Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science. 2023 vol. 25 no. 4 pp. 136–150
ISSN: 1994-6309 (print) / 2541-819X (online)
DOI: 10.17212/1994-6309-2023-25.4-136-150

NSTU NETI

Obrabotka metallov -
Metal Working and Material Science

Journal homepage: http://journals.nstu.ru/obrabotka_metallov

Ultrasonic vibration-assisted hard turning of AISI 52100 steel: comparative evaluation and modeling