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Research Article

Machining of Tungsten Heavy Alloy under Cryogenic Environment

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Abstract

The alloys of Nickel, Cobalt, Titanium, Tungsten belongs to the group of super hard alloys among them, tungsten is more used in industries as it is cheap when compared to other alloys and is easy to manufacture. The machining of super hard alloy tungsten is very difficult and costlier process as it requires harder cutting tools. Though carbide tools are extensively used, these take high machining time and tool failures which lead to decrease in productivity. To overcome the above, advanced techniques are being practiced in machining of tungsten alloy, one such technique is cryogenic cooling. Nitrogen is more preferable in machining to dissipate heat generated because it is cost effective, safe, non flammable and environmental friendly gas, in addition to that it cannot contaminate work piece, no separate mechanism for disposal. An experimental investigation has been carried out on machining of tungsten heavy alloys under cryogenic environment. The material removal rate, surface integrity and cutting forces were studied for both conventional coolant as well as cryogenic coolant. The chip morphology was measured for evaluation of shear stress and shear strain under cryogenic machining.

Keywords: *Tungsten heavy alloy, Cryogenic coolant, cutting forces, material removal rate, surface integrity.*

1. Introduction

The alloys of Nickel, Cobalt, Titanium, Tungsten belongs to the group of super hard alloys among them Tungsten is more used in industries as it is cheap when compared to other alloys and is easy to manufacture. Tungsten is the most prominent metal which has high resistance to wear and high strength even at high temperatures, it is because of the density, high melting and boiling points of tungsten. Therefore it is most widely used in nozzles of rockets, space vehicles, protective shield for space vehicles and other high temperature application. Tungsten directly cannot be used for above purposes, but it can be made into an alloy, which is called Tungsten Heavy Alloy (WHA) (German, (1994), Hill and Abbaschian, (1991)).

The machining of super hard alloy tungsten is very difficult and costlier process as it requires tools made of carbide or diamond. Though carbide tools are extensively used, these take high machining time which lead to decrease in productivity. The reason behind elapsed machining time was due to the tool wears off while machining because of high temperatures which are generated at the machining area. So, to increase productivity the heat generated on the machining area must be dissipated this is achieved by using cryogenic coolants instead of using water soluble conventional coolants (Pusavec, (2012)).

Hydrogen, Helium, Neon, Argon, Krypton, Xenon, Methane, Ethane and propane belongs to Cryogenic chemicals among them Nitrogen is more preferable in machining because it is cost effective, safe, non flammable and environmental friendly gas. The liquid form of nitrogen which is at a very low temperature is pumped on the machining area to dissipate heat generated. The other advantage of cryogenic coolant instead of conventional coolants is that it cannot contaminate work piece, no separate mechanism for disposal. The chips which are produced while machining can be recycled easily as nitrogen evaporates rapidly in atmospheric temperature (Dhananchezian *et al.* (2009).

The forces are induced in the cutting tool while cutting the metal. These cutting forces play an important role in metal cutting mechanism, tool life, power required for cutting etc. High cutting forces leads to failure of cutting tool and high power requirement of machine tool. These dynamic cutting forces are measured accurately by piezoelectric cutting force dynamometer (Poon and Bhutan, (1995)). Another important parameter is surface integrity. It is also linked with the above factors described in cutting forces. The surface integrity in machining describes the quality of surface generated after machining such a roughness or waviness etc. This surface finish can be measured accurately by diamond stylus based roughness instruments (AG**,** 2003).

