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Study on Grindability of Ti-6Al-4V Using Solid Lubricants

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ABSTRACT : Ti-6Al-4V is known as Aerospace metal and also ASTM Grade 5. This alloy has got the popularity due to its low density, high strength to weight ratio and also for its high temperature strength. This grade of Ti-Alloy is used for aerospace, military, aircraft turbine engine compressor blades etc. Grinding is a high specific energy consuming process. At the time of grinding there are three types of actions taking place in between the grinding wheel and the surface to be ground. These are shearing, ploughing, and rubbing for different conditions of grit shape. Shearing is the process of metal removal, and the other two actions are unwanted during the process and results frictional loss. Hence to decrease the specific energy of grinding solid lubricants can be used which will reduce the frictional losses (rubbing component) and thereby decrease the grinding forces. A part of heat generated by grinding this alloy is carried out by the solid lubricants as they have good thermal conductivity. Lubricity property of the solid lubricants will reduce the frictional forces which in turn reduces the forces and specific energy consumption during grinding.

KEYWORDS : Titanium, shearing, ploughing, Ti-6Al-4V, Taguchi OA method

I. INTRODUCTION

Titanium is Hard-to-machine materials as Ti-alloy (Ti-6Al-4V) has low thermal conductivity, high chemical reactivity at elevated temperature and low modulus of elasticity. After alloying its machinability decreases. For closed tolerance and good surface quality a product need to be grounded. Ti-6Al-4V is known as Aerospace metal and also ASTM Grade 5. This alloy has got the popularity due to its low density, high strength to weight ratio and also for its high temperature strength. This grade of Ti-Alloy is used for aerospace, military, aircraft turbine engine compressor blades etc. The blades are dynamically loaded. For good fatigue property the components should be grounded. The grinding zone temperature is much higher than other machining shear zone. But due to Ti-alloy's low thermal conductivity heat accumulation occurs on the surface which may lead to residual tensile stress, surface cracks and redeposition on the ground surface as a result the fatigue life of the product decreases. Grinding is traditionally regarded as a final machining process in the production of components requiring smooth surface and fine tolerances. Grinding virtually remains unchallenged in machining of materials of extreme hardness or brittleness which otherwise cannot be efficiently shaped by other methods.

In order to reduce the frictional components of grinding force, solid lubricants can be used effectively at the grinding zone. As friction is a contributor to heat generation which degrades the ground surface, application of such solid lubricants can help in minimizing the temperature generation. Ti-alloy is a bad conductor of heat and its chemical reactiveness at elevated temperatures is also high. Hence it becomes more important to control the grinding zone temperature while grinding this type of alloy. The main aim of using solid lubricants is to reduce the frictional component of the grinding force which will lead to overall improvement in the grindability of the alloy.

Titanium alloys are typically difficult-to-cut materials due to the high strength at elevated temperatures, low modulus, low thermal conductivity and high chemical reactivity. Sun and Guo [10] says surface roughness value for end milling of Ti-6Al-4V in cutting and feed directions increases with feed and radial depth-of-cut, while it also increases in cutting direction in the low speed range but decreases in the high speed range. Surface roughness value in feed direction decreases with cutting speed. The variation ranges of surface roughness values in both directions are within 0.6–1.0μm. Compressive residual normal stresses in cutting and feed directions increase with cutting speed and have a maximum around the speed of 80m/min. The compressive residual normal stress in feed direction is about 30% larger than that in cutting direction. The magnitudes of residual shear stress are much smaller than those of the residual normal stresses. Compressive residual normal stress decreases in general with feed. The highly nonlinear coupling of mechanical and thermal loading determines the characteristics and magnitudes of residual stress profiles. The β phase seems to experience more deformation and volume shrinkage in the near surface with the cutting speed. However, phase transformation was not observed. The variation of β phase volume trend is qualitatively consistent with that of residual stress. The microhardness at surface is about 70– 90% larger than the bulk material.

