α ≤ 180°			α = 360°		α ≤ 180°			α = 360°	
		Size >15 mm	6 mm ≤ size ≤ 15 mm	Size <6 mm	Size >6 mm	Size ≤6 mm	Size >15 mm	6 mm ≤ size ≤ 15 mm	Size <6 mm	Size >6 mm	Size ≤6 mm
		0	1	2	3	4	5	6	7	8	9
Parts severely nest or tangle or are flexible but can be grasped and lifted by one hand (with the use of grasping tools if necessary) (2)	8	4.1	4.5	5.1	5.6	6.75	5	5.25	5.85	6.35	7

TWO HANDS or assistance required for LARGE SIZE

		Parts can be handled by one person without mechanical assistance									Two persons or mechanical assistance required for parts manipulation
		Parts do not severely nest or tangle and are not flexible								Parts severely nest or tangle or are flexible (2)	
		Part weight <10 lb				Parts are heavy (>10 lb)					
		Parts are easy to grasp and manipulate		Parts present other handling difficulties (1)		Parts are easy to grasp and manipulate		Parts present other handling difficulties (1)			
		α ≤ 180°	α = 360°	α ≤ 180°	α = 360°	α ≤ 180°	α = 360°	α ≤ 180°	α = 360°		
		0	1	2	3	4	5	6	7	8	9
Two hands, two persons or mechanical assistance required for grasping and transporting parts	9	2	3	2	3	3	4	4	5	7	9

Figure 2.5: Original classification system for part features affecting manual handling time (Source: Boothroyd Dewhurst, Inc.)

2.3.3 Work Study

Work study is a generic term for those techniques, method study and work measurement which are used in the examination of human work in all its contexts. And which lead systematically to the investigation of all the factors which affect the efficiency and economy of the situation being reviewed, in order to effect improvement. (Telsang, 2006). Work study encompasses both method study and work measurement. The link between the two is very close. In method study, the aim is to reduce the work content and to establish the best way of doing the job. In work measurement the aim is to establish time standards for an operation.

The definition of a method study according to the British Standards Institution (BS 318) is given as follows: 'Method study is the systematic recording and critical examination of existing and proposed ways of doing work as a means of developing and applying easier and more effective methods and reducing cost.'

According to Telsang (2006) method study scope lies in improving work methods through process and operation analysis, such as:

i. Manufacturing operations and their sequence
ii. Workmen
iii. Materials, tools and gauges
iv. Layout of physical facilities and work station design
v. Movement of men and material handling
vi. Work environment

Process and operation analysis is best achieved by presenting the facts of the operation in the form of charts. Flow process charts are a popular means of capturing the information of a process. For easy grasping of the process, symbols are employed to describe what type of event is taking place in the whole sequence of events making up the production cycle. Figure 2.6 presents the standard symbols used during method study recording techniques.

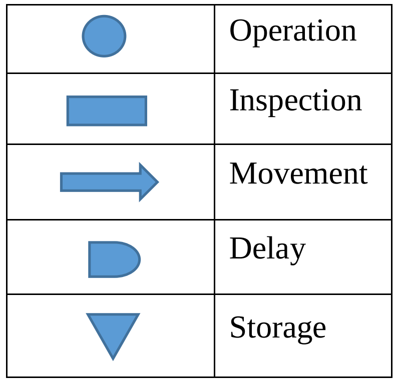


Figure 2.6. Method Study Symbols

Elaborating the meaning of each symbol further:

i. Operation – when a workpiece has a change in its physical or chemical characteristics. In the context of this study, milling is treated as an operation.

ii. Inspection – when a workpiece is examined and compared to specifications. Checking the dimensions of the workpiece is considered as an inspection

iii. Transportation – this describes the movement of workers, materials, equipment and workpieces from one location to another

iv. Delay – also considered as temporary storage is when the immediate performance of the next activity in the sequence does not take place.

v. Storage – when the workpiece is kept in authorized inventory and kept against unauthorized removal. In the context of this study, pre-cooling of mild steel is treated as storage under cryogenic conditions.

Work Measurement is defined by the British Standard Institution as ‘The application of techniques designed to establish the time for a qualified worker to carry out a specified job at a defined level of performance. Figure 2.5 is an example of a time standard for handling of parts of certain size or weight during an automation process.

CHAPTER 3
METHODOLOGY

3.1 Sample Cooling Treatment Plans

Four samples consisting of 6 workpieces were machined under different cooling processes as shown in Table 3.1. The workpieces were 100 mm in length and 25 mm in diameter.

Table 3.1. Treatment Plan of Each Sample

Sample No.	No. of Pieces	Treatment Plan	Sample Length (mm)	Sample Diameter (mm)
1	6	Cool using soluble oil at Tool/Workpiece Interface	100	25
2	6	Pre-cool in LN2	100	25
3	6	Pre-cool in LN2, then raise to ambient temperature (24ºC)	100	25
4	6	Dry Machining	100	25

3.2 Milling Operation

The milling operation consisted of slot milling using a 16 mm diameter end mill. The CNC program was consistent for each workpiece and sample except for programming of the coolant. The M-code for switching on coolant was used only for sample 1 and disabled for the other 3 samples. Figure 3.1 shows the YCM Supermax 65A machine (year of make: 1996) used for the milling operation. Figure 3.2 shows the part program on the display. Figure 3.3 shows the cutting tool used during the milling operation. Figure 3.4 depicts an end elevation of the workpiece-tool-vice set-up. The milling operation parametres were capture in the process plan as given in Table 3.2.

Figure 3.1. Supermax 65A Machine

Figure 3.2. Part Program Displayed

Figure 3.3. Tool Used for Milling Operation

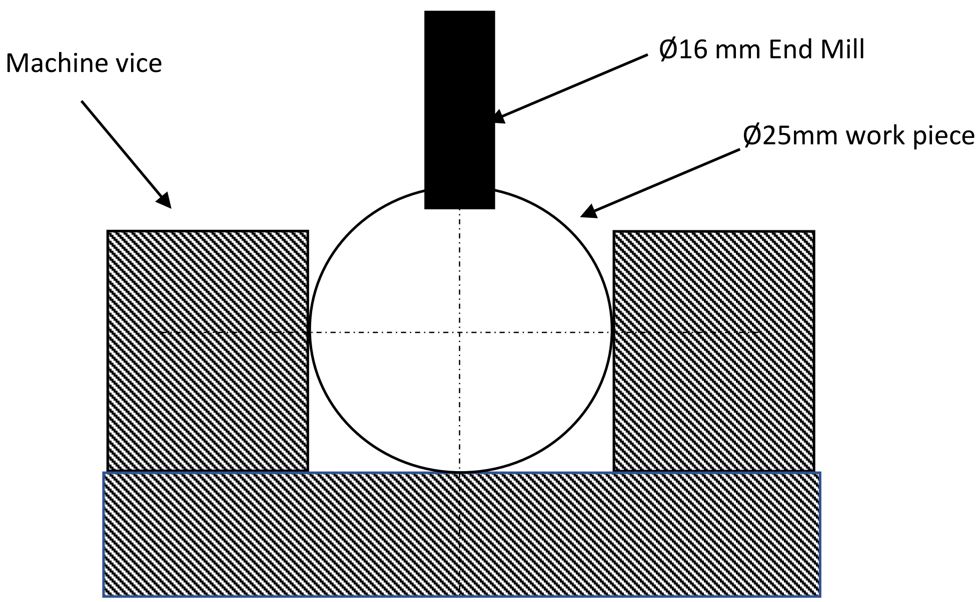


Figure 3.4. Milling Operation Set-Up

The machine tool parameters during milling operation:

Maximum cutting depth: 0.33*16 mm = 5.28 mm Equation 3.1

Maximum cutting width: 0.7*16 mm = 11.2 mm Equation 3.2

Feed per tooth, roughing: 0.05 mm/tooth

Feed per tooth, finishing: 0.03 mm/tooth

Cutting Speed milling: 30 m/min

Cutting Speed drilling: 20 m/min

Spindle Speed: $S = \frac{Cutting\ speed\ (\frac{mm}{\text{min}})}{\pi \times diametre\ cutter} = \frac{30000}{\pi \times 16} = 596\ rev/min$Equation 3.3

Feed rate: $F = S \times F_{per\ tooth} \times Number\ of\ teeth$Equation 3.4

$$F = 596 \times 0.05 \times 2 = 119.2\ mm/min$$

Table 3.2. Milling Process Plan

MATERIAL						Fe 360		
CUTTING SPEED (m/min)						Milling:		30
						Drilling:		20
No.	**Process/Sketch**	**Tool**		**Spindle Speed (rpm)**	**Feed rate (mm/min)**	**Max. Cutting**		
		Description	**No.**			**Depth (mm)**	**Width (mm)**	
1	Roughing contour	End-mill Ø16	2	596	119.20	5.00	11.00	
2	Finishing contour	End-mill Ø16	2	596	72.00	5.00	1.00	

The procedure for each run was similar for all 4 samples involving:

1) Measuring the weight of the 16 mm diameter end mill before machining operation
2) Loading the 16 mm diameter Slotting mill on CNC tool magazine
3) Measuring weight of sample workpiece
4) Mounting workpiece in vice
5) Loading program on CNC
6) Carrying out Milling operation
7) Measuring temperature of workpiece during milling operation
8) Unloading the workpiece from vice
9) Cleaning vice
10) Measuring the weight of the workpiece following machining operation and
11) Measuring the weight of the 16mm end mill.

3.3 Pre-Cooling Method

The pre-cooling process was carried out with the use of a YDS-10Dewar as shown in Figure 3.5. This Dewar comes with six buckets. It is normally used for artificial insemination in animal husbandry. It was adapted for use as a liquid nitrogen bath. For sample 2 the workpieces were pre-cooled for 5 minutes prior to machining. The Dewar is not sealed tight to allow for nitrogen vapours to escape with rise in temperature. This is a safety feature of the Dewar, as there is a risk of explosion when the temperature of the nitrogen rises to ambient temperature. This limits the duration of storage of the liquid nitrogen in a Dewar, when the system is uninterrupted, to under five days.

Inserting the buckets (containing mild steel pieces in upright position) in the Dewar was done one at a time. The temperature of the liquid nitrogen vapours necessitated the use of leather gloves to prevent cold burns. Appendix B gives the material safety data sheet (MSDS) of liquid nitrogen as published by Afrox. The quantity of liquid nitrogen used was 7 kilograms and cost ZMW 202.72 ($2.03). During the pre-cooling procedure, the Dewar was able to accommodate 2.3 kilograms of steel workpieces at any one time.