Pusavec et al. (2011) studied and presented results of the influence of cryogenic machining on the process stability. The stability diagrams were obtained

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experimentally using the coarse-grained entropy rate estimator for chatter detection from measured cutting forces. In comparison with conventional machining, enlarged stability windows were observed for the case of cryogenic machining. Based on the defined specific force models in turning operations, it was shown that a higher machining stability is achievable in cryogenic machining due to the reduction of specific cutting force components, in comparison with dry machining. Kakinuma *et al.* (2012) proposed a proposed cryogenic micromachining of polydimethylsiloxane (PDMS) for the fabrication of micro fluidic chips. The machining characteristics of cryogenic micromachining were experimentally analyzed from the viewpoint of ultra-precision machining. Umbrello *et al.* (2012) was produced an experimental study of cryogenic machining of hardened AISI 52100 steel, and focused on surface integrity. Experiments were performed under dry and cryogenic cooling conditions using CBN tools varying cutting speeds, work-piece hardness and tool geometry. Surface integrity parameters were investigated to establish the effects of cryogenic cooling on the surface integrity of the machined component, and results were compared with those from dry hard machining. Overall, cryogenic cooling provides improved surface integrity leading to extended product life and performance.

Courbon *et al.* (2013) investigated the cooling and/or lubrication capabilities of a nitrogen jet under extreme contact conditions using a dedicated tribometer for the machining of Ti6Al4V and Inconel718 with carbide tools. It was observed that neither liquid nor gas nitrogen is able to decrease friction coefficient and adhesion onTi6Al4V, it was proved to be efficient on Inconel718 with a prevailing effect of the liquid phase. In both cases, applying gas nitrogen decreases the amount of heat transmitted to the pin but this can be drastically enhanced by using liquid nitrogen. Finally, this was provided a quantitative data regarding friction coefficient under dry and cryogenic conditions. Kaynak *et al.* (2013) studied a tool wear rate and comparative cooling like effects on NiTi shape memory alloys. In which cryogenic cooling on tool-wear rate and progressive tool-wear by comparing the new findings from cryogenic machining with results obtained from minimum quantity lubrication and dry machining conditions.

The machinibaility study has been carried out under cryogenic coolant as well as water based coolant on these alloys. The MRR, Cutting forces and surface roughness values were studied in machining of three different Tungsten alloys under the both environment.

2. Experimental Setup

2.1 Work Material

Tungsten has a high range of melting point and density (Table 1). Tungsten Heavy Alloys (WHA) are processed by powder metallurgy route. Where powder form of tungsten is produced by ball milling and other material like Nickel, Cobalt, Ferrous are added to enhance the properties. These mixtures of powders are oxidized by heated in range of 700^0C to 900^0C in presence of hydrogen and then processed by sintering and swaged. Three different tungsten alloys such as 90%, 93% & 95% by weight have been prepared with tungsten particle size of 6 microns as base and Nickel elements of size 6 micron, Cobalt particles of 4 micron, Iron elements size of 5 micron compositions. The mechanical properties of the alloys are shown in Table 2.

Table 1 Physical Properties of Tungsten

Density	19.3 g/cm^3
Melting Temperature	3387 °C
Specific Heat	134 J/Kg K
Coefficient of Thermal Expansion	4.6 x 10^{-6} /K
Thermal Conductivity	173 W/m K
Electric conductivity	18.2 m/ohm mm^2

Table 2 Mechanical Properties of WHA

	Tensile strength	% elongation	Impact strength
Alloy 1	1400 MPa	10%	65 J
Alloy 2	1435 MPa	7%	45 J
Alloy 3	1420 MPa	4%	14 J

It was observed that the strength of the WHA was much higher when compared with high strength steel like stainless steel etc. It was observed that Impact strength and percentage elongation of the material were increasing the alloying elements. It indicates the alloying elements bringing higher impact strength and ductility to the composition which are desirable for engineering components.

2.2 Cutting Tool

Sandvik make brazed uncoated solid carbide inserts of grade K20 (ISO 6 R 2525) external profiling right hand cutting tool were used with 25 mm square cross section tool holder. The tool insert has 12° rack angle, 18° Clearance angle, 1.2 mm nose radius and the dimension of the insert are 20 x 15 x 8 mm size.

