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An Experimental Investigation on Machinability of Titanium and Steels using Cryogenic Machining

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Abstract: -- **Machinability is a property or quality of any material that can be clearly defined and quantified, to indicate how easy (or difficult) it is, to perform machining operations on it. In fact, the term is ambiguous, but the machinability of any material can be assessed using parameters like (i) tool life (ii) cutting forces (iii) power consumption (iv) surface finish and (v) chip morphology. In the current paper machinability of the materials like Mild steel, Stainless Steel and Titanium are studied; however special emphasis is given to Titanium as it difficult to machine due to high cutting forces, temperatures, chemical reactions with tools, and a relatively low modulus of elasticity. Titanium does not form a built-up edge on tools which is a common problem while machining steels and this result in good surface finishes even at low cutting speeds. The lack of a built-up edge, however, increases the alloying and abrading action of the thin chip which races over a small tool-chip contact area under high pressures. The combination of above characteristics and relatively poor thermal conductivity of titanium results in abnormally high tool-tip temperatures. To overcome this, one of the best techniques available is Cryogenic Machining. Cryogenic machining is a process in which the traditional lubro-cooling is replaced by liquid nitrogen (LN2). Liquid nitrogen is more preferable in machining to dissipate heat generated because it is cost effective, safe, non-flammable and environment friendly gas. In addition, it does not contaminate work piece and no separate mechanism for disposal is required. In the current paper, the overall machining is done on turning machine and the parameters like Cutting forces, Surface finish, Temperature at cutting area and power consumption are obtained for the three materials. The overall results are tabulated and the conclusions are drawn accordingly. The main objective of the research is to improve the machinability of materials by using Cryogenic Machining techniques.**

Index Terms— **Cryogenic Machining, LN2, Cutting forces, Titanium, Surface finish, MAT Lab..**

I. INTRODUCTION

Machinability is a property or quality of any given material which can be clearly defined and quantified, thus indicating how easy (or difficult) it is, to perform mechanical operations on it. In fact, that term is ambiguous, but the machinability of a material can be assessed by employing criteria such as (i) tool life (ii) cutting forces or power consumption (iii) surface finish and chip morphology. Examination of different parameters like cutting forces, temperature at the cutting area, power consumption of the machine tool and surface roughness of the machined surface help in the determination of the machinability of the materials. In the current research, the main focus is on the titanium and the other two materials stainless steel and mild are studied for the comparison of machinability with the titanium.

Titanium exhibits high strength-weight ratio even at elevated temperatures and has exceptional corrosion resistance. These characteristics are the main cause for the rapid growth of the titanium industry over the last 40 years. The major application of the material in the aerospace industry, both in air frames and engine components. Non aerospace applications take advantage mainly of their excellent strength properties in applications like steam turbine blades, superconductors, missiles etc. Corrosion resistance advantage of Titanium is used in marine- services, chemical petro-chemical, electronics industry, bio- medical instruments etc. Due to their high specific strength and exceptional corrosion resistance, titanium and it alloys are widely used in the engineering field, namely in the aerospace, automotive and biomedical parts. In many applications, these materials replace steels and aluminum alloys, which usually results in weight and/or space saving, increase of system efficiency by rising the service temperature, and removal of need of protective coatings that should be used in steels.

The low thermal conductivity, low elastic modulus, maintenance of high hardness at elevated temperatures, and high chemical reactivity are the main factors for low machinability Titanium and it alloys. These factors may result in rapid tool wear, low material removal rate, and degradation of surface integrity of machined parts. Several strategies have been used with some success in the development of machinability these materials. One of such strategies is cryogenic machining, in which the traditional lubro-cooling liquid (an emulsion of oil into water) is replaced by a jet of liquid nitrogen. Cryogenic machining is useful in rough machining operations, in order to increase the tool life. It can also be useful to preserve the integrity and quality of the machined surfaces in finish machining operations. Cryogenic machining tests have been performed by researchers since several decades, but the actual commercial applications are still limited to very few companies Cryogenic machining is possible for turning and milling operations. In the current paper, machinability study has been carried out using cryogenic coolant as well as water based coolant on Lathe machine where power consumption, cutting forces and surface roughness values were studied in machining of Titanium Grade-2 material, Stainless Steel (SS 304) and low carbon Mild Steel.

