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Effect of Pre-Cooling Low Carbon Steel in Liquid Nitrogen on Productivity of a Milling Operation

Vladislav Gordic
MEng Student, Department of Mechanical Engineering
School of Engineering, University of Zambia
Lusaka, Zambia

Dr. Henry M. Mwenda
Department of Mechanical Engineering
School of Engineering, University of Zambia
Lusaka, Zambia

Dr. Terence Malama
School of Mechanical, Industrial & Aeronautical Engineering
University of the Witwatersrand
Braamfontein East Campus, Yale Road
Johannesburg, South Africa

***Abstract*—In machining operations, 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 shopfloor productivity. This research sought to study the impact that pre-cooling of mild steel had on human and machine productivity. 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. Results of the pre-cooling treatment plan presented three significant effects on productivity. Firstly, handling time of workpieces at -40°C was higher than when the parts were at ambient temperature. Secondly, the pre-cooled workpiece itself served as the heat sink. Heat from the cutting zone was not adequately dissipated away from the cutting zone. Thirdly, the machine did not have any feature that could compensate for material contraction/expansion due to temperature. The research demonstrated the importance of accounting for the thermal contractions and expansions during the CNC programming. Reduction in human productivity when handling workpieces cooled to sub-zero temperatures was also an important factor**

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

I. 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 [1]. There are known health risks for machine operators working in an environment where there is a presence of the emulsion mist [2].

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 [1]. It remained to be known what factors could be controlled at the interface between the machine operator and the cryogenic system to improve productivity. This study aimed to provide a clear answer to this unknown.

II. LITERATURE REVIEW

A. *Coolant Applications in Machining*

Problems related to machining operations are caused by heat produced at the tool and workpiece interface. In machining operations, 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 [3]. An equation to predict the increase in temperature at the interface of the cutting tool and chip is given by Cook [4]:

$$\Delta T = \frac{0.4U}{\rho C}\left(\frac{v t_o}{K}\right)^{0.333} \qquad \text{Equation 1}$$

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 [5]:

$$T = Kv^m \qquad \text{Equation 2}$$

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

Due to the excessive heat generated, application of cutting fluids is a necessary means to control temperatures for optimal cutting conditions. According to Groover, cutting fluid is any liquid or gas that is applied directly to the machining operation to improve cutting performance [3].

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.

There are various methods in which cutting fluids are applied to machining operations. 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 [6].

B. 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 [7]. Cryogenic technology in its earliest stages was mainly used in oxygen-acetylene welding and oxygen furnaces for steel production [8].

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 [8].

The effect of cryogenic treatment on the tool materials was first reported by Gulyaev 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 [9]. Studies have found that using cryogenic machining methods increases tool life by up to four times [10]. Additionally, cryogenic machining methosds improves the machinability of low carbon steels by reducing the ductility and toughness [11]. 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).

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 or the combination of these techniques [12]. 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.

C. Machine and Human Productivity

Productivity can be 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 [13]. Productivity is usually expressed in terms of a ratio of output to input:

$$Productivity = \frac{Output}{Input} \qquad \text{Equation 3}$$

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

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 of a full-casting design with large-sized ball screws and sliding guideways, these provide for digital control and drive for precision [14].

Malama 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 [15]. Figure 1 and equation 4 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 [16]. In the same study, Malama reported that critical dimensions were within tolerances.

$$\left.\begin{aligned} UCL &= \bar{x} + 3\frac{\overline{mr}}{d_2} \\ CL &= \bar{x} \\ LCL &= \bar{x} - 3\frac{\overline{mr}}{d_2} \end{aligned}\right\} \text{Equation 4}$$

where,

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

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

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

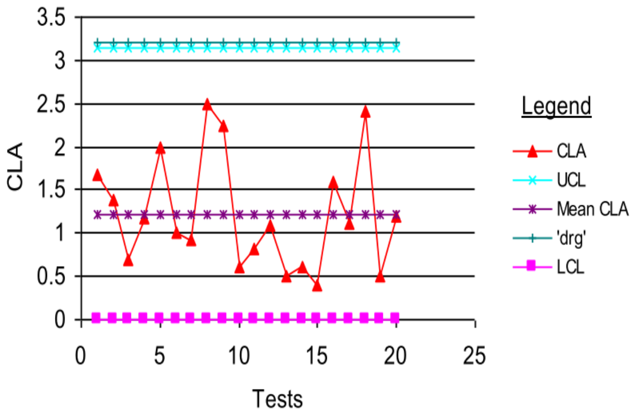

Fig. 1. Control Chart for Individual CLAs [15]