Sun and Guo 2008 [9] shows chip width decreases with the increased cutting speeds and feed for end milling of Ti-6Al-4V. The radial depth of cut has a very slight influence on chip length and width. But radial depth of cut may significantly affect chip thickness. The saw-tooth width (distance between neighboring peaks) and height (peak-to-valley distance) becomes larger compared with those from by low cutting speeds. The increased saw-tooth phenomenon indicates more machining instability which could be one important reason for chattering in high-speed milling Ti–6Al–4V. With increase in the cutting speed, shear bands become larger and wider.

cBN tool which is a very hard material (next to diamond) is much suitable for high speed machining of Ti alloys (200-400m/min) [1]. The prominent reason for tool wear is diffusion-dissolution. This is due to the high chemical reactivity of Titanium alloys under high temperature. In this diffusion-dissolution reaction, it is Cobalt, the sintering element in cBN which readily reacts with Titanium and gets diffused- dissolved. After the diffusion-dissolution of the binder - Cobalt, Boron had also undergone diffusion-dissolution which is proven by EDX analysis. Tool life is mainly affected by the increase in depth of cut, which in turn produce high temperature that enhances the chemical reactivity and thereby the tool wears.

The machinability rate of Ti-6Al-4V is higher than that of Ti555.3. Comparing the maximum cutting speed of the two alloys, it can be deduced that the machinability of the latter could be approximately 56% of the former. There is a close relationship between the machinability rate and the mechanical properties of the work material (hardness and hot tensile strength), chemical composition (Mo equivalent value) as well as the chip morphology, specific cutting force (K_c), and specific feed force (K_k). Higher K_k and K_c values are observed for Ti555.3 than for Ti-6Al-4V in all the cutting speed conditions investigated. The difference between the K_k values (800MPa) is significantly higher than the respective K_c values (400MPa). The presence of adiabatic shear bands in the chips of Ti555.3 alloy could increase the fluctuations in the mechanical and thermal loads over the tool rake face leading to an accelerated tool wear by diffusion wear mechanism [2].

Grinding of titanium with the application of newly developed grinding tools (mono-layered super abrasive cBN) is still difficult due to chemical interaction between the workpiece material and the grinding wheels [12]. As it is known, these problems occur under dry condition, but could not be improved with an application of liquid nitrogen as a cutting fluid. The usage of traditional fluids like alkaline soap and cutting oil gave better results in respect to process forces, chip formation and the ground surface. MoS_2 as a lubricant ranks between the grinding under dry environment and the application of lubricants like oil or alkaline soap.

Surface roughness values recorded when machining Ti-6Al-4V alloy at the cutting conditions investigated are generally below the 1.6 mm rejection criterion for finish turning [3]. Surface finish generated when machining Ti-6Al-4V with PCD tools are generally acceptable and free of physical damages such as tears, laps or cracks in all the cutting conditions investigated. Micro-structural examination of the machined surfaces revealed no plastic deformation after finish machining at the cutting conditions investigated. Machining at high-speed conditions with PCD tools tend to soften the machined surfaces under coolant pressures of 11 and 20.3 MPa due to efficient cooling of the cutting interface by the high-pressure coolant. Hardening of machined surface was observed after machining with conventional coolant flow due to irregular cooling effect that tends to promote rapid quenching effect.

An alternative way to extract the advantages of solid lubricant application in grinding throughout the usage of the wheel, solid lubricant molded resin wheels were developed with graphite and CaF_2 separately, by including solid lubricants during the molding stage of the wheel [6, 7, 8]. Trials to make such wheels with vitrified bonding failed due to higher vitrifying temperature and non-availability of a good reduction furnace for firing. The effectiveness of lubricants was evident from the improved process results related to friction. The wheel wear depended on the type of the lubricant used. It was higher with graphite and lower with CaF_2. Saturation in lubricant effectiveness could be observed on increase of the quantity of lubricant.