II. APPLICATIONS

Grade 2 Titanium is called the “workhorse” of the commercially pure titanium industry. It shares many of the same qualities as Grade 1 titanium, but it is slightly stronger. Both are equally corrosion resistant.

Titanium Grade 2 may be considered in any application where formability and corrosion resistance are important, and strength requirements are moderate. Some examples of aerospace applications have included airframe skins in "warm" areas, ductwork, brackets, and galley equipment. Ti Grade 2 has also been widely used in marine and chemical applications such as condensers, evaporators, reaction vessels for chemical processing, tubing and tube headers in desalinization plants, and cryogenic vessels. Other uses have included items such as jigs, baskets, cathodes and starter-sheet blanks for the electroplating industry, and a variety of medical applications.

III. EXPERIMENTAL PROCEDURE

In the current experiment, the machinability parameters of the titanium are found out for the both normal machining and the cryogenic machining. The below mentioned order is followed to obtain the different machinability parameters

- Material Selection and chemical composition Test
- Vickers Hardness and UTM Testing
- Machining Test

A. Material Selection and chemical composition test

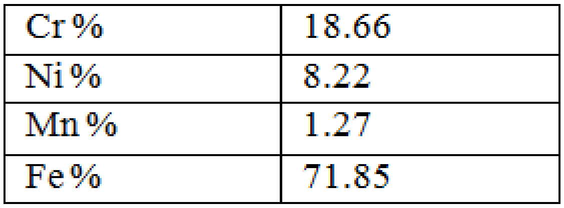
Titanium (Grade-2), Stainless Steel (SS 304) and Mild Steel materials in round bar form are selected for machining. The dimensions that chosen are given below

- Dia 25 mm X 200 mm length – Normal Machining
- Dia 25 mm X 200 mm length – Cryogenic Machining

The optical Emission Spectrometer is used to find out the chemical composition of the above selected materials. The following is the result of the tests shown in Table 1- 3

C %	0.17
Si %	0.20
Mn %	0.54
P %	0.16
Fe %	98.7

Table 1 Chemical Composition of Mild Steel



Cr %	18.66
Ni %	8.22
Mn %	1.27
Fe %	71.85

Table 2 Chemical Composition of Stainless Steel (SS 304)

V %	0.17
Al %	0.61
Ti %	99.10

Table 3 Chemical Composition of Titanium

B. Vickers Hardness and UTM Testing

For the selected materials, the Vickers hardness and UTM testing is performed to determine the hardness and strength of the material. The obtained result is shown below Table 4

Location (Surface)	Impression 1	Impression 2	Impression 3	Average (HV)
Titanium Grade -2	207	209	207	207.67
Stainless Steel (SS 304)	339	342	339	340
Mild Steel	168	167	167	167.33

Table 4 Vickers Hardness Testing Results

The UTM Testing is performed on a FIE Universal Testing Machine 40KN and the input data is shown in the Table 5-10

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Specimen Type	Round
Initial Diameter	10.57 mm
Final Diameter	0 mm
C/S Area	87.74 mm^2
Original Gauge Length	50 mm
Final Gauge Length	62.6

Table 5 Input data to the specimens (Mild Steel)

	Values
Ultimate Load	46.480 KN
Ultimate tensile Strength	529.687 N/mm^2
Elongation	25.200 %
Yield Strength	31.960 KN
Yield Stress	364.217 N/mm^2

Table 6 UTM Testing Result of Mild Steel

Specimen Type	Round
Initial Diameter	12.7 mm
Final Diameter	0 mm
C/S Area	126.677 mm^2
Original Gauge Length	50 mm
Final Gauge Length	70.9.67
Extensometer Gauge Length	25 mm

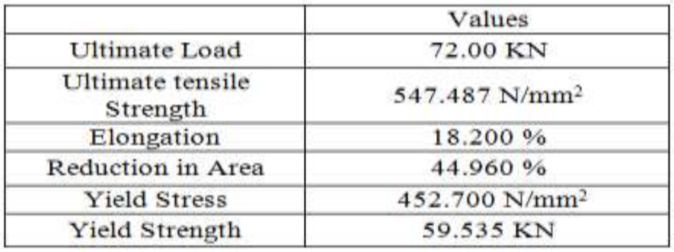
Table 7 Input data to the specimens (Stainless Steel)