2.3 Sample Preparation

The sintered and swaged tungsten alloy samples were non uniform in nature due to the process conditions, these samples were rough turned under low spindle speed and feed to get uniform circular diameter and size. Later cylindrical grinding operation was performed by HMT make K150 cylindrical grinding machine to nullifying the surface irregularities generated during rough turning operations and to achieve true cylindrical reference surface of 36mm x 120 mm long.

2.4 Dynamometry

A Piezoelectric based precision multi component cutting force dynamometer of Kistler, Singapore Model 9265B has been installed on conventional Turning machine of HMT make, model NH 26 by replacing the tool post with dynamometer clamping plate. The cutting tool was inserted into the tool post of dynamometer. The parallelism and perpendicularity of cutting tool movement against the machine bed and height of the tool tip against spindle axis was ensured to be within 10 microns by the dail indicator. The multi channel charge amplified was connected to Dynamometer and personal computer system, where the Dynoware software was installed to record and anslyse the measured force data.

2.5 Water based soluble coolant

The water soluble emulsion oil, Servosynth cut 18 of Indian Oil Corporation Ltd., Hyderabad was used mixed into the water of around 3% volume concentration was used as coolant. The characteristics of the servosynth cut oil and water were tabulated shown as table 3 and table 4 respectively.

Table 3 Characteristics of Servosynth cut oil

Density @ 23° C	0.986 g/ml
Kinetic Viscosity @ 40° C	190 Cst
PH of 2.5% emulsion	9.0

Table 4 Characteristics of water

Specific Heat	4.2 KJ /kg K
Boiling point	100 ° C
Thermal Conductivity	0.58 W/m K
Coefficient of heat transfer	100 W/m^2K

2.6 Machining Parameter

The machining parameters for experimentation under emulsion abased water soluble conventional coolant and cryogenic fluid were identified from the experience during rough turning of sample and published data of cutting tool manufacturer. The parameters are shown in table 5.

Table 5 Cutting Parameter

Parameter	Value
Spindle speed	930 rpm
Feed	0.05 mm/rev
Depth of Cut	0.03 mm

2.7 Experimentation and Observations

The experiments were conducted under water based coolant. The cutting time was recorded for machining of 50 mm length by a precision stop watch. The weights of the machined samples were recorded. The material removal rate grams per second were calculated by a precision digital weight calculator of least count 0.0001 gram. The recorded weight difference is used to calculate material removal rate. The observed data of cutting forces in Newton were reported in table 6. The Surface roughness of the samples were measured by Taylor habson, UK make Form Taly surf Intra II instrument with 2 microns diamond tip and 0.8 cutoff value and sample length was 10 mm along the longitudinal direction of the sample.

Table 6 Observations under water based coolant

Sample	MRR (gm/s)	Cutting forces (N)			Surface Roughness (μRa)
		F_X	F_Y	F_Z	
Alloy 1	40.55	41.5	61.72	53.21	1.4948
Alloy 2	45.18	50.23	52.96	33.45	1.1889
Alloy 3	43.27	63.67	54.88	33.41	1.4540

2.8 Data Analysis

It is observed that discontinuous tiny chips were formed while machining. The chips were inspected by Optical Profile Projector of M/S BATY International, UK make model SM20 under 10 X magnification to determine chip thickness and width dimensions. The shear angle, shear stress and shear strain were calculated by Merchant diagram from the chip dimensions and cutting force values shown in Table7.

Table 7 Result under Water Based Coolant

Samples	Chip Dimensions (mm)		Shear Stress (MPa)	Shear Angle (Ø)	Shear Strain (ε)
	Thickness	Width			
Alloy 1	0.0735	0.3886	651.4	36.7	4.04 E-6
Alloy 2	0.1295	0.4221	848.8	22.04	2.16 E-6
Alloy 3	0.0950	0.3206	1041.6	29.44	6.469 E-6

As the availability of the samples was limited, hence the samples were reused to carry out the cryogenic environmental trials. The samples were ground by cylindrical grinding operation.