Experimental findings reveal that the friction generated between tool and workpiece has been significantly reduced in molybdenum disulphide assisted machining as compared with graphite and wet assisted machining [11]. So, this methodology appears to offer considerable benefits over other methods of machining AISI 1045 steel. This work also emphasizes that proper selection of solid lubricant is essential for making it an interesting alternative to eliminate cutting fluids in metal cutting and hence making the machining environmental friendly. Although the lubricating action has been successfully taken care off in the proposed method, an effective means for substituting flushing action and tool cleaning, have yet to be identified in order to make solid lubricant assisted machining as viable alternative to conventional machining with cutting fluids. The below setup (Fig. 1) was developed by the authors and the fine solid lubricant powder was loaded into the hopper of the feeder. The powder is pushed out of the hopper through square box with the help of the blades placed around the periphery of the motor driven shaft. The powder, pushed out through the square box, was transferred first to rectangular channel and from there to the machining zone. In order to assist the smooth flow of solid lubricant powder, a vibrator was placed on the top of the hopper.

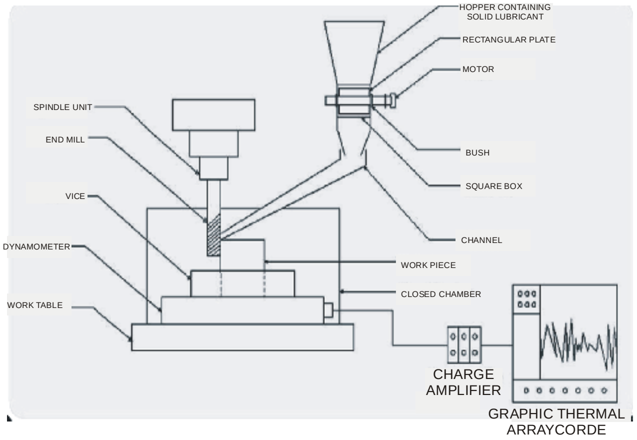

Fig. 1 Schematic of solid lubricant supplying setup

Turely et.al (Turley 1985) explained about the surface roughness generated during grinding of Ti-6Al-4V alloy and also observed that redeposition arise readily using conventional grinding practices. Venugopal et.al (K A Venugopal 2003; Venugopal, Paul *et al.* 2007) explained the tool wear phenomenon in cryogenic turning of Ti-6Al-4V alloy and concluded that cryogenic cooling with nitrogen jet substantially reduce the crater and flank wear [4,14]. The major cause of crater wear is adhesion-dissolution-diffusion wear which takes place because of the high chemical reactivity of the Ti - alloy. The benefit of cryogenic cooling has been found to be substantial at moderate cutting velocity of 70m/min. Edge depression of cutting tool insert also significantly decreased by using cryogenic cooling.

The effect of coolant pressure on chip formation while turning Ti-6Al-4V alloy and concluded that by application of High Pressure Coolant directly into the secondary shear zone results in smaller chips and also increases the tool life by almost 3 times [5]. At 90 bar the frequency of chip serration, shear band thickness and average chip thickness increases compared to 6 bar pressure of the coolant supplied.

Xipeng Xu *et.al* (Xu and Yu 2002) described the adhesion of abrasive and Ti-6Al-4V interface at elevated grinding temperature [15]. They found out that high temperatures generated in grinding can cause the abrasive-workpiece adhesion and consequently ground workpiece surface roughness increases. Also the adhesive and diffusive wear rate of the abrasive grits increase and hence attempts must be made to control the interface temperature which will eventually minimize the work piece surface damage and maximize wheel life.

There are various attempts made for using solid lubricants for various materials and various machining processes. As Ti-6Al-4V is a ductile material, long chips may form during grinding and may clog the inter grit spacing which leads to wheel loading. In order to reduce the frictional components of the grinding forces, solid lubricants may give good results. The aim of the present paper is to study the performance of grinding forces for the grinding of Ti-6Al-4V using solid lubricants. The responses which need to be studied are Tangential and normal forces in grinding and surface roughness using solid lubricants.

