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# Vibration-Assisted Grinding with a Newly Developed Rotary Mechanism using Induction Motor

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## Abstract

This paper presents the analysis of mechanisms of removal in vibration-assisted grinding process. It is known that generally for machining, application of vibration helps to increase material removal rate, reduces tool wear rate and increases depth of machining. As the failure of a component originates from the surface, effect of vibrations on components generated using a variety of grinding process is to be analyzed. In this work, vibration-assisted grinding is carried out on a milling machine. The machine is equipped with a grinding wheel on which small frequency vibrations are applied. The resultant path of the tool is analytically evaluated. Longitudinal vibrations are developed by using a rotary mechanism. It was demonstrated that there are several favorable effects of vibrations in grinding process including: reduced tool forces, better surface finish and improved tool life. It is observed that the application of vibrations improve the process characteristics in grinding, to a large extent.

**Keywords**: Grinding, Dynamics, Vibrations, Tool forces, Rotary mechanism, Induction motor

## Introduction

Molds and dies for high precision optical components have led to a demand for high quality surface finish. Complex geometries constructed on hard mold materials are very difficult to fabricate. In order to obtain the mirror finishing of the mold surface, polishing is usually required [1,2]. However, polishing is a time consuming process and not suitable for microstructures. In recent years, the use of vibration-assisted grinding in finishing the mold surface is a potential technique to overcome these technological limits [3-6]. Vibration-assisted machining (VAM) adds small-amplitude, high-frequency tool displacement to the cutting motion of the tool [7]. The tool tip is driven in a small reciprocating (1D VAM) or elliptical motion (2D VAM) whose centroid moves in the direction of the cutting velocity. For appropriate combinations of cutting velocity, tool amplitude and frequency, the tool periodically loses contact with the chip (or leaves the workpiece entirely, in the case of 2D VAM) [8]. As a result, machining forces can be reduced and thinner chips can be generated. This in turn leads to improved surface finishes, better form accuracy, and near-zero burr compared to conventional machining. Tool life, especially of diamond tools cutting ferrous materials, is dramatically extended by VAM [9]. When cutting brittle materials, VAM has also been found to increase the depth of cut for which ductile-regime cutting can be achieved, allowing complex optical shapes to be made without grinding and polishing [10,11].

Vibration-assisted machining (VAM) adds small-amplitude, high-frequency tool displacement to the cutting motion of the tool [12]. The tool tip is driven in a small reciprocating (1D VAM) or elliptical motion (2D VAM) whose centroid moves in the direction of the cutting velocity. For appropriate combinations of cutting velocity, tool amplitude and frequency, the tool periodically loses contact with the chip (or leaves the workpiece entirely, in the case of 2D VAM) [13]. As a consequence, machining forces can be reduced and thinner chips can be generated. This in turn leads to improved surface finishes, better form accuracy, and near-zero burr compared to conventional machining [14]. Furthermore, tool life, especially of diamond tools cutting ferrous materials, is dramatically extended by VAM. When cutting brittle materials, VAM has also been found to increase the depth of cut for which ductile-regime cutting can be achieved, allowing complex optical shapes to be made without grinding and polishing. It appears that a fundamental understanding of the analysis of the vibration assisted process is not yet carried out. Therefore, this paper addresses the important research issues in vibration assisted grinding process. This paper is divided into four sections: i) mechanisms of conventional grinding, ii) effect of vibrations on grinding process, iii) experimental analysis of grinding and iv) comparative analysis of grinding. The mechanisms of removal in vibration is therefore, characterized in detail, in the following sections.

## Fundamental Mechanisms of a Practical Grinding Process

Grinding is used to finish workpieces that must show high surface quality (e.g., low surface roughness) and high accuracy of shape and dimension. As the accuracy in dimensions in grinding is on the order of 0.000025 mm, in most applications it tends to be a finishing operation and removes comparatively little metal, about 0.25 to 0.50 mm depth. However, there are some roughing applications in which grinding removes high volumes of metal quite rapidly. Thus, grinding is a diverse field. The grinding machine consists of a bed with a fixture to guide and hold the work piece, and a power-driven grinding wheel spinning at the required speed.