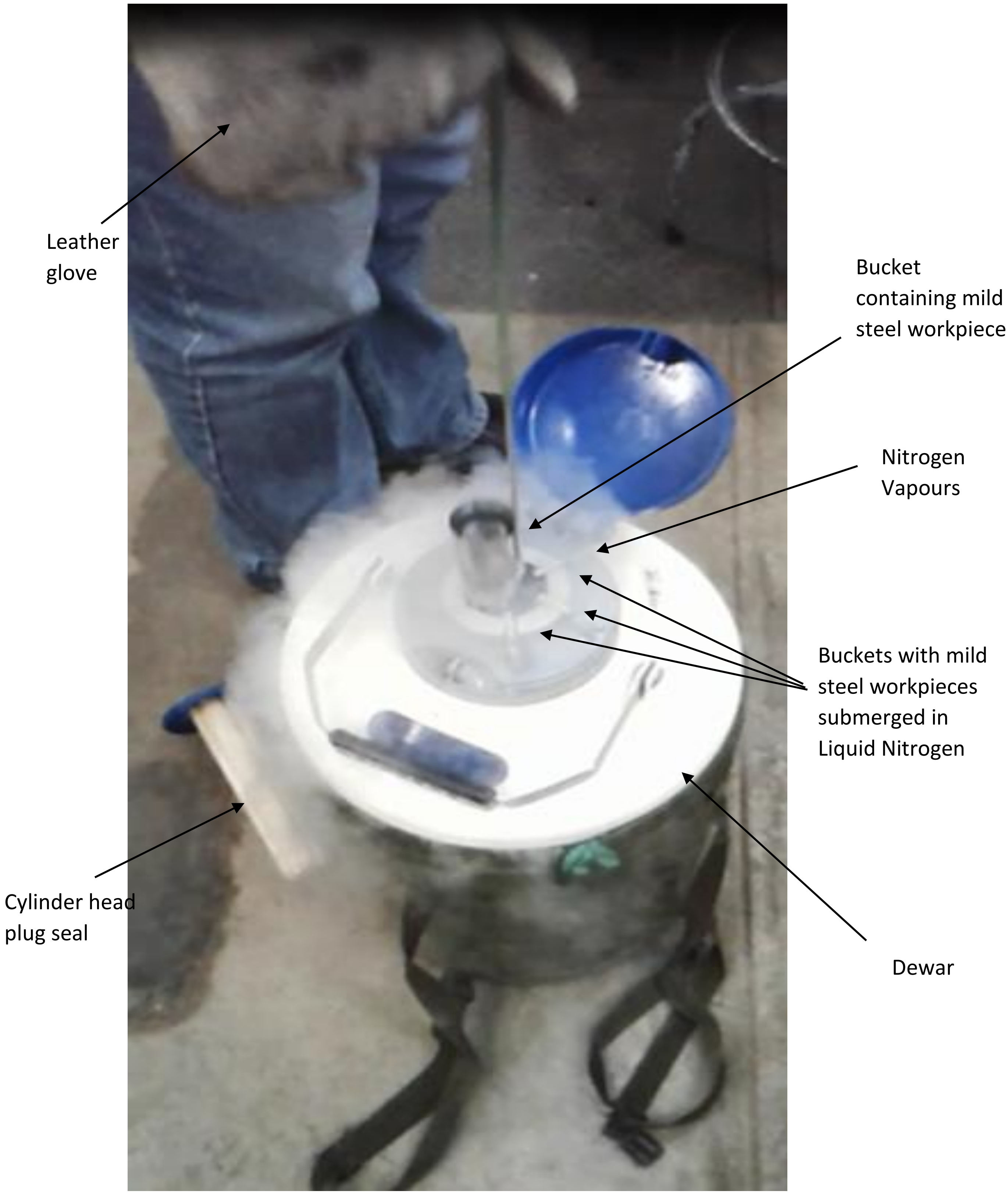


Figure 3.5. Dewar Used for Pre-cooling Procedure

3.4 Surface Texture Tests

Surface texture tests were done using the Taylor Hobson Talysurf 4 (THT) machine shown in Figure 3.6. The surface of interest was the bottom part of the milled surface as depicted in Figure 3.7.

Settings on the machine:

i. Meter cut-off length setting: K (0.8 mm). Used for 5 sampling lengths.
ii. Traversing length is 3.8 mm.
iii. Pen shift: V (4)
iv. Normal Use (N)
v. CLA magnification: 2000 (2.5)
vi. Scale used: Top with magnification position of 3 (reading multiplied by 10). Each small division represents 0.1 micrometres

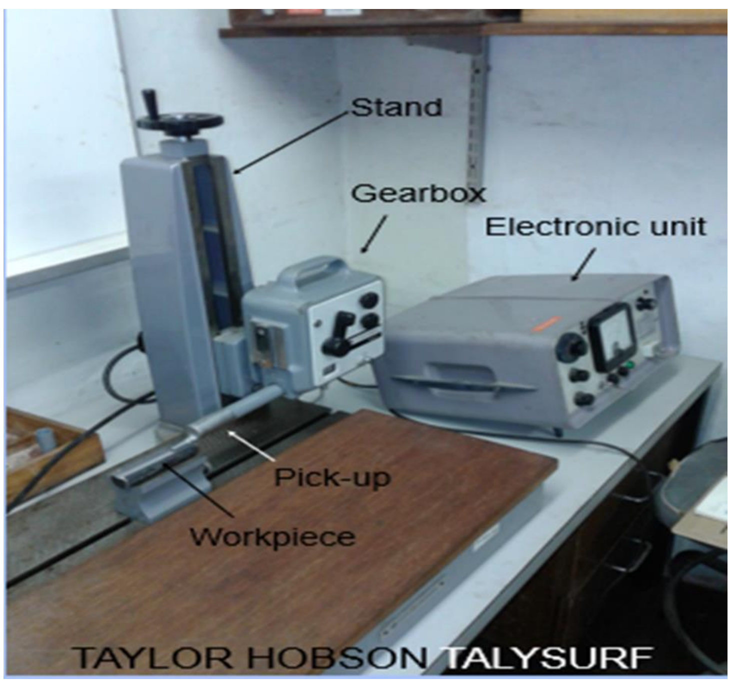


Figure 3.6. Taylor Hobson Talysurf Setup

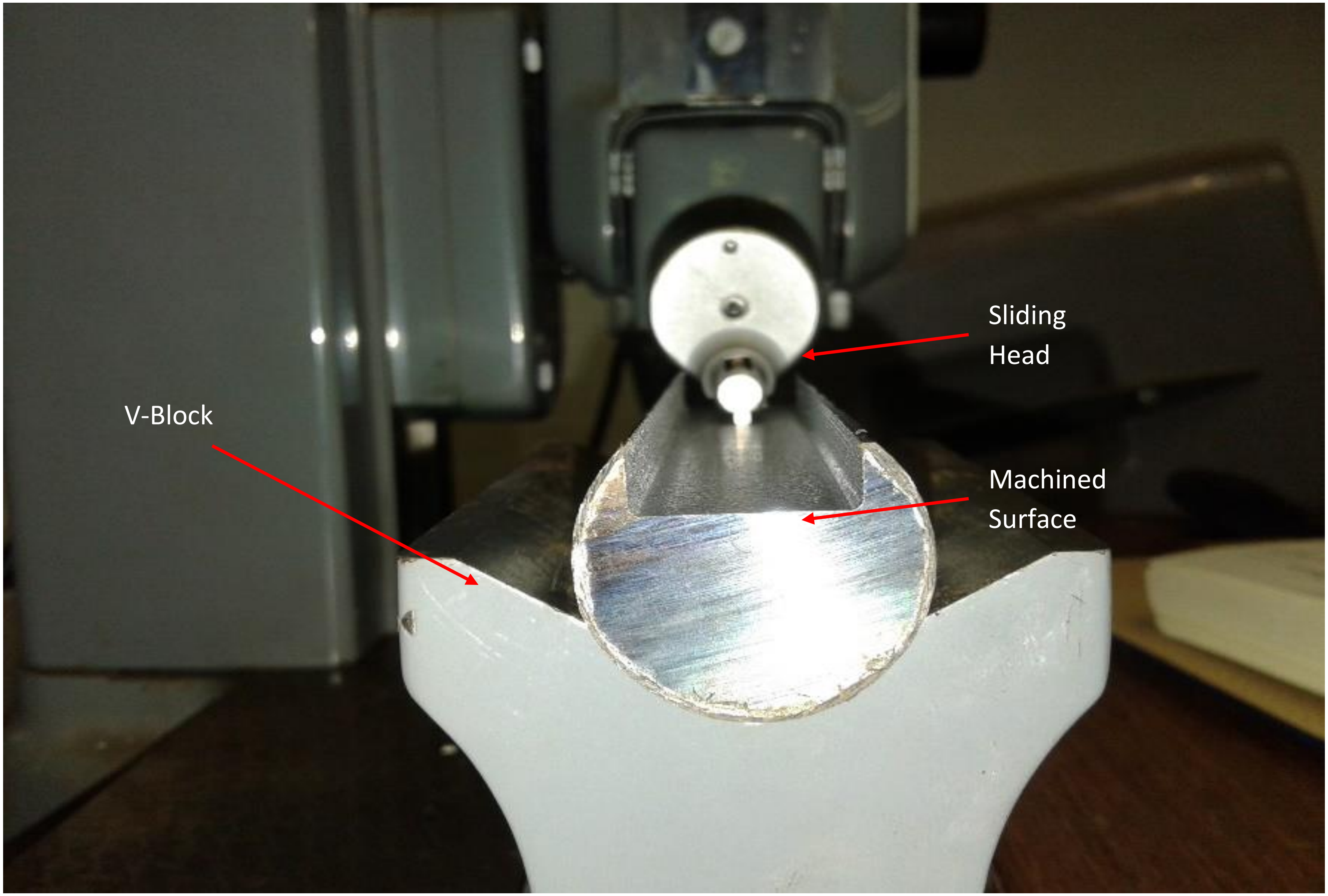


Figure 3.7. Surface under test

3.5 Microstructure Tests

The purpose of this test is to determine any changes in the microstructure when mild steel is subjected to near-cryogenic temperatures. The pre-cooling process enables the workpieces to cool to -40°C.

The procedure of carrying out the microstructure investigations was as follows:

1. One workpiece was collected from each treatment plan. Cut into smaller pieces and the section was polished using Buelher Metaserv Hand-grinder and Universal Polisher as shown in Figures 3.8 and 3.9.
2. Etchant used was Nital: 2 cm^3 of Nitric Acid and 98 cm^3 of Alcohol (Ethanol)
3. Etchant was cleaned using Ethanol
4. Sections of each sample were placed under an Olympus CH-2 microscope and images captured using Sony MTV-3 CCD Color Video Camera (Model DXC-107P) as shown in Figures 3.10 and 3.11.
5. Magnification details of the objective lens used are as follows:
    - MD Plan 80
    - 0.9
    - IC 80
    - ∞/0
    - f = 180
    - 117000
6. Images captured at 3 positions of the section as depicted in Figure 3.12:
    - Area just beneath the machined surface
    - Diametric centre of the workpiece
    - Near-edge of the workpiece

    The above positions selected for further investigation on any microstructure changes in the workpiece. The area underneath the machined surface, being subjected to both extreme hot and cold temperatures, would be of main interest. While the other points along the cross section would indicate the rate and extent at which the changes are taking place in the material.