II. EXPERIMENTAL SETUP

Titanium ASTM Grade 5 alloy generally known as Alpha-beta alloy has been used in the present study. The chemical composition of the work material used is given in the Table 1.

Table 1. Tested composition of the Material.

Al	C	Fe	V	Ti
5.87	0.04	0.16	4.22	Remainder

The material that was obtained was in the form of a cylindrical bar. For the present experimentation the bar was cut into slices of about 10 mm by power saw and then squared pieces of dimensions of 60 mm × 60 mm are cut by a slitting saw. The squared pieces are made flat on both the surfaces by a surface grinder to get uniform thickness of the slice exactly to 9mm and then each slice was cut into 9 pieces of dimensions 19 mm × 19mm × 9 mm by using the slitting saw. Specification of Solid Lubricant used for the experiment are shown in table 2.

Table 2 Specification of Solid Lubricants.

Graphite	Molybdenum Sulphite (MoS$_2$)
• Make- CHD Laboratory Reagent	• Make- Molykote Z powder
• Particle size- 50 μm (> 99.5%)	• Purity- 98%
• Max. Impurity- 0.2%	• Particle size- 3 to 4 μm
• Density- 2.25g/cc	• Density- 4.8g/cc

The grinding experimentation has various process parameters which were used to analyze their individual and/or mutual response on results, and different number of levels of each parameter was used. Hence there would be different combinations of parameters at each level. In order to systematically arrange the combinations to easily analyze the results a methodology is followed which is known as design of experiments. For deciding the combinations there are some standard rules available in design of experiments such as Response Surface Method (RSM), Taguchi method etc.

Taguchi method is a robust method used to improve the quality of the product and process. The highest possible performance is obtained by determining the optimum combination of design factors. In Taguchi method optimum design is determined by using design of experiment principles and consistency of performance is achieved by carrying out the trial conditions under the influence of the noise factors. Taguchi method does not require rigorous knowledge and it also decreases the total number of experiments i.e., for grinding there are generally three process parameters, and if four levels of each parameter are chosen then the total number of experiments will be 16. For grinding there are three process parameters such as cutting speed, the table feed and the depth of cut. In this work 4 levels at each parameter had been chosen. For design of experiments by using Taguchi OA L16 was preferred. Table 5.5 gives the values of parameters chosen for each level.

III. RESULTS AND DISCUSSION

By using Design of Experiments Taguchi OA method the combinations of the process parameters with their levels and measured responses are shown in Fig. 2. All the experiments were done for three conditions of Grinding with SiC grinding wheel (GC60K5V) for grinding Ti-6Al-4V alloy and the environments chosen were Dry, Graphite assisted and MoS_2 assisted. Fig. 2., represents the graphs plotted by Lab View for the variation of forces with time while grinding Ti-6Al-4V alloy. Lab View also generates spread sheets for each force. From the graphs the average grinding forces were calculated and gives results for the values of forces and the Specific Energy consumption for Grinding in each ccondition of grinding.

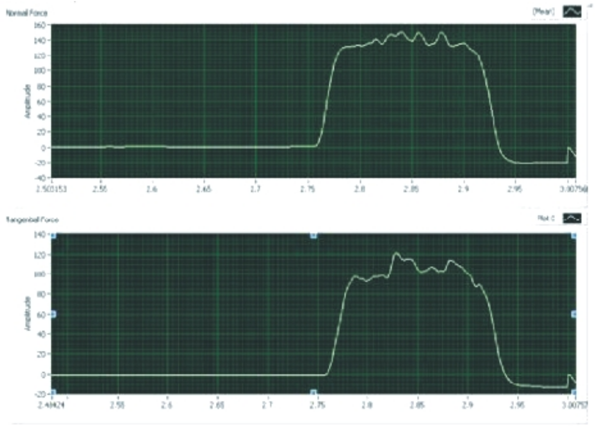

Fig. 2. Graphs generated by Lab View to represent the variation of forces with time.