In another study, it was proved that the Supermax 65 A can be adapted to carry out turning operations [17]. 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 the image below. The turning operation was able to obtain dimensional results with high accuracy. From measurements taken on turned workpieces. 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.

In a production process where manual handling processes are required, there are certain part features that affect manual handling time significantly. Boothroyd lists the following part features [18]:

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 into 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.

Time standards can be used alongside method studies to analyze the efficiency of methods employed during processing of a part. According to Telsang method study scope lies in improving work methods through process and operation analysis, such as [19]:

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 are 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.

III. METHODOLOGY

Four samples consisting of 6 mild steel (AISI/SAE No. 1020) workpieces were machined under different cooling processes, as shown in Table I.

TABLE I. 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 room temperature	100	25
4	6	Dry Machining	100	25

The milling operation consisted of slot milling using a 16-millimetre 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 2 below is the YCM Supermax 65A machine (year of make: 1996) used for the milling operation.

Fig. 2. YCM Supermax 65A CNC Machine

The machine tool parameters during milling operation were as follows:

- Max. cutting depth: $0.33 * 16\text{mm} = 5.28\text{ mm}$
- Maximum cutting width: $0.7 * 16\text{mm} = 11.2\text{ mm}$
- 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

Thus,
Spindle Speed,

$$S = \frac{Cutting\ speed\ (\frac{mm}{min})}{\pi \times diametre\ cutter} = \frac{30000}{\pi \times 16} = 596\ rev/min \quad \text{Equation 5}$$

And,
Feedrate,

$$F = S \times F_{per\ tooth} \times Number\ of\ teeth \quad \text{Equation 6}$$
$$F = 596 \times 0.05 \times 2 = 119.2\ mm/min$$

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 the weight of sample workpiece
4) Mounting workpiece in a vice
5) Loading program on CNC
6) Carrying out Milling operation
7) Measuring the temperature of the workpiece during the 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 diameter end mill.

The pre-cooling process was carried out with the use of a YDS-10 Dewar as shown in figure 3. 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 the rise in temperature. This is a safety feature of the Dewar, as there is a risk of explosion when the temperature of 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 an 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. 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 mild steel workpieces at any one time.

Fig. 3. Pre-cooling process

IV. RESULTS AND ANALYSIS

Process flow charts (figures 4 to 7) were developed for each sample being processed consisting of five process classifications which are:

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 Productivity Index (PI) of the number of machining operations divided by the total number of stages in a complete processing cycle. If the value of a workpiece is increased during a machining process, then, it follows that the higher PI is, the more productive the process is.

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. However, 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).