3. Experimentation under Cryogenic Coolant

Liquid nitrogen facility has been established at DMRL. The physical properties of nitrogen were tabulated in table 8.

Table 8 Properties of Nitrogen

Density	1.25 g/cm^3
Melting Point	- 209.8 °C
Boiling Point	- 195.8 °C
Specific Heat	1.04 KJ/Kg K
Thermal Conductivity	25.9 W/m K
Coefficient of heat transfer	32 W/m^2K

The liquid nitrogen was collected in double walled polymer based insulated container of 25 liters capacity. The pressure pump of 2 lit/min capacity was fitted to the container. The nozzle of 3 mm diameter tip diameter was connected at the one of the half inch plastic pipe, which second end was fitted into the pressure pump. The fittings were cross checked to ensure no leakages while discharging the liquid nitrogen. The exit velocity of liquid nitrogen was calculated mass continuity equation as shown in eqn 1.

$$Q = A_1V_1 = A_2 V_2 \qquad (1)$$

Here, Q is the discharge of fluid, A_1 is the area of nozzle at entry and V_1 is velocity of fluid entry, A_2V_2 are parameter of nozzle at exit.

It was found that the nozzle has exit velocity of 4.7 m/sec from the above equation 1 under full valve open condition. It is ensured that nozzle is positioned near to the cutting tool and cryogenic liquid is falling on the tool tip. The machining trials were conducted under on three samples with the above cutting parameters under installed dynamometer set up as shown in fig.2 The liquid nitrogen was evaporated into atmosphere by collecting heat from the cutting tool immediately as the boiling point of nitrogen is lower than environment temperature at atmospheric pressured. Safety measures have been practiced while carrying experiments to avoid cool burns and injuries on the skin by liquid nitrogen. The time was recorded for machining of 50 mm length by a precision stop watch. Similarly the MRR was calculated and the cutting forces, surface roughness, chip dimensions

Fig. 2a. Experimental setup of Liquid N_2

Fig. 2b. Cutting under Liquid N_2 Environment

3.1 Observations under liquid Nitrogen

The observed cutting forces, MRR and Surface Roughness were reported in table 9.

Table 9 Observations under Liquid Nitrogen

Sample	MRR (gm/s)	Cutting forces (N)			Surface Roughness (µRa)
		F_X	F_Y	F_Z	
Alloy 1	128	31.25	43.15	28.93	0.5317
Alloy 2	120	33.87	47.65	35.88	0.2716
Alloy 3	108	31.13	39.1	31.56	0.418

3.2 Data Analysis

The calculated shear stress and shear strain were recorded in table 10.

Table 10 Chip Dimension Result under Liquid Nitrogen

Samples	Chip Dimensions (mm)		Shear Stress (MPa)	Shear Angle (Ø)	Shear Strain (γ)
Alloy 1	0.1236	0.3645	160.85	23.70	9.99×10^{-7}
Alloy 2	0.0715	0.3928	389.5	37.6	1.17×10^{-5}
Alloy 3	0.132	0.432	617.9	21.64	3.83×10^{-6}

It was observed that material has low value of shear stress due to shearing of material under low cutting forces as compared with water based coolant.

4. Results and Discussion

Machining experiments were conducted on tungsten heavy alloys under both water soluble coolants and cryogenic coolants (Liquid Nitrogen). The machinability of tungsten alloy under cryogenic coolants is found to be very good.

The heat will be generated between the cutting tool and work-piece due to friction while cutting. The produced heat will be carried away by chips and remaining will be dissipating into work piece and cutting tool. The absorbed heat will soften the cutting tool (poor performance) thereafter deformation of cutting tool or formation of built up edge or failure of cutting tools which results to surface irregularities on machined samples.

The liquid nitrogen has huge amount of heat carrying away capability due to its very low temperature in liquid form. The liquid nitrogen has played a key role in effective and efficient cooling during machining by protecting the cutting tool from deformation and built up edge formation. Therefore the samples were observed in good surface finish. The liquid nitrogen also decreased the cutting forces, the reason may be the tungsten alloy has lost their ductility and failure happened under brittle.