Figure 3.8. Polishing of sample workpiece section to expose the grain

Figure 3.9. Polished and etched sections from all 4 samples

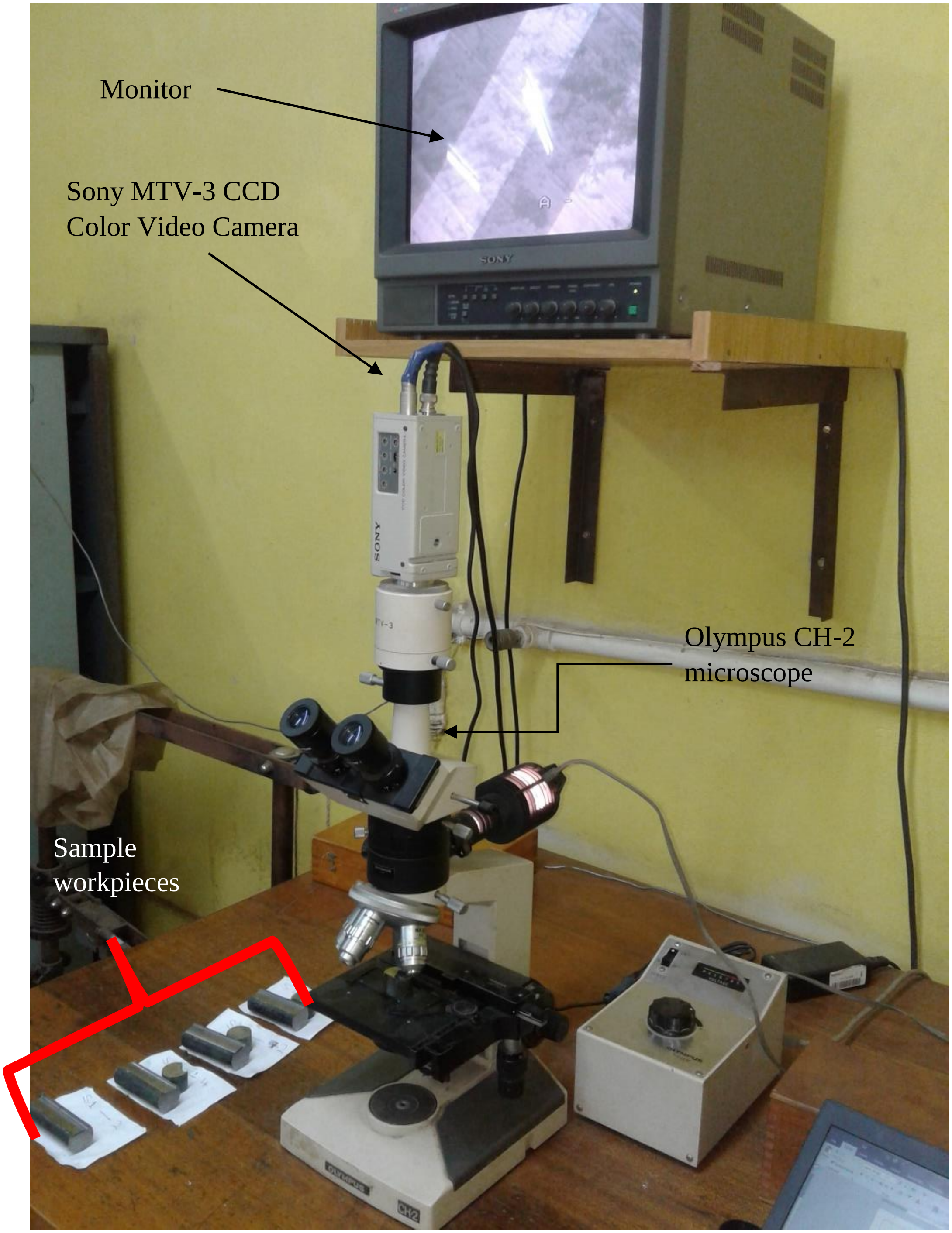


Figure 3.10. Microstructure test set-up

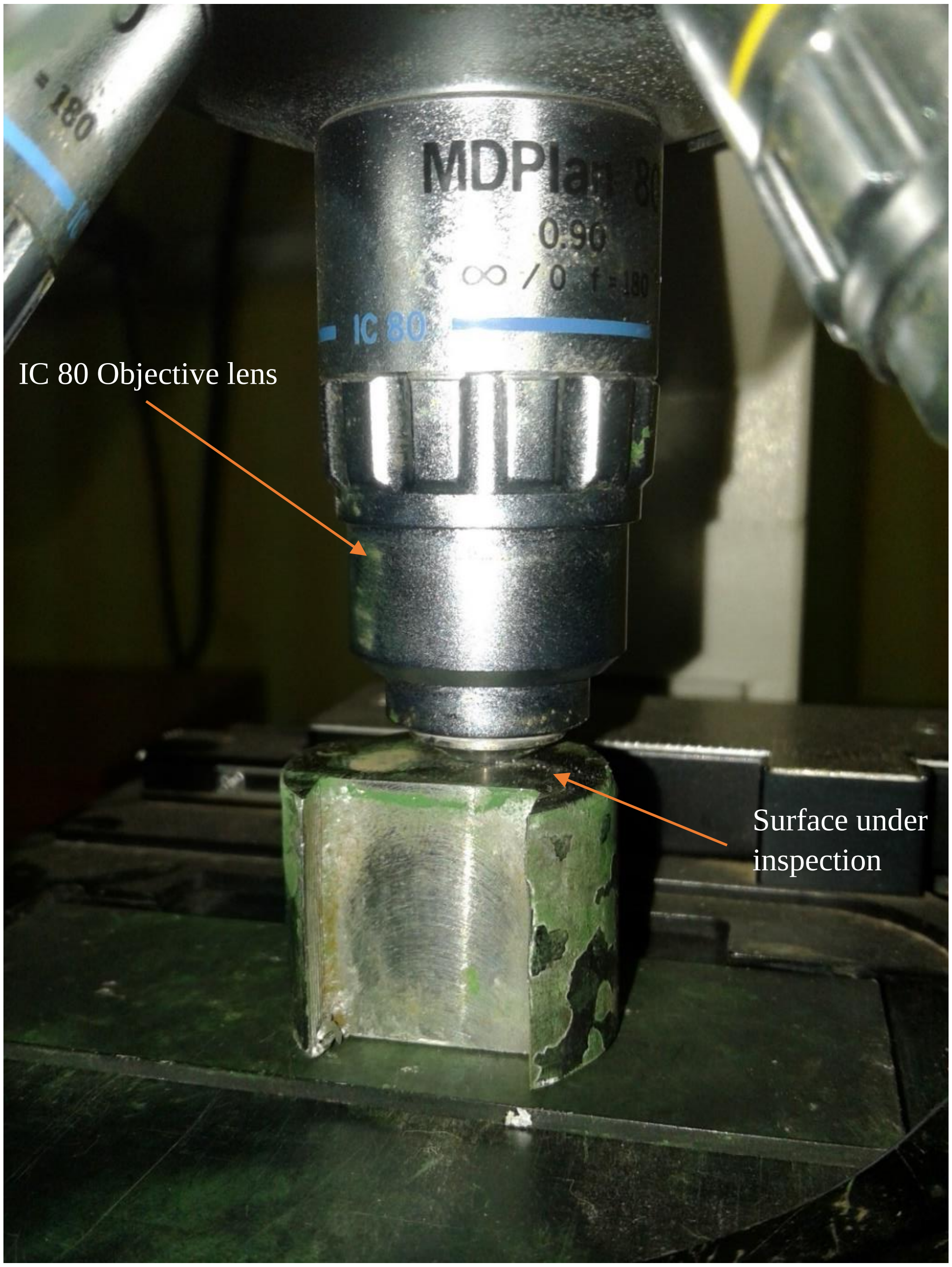


Figure 3.11. Image taken just below the machined surface

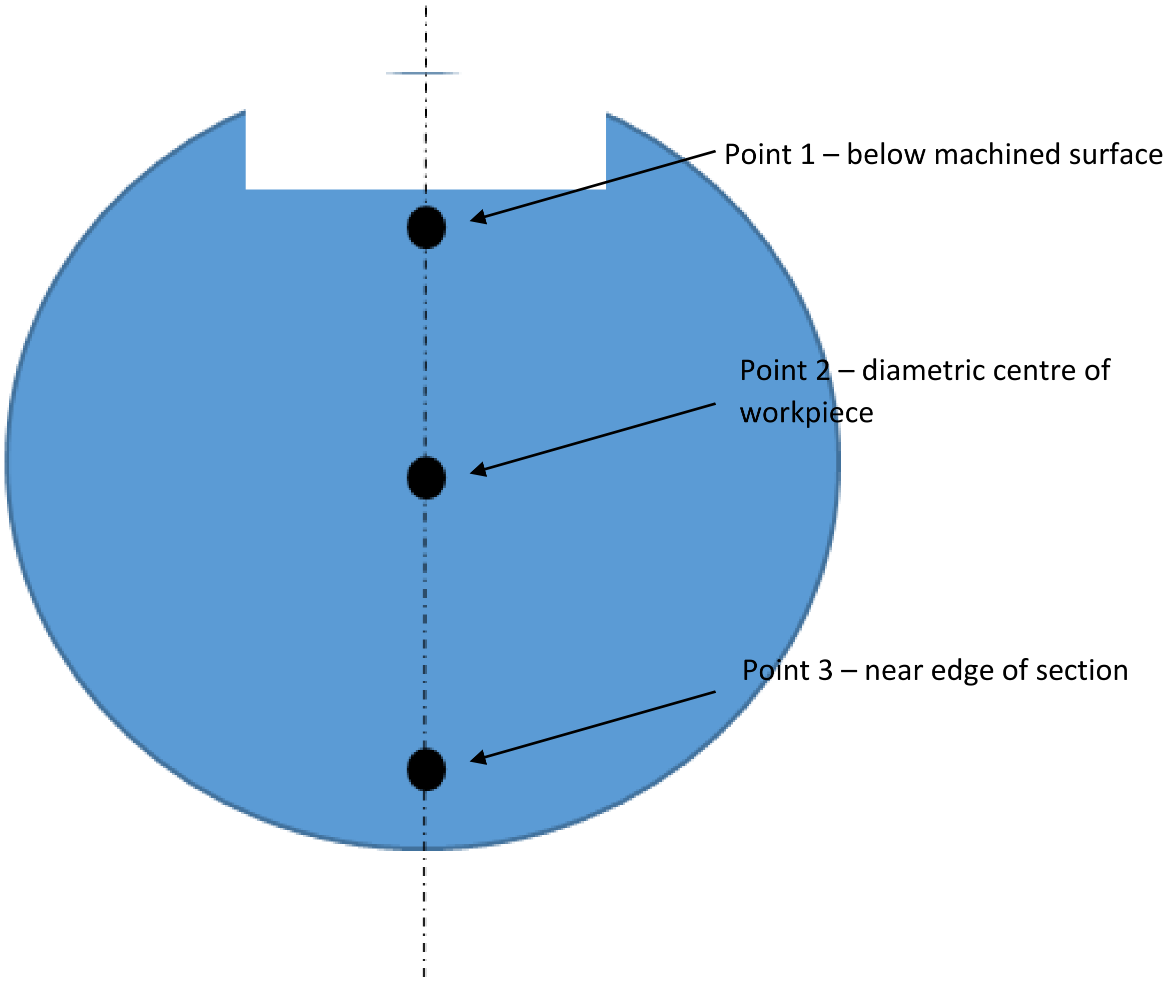


Figure 3.12. Position where microstructure images were captured

3.6 Study Limitations

The major limitation encountered during the study was keeping the liquid nitrogen in its liquid phase during the experiment. The vessel used is not sealed tight under pressure (as a safety precaution), which allows for nitrogen vapours to form and escape containment. Consequently, this reduces the efficiency of pre-cooling technique. This is essentially due to the design of the vessel in question which is used for artificial insemination in livestock. For future studies on the pre-cooling technique, it is recommended to use a vessel that allows for containment for longer periods.

CHAPTER 4
RESULTS AND DISCUSSION

4.1 Process Flow

Process flow charts (Figures 4.1-4.4) were developed for each sample being processed. Each chart consists of five process classifications:

1. Operation
2. Movement
3. Inspection
4. Delay
5. Storage

From the above, value is only added to the workpiece during the 'operation' stage. However, the other stages only contribute to the general housekeeping and preparation of the workstation for subsequent workpieces to be processed. To improve on the productivity from the process' point of view requires either:

1. Fewer stages in the processing cycle or
2. A higher ratio of the number of operations divided by the total number of stages in a complete processing cycle.

Further, from the analysis of each sample chart, it is possible to determine which were the most productive from the process point of view. Each treatment plan had the same number of operations as each had only one machining operation. But for each unique treatment plan, there are up to two additions to the process cycle. It can be observed therefore that processes of sample 1 and 4 are more productive since they have fewer steps, that is, five in total. Further, processes for sample 3 and 4 are less productive due to the addition of the pre-cooling stage (which are shared by both processes) and raising the temperature to ambient (unique to sample 3).

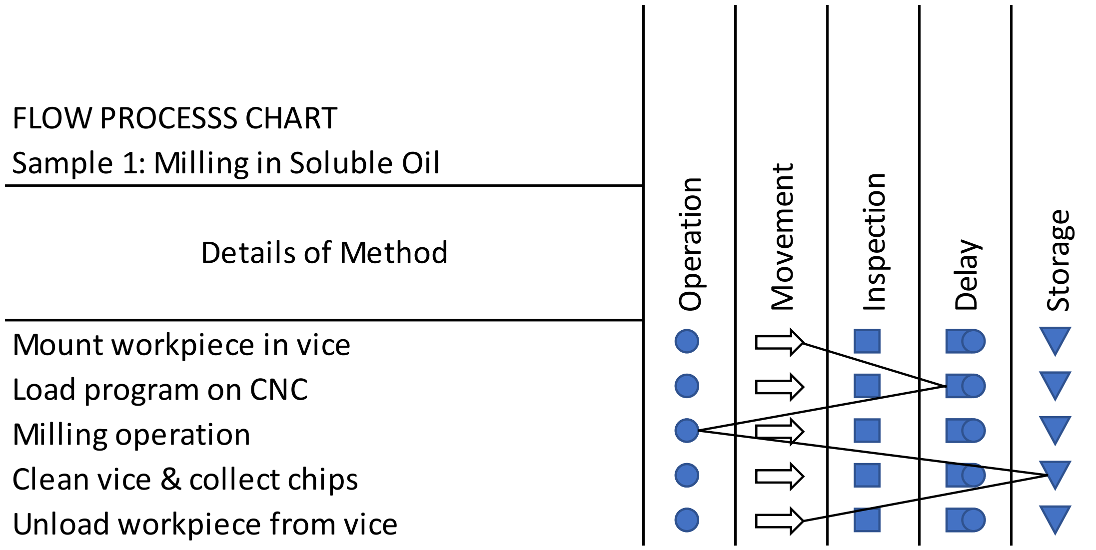


Figure 4.1. Flow Process Chart for Milling in Soluble Oil

From Figure 4.1,

$$\frac{No.\ of\ Operations}{Total\ No\ of\ Stages\ in\ Cycle} = \frac{1}{5} = 0.200$$