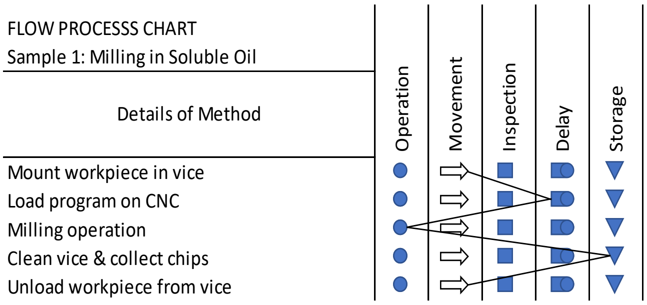

Figure 4 Flow Process Chart for Milling in Soluble Oil

From figure 4 the *PI* for sample 1 is given by,

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

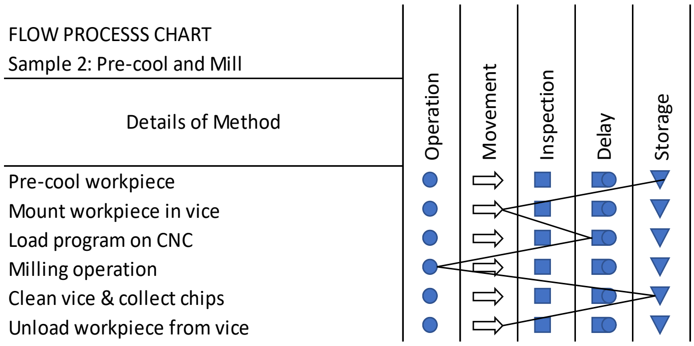

Fig. 5 Flow Process Chart for Pre-cooling and Milling

From figure 5 the *PI* for sample 2 is given by,

$$\frac{\text{No. of Machine Operations}}{\text{Total No. Stages in Cycle}} = \frac{1}{6} = 0.167$$

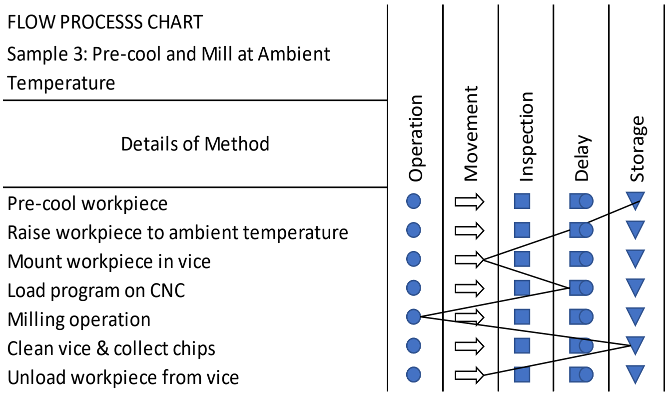

Fig. 6. Flow Process Chart for Pre-cooling and Milling at Ambient Temperature

From figure 6 the *PI* for sample 3 is given by,

$$\frac{\text{No. of Machine Operations}}{\text{Total No. of Stages}} = \frac{1}{7} = 0.143$$

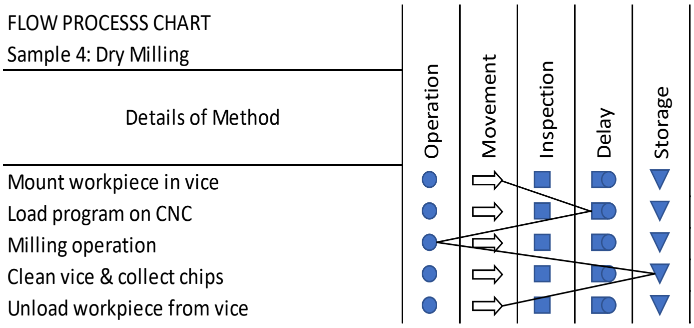

Fig. 7. Flow Process Chart for Dry Milling

From figure 7 the *PI* for sample 4 is given by,

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

The *PIs* are summarised in the bar chart in figure 8.

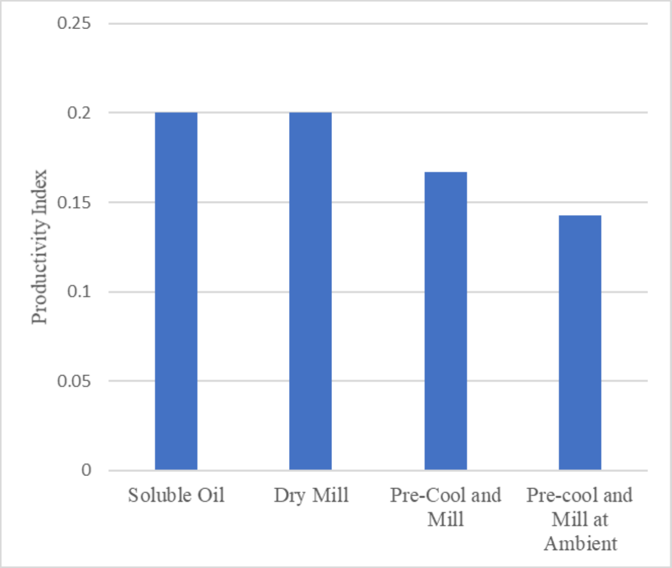

Fig. 8. Process productivity index for each treatment plan

The results tabulated in Table II and presented in figure 9 show that pre-cooling followed by milling at ambient increases the cycle time by three times. Pre-cooling and milling take 5 minutes longer than both dry milling and machining with soluble oil.