The Values of MRR, Surface Roughness and Cutting Force were shown in graphical representation as shown in figure 3a,3b and 3c for both water based coolant and cryogenic coolant.

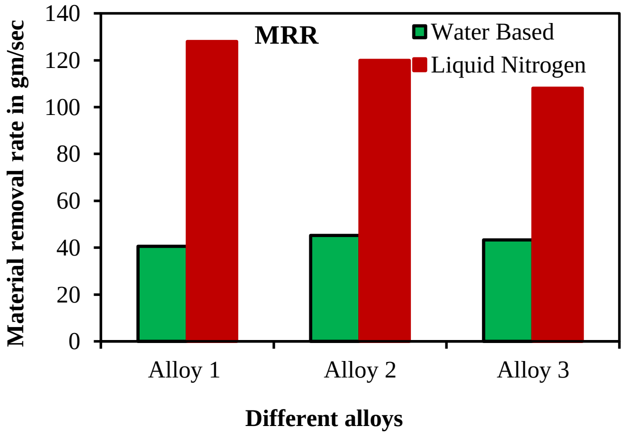

Fig.3a. Result of MRR

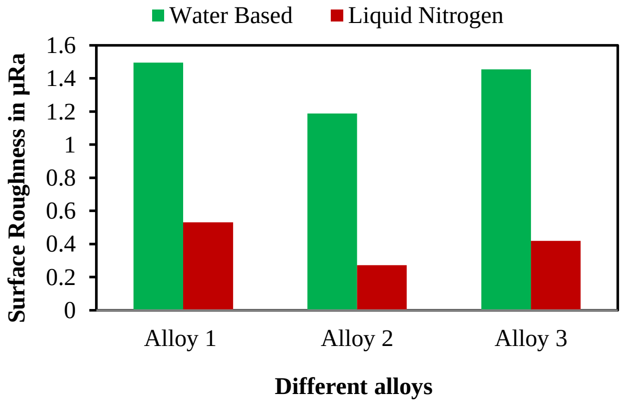

Fig.3b. Result of Surface Roughness

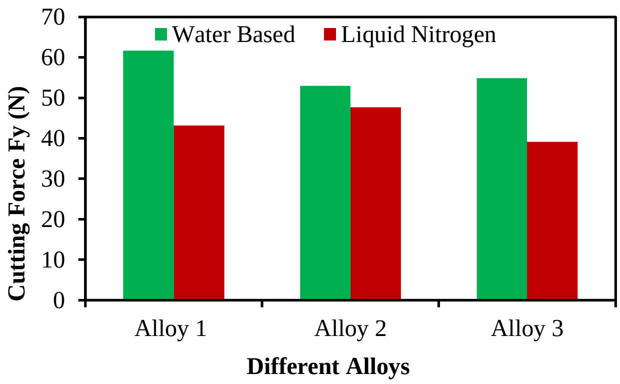

Fig.3c. Result of Cutting Force

5. Conclusion

By conducting experiments on three different alloys of Tungsten under cryogenic and conventional conditions noticeable results has been obtained

- It was observed that more than 3 fold increase in MRR by cryogenic coolant when compared with conventional water soluble coolant. This concludes that the productivity of the component increases.
- It was observed that surface finish of average value of 0.4 micron Ra was achieved, it was a remarkable achievement in bringing fine surface finish value and therefore high part quality. The value is equivalent to polishing finish value. Therefore the subsequent grinding operations can be eliminated. Economy.
- The cutting forces observed were very low and around 40% lesser in liquid nitrogen when compared with water based coolant. The low cutting forces leads to better performance of machine tool, tool life etc.
- It can be concluded from the above observations that the liquid nitrogen is an advantageous and alternative coolant for machining of hard materials. The usage of liquid nitrogen also reduces the environmental harms causes by hydro carbons from petroleum based mineral oils.

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