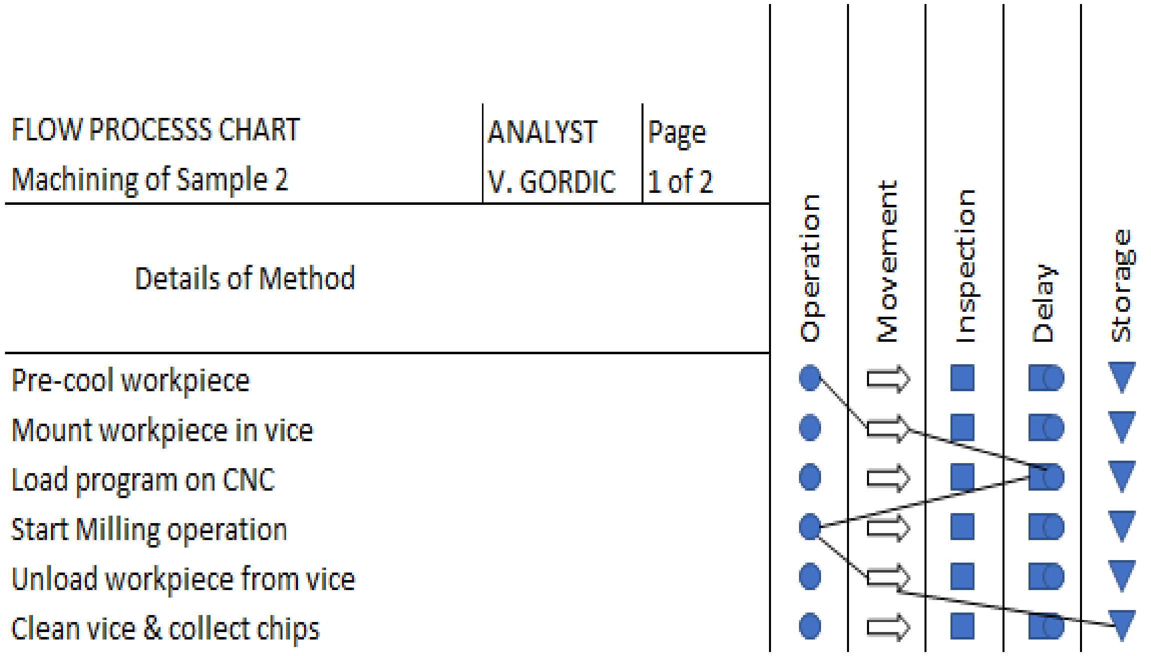


Figure 4.2. Flow Process Chart for Pre-cooling and Milling

From Figure 4.2,

$$\frac{No.\,of\ Operations}{Total\ No.\,Stages\ in\ Cycle} = \frac{2}{6} = 0.333$$

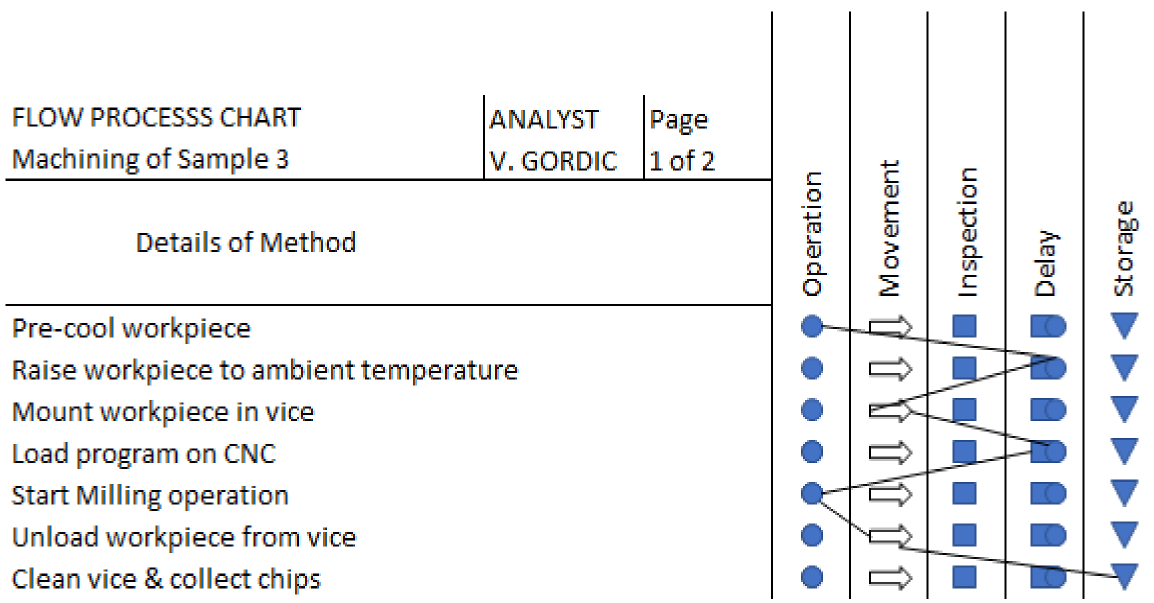


Figure 4.3. Flow Process Chart for Pre-cooling and Milling at Ambient Temperature

From Figure 4.3,

$$\frac{No. of\ Value\ Add\ Operations}{Total\ No.\ of\ Stages} = \frac{2}{7} = 0.286$$

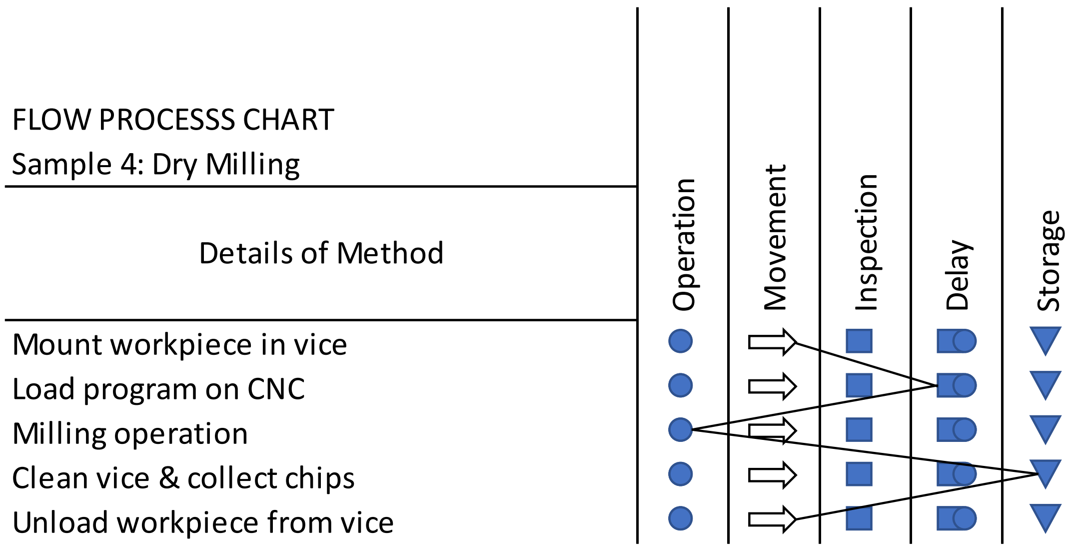


Figure 4.4. Flow Process Chart for Dry Milling

From Figure 4.4,

$$\frac{No. of\ Operations}{Total\ No. of\ Stages\ in\ Cycle} = \frac{1}{5} = 0.200$$

The ratios of operations to the total number of stages in the cycle for each treatment plan are summarized in the bar chart in Figure 4.5. The most productive treatment plan from the process point of view is pre-cooling and milling, with its higher ratio of operations to number of stages in cycle compared with milling at ambient, dry milling and milling under soluble oil.

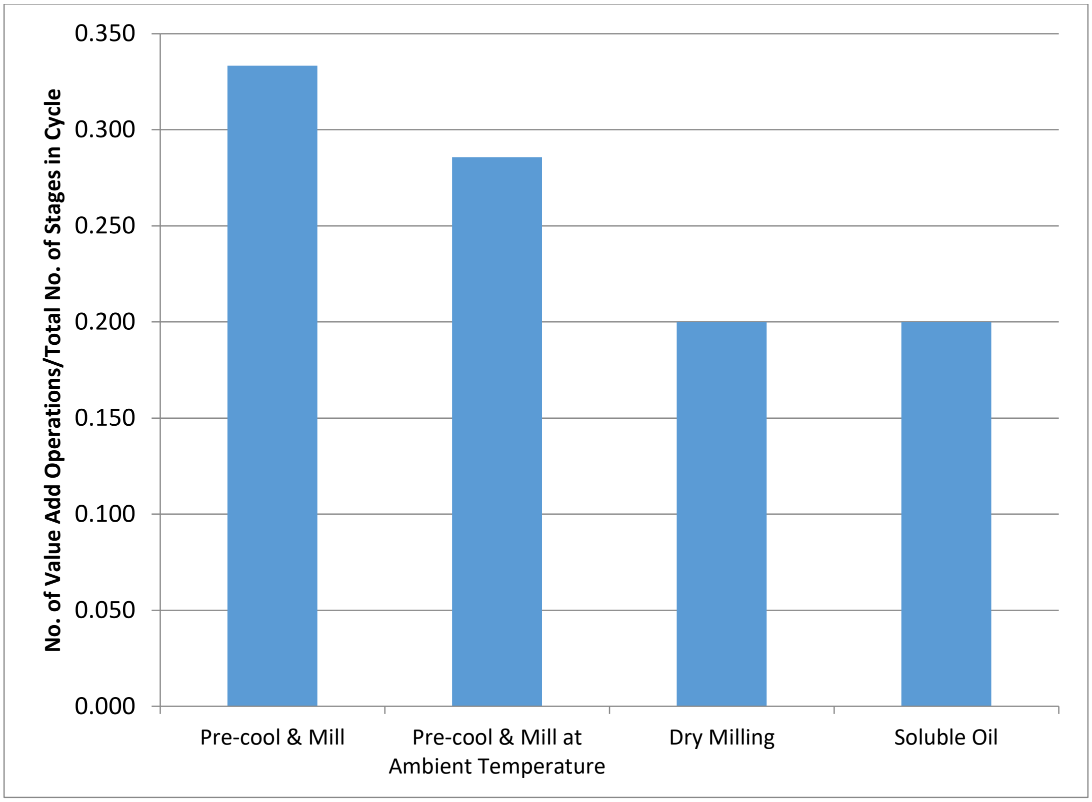


Figure 4.5. Ratio of Operation to the Total No of Stages for Each Treatment Plan

The results tabulated in Table 4.1 and presented in Figure 4.6 show that pre-cooling followed by milling at ambient temperature (24° C) increases the cycle time by three times. Pre-cooling and milling take 5 minutes longer than both dry milling and machining with soluble oil. The standard deviation (σ) of each sample is calculated using the formula:

$$\sigma = \sqrt{\frac{\sum x-\bar{x})^2}{n-1}} \qquad \text{Equation 4.1}$$

Where:

σ is the standard deviation for the sample

x is the individual data value for each workpiece

$\bar{x}$ is the sample mean

n is the number of data points

Table 4.1. Average Cycle Times of Each Treatment Plan **(s)**

Treatment Plan	Pre-cool & Mill at Ambient Temperature	Pre-cool & Mill	Dry Milling	Soluble Oil
Workpiece 1	4288	727	375	395
Workpiece 2	4290	725	419	360
Workpiece 3	4291	702	393	370
Workpiece 4	4299	709	384	403
Workpiece 5	4295	689	385	385
Workpiece 6	4290	700	395	384
Average Time (s)	**4292.17**	**708.67**	**391.83**	**382.83**
σ_τ	**4.07**	**14.90**	**15.11**	**15.79**