TABLE II. AVERAGE CYCLE TIME OF EACH TREATMENT PLAN

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 Cycle Time(s)	**4292**	**709**	**392**	**383**

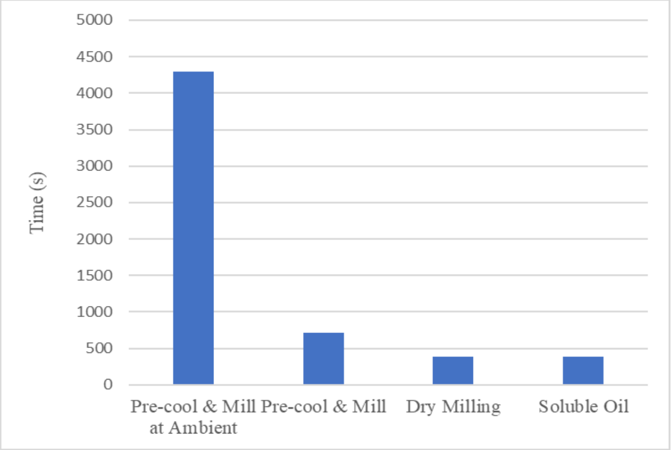

Figure 9 Average Cycle Times

V. DISCUSSION

Cryogenic machining by use of liquid nitrogen is a progressive step in material removal processes. However, the analysis of results on mild steel shows significant drawbacks when pre-cooling is applied as a treatment plan. The first drawback is that it increases investment in personal protective equipment for the machine operator. Handling of workpieces at -40°C increases the risk of severe cold burns and frostbite. Workpieces at -40°C ordinarily increase the time required to mount a workpiece 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), it is not a recommended approach for larger workpieces.

The second drawback is that there is little lubrication at the tool-workpiece interface. When the pre-cooled workpiece was extracted from the Dewar, the air film around the workpiece froze, creating a layer of frost around the workpiece. This layer provides temporal lubrication but soon evaporates during the rough cut of the milling operation as temperatures exceed that of the boiling point of water. The water composition of the film also has the potential to increase the corrosion rate of the material. On the shop floor, this becomes a quality control problem.

A third drawback is closely related to the second and has to do with the machine response to the workpiece temperature. According to the observation of the cuts during the milling of the sub-cooled and machined workpieces, the machine did not compensate for material shrinkage/expansion due to temperature. When a mild steel part is cooled to -40°C the volume of the part shrinks on average by 0.216% which for the workpiece dimensions used for each sample represents 107.517mm³. On the second pass, the machine does not compensate for the high temperatures. When mild steel is heated to 150°C, the volume of the part increases on average by 0.468% which for the workpiece dimensions used for each sample represents 232.953mm³. A failure to compensate for temperature effects on workpiece geometry has a negative impact on the accuracy of the part produced.

VI. CONCLUSION

Pre-cooling of steel workpieces in liquid nitrogen is effective in creating a temporal heat sink for heat generated at the tool-workpiece interface. However, handling of workpieces requires increased investment in protective equipment. The extremely low temperatures also make handling of workpieces more difficult, thereby increasing setting up time. During programming of the CNC machine, it is important to account for the thermal contractions and expansions as these will have a direct effect on the accuracy of the part dimensions and the surface texture. For these reasons, it can be concluded that pre-cooling of steel workpieces reduces productivity on the shop floor during milling operations on a CNC vertical milling centre. It is therefore not a recommended treatment plan for mild steel milling.

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