	Values
Ultimate Load	89.040 KN
Ultimate tensile Strength	702.873 N/mm^2
Elongation	41.800 %
Reduction in Area	68.750 %
Yield Stress	369.002 N/mm^2
Yield Strength	46.744 KN

Table 8 UTM Testing Result of Stainless Steel

Specimen Type	Round
Initial Diameter	12.82 mm
Final Diameter	9.1 mm
C/S Area	129.082 mm^2
Original Gauge Length	50 mm
Final Gauge Length	56.32
Extensometer Gauge Length	25 mm

Table 9 Input data to the specimens (Titaniu



	Values
Ultimate Load	72.00 KN
Ultimate tensile Strength	547.487 N/mm^2
Elongation	18.200 %
Reduction in Area	44.960 %
Yield Stress	452.700 N/mm^2
Yield Strength	59.535 KN

Table 10 UTM Testing Result of Titanium

C. Machining Test

The orthogonal cutting trials were carried out on HMT make High precision Lathe NH 22 (Figure 1), which has a 7 kW motor power and the spindle rotation speed ranges from 40-2040 rpm in forward and 60-1430 rpm in reverse. Carabid Tipped Tool is used for entire experiment. In this Investigation the parameters depth of cut, Speed and feed are varied. In this experiment when one parameter is varied the other are kept constant. The other parameters like feed, coolant discharge rate, length of cut are kept constant. For each and every experiment the following are found out

- Determination of Cutting Forces
- Temperature at the cutting Area
- Surface roughness after machining

Figure 1 HMT Lathe NH 22

Figure 2 Machining operation on Lathe

- **Determination of cutting forces**

In this experiment cutting forces which are generated while machining the material are first determined by the lathe tool dynamometer and later using the PC interfacing device the values are transferred to the computer. Using the values, a graph showing the different cutting forces is generated by the computer. Using this graph, the cutting forces are noted by taking highest peak for the respective force. The sample graph is shown below in Figure 3

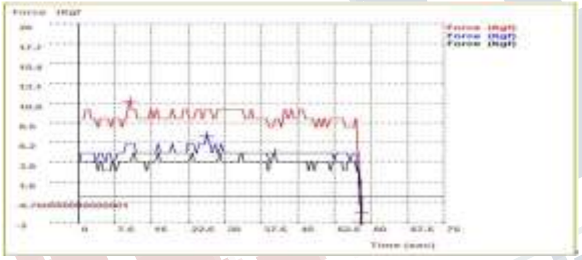


Figure 3 Sample graph generated by PC interfacing Dynamometer

The Lathe tool dynamometer is shown in Figure 4 and the PC interfacing unit is shown in the Figure 5

Figure 4 Lathe Tool Dynamometer

Figure 5 PC Interfacing Unit

The cutting forces which are determined by using the PC - Interfacing dynomometer for every experiment are tabluted below tables for normal machining and for Cryogenic machining with their respective machining inputs

Variation	Values	Cutting Force (F_c) Kgf		Axial Force(F_f) Kgf		Feed Force(F_t) Kgf	
		I	II	I	II	I	II
Depth Of Cut	0.3	17.5	2.5	8.6	2	4.5	1.9
	0.6	19	3	11	1.5	6	1.2
	0.9	18	4	11	3.1	7	2.3
Speed	88	16.5	11.1	11	8.1	10	6.2
	192	14.5	10	6.8	6	12	5
	325	15.4	10	8.7	4.8	6.5	5.2
Feed	0.03	18.5	5.6	9.5	6.7	9.3	3.5
	0.06	15.2	14	8.1	5.2	4.8	4
	0.09	17	13.4	10.6	7	5	6.1

Table 11 Cutting Forces generated in Normal Machining (I) and Cryogenic Machining (II) in machining Mild Steel

Variation	Values	Cutting Force (F_c) Kgf		Axial Force(F_f) Kgf		Feed Force(F_t) Kgf	
		I	II	I	II	I	II
Depth Of Cut	0.3	17	15.2	11	6.1	9	13
	0.6	18	22	14	11	10	18
	0.9	23	28	12	21	6.2	14
Speed	88	17	16	12	9	10	9
	192	31.2	16	6.2	11	6.1	12
	325	16	17	9	8	6	9
Feed	0.03	20	6.1	13	13	10	6
	0.06	27	13.1	18	12	8	12
	0.09	35.7	7	17	11	14	8