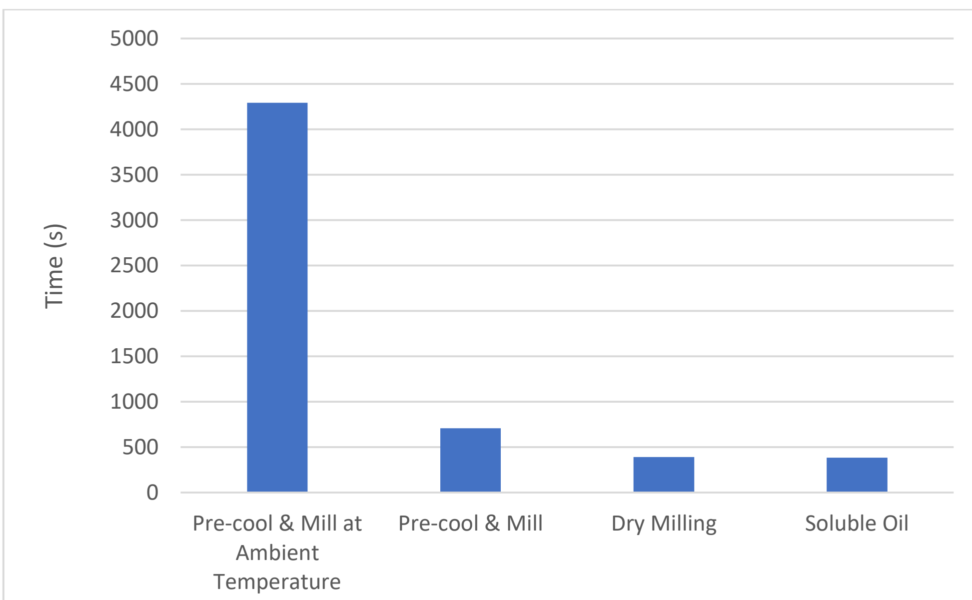


Figure 4.6. Average Cycle Times

Further breaking down the times that can be controlled by the machine operator, it was found, as presented in Table 4.2 and Figure 4.7, that it takes longer to mount the workpiece when it has been pre-cooled and milled. It was also observed from Figure 4.7 that after 2 runs, there was a dramatic drop in the time taken to mount the workpiece that had been pre-cooled. This drop is indicative of a learning curve the machine operator undertook as they gradually adapted to handling parts at near cryogenic conditions. Handling of workpieces at -40°C increases the risk of severe cold burns and frostbite. As seen in Figure 4.7 workpieces at -40°C increases the time taken to mount in the vice since tongs are used. For the remainder of the trials, the operator was able to handle the workpieces, using leather gloves. While this may be practical for smaller workpieces (under 1 kg); from an ergonomic point of view, it is not a recommended approach for workpieces larger than 1 kg.A pre-cooled and milled workpiece took 20-30 seconds to mount in the vice. A workpiece that had been machined using soluble oil took 10-20 seconds to mount in the vice. A workpiece that had been cooled and then raised to ambient temperature took 10-20 seconds to mount in the vice. The workpiece that had been dry milled took 5-10 seconds to mount.

Table 4.2. Mounting of Workpiece Times **(s)**

Treatment Plan	**Pre-cool & Mill at Ambient Temperature**	**Pre-cool & Mill**	**Dry Milling**	**Soluble Oil**
Workpiece 1	10	57	9	22
Workpiece 2	12	51	8	31
Workpiece 3	12	29	13	17
Workpiece 4	14	25	9	18
Workpiece 5	14	25	7	9
Workpiece 6	11	26	12	15
Average Time (s)	**12.17**	**35.50**	**9.67**	**18.67**
$\boldsymbol{\sigma_\tau}$	**1.46**	**13.26**	**2.13**	**6.75**

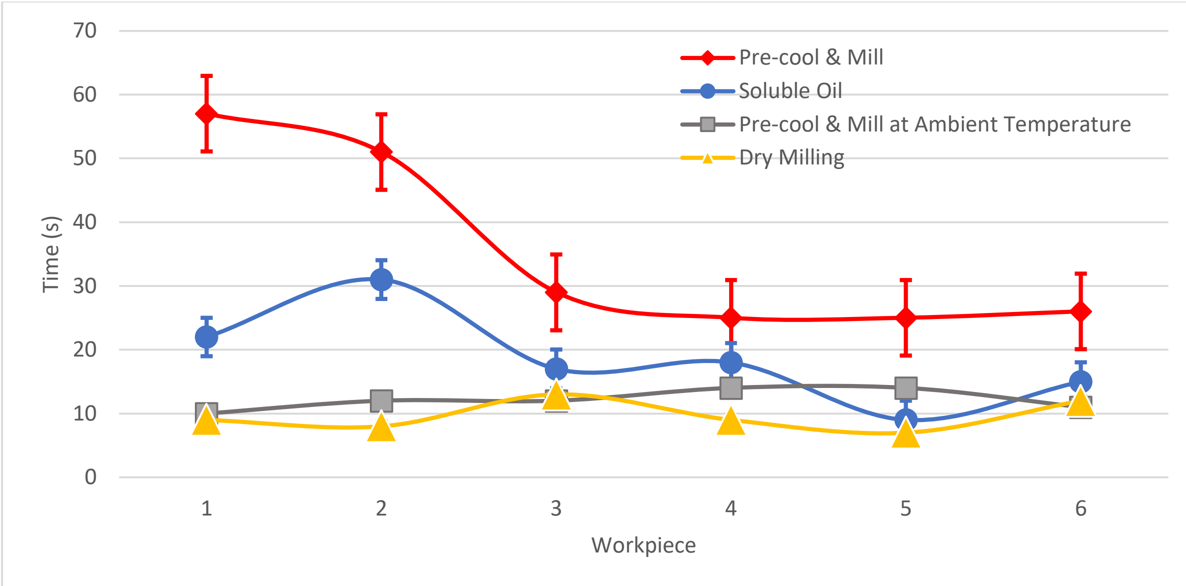


Figure 4.7. Time Taken to Mount Workpiece

It was observed from the data in Table 4.3 and Figure 4.8 that the best times for unloading a workpiece were achieved by the dry milling and pre-cooling and milling at ambient treatment plans. Pre-cooling and milling recorded the worst times.

Table 4.3. Unloading the Workpiece Times **(s)**

Treatment Plan	**Pre-cool & Mill at Ambient Temperature**	**Pre-cool & Mill**	**Dry Milling**	**Soluble Oil**
Workpiece 1	6	14	11	30
Workpiece 2	7	16	10	11
Workpiece 3	5	13	9	5
Workpiece 4	10	13	7	10
Workpiece 5	11	14	7	12
Workpiece 6	7	11	8	10
Average Time (s)	**7.67**	**13.5**	**8.67**	**13.0**
σ_τ	**2.34**	**1.64**	**1.63**	**8.67**

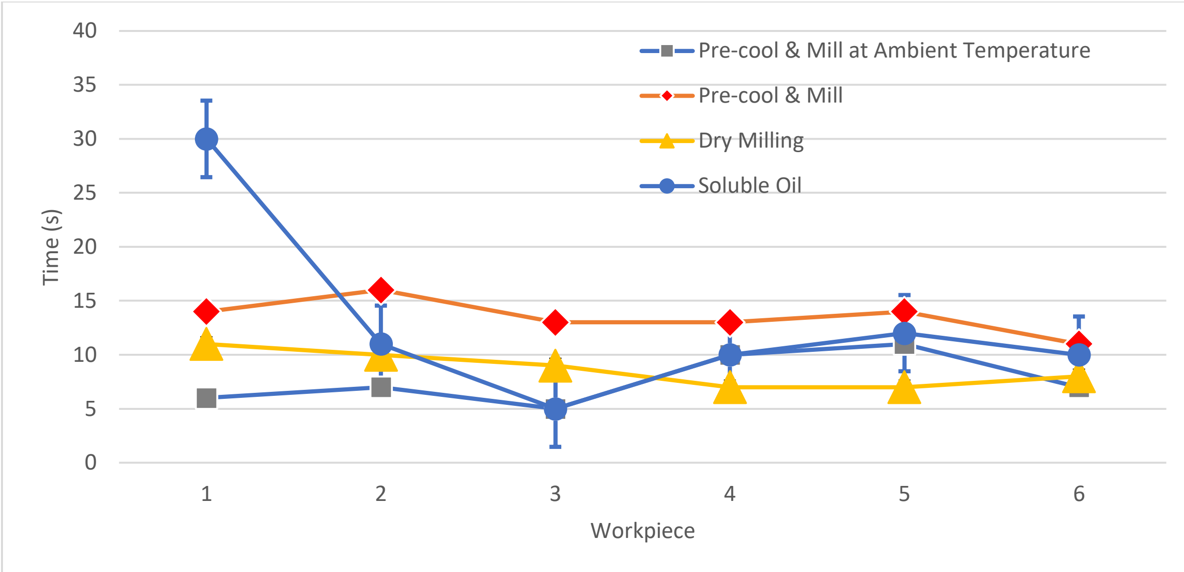


Figure 4.8. Time Taken to Unload the Workpiece

With regards to cleaning the vice, it was observed from Table 4.4 and Figure 4.9 that pre-cooling and milling treatment plan gave the best times. A possible reason for this that there is less moisture present when the part has been pre-cooled and milled, so chips do not adhere to the vice surface. For parts pre-cooled and milled at ambient temperature, it was observed that there was moisture present. This moisture came about as the film of frost melted at room temperature, when it was removed from the dewar. This frost caused the chips to adhere to the vice surface, which made cleaning more challenging.

Table 4.4. Cleaning of Vice Times (s)

Treatment Plan	**Pre-cool & Mill at Ambient Temperature**	**Pre-cool & Mill**	**Dry Milling**	**Soluble Oil**
Workpiece 1	34	8	17	25
Workpiece 2	28	8	62	6
Workpiece 3	30	10	36	9
Workpiece 4	35	7	31	29
Workpiece 5	28	8	28	26
Workpiece 6	28	17	33	16
Average Time (s)	**30.50**	**9.67**	**34.5**	**18.5**
$\boldsymbol{\sigma_\tau}$	**3.21**	**3.72**	**14.98**	**9.61**

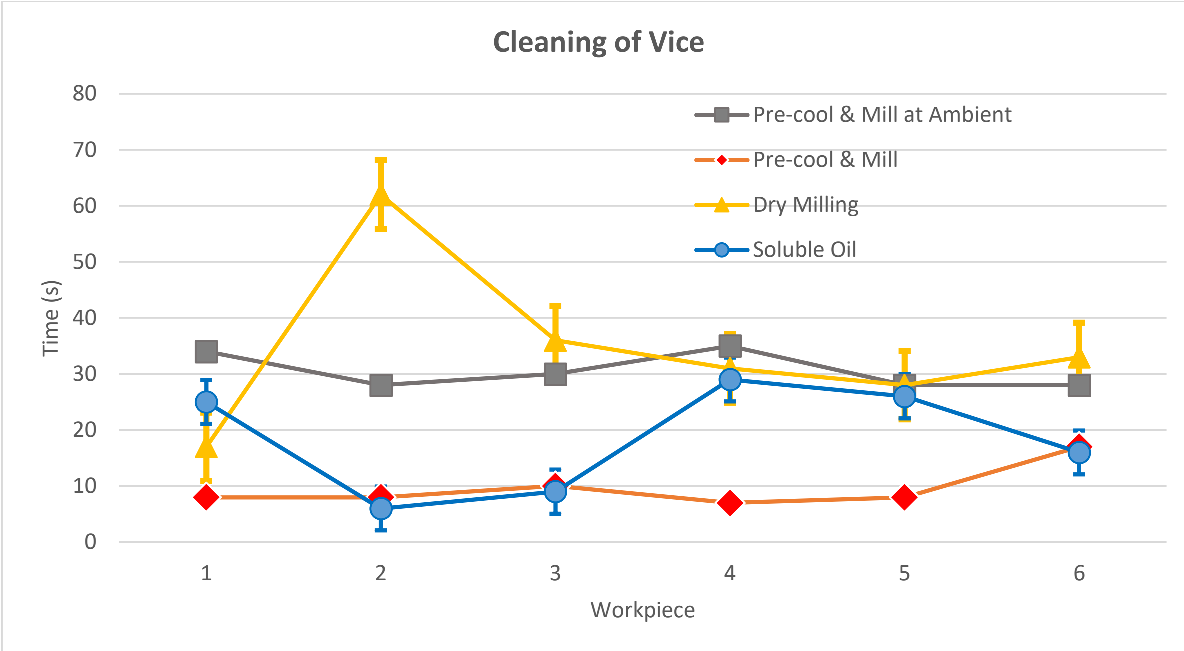


Figure 4.9. Time Taken to Cleaning the Vice

4.2 Surface Roughness

Table 4.5 and Figure 4.10 shows that workpieces machined using soluble oil showed the best surface roughness results in the range of 0.42 µm to 1.45 µm. An increasing trend in surface roughness was seen for workpieces that were pre-cooled and milled (Figure 4.10). With pre-cooled and machined workpieces Centre Line Average (CLA) values rising from 1.74 - 2.35 µm, shows that each part machined in sequence was progressively getting worse in surface texture. On the shop floor this upward trend becomes a quality control problem.

