Investigations on the machinability of titanium alloy using low frequency vibration assisted turning under minimum quantity lubrication

V G Umasekar*1, M Gopal 2 and C Shravan Kumar 3

1 Assistant Professor, Department of Mechanical Engineering, SRM Institute of Science and Technology, Chennai, India
2 Professor, Department of Mechanical Engineering, SRM Institute of Science and Technology, Chennai, India
3 Research Assistant Professor, Department of Mechanical Engineering, SRM Institute of Science and Technology, Chennai, India

Email: umasekag@srmist.edu.in

Abstract. Titanium alloy found major applications in aerospace, automobile and chemical factories due to its large strength at elevated temperature, good corrosion resistance, low thermal conductivity and light weight. Because of its superior qualities, this alloy found difficult to machine. The machinability of titanium alloy can be improved by adding low frequency vibrations (less than 1000 cycles per second) to the cutting tool. An enhancement in the machining performance can be attained by applying minimum quantity lubrication (MQL) in the cutting zone. In this study an attempt has been made to enhance the machinability of Ti6Al4V alloy by using MQL technique during low frequency vibration assisted turning (LFVAT). Experiments were conducted and the influence of low frequency vibrations plus MQL on the turning process was estimated by measuring the average surface roughness, main cutting force and tool wear. The performance of LFVAT, LFVAT + MQL, conventional turning (CT) and CT+MQL compared in terms of the aforesaid output parameters.

1. Introduction
The industrial sectors like aerospace, automobile, marine, power generation and chemical generally requires materials with excellent properties like high strength, good corrosion resistance, high fatigue strength, light weight and low thermal conductivity. Titanium alloy is commonly recommended to make the critical components in these industries. However the superior qualities of this alloy leads to difficulties in machining during the manufacturing of the components. The low thermal conductivity leads to poor heat dissipation from the cutting zone which create larger thermal gradients and in turn fast tool wear. High elastic modulus cause higher deflection of the workpiece during machining. This induces chatter and vibration that increase the temperature and affects the surface quality [1]. Hence the machining of the titanium alloy results in higher cutting forces, excessive temperature, lesser tool life and poor surface integrity.

In order to overcome the difficulties associated with the titanium alloy machining, researcher attempted several techniques like applying high pressure coolant/cryogenic coolant/minimum quantity lubrication, thermal/laser assisted machining technique, rotary turning technique, machining with textured tool inserts, vibration assisted machining technique (low frequency vibration <1000 Hz or
Ultrasonic vibrations (20 KHz). Now a day hybrid machining methods are those techniques for solving difficulties in the machining of intricate metals. Hybrid metal removal processes can be stated as a union of 2 or more machining operations, which are simultaneously performed during machining operations [2]. In this study an attempt has been made to increase the machinability of Ti6Al4V alloy by applying the MQL technique during low frequency vibration assisted turning (LFVAT).

Adding low frequency high amplitude vibrations to the main cutting movement of the tool is called as low frequency vibration assisted turning. Vibration assistance leads to intermittent cutting action which in turn reduces the cutting force, cutting temperature and tool wear. LFVA is used to improve the performance of different machining processes like drilling, milling, turning, grinding and wire cut EDM. R.C.Skelton [3] performed experimental study on the low frequency vibration assisted turning (<125 Hz, 102 μm, Dry condition) on mild steel specimen. The author studied vibration assistance in the feed direction and tangential direction. They reported that low frequency vibration assistance in tangential direction reduced the cutting forces compared to CT at lower cutting velocities. The vibration assistance in the feed direction reduced the cutting force only to a small amount. But feed force reduced to considerable amount.

Naresh kumar maroju et al. [4] performed experimental and numerical studies on the low frequency vibration assisted turning (at 500 Hz, 250 μm, Dry condition) on Ti6Al4V, AISI 4340 and Al 2024 T351 alloys. They reported that low frequency vibration assistance reduced the machining forces; effective stresses and temperature compared to CT. Vibration assistance induce compressive residual stress on the specimen. LFVAT produced low tool wear and surface roughness in comparison to CT. Ibrahaim et al. [5] performed the study on the effect of low frequency vibrations (at 100 Hz, 130 μm, wet condition) in the axial direction while grinding the Inconel 718. The author found that the application of low frequency vibrations reduced the cutting forces by 35-40%, increased the material removal rate, extended the wheel life by 25-35% and improved the surface finish by 20-30%.

Tatsuya Sugihara et al. [6] studied the effect of ultra-low frequency vibrations from 1 to 10 Hz in the turning of titanium alloy. The author observed that crater wear reduced axial direction while grinding the Inconel 718. The author inferred that this technique reduced the crater wear at dry cutting condition. Naresh kumar maroju et al. [7] analysed the effect of high and low frequency vibrations in the turning of different engineering materials. The authors observed that both high frequency turning and low frequency turning reduced cutting forces, stress and temperature compared to conventional turning. They also inferred that low frequency turning process is limited by the material hardness.

From the literature study very little work is reported in the low frequency vibration assistance in the turning process. In this work, low frequency vibration is applied to the tool during turning process along with minimum quantity lubrication to increase the machinability of Ti6Al4V. The objective of this work involves development of a low frequency vibration assisted turning (LFVAT) setup and conducting low frequency vibration assisted turning with and without MQL and measure surface roughness, cutting force and tool wear. Compare the performance of LFVAT, LFVAT + MQL, CT and CT+MQL in terms of the surface roughness, cutting force and tool wear.