A. Effect of Depth of Cut on Grinding Forces

Fig. 3 shows the variation in Normal Force with Depth of cut. From the figure it is clearly observed that by increasing the depth of cut the normal forces increase due to increase in average chip thickness.

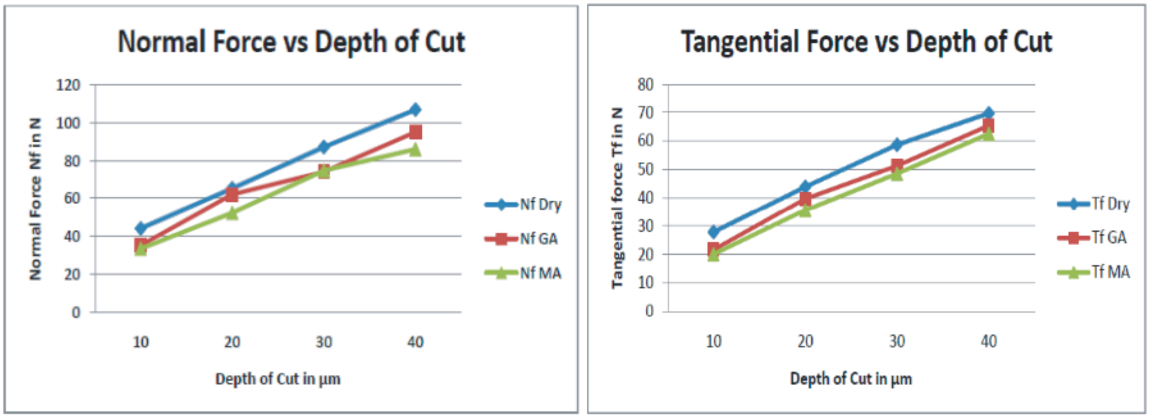

Fig. 3 Variation of Normal Forces and Tangential Force with Depth of Cut.

By using solid lubricants like graphite (50 µm sized) and MoS_2 (3- 4µm sized) powder at the grinding zone for grinding of Ti-6Al-4V alloy it has been found that the normal force value decreases to some extent. This decrease in force value is due to the decrease in the frictional component. The force decreases to a more extent in case of MoS_2 as compared to graphite which indicates the lubricity property of the MoS_2 is better than graphite in the present experimentation.

Fig. 3 shows the variation of tangential force with the depth of cut. The trend of the plot is similar to that observed for the normal force and only the magnitude is less for the tangential force. The main cause of the increase in tangential force with increase in depth of cut is the increase in the average chip thickness formed. The use of the solid lubricants has been found to be effective for grinding of this type of Ti-alloy. Graphite gives an intermediate value for tangential force between dry and MoS2 assisted grinding of this Ti-alloy.

Fig. 4 represents the variation of the specific energy required with the depth of cut. It can be noticed from the figure that the specific energy consumption goes on decreasing as the depth of cut increases. By increasing the depth of cut, the contribution of ploughing and rubbing components to specific energy consumption decreases which in turn lead to the decrease in the overall specific energy consumption. And the use of solid lubricant at the grinding zone while grinding of Ti-6Al-4V alloy further reduces the rubbing or frictional component of the specific energy and consequently the specific energy consumption decreases by a larger extent. Here also it is observed that MoS2 assisted grinding gives the lowest specific energy consumption thereby proving that it works better than the graphite as solid lubricant.