Table 4.5. Centre-line Average Values (µm)

Treatment Plan	Pre-cool & Mill at Ambient Temperature	Pre-cool & Mill	Dry Milling	Soluble Oil
Workpiece 1	2.21	1.74	0.94	1.07
Workpiece 2	2.43	1.79	2.50	1.16
Workpiece 3	2.20	1.90	1.40	0.97
Workpiece 4	2.35	2.08	2.50	0.42
Workpiece 5	2.50	2.20	1.54	1.45
Workpiece 6	2.50	2.35	0.75	1.05
Average CLA (µm)	**2.36**	**2.01**	**1.61**	**1.02**
σ_{CLA}	**0.135**	**0.242**	**0.751**	**0.338**

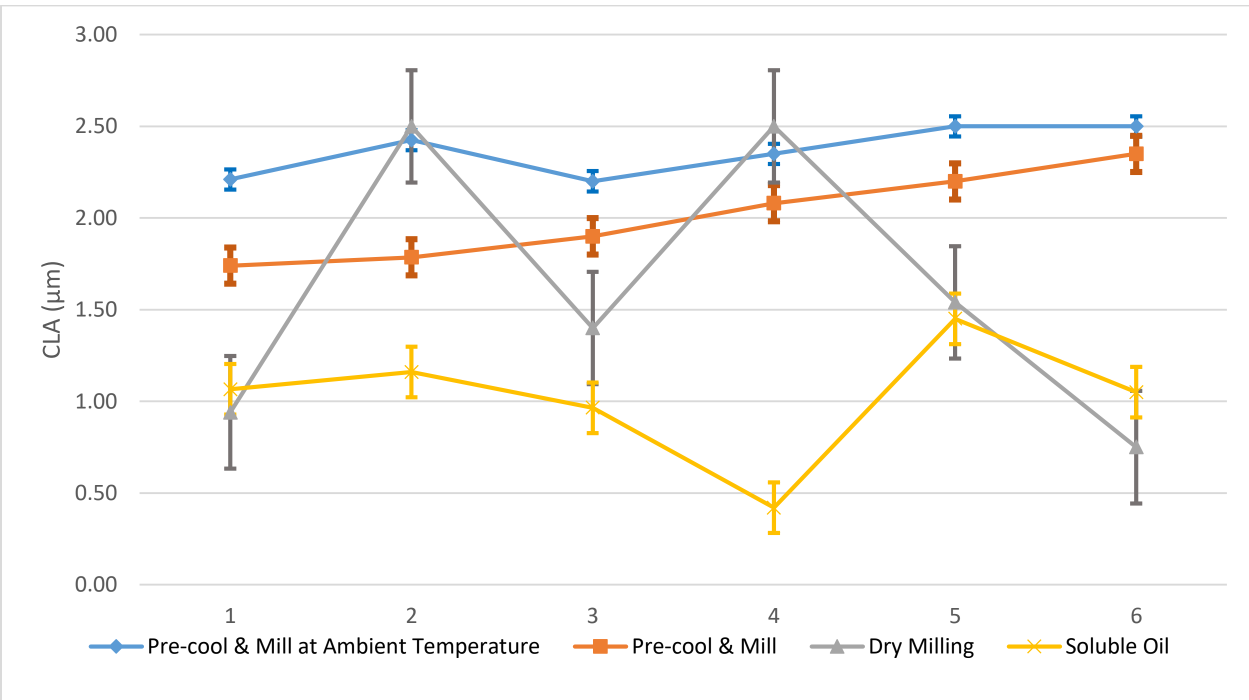


Figure 4.10. Centre-Line Average (CLA) Values

4.3 Material Removal Rate

From the data in Table 4.6 and Figure 4.11 it is evident that the highest material removal rates (MRR) were seen for workpieces that were pre-cooled and raised to ambient temperature: 0.159 -0.299 g/s. Workpieces machined using soluble oils had material removal rates in the range of 0.227 – 0.261 g/s. Significantly lower material removal rates were seen for workpieces that were pre-cooled and machined, falling in the range of 0.142 – 0.169 g/s. That of dry-milling was in the range of 0.161 – 0.175 g/s.

It was observed during the milling of the pre-cooled and machined workpieces that the first pass of the tool removed very little or no material at all. The first pass was more characteristic of a finish cut. The second pass, however, was characteristic of a rough cut than a finish cut. This anomaly is as a result of contraction of the part after it was removed from the dewar. The CNC VMC machine does not have any in-built features or sensors to determine the temperature of the part being machined. Therefore, it is unable to automatically adjust the program to compensate for the depth of cut. However, it has tool length compensation which can be used when the temperature induced dimensional changes have been accounted for by the machine operator and the part program modified accordingly. Research has been done using 14 temperature sensors to study actual temperature fields around the machine and using a proposed thermal compensation system, variations in displacement on the x- and y- axis can be controlled within 20 µm (Chen, et al. 2016)

Table 4.6. Material Removal Rate (g/s)

Treatment Plan	Pre-cool & Mill at Ambient Temperature	Pre-cool & Mill	Dry Milling	Soluble Oil
Workpiece 1	0.16	0.15	0.28	0.25
Workpiece 2	0.17	0.16	0.16	0.25
Workpiece 3	0.17	0.16	0.28	0.26
Workpiece 4	0.17	0.17	0.30	0.26
Workpiece 5	0.17	0.14	0.28	0.25
Workpiece 6	0.16	0.16	0.27	0.23
Average Cycle Time (s)	**0.17**	**0.16**	**0.26**	**0.25**
σ	**0.005**	**0.009**	**0.051**	**0.012**

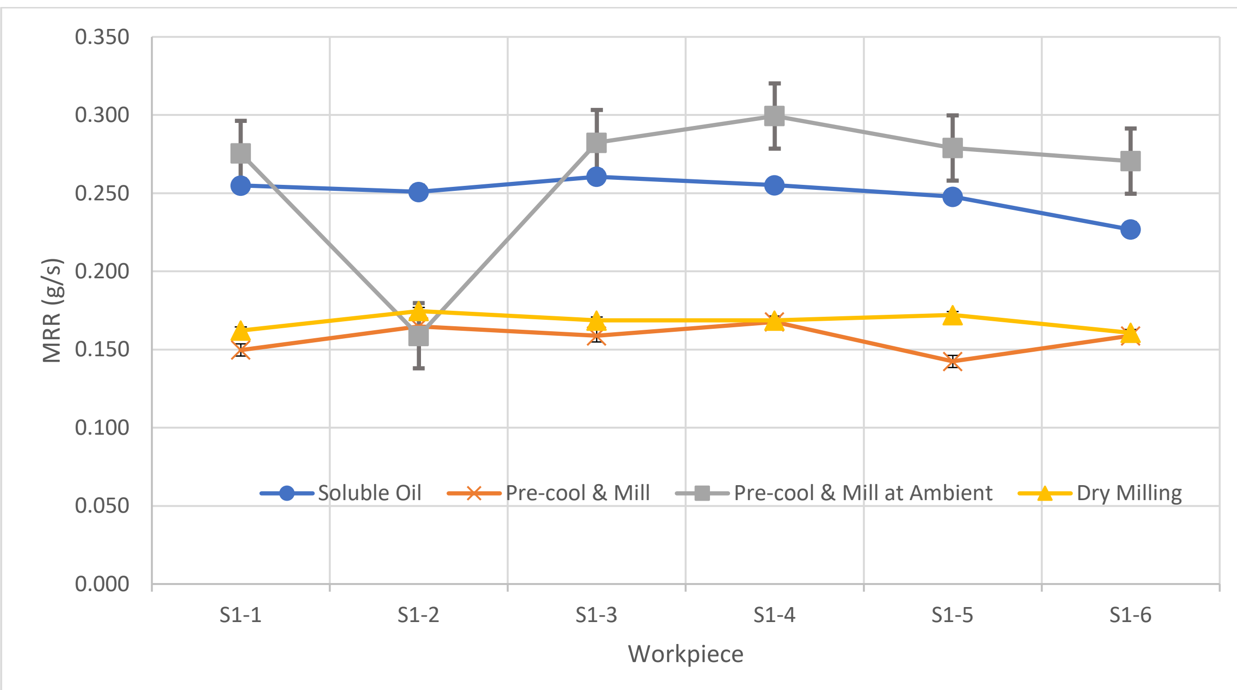


Figure 4.11. Material Removal Rate (MRR)

4.4 Temperature Profiling of Machining Operation

Thermal images (Figures 4.12-4.15) captured for workpieces under different treatment plans shows that workpieces machined using soluble oils had the lowest temperatures, not exceeding 24.1 °C. Workpieces machined under cryogenic treatment plans and machined recorded temperatures as high as 150 °C. Dry milled workpieces were also recording temperatures as high as 150 °C at the tool-work-piece interface.