Table 12 Cutting Forces generated in Normal Machining (I) and Cryogenic Machining (II) in machining Stainless Steel

Variation	Values	Cutting Force (F_c) Kgf		Axial Force(F_f) Kgf		Feed Force(F_t) Kgf	
		I	II	I	II	I	II
Depth Of Cut	0.3	12	15	11	12	10	6
	0.6	13.2	15	13	12	11	6
	0.9	15	20	16	18	13	10
Speed	88	23	17.5	6	19	10	8
	192	6.1	12	4.1	12	7	6
	325	22	11	6.5	7	8	2
Feed	0.03	6.1	10	4	12.5	7	9.5
	0.06	17	22	10	13	7	6
	0.09	21.5	4.2	7.8	0.8	12	7

Table 13 Cutting Forces generated in Normal Machining (I) and Cryogenic Machining (II) in machining Titanium

- **Determination of Temperature at cutting Area**

The temperature at the cutting area is measured using the MT-4 Infrared thermometer (Figure 6) for every specimen machining. The temperatures obtained for each experiment are tabulated in the Table 7

Figure 6 MT 4 Infrared thermometer

- Surface Roughness after machining

The specimens which are machined on the HMT Lathe NH22 are tested on the Habson Surfonic 3+ tester (Figure 7) for determination of surface roughness. The results obtained are tabulated in the Table 14 - 16

Figure 7 Surface Roughness Tester

The results of Temperature determination and surface roughness testing are tabulated in the below tables Normal Machining

Variation	Values	Temperature at the cutting area (˚C)		Surface Roughness R_a(µm)	
		I	II	I	II
Depth Of Cut	0.3	34	30.1	20.1	23.7
	0.6	37	30.4	24.1	24.9
	0.9	38.2	38.2	23.6	28.9
Speed	88	31.1	37.3	28	29.5
	192	33.1	26	22.4	16.5
	325	35	30.1	15.5	14.3
Feed	0.03	32.5	30.5	26	15.6
	0.06	33.7	29	25.7	17.3
	0.09	34	28.5	23.4	21.9

Table 14 Temperature at cutting area and surface roughness for Normal Machining (I) and cryogenic machining (II) in machining of Mild Steel

Variation	Values	Temperature at the cutting area (˚C)		Surface Roughness R_a(μm)	
		I	II	I	II
Depth Of Cut	0.3	30.8	23.1	34.7	9.5
	0.6	30.3	26.3	15.9	3.2
	0.9	30.7	28.6	5.2	11.9
Speed	88	28.4	21.4	12.9	7.9
	192	28.6	18.8	13.2	5.1
	325	28.7	28.4	17.7	3.2
Feed	0.03	32.4	18.6	14.9	6.5
	0.06	30.5	23.1	14.3	4.2
	0.09	30.6	21	11	18

Table 15 Temperature at cutting area and surface roughness for Normal Machining (I) and cryogenic machining (II) in machining of Stainless Steel

Variation	Values	Temperature at the cutting area (˚C)		Surface Roughness R_a(μm)	
		I	II	I	II
Depth Of Cut	0.3	31.6	21.5	25.4	9.4
	0.6	32.9	22.9	24.6	6
	0.9	32.4	24.6	12.2	4.9
Speed	88	33.7	22.6	27.3	20.9
	192	32.2	20.6	32.6	14.5
	325	31.3	18.6	23.1	7.7
Feed	0.03	32	24.1	27.4	8.9
	0.06	32.2	21.6	44.1	7.8
	0.09	33	20.4	33	4.9

Table 16 Temperature at cutting area and surface roughness for Normal Machining (I) and cryogenic machining (II) in machining of Stainless Steel

IV. RESULTS AND DISCUSSION

A. Calculations

Using the data acquired in the machining test, power consumption is calculated for all the experiments for the both normal and cryogenic machining and tabulated in the Table 9

Power consumption :