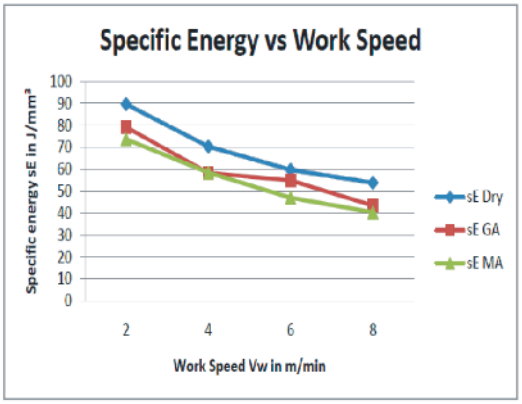

Fig. 4 Variation of Specific Energy with Depth of Cut.

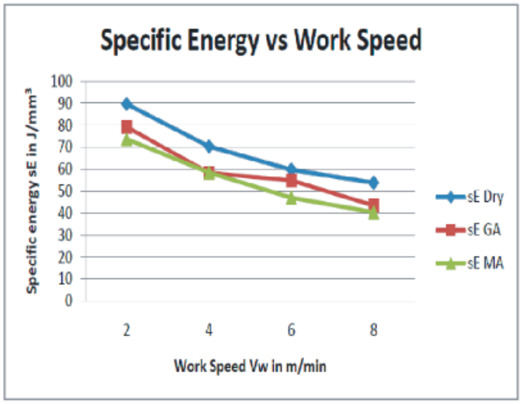

Fig. 5 Variation of Specific Energy with Work Speed.

B. Effect of Work Speed on Cutting Forces and Specific Energy

Fig. 5 shows the variation of the specific energy with the work speed. The trend is natural. Due to increase in work speed the the amount of energy consumed for removing unit volume of material decreases. Here the use of MoS2 gives the better results than graphite assisted and dry grinding of the Ti-alloy.

Fig. 6 represents the variation of normal force with the table speed. The normal force increases by increasing the table speed or the work velocity. The rise in the normal force again occurs mainly because of the increased chip load at higher work velocity condition.

Fig. 6 shows the variation of tangential force with respect to work speed. By increasing the work speed the tangential force increases expectedly. Also the use of solid lubricant gives improved results as the solid lubricant decreases the frictional force. MoS_2 give better than graphite.

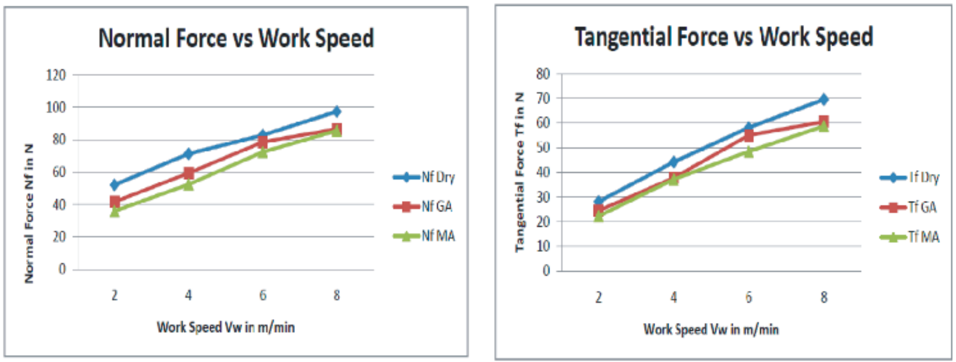

Fig. 6 Variation of Normal Forces and Tangential Force with Work Speed.

C. Effect of Cutting Speed on Cutting Forces and Specific Energy

Fig. 7 gives the trend of variation of normal force with the cutting speed. By increasing the cutting speed the average chip thickness decreases, which will result in decrease in the normal force. By using solid lubricants the frictional force component decreases which will in turn decreases the normal force. Here also the use of MoS_2 gives better results.

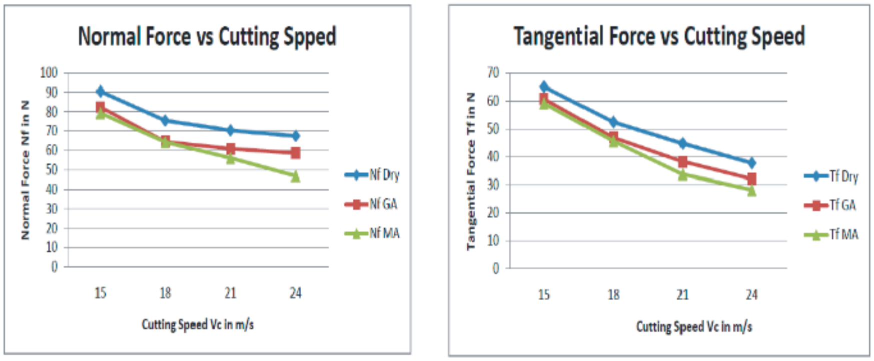

Fig. 7. Variation of Normal Forces and Tangential Force with Cutting Speed.

Fig. 8 shows the variation of specific energy consumption with the cutting speed. MoS_2 give the best results.

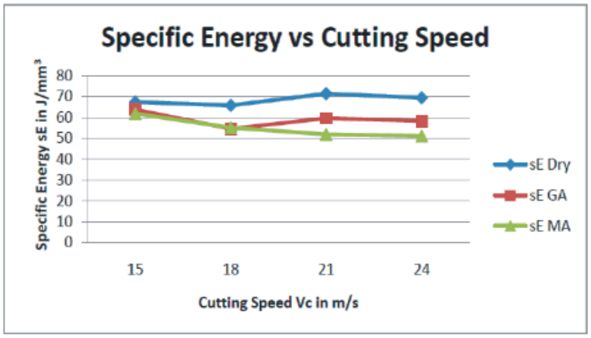

Fig. 8. Variation of Specific Energy with Cutting Speed

From the experiments it was found that, by using solid lubricants at the grinding zone, the forces were reduced in between 5% to 20%. The reduction of forces was due to the lubricity properties of graphite and MoS_2, however for dry grinding the specific energy consumption was more. A large amount of energy consumed was lost in the form of heat energy, which may lead to increase in the grinding zone temperature. As Ti-6Al-4V alloy has a low thermal conductivity the heat generated were not dissipated and localized heating occurs on the surface. Localized heating may lead to higher redeposition on the ground surface, surface cracking etc. At elevated grinding zone temperature chemical reaction may take place in between SiC and Ti and can degrade the abrasive property of SiC, henceTi-6Al-4V was preferred for lower cutting speeds. Due to lubricity action the specific energy consumption decreases which may lead to lower grinding zone temperature. Hence by using solid lubricant higher cutting speed may be attended, which in return improve grindability of Ti-6Al-4V alloy.

IV. CONCLUSIONS

The present experimental investigations led to the following conclusions :

(*i*) Grinding of Ti-6Al-4V alloy under dry conditions resulted in higher grinding forces and high specific energy requirement. Consequently grinding damages are more if the Ti-alloy is ground under dry condition.

(*ii*) Suitable solid lubricants like graphite and MoS2 may be used to grind this type of Ti-alloy. The lubricity property help in reducing the frictional forces generated during grinding process. Since frictional forces are quite prominent during grinding, effective control of the friction forces result in lesser force generation and less specific energy consumption which in turn reduce the damages to the ground workpiece.

(*iii*) The solid lubricants must be able to access the grinding zone and then only they will be able to reduce friction. A suitable set-up for carrying the solid lubricants to the grinding zone has been developed and fabricated and its efficacy has been validated through experiments.

(*iv*) The experimental trials conducted proved that graphite acts as a solid lubricant under moist condition. However MoS2 acted as a better lubricating agent.

(*v*) Both the solid lubricants used in the present study have been able to reduce the forces and specific energy consumption by around 5% to 20% but the reduction is found to be more when grinding is performed with MoS2 as the solid lubricant.

(*vi*) The solid lubricants thus, by reducing forces and specific energy consumption, resulted in better grindability of the Ti- alloy.

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