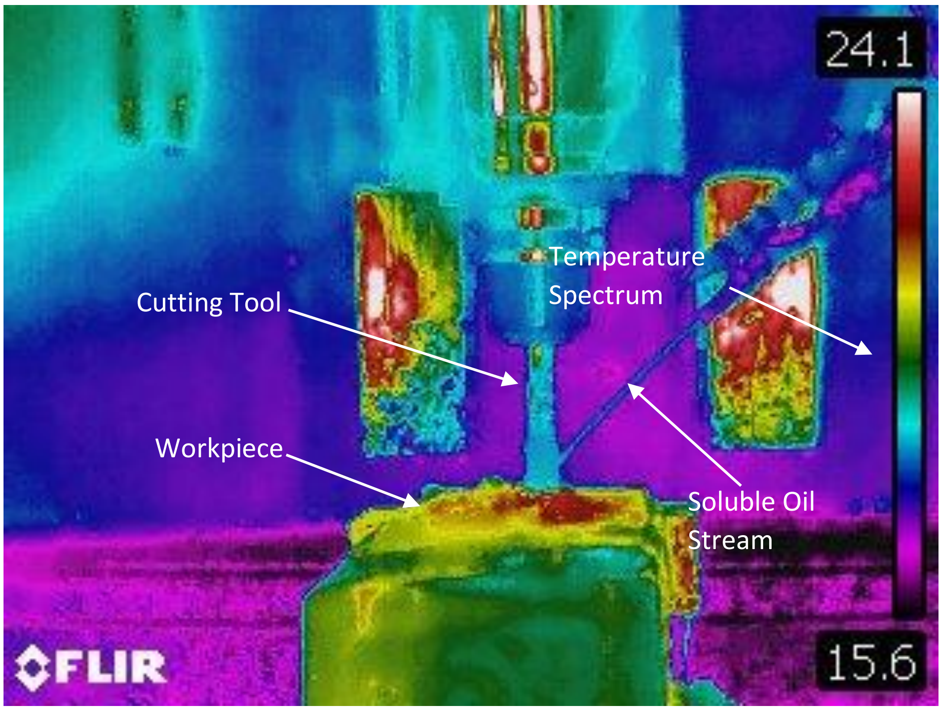


Figure 4.12. Thermal Image of Workpiece Machined Using Soluble Oil

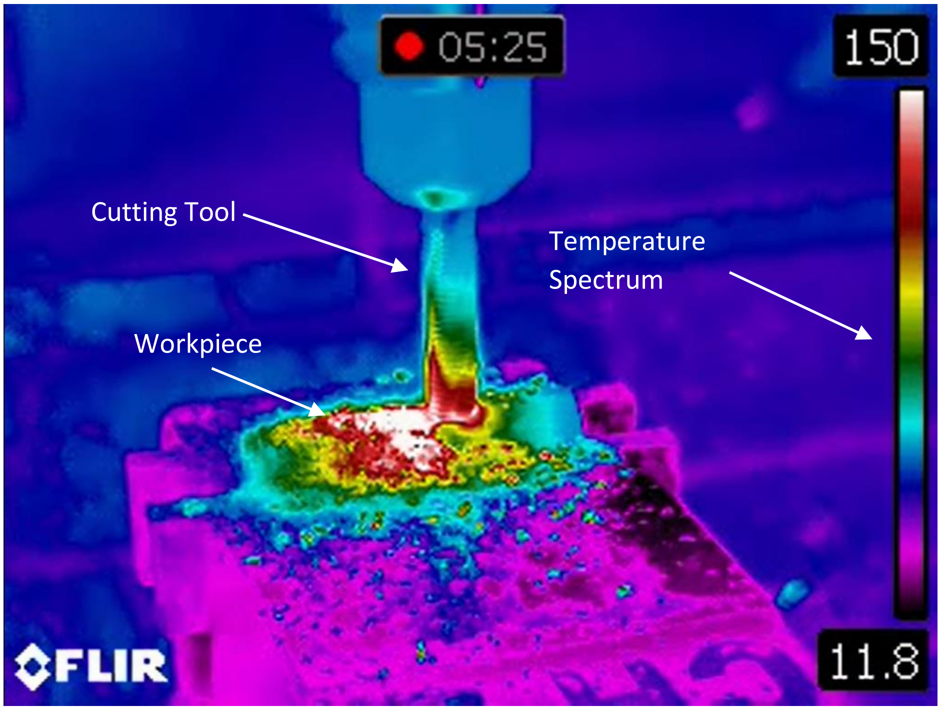


Figure 4.13. Thermal Image of Workpiece Pre-cooled and Machined

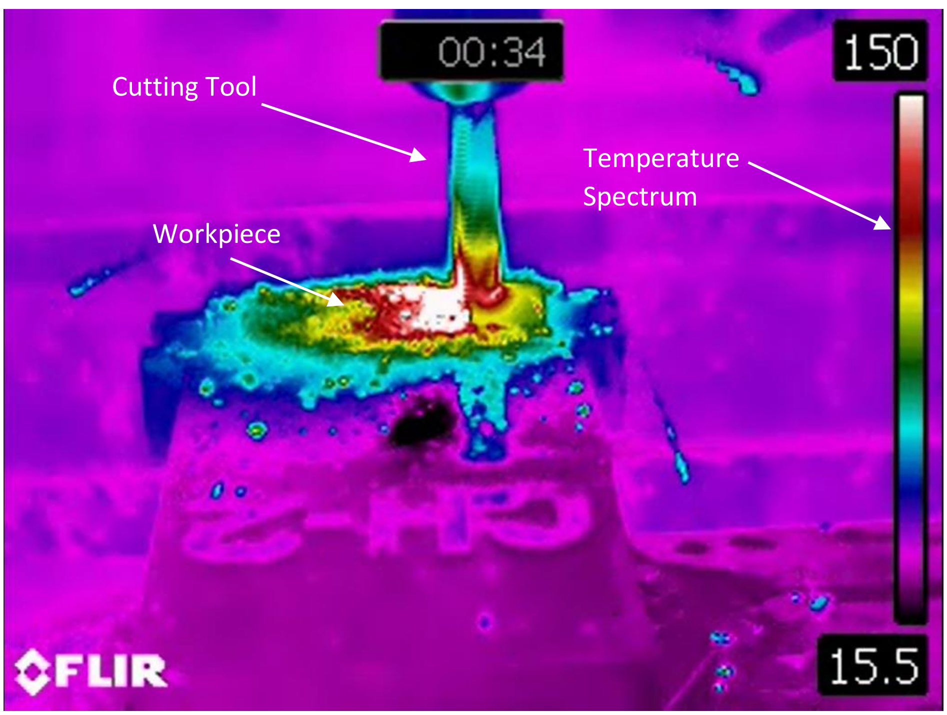


Figure 4.14. Workpiece Pre-cooled and Raised to Ambient Temperature

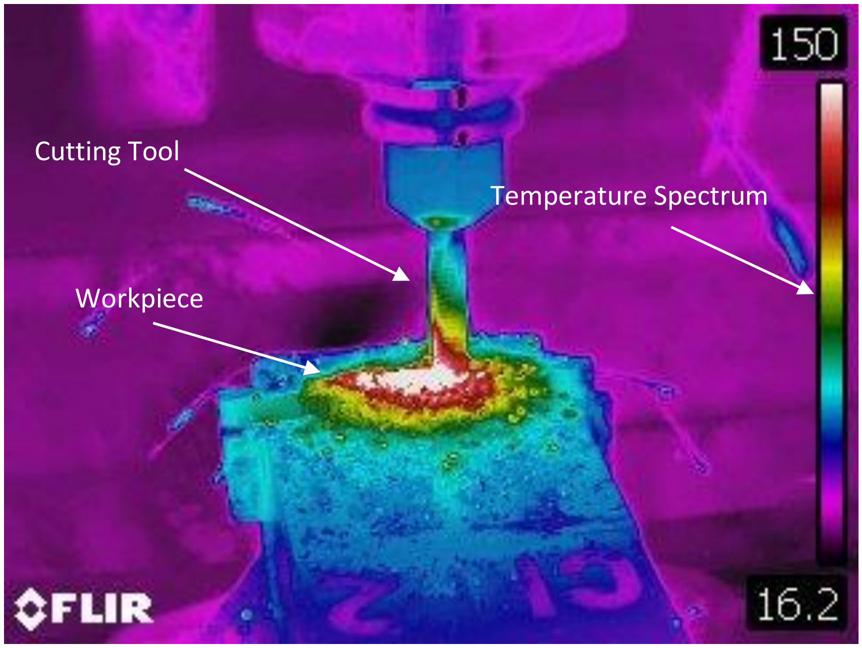


Figure 4.15. Thermal Image of Workpiece Dry Milled

Figure 4.16 shows how workpieces that were cryogenically cooled were extracted from the liquid nitrogen Dewar at temperatures as low as -40 °C, having been pre-cooled for 5 minutes. Workpieces that were cooled to -40°C and raised to ambient temperature (24ºC) took approximately 1 hour to get to ambient temperature. This was the contributing factor to increased cycle time.

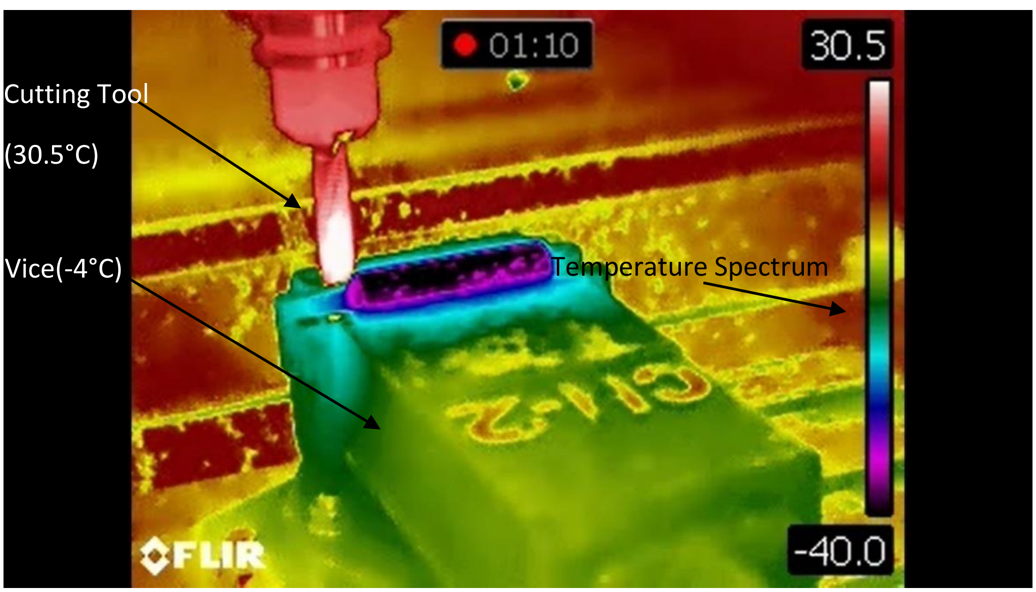


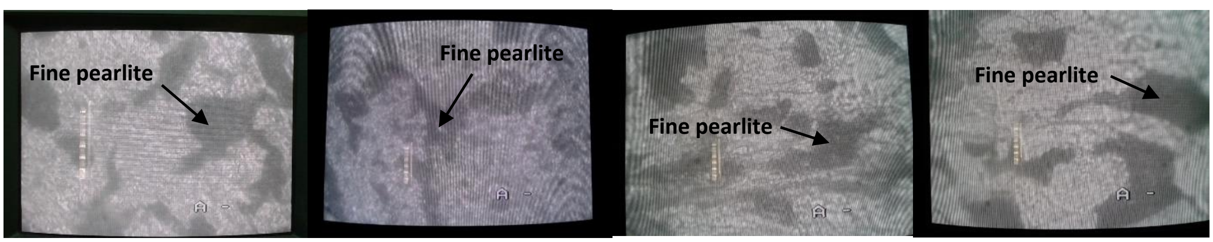
Figure 4.16. Thermal Image of Pre-cooled Workpiece Immediately Mounted on Vice

4.5 Microstructure Analysis

Images from all four samples are grouped together to compare the form and composition of the grain (Figures 4.17 to 4.19). Dark areas on the optical micrograph show regions were fine pearlite has developed. Pearlite is a mixture of two phases, ferrite and cementite (Bhadeshia 2017). A high presence of pearlite has a tendency to make machining difficult. To alleviate this the steel needs to undergo heat treatment in order for the cementite to spherodise.

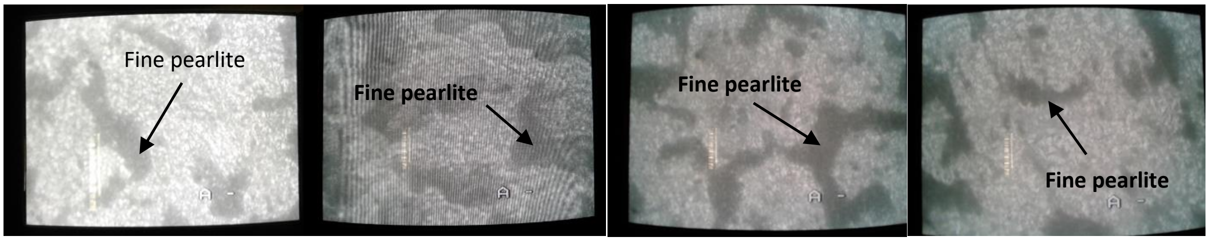
The micrographs of each sample show that the area under the machined surface (Point 1 on Figure 3.12) had a relatively equal presence of pearlite of random but somewhat elongated shapes. A similar arrangement is seen at mid-points (Point 2 on Figure 3.12) and end points (Point 3 on Figure 3.12) of each sample workpiece.

This reveals that the pre-cooling process has no direct effect on the microstructure of steel with regards to its phase formations.



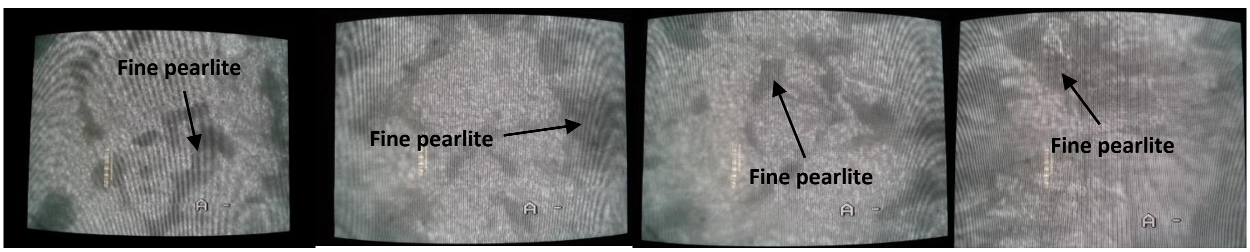
a) b) c) d)

Figure 4.17. Microstructure Images taken at Point 1 (see Figure 3.12) below the machined surface a) Soluble oil b) Pre-cool and Mill c) Pre-cool, raise to ambient temperature and mill d) Dry Milling



a) b) c) d)

Figure 4.18. Microstructure Images taken at Point 2 (see Figure 3.12) at the diametric centre of the workpiece a) Soluble oil b) Pre-cool and Mill c) Pre-cool, raise to ambient temperature and mill d) Dry Milling



a) b) c) d)

Figure 4.19. Microstructure Images taken at Point 3 (see Figure 3.12) near the lower edge of the workpiece section a) Soluble oil b) Pre-cool and Mill c) Pre-cool, raise to ambient temperature and mill d) Dry Milling

CHAPTER 5

CONCLUSION, RECOMMENDATIONS & AREAS OF FUTURE RESEARCH

5.1 Conclusion

The research was successful in determining the effects of a pre-cooling treatment plan on factors affecting human and machine productivity. It was discovered that the low temperatures (-40°C) encountered by the machine operator during the pre-cooling process of steel (AISI/SAE No. 1020) workpieces in liquid nitrogen makes handling of workpieces more difficult. The research revealed that the use of protective gloves to handle the workpieces increases the setup time and from an ergonomic perspective hinders human productivity. The research also revealed that the part surface quality is poorer when it has been pre-cooled and milled immediately as compared to using other conventional cooling methods. The research also revealed that the CNC VMC machine does not respond positively to temperature-induced dimensional changes of the workpiece. It is therefore recommended to account for the thermal contractions and expansions during the programming of the CNC VMC machine, by making careful use of the tool length compensation function. From a process point of view, pre-cooling and machining is a more productive approach to take. Applying it to pre-cooling small parts (less than 1 kg) in bulk is practical, provided that the cryogen bath has the ability to retain liquid nitrogen for long periods without incurring losses. However, the machine operator must be wary that there will be temperature-induced dimensional changes that can have a direct effect on the accuracy of the part dimensions and the surface texture. From the foregoing, it can be concluded that the pre-cooling method of steel (AISI/SAE No. 1020) workpieces reduces productivity on the shop floor for both the machine operator and the CNC VMC machine combined, at small quantities; but has the potential for increasing productivity for the process designer, provided that the quantities processed are of small mass and in high quantities.