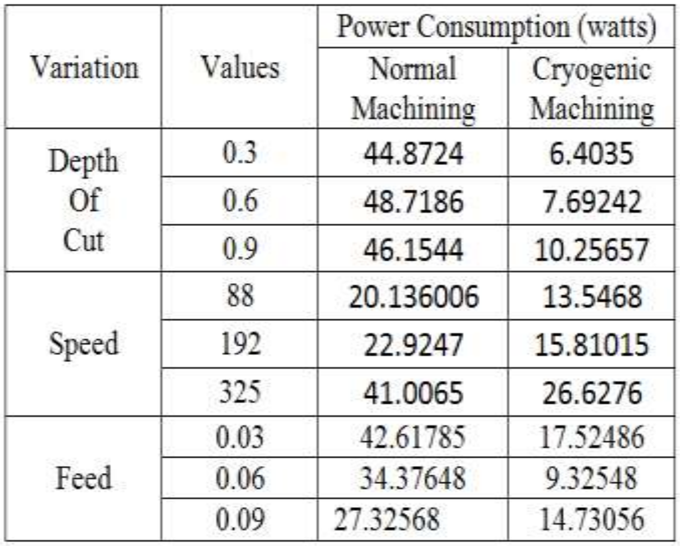
$$P = F * V \qquad \text{(watts or kilo watts)}$$

where F = cutting force
V = cutting velocity

Cutting velocity :

$$V = \pi DN \qquad \text{(mm/min)}$$

Where D = Diameter of work piece
N = Speed in rpm



Variation	Values	Power Consumption (watts)	
		Normal Machining	Cryogenic Machining
Depth Of Cut	0.3	44.8724	6.4035
	0.6	48.7186	7.69242
	0.9	46.1544	10.25657
Speed	88	20.136006	13.5468
	192	22.9247	15.81015
	325	41.0065	26.6276
Feed	0.03	42.61785	17.52486
	0.06	34.37648	9.32548
	0.09	27.32568	14.73056

Table 17 Power consumption for both normal and Cryogenic machining in machining Mild Steel

Variation	Values	Power Consumption (watts)	
		Normal Machining	Cryogenic Machining
Depth Of Cut	0.3	23.66	38.46
	0.6	26.03	38.46
	0.9	23.65	39.44
Speed	88	20.79	15.82
	192	12.03	23.66
	325	73.45	36.72
Feed	0.03	12.03	19.72
	0.06	33.53	43.39
	0.09	42.40	8.28

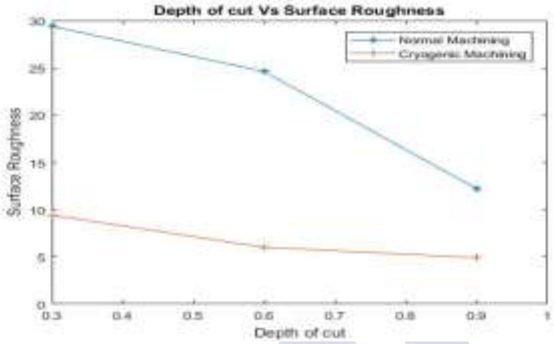
Table 18 Power consumption for both normal and Cryogenic machining in machining Stainless Steel

Variation	Values	Power Consumption (watts)	
		Normal Machining	Cryogenic Machining
Depth Of Cut	0.3	23.66	38.46
	0.6	26.03	38.46
	0.9	23.65	39.44
Speed	88	20.79	15.82
	192	12.03	23.66
	325	73.45	36.72
Feed	0.03	12.03	19.72
	0.06	33.53	43.39
	0.09	42.40	8.28

Table 9 Power consumption for both normal and Cryogenic machining in machining Titanium

B. Graphs

The graphs are plotted for surface roughness, Temperatures and power consumption using the MAT LAB Software and are a typical graph is shown in Figure 8



V. CONCLUSION

- Using Liquid Nitrogen as coolant is affordable in the case of machining of titanium as it reduces the temperature at the cutting area which is a major reason for the difficulty of machining titanium but it may not be a good idea in case of machining Mild Steel and some grades of stainless steel.

- The machining of the titanium is one of the major issues in the production sector, and this project attempts to suggest the correct machinability parameters to machine titanium and helps to study the variation of different machinability parameters while machining titanium

- Good surface roughness, low temperatures at the cutting area, reduced cutting forces are observed when liquid nitrogen (Cryogenic Machining) is used as coolant.

- Replacing the LN2 with the traditional coolant will not be a good idea if the production is less as the handling and dispensing costs may be higher if the production is in small scale.

- The experimental data show that the machinability of Titanium material is difficult than the mild steel and Stainless materials.

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