The speed is determined by the wheel's diameter and manufacturer's rating. The user can control the grinding head to travel across a fixed work piece, or the work piece can be moved while the grind head stays in a fixed position. Fine control of the grinding head or tables position is possible using a vernier calibrated hand wheel, or using the features of numerical controls. Grinding machines remove material from the work piece by abrasion, which can generate substantial amounts of heat. To cool the work piece so that it does not overheat and go outside its tolerance, grinding machines incorporate a coolant. The coolant also benefits the machinist as the heat generated may cause burns. In high-precision grinding machines (most cylindrical and surface grinders), the final grinding stages are usually set up so that they remove about 200 nm (less than 1/10000 in) per pass - this generates so little heat that even with no coolant, the temperature rise is negligible. The conventionally used grinding machines are: (a) *Belt grinder***:** This is usually used as a machining method to process metals and other materials, with the aid of coated abrasives. Sanding is the machining of wood; grinding is the common name for machining metals. Belt grinding is a versatile process suitable for all kind of applications like finishing, deburring, and stock removal. (b) *Bench grinder:* This is usually has two wheels of different grain sizes for roughing and finishing operations and is secured to a workbench or floor stand. Its uses include shaping tool bits or various tools that need to be made or repaired. Bench grinders are manually operated. (c) *Cylindrical grinder:* This includes both the types that use centers and the centerless types. A cylindrical grinder may have multiple grinding wheels. The workpiece is rotated and fed past the wheel(s) to form a cylinder. It is used to make precision rods, tubes, bearing races, bushings, and many other parts. (d) *Surface grinder:* This includes the wash grinder. A surface grinder has a "head" which is lowered, and the workpiece is moved back and forth past the grinding wheel on a table that has a permanent magnet for use with magnetic stock. Surface grinders can be manually operated or have CNC controls. (e) *Tool and cutter grinder and the D-bit grinder:* These usually can perform the minor function of the drill bit grinder, or other specialist tool room grinding operations. (f) *Jig grinder:* This as the name implies, has a variety of uses when finishing jigs, dies, and fixtures. Its primary function is in the realm of grinding holes and pins. It can also be used for complex surface grinding to finish work started on a mill. (g) *Gear grinder:* This is usually employed as the final machining process when manufacturing a high-precision gear. The primary function of these machines is to remove the remaining few thousandths of an inch of material left by other manufacturing methods (such as gashing or hobbing)

It is evident that grinding is an abrasive machining process that uses a grinding wheel as the cutting tool. Grinding is usually a final process. So the surface quality is to be maintained. The importance of surface quality in machining can be attributed to the fact that in most of the components or systems, failure originates from the surface. Hence the surface quality should be maintained.

## Vibration-Assisted Grinding

Vibration assisted grinding is a grinding method in which a certain frequency of vibration with an amplitude of about 10 µm is superimposed to the cutting tool or the workpiece to achieve better cutting performance. When a high frequency vibration (more than 16 kHz) is applied to the cutting tool or the workpiece, it is known as the ultrasonically assisted grinding. The introduction of small amplitude vibrations in different machining processes, including drilling, turning, milling, and grinding, can be found in the literature [2-13]. Vibration-assisted machining was initiated in the 1960 s. Skelton applied a vibration with a frequency of 0–125 Hz along feed or tangential direction in turning [2]. Lower cutting forces were found in the

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study. The reduction of cutting force was attributed to the separating of the tool from the workpiece in vibration-assisted turning. However, because the vibration frequency was low in this study, the reductions in cutting forces were only feasible at low cutting velocities. Nath and Rahman [3] showed that cutting forces and tool flank wear were only 15%–25% in vibration-assisted turning Inconel 718, compared to that of conventional cutting, with a frequency of 19 kHz and an amplitude of 15 lm. Babitsky et al. [4] observed that improvement of surface finish and roundness were up to 25%–50% in vibration-assisted turning of aviation materials. Vibration-assisted machining is also suitable for cutting brittle and composite materials [5,6]. The elliptical vibration-assisted cutting was developed by Moriwaki and Shamato [7] for better cutting performance and complex workpiece geometries. Analysis and simulation also justified that the vibration-assisted machining could reduce cutting forces, cutting temperatures, and improve surface roughness [3,8].

Toews et al. [9] applied vibration frequencies below 200 Hz on the workpiece in drilling aluminum 6061. Lower drilling forces were detected when the vibration conditions were appropriately chosen. Liao et al. [10] studied the effect of ultrasonic vibration on drilling Inconel 718. Experimental results showed that lower thrust forces and longer tool life were achievable. The best vibration condition was 31.8 kHz for frequency and 4 lm for amplitude. The application of ultrasonic vibrations in grinding was also shown to reduce the grinding force as much as 78% and to improve the surface finish by 10% [11]. Isobe et al. [12] verified mirror surface grinding for mold steels by superimposing ultrasonic vibrations on the tool. The high quality of workpiece roughness Rz of 0.14 lm was attained. The vibration frequency was up to 60 kHz. It was also found that when the spindle speed increased from 4000 to 9000 rpm, the surface roughness Rz deteriorated from 0.24 to 0.80 lm. For the cutting condition of feed of 500–1000 mm/min and cross feed of 10 µm, scratches on the finished surface were seen. Hara et al. [13] investigated the effects of the cutting edge shape in vibration-assisted grinding. The cutting edge of the grinding tool was trimmed before grinding tests. Experimental results showed that the ground surface finish was improved by grinding with truncated grits. However, the truncation of the grinding grits caused the thrust force to increase.