5.2 Recommendations

To improve further on the research method employed and the results to be more interesting, the author proposes an increased number of specimens per sample. Different operations such as slab milling and drilling can also be studied under cryogenic conditions to determine the effect of pre-cooling on productivity under each.

5.3 Areas of Future Research

For future research, it is recommended that studies be undertaken on the CNC VMC to determine the effect of a direct supply of liquid nitrogen at the tool-workpiece interface on machine and human productivity.

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APPENDICES

Appendix A: Machine Program For Milling Operation

CNC Program for Milling of Sample 1

```
N5      G40 G54 G17 G69 G80;
N15     G91 G28 Z0;
N25     T5 M6;
N35     S596 M3;
N45     G00 G90 G41 X-5 Y56 D54;
N55     X-4;
N65     G43 Z10 H5;
N75     G01 Z-5 M8 F120;
N85     X120;
N95     Z20;
N115    G00 G90 G41 X-5 Y55 D52;
N125    X-4;
N135    G43 Z10 H5;
N145    G01 Z-10 F72;
N155    X120;
N165    G91 G28 Z0 Y0 X0 M9;
N175    M30;
```

CNC Program for Milling of Samples 2, 3 & 4

```
N5      G40 G54 G17 G69 G80;

N10     G91 G28 Z0;

N15     T5 M6;

N20     S596 M3;

N25     G00 G90 G41 X-5 Y56 D54;

N30     X-4;

N35     G43 Z5 H5;

N40     G01 Z-5 F120;

N45     X100;

N50     Z20;

N55     G00 G90 G41 X-5 Y55 D52;

N65     X-4;

N70     G43 Z5 H5;

N75     G01 Z-10 F72;

N80     X100;

N85     G91 G28 Z0 Y0 X0;

N90     M30;
```

Appendix B: Liquid Nitrogen Material Safety Data Sheet (Source: Afrox)

AFROX
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MATERIAL SAFETY DATA SHEET (MSDS)
LIQUID NITROGEN

(Please ensure that this MSDS is received by an appropriate person)

DATE: June 2015 Version 3

Ref. No.: MS006

1 PRODUCT AND COMPANY IDENTIFICATION

Product Name	LIQUID NITROGEN
Chemical Formula	N_2
Company Identification	Afrox Zambia Ltd Plot No 901 Chisokone Avenue Ndola, Zambia Tel. No: +260212611801-5 Fax No: +260212614651
EMERGENCY NUMBER	**+260212611801** **(24 hours)**

2 COMPOSITION/INFORMATION ON INGREDIENTS

Chemical Name	Nitrogen
Chemical Family	Inert gas
Chemical Abstract Service Number (CAS No.)	7727-37-9
United Nations Number (UN No.)	1977
Emergency Response Guide Number (ERG No.)	120
Hazchem Warning	2.2 Non- flammable gases

3. HAZARDS IDENTIFICATION

Main Hazards: Extremely cold liquid (-196°C) can cause severe frostbite and cold burns. Nitrogen gas can act as an asphyxiant as it dilutes the concentration of oxygen in air below the levels necessary to support life. Rescue workers may require self-contained breathing apparatus and protective clothing.

Adverse Health Effects: Inhalation of nitrogen in excessive concentrations can result in dizziness, nausea, vomiting, loss of consciousness, rapid breathing, asphyxiation without

Biological Hazards: Contact between the skin and liquid Nitrogen or uninsulated piping or vessel containing it, can cause severe cold burn injuries.

Environmental Hazard: No known effects to the environment, but in confined space ensure adequate ventilation.

Chemical Hazards. Nitrogen is relatively inert to most materials under ordinary conditions. It becomes more reactive at elevated temperatures when it combines with hydrogen, oxygen and some metals.

3.1. Label elements

- **Labelling pictograms**

- **Signal word:** Warning
- **Hazard Statements:**

H281	Contains refrigerated gas: may cause cryogenic burns or injury

- **Precautionary Statements**

P282	Wear insulating gloves/face shield/eye protection.
P336+P315	Thaw frosted parts with lukewarm water. Do not rub affected area. Get immediate medical examination
P403	Store in well ventilated place.

4 FIRST AID MEASURES

Skin/Eye Contact: Immediately flush with large quantities of tepid water for at least 15 minutes.
In case of frostbite, spray with tepid water for at least 15 minutes. Apply a sterile dressing, and obtain medical assistance.

Ingestion or Swallowing: Ingestion is not considered a potential route of exposure

Inhalation: In high concentration may cause asphyxiation. Symptoms may include loss of mobility/consciousness. Remove victim to fresh air wearing self-contained breathing apparatus. Apply artificial respiration if victim is not breathing. Obtain medical assistance.

5 FIRE FIGHTING MEASURES

Special hazards: Exposure to fire may cause containers or vessels to rupture/explode. Nitrogen is non-flammable.
Extinguishing media As Nitrogen is an inert gas; it does not contribute to a fire, but could help with the extinguishing by reducing the oxygen content of the air by dilution to below the level to support combustion. Keep the PCC, bulk tank or tanker cool by spraying with water if exposed to fire.

Special protective equipment for fire fighters: In confined space use self-contained breathing apparatus.

6 ACCIDENTAL RELEASE MEASURES

MATERIAL SAFETY DATA SHEET (MSDS)
LIQUID NITROGEN
(Please ensure that this MSDS is received by an appropriate person)

Personal Precautions Do not enter any area where nitrogen has been spilled or a serious leak has occurred unless tests have shown that it is safe to do so. If the area must be entered by the emergency personnel, self-contained breathing apparatus, leather gloves, and appropriate foot and leg protection should be worn.

Environmental Protection Liquid nitrogen poses no harm to the environment.
Small spills Shut off the source of escaping nitrogen. Ventilate the area.

Large spills Evacuate the area. Shut off the source of the spill/leak if this can be done without risk. Prevent liquid nitrogen from entering sewers, basements and work pits. If tanker has overturned, do not attempt to right or move it. CONTACT THE NEAREST AFROX BRANCH. Restrict access to the area until is fully ventilated. Ventilate the area using forced-draught if necessary. Monitor the surrounding area for Oxygen level. Oxygen must be at least 19.5% before personnel may be allowed into the area without self-contained breathing apparatus. Large spills can also be dispersed using a water fog spray.

7 HANDLING AND STORAGE

Safe handling When Liquid nitrogen is held in any closed vessel or space, there must be an appropriate pressure relief device because of the large pressure increases that can occur as the liquid nitrogen is vaporised. Use only containers designed for cryogenic liquids. Do not use any stopper or other device that will interfere with venting of gas. Unauthorised modification to these liquid containers is forbidden.

Storage Store in a cool and well-ventilated area. If containers are stored outside, provide shelter to protect against extreme weather conditions. Excessive exposure to any heat could cause the internal pressure to increase significantly with the consequent loss of liquid product that has vaporised. Keep out of reach of children.

Personal Protective Equipment Wear face shield; leather gloves and leather apron when using or decanting liquid nitrogen. Do not put hands (even in the best gloves) in the cryogenic liquid. Wear safety boots and overalls.

8 EXPOSURE CONTROLS/PERSONAL PROTECTION

Occupational Exposure Hazards As nitrogen is a simple asphyxiant, avoid any areas where spillage has taken place unless entering with self-contained breathing apparatus. Only enter once testing has proved the atmosphere to be safe.

Engineering Control Measures Engineering control measures are preferred to reduce exposure to oxygen-depleted atmospheres. General methods include forced-draught or exhaust ventilation systems. Ensure that sufficient fresh air enters at, or near, floor level.

Personal Protection Face shield, leather gloves, leather apron and Safety shoes, or boots, should be worn when handling containers.

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MATERIAL SAFETY DATA SHEET (MSDS)
LIQUID NITROGEN

(Please ensure that this MSDS is received by an appropriate person)

9 PHYSICAL AND CHEMICAL PROPERTIES

PHYSICAL DATA

Chemical Symbol	N_2
Molecular Weight	28,01
Boiling point @ 101,325 kPa	-195,8°C
Density, liquid @ boiling point	803,6 kg/m^3
Relative density (Air = 1) @ 101,325 kPa	0,967
Latent heat of vaporisation @ boiling point	199,1 kJ/kg
Colour	None
Taste	None
Odour	None

10 STABILITY AND REACTIVITY

Conditions to avoid The dilution of the oxygen concentration in the atmosphere to levels which cannot support life.

Incompatible At the temperature of liquid nitrogen ordinary carbon steels, and most alloy steels lose their ductility, and are therefore considered to be unsatisfactory.

Materials Metals and alloys that have satisfactory ductility include austinitic stainless steel (i.e. types, 304 and 316), and nickel-chromium alloys, nickel, Monel 400, copper, brasses, bronze and aluminium.

Hazardous Decomposition Products None

11 TOXICOLOGICAL INFORMATION

Acute Toxicity	None
Skin & eye contact	none
Carcinogenicity	Severe cold burns could result in cancerous growth.
Reproductive Hazards	No known effect

For further information see Section 3. **(Adverse Health Effects).**

12 ECOLOGICAL INFORMATION

It does not pose a hazard to the ecology but it can cause frost damage to vegetation

13 DISPOSAL CONSIDERATIONS

Disposal Methods Small amounts may be allowed to evaporate to atmosphere under controlled conditions. Large amounts should only be handled by the gas supplier.

Disposal of packaging The disposal of containers must only be handled by the gas supplier.

14 TRANSPORT INFORMATION

ROAD TRANSPORTATION

United Nations Number (UN No.)	1977
Emergency Response Guide (ERG No.)	120
Hazchem warning	2.2 Non-flammable gases

SEA TRANSPORTATION

IMDG	1977
Class	2.2
Packaging group	
Label	Non-flammable gas

AIR TRANSPORTATION

ICAO/IATA Code	1977
Class	2.2
Packaging group	
Packaging instructions	
- Cargo	202
- Passenger	202
Maximum quantity allowed	
- Cargo	500 kg
- Passenger	50 kg

15 REGULATORY INFORMATION

Risk Phrase	Description	Safety Phrase	Description
R 35	Cause severe burns	S 2	Keep out of reach of children
R 41	Risk of serious damage to eyes	S9	Keep container in a well-ventilated area
R 44	Risk of explosion heated under confinement	S12	D o not keep the container sealed
R45	May cause cancer	S15	Keep away from heat
		S36	Wear suitable protective clothin g
		S51	Use only in well-ventilated areas

Refer to SANS 10234 for explanation of the above.

16 OTHER INFORMATION

This MSDS has been compiled using the following sources of information;

Compressed Gas Association, Arlington, Virginia
Handbook of Compressed Gases - 3rd Edition
Matheson. Matheson Gas Data Book - 6th Edition
SANS 10234 – Globally Harmonised System of classification and labelling oc chemical substances
SANS 11014-1- Safety Data Sheet for chemical products.
Emergency Response Handbook SABS – Annex A of SABS 0232-3

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