2. Experimental work

This study deals with the turning of grade 5 titanium alloy at various machining conditions. To perform the experimental runs, a PSG A141 centre lathe machine was used. The machining parameters, vibration parameters, tool insert details, workpiece details and lubrication details that were employed in this work are listed in table 1. The different machining experiments that performed in this study were CT, LFVAT, CT+MQL, LFVAT+MQL.

The low frequency vibration is generated with the eccentric rotation mass (ERM) motor. A DC motor with speed control circuit is used. An eccentric mass attached at certain distance from the motor shaft centre provided unbalance force and in turn the vibration. This vibration is transferred to the tool by direct contact by a fixture plate. This plate holds the ERM motor and tool holder in proper position
as shown in the figure 1. The frequency of vibration in the experiment can be altered by controlling the speed of the DC motor.

The experimental setup as shown in figure 2 consists of low frequency vibration generating system, kistler dynamometer, DC motor speed control circuit and MQL system. In vibration assisted turning the workpiece velocity should be lesser than the critical velocity then only interrupted type cutting benefit can be obtained. The critical velocity can be calculated by the formula \( v = 2\pi f a \) (1.356 m/min). The turning experiment is performed for a length of 15 mm on the workpiece. If the vibration generating unit is switch off then the turning operation will be conventional one. After performing each experiment, the average cutting force, average surface roughness and flank wear results were acquired. The average cutting force value obtained from the kistler dynamometer (9257B) data acquisition unit along with dynoware software. The average surface roughness of the turned workpiece was measured using Surfcom contact type surface roughness testing equipment. The amount of flank wear was measured in the tool makers microscope. The obtained results were shown in the table 2.
Table 1. Experimental conditions.

| Work piece | Titanium alloy  |
|------------|----------------|
| Diameter:  | 10 mm          |
| Length:    | 150 mm         |
| Hardness:  | 30 HRC         |
| Tool       | Coated tungsten carbide tool  |
|            | CNMG120408 TN4000 |
|            | Nose radius 0.8 mm |
| Vibration conditions | Type: Eccentric rotation mass motor  |
|            | Direction: Tangential or cutting direction  |
|            | Frequency (f): 40 Hz  |
|            | Amplitude (a): 0.09 mm |
| Turning parameters | Cutting velocity: 1.2 m/min  |
|            | Feed rate: 0.11 mm/rev   |
|            | Depth of cut: 0.1 mm    |
| Machining conditions | Conventional turning (CT)  |
|            | Low frequency vibration imposed turning (LFVAT)   |
|            | Conventional turning with minimum quantity lubrication (CT+MQL) |
|            | Low frequency vibration superimposed turning with small quantity lubrication (LFVAT + MQL) |
| Lubrication | Type: vegetable oil (sunflower oil) |
|            | Flow rate: 200 ml/hr    |
|            | Air pressure 6 bar      |

Table 2. Experimental results.

| S.no | Experiment condition | Average cutting force(N) | Average surface roughness (μm) | Flank wear (mm) |
|------|----------------------|--------------------------|-------------------------------|-----------------|
| 1    | CT                   | 162                      | 0.48                          | 0.16            |
| 2    | CT+MQL               | 117                      | 0.39                          | 0.14            |
| 3    | LFVAT                | 79                       | 0.33                          | 0.15            |
| 4    | LFVAT+MQL            | 53                       | 0.29                          | 0.12            |

3. Results and discussion

3.1. Average cutting force

Figure 3 shows the machining force during different turning conditions. The vibration applied turning (dry condition) of titanium alloy yields lower average cutting force in comparison to CT. The percentage reduction in average cutting force is 51% in comparison to CT. The force reduction was due to the intermittent cutting action of the tool and low friction between the tool and workpiece. The machining condition that combines LFVAT and minimum quantity lubrication yields lower average cutting force compared to CT+MQL. The percentage reduction in average cutting force is 54.7 in contrast to CT. The lubrication action of the oil in the cutting zone is the reason behind the low cutting force.
3.2. Average Surfaces roughness

The average surface roughness (Ra) during different turning conditions is shown in the figure 4. The LFVAT (dry condition) of titanium alloy provide good surface finish than regular turning operation. The percentage reduction in average surface roughness is 32% compared to conventional turning. The improvement in the surface finish is due the pulsating nature of the cutting. In conventional turning the tool contacts 100% of the time where as in vibration assisted machining, the cutting takes place only a portion of the vibration cycle. This cause low machining force and good surface finish. The LFVAT+MQL condition produce lesser average surface roughness with respect to CT+MQL. The average surface roughness is reduced by 27.2% compared to CT+MQL. The reduction in the average surface roughness in this case is due the combined effect of lubrication and intermittent cutting.

3.3. Tool wear

Figure 5 shows the flank wear occurred at various turning experiments. The low frequency turning of titanium at dry condition leads lesser flank wear in comparison to CT. The flank wear reduced by 16.6% compared to CT. The tool flank wear is reduced because of the low tool work contact ratio of LFVAT. The hybrid cutting condition (LFVAT+MQL) yielded small tool wear compared to
CT+MQL. The percentage reduction in the flank wear is 25.3 compared to CT+MQL. The reason for the improved tool life in LFVAT+MQL is the combination of the lubrication and intermittent cutting.

![Figure 5. Flank wear observe at different cutting conditions.](image)

4. Conclusion

This work reveals that the low frequency vibration assistance during turning of titanium alloy improved its machining performance. The added low frequency vibration reduced the average cutting force, surface roughness and flank wear by 51%, 32% and 16.6% respectively in comparison to CT. The addition of MQL with LFVAT reduced the cutting force surface roughness and tool by 54.7%, 27.2% and 25.3% respectively compared to CT+MQL. Hence, the hybrid method (LFVAT + MQL) can be considered as a suitable method for the machining of titanium alloy.

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