Although the vibration-assisted machining is an effective technique for improving cutting performance, it is not easy to improve the dimensional accuracy down to the order of 1 µm if the amplitudes of vibrations of the tool or workpiece are more than 10 µm.

## Principle of a Vibration-Assisted Machining Process

In 1-D vibration-assisted machining the tool is driven harmonically in a linear path parallel to the workpiece upfeed motion. For VAM frequency *f*, vibration amplitude *A*, and upfeed velocity *V*, the position *X(t)* and velocity *X'(t)* of the tool relative to the workpiece are

$$X(t) = A * \cos(2\pi ft) + V * t \qquad (1)$$

$$X'(t) = -2\pi f * A * \sin(2\pi ft) + V \qquad (2)$$

From Eq. (2), when $2\pi fA < V$ the tool will separate from the uncut work material for a portion of each cycle. This is depicted in Figure 1.

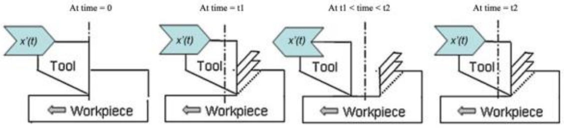

**Fig: 1. 1-D Vibration assisted machining mechanism**

At *t* =0 the tool initially contacts the workpiece. At *t=t1* it has finished cutting and is about to move backwards relative to the work. Between *t1* and *t2* the tool is separated from the work and not cutting. At *t=t2* the tool is again in contact with the uncut work material and is about to cut. Figure 2 shows 2-D vibration-assisted machining. The tool moves at frequency *f* in an ellipse with horizontal amplitude *A* and vertical amplitude *B*. The horizontal position and velocity relative to the work are again given by Eq. (1) and Eq. (2). The vertical position *Z(t)* and vertical velocity *Z.(t)* are

$$Z(t) = B * \sin(2\pi ft) \qquad (3)$$

$$Z'(t) = 2\pi f * B * \cos(2\pi ft) \qquad (4)$$

Again, when $2\pi f * A < V$ the tool will separate from the uncut work material for a portion of each cycle [14].

## Experimental Work

The grinding tests are conducted with a milling machine equipped with a small grinding wheel. In order to study the influence of small-amplitude vibrations in grinding actuated workpiece holders have been designed and fabricated. Frequency generation is employed by small induction motor having a wheel is attached to it, and the wheel having certain number of tooth. Attachment made on the work piece is in contact with the tooth. In such a way that while rotating the wheel, work piece is vibrating laterally. Amplitude of vibration is depends on height of the tooth. Frequency of vibration depends on number of tooth on the wheel and speed of the wheel. Work piece is clamped on the machine table and clearance is provided (1 mm). Grinding tool is attached to the spindle is rotating at high speed (20000 rpm) direction of feed is same as the direction of vibration of the work piece. In order to analyses the surface finish of the work piece and cutting force of the milling cutter , we have to select 3 different parameters: i) Rotating speed of the grinding wheel, ii) Frequency of vibration, and iii) Amplitude of vibration, see Fig. 2.

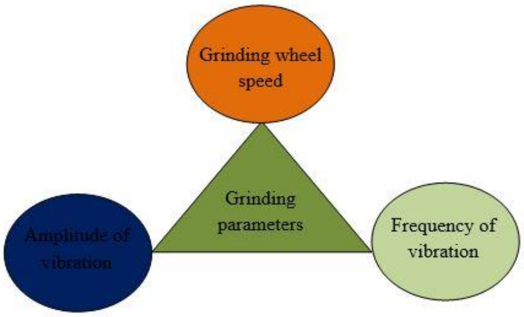

**Fig.2 Grinding parameters**

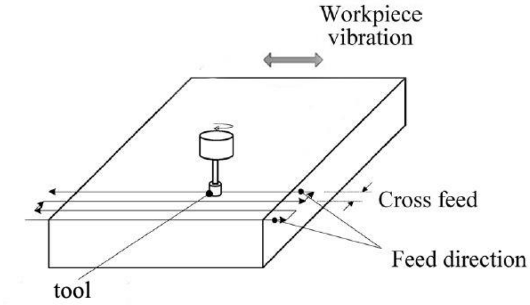

**Fig. 3. Tool path for grinding operation**

The calculation part regarding the vibration attachment, based on the tool path (Fig. 3) is given:

Speed of the wheel = 1600 rpm ( other two are 2000, 2500 rpm)
= 1600/60 rps
= 26.666 rps
No of tooth on the wheel = 20
Frequency = no of cycles / second
= 26.666 * 20
= 533.4 Hz
Amplitude of vibration (from mean position)= height of the teeth/2
= (1mm)/2 = 500 µ

Other two amplitude of vibrations are ( 0.25mm, 0.75mm)

Spindle speed is designed as: 20000,15000 ,25000 rpm

Considering the effect of vibrations, the rotary mechanism for generating longitudinal vibration is shown in Fig. 4.

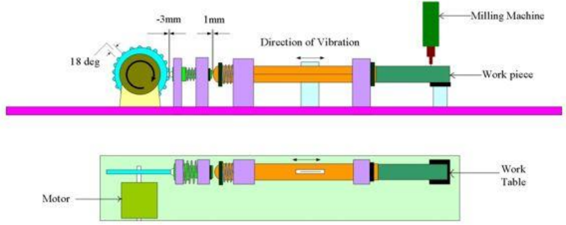

**Fig: 4. Rotary mechanism for generating longitudinal vibration**

## Benefits of Vibration Assisted Grinding

### Cutting Dynamics and Reduced Tool Forces

Due to the interrupted cutting in vibration assited grinding, small chip are formed during each machining cycle, at lower tool force. The high vibration frequency means that many cycles take place in a specified time interval. Hence in vibration assisted grinding many small chips are made, instead of a large continuous chip as in conventional grinding. Moreover, the tool moves with lower average force for a much larger cumulative distance in repetitive passes, compared to conventional grinding in the same amount of time. For the same volumetric material removal, the work performed by vibration assisted grinding is therefore consistent with that of conventional grinding.

### Extended Tool Life

Increase in surface roughness with cumulative machining distance can be used as an indication of tool wear. Thermo chemical mechanisms are mainly responsible for diamond tool wear in ferrous metals. Vibration assisted grinding's interrupted cutting extends tool life by reducing the duration of tool work contact, limiting the time for these mechanisms to operate. VAM may also reduce tool temperature, limiting the driving potential for the relevant reactions. Tool life in ferrous metals for 2-D vibration assisted grinding is superior because in 1-D vibration assisted grinding the tool cutting edge can chip from accidental contact with the workpiece during the non cutting portion of the machining cycle.

### Surface Finish and Form Error

Surface finish in vibration assisted grinding is frequently superior to conventional Grinding for the same combination of tool and workpiece materials. The cyclic nature of vibration assisted grinding allows the tool to traverse the cut area from the preceding cycle and remove material peaks left over from the last pass. Small upfeed velocity and horizontal speed ratio give low theoretical surface roughness by maximizing the overlap between successive cycles. The smaller forces in 2-D vibration assisted grinding, and the smaller average forces in 1-D vibration assisted grinding, lead to improved form accuracy and surface finish by decreasing relative vibration between tool and work. The reduced tool forces also inhibit chatter.

## Conclusions

A new mechanism for generating vibration to the workpiece using high speed induction motor is designed and fabricated. The interrupted cutting characteristic of vibration-assisted grinding leads to significant reduction in tool forces, extended tool life, and improved surface finish. The cutting dynamics differ between 1-D and 2-D VAM. The best surface finish happens at a lower feed when the vibration frequency is increased. Larger amplitude is expected to improve surface finish in small-amplitude vibration-assisted grinding. Vibrations between tool and the workpiece can reduce the average cutting force, so tool wear is reduced and cutting time extends. In this study, the vibration-assisted grinding can extend tool life more than twice as that in conventional grinding. The introduction of MQL can further increase the tool life in vibration-assisted grinding. However, improvement of surface finish may not be significant without properly selecting lubricating parameters.

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## Recommendations For Future Work

The recommendations for future work are summarised as follows:

1) Further research on dynamic machine behaviour for micro grinding machines can be done and should focus on the cutting tool and condition monitoring.
2) Re-assessment of the framework of design concept. The assembly and machine component error should especially be taken into account.
3) More understanding of vibration assisted machining mechanism phenomena in precision engineering to develop a robust knowledge and to implement new machine technology.
4) Investigation into the lubrication and coolant potential in vibration assisted micro-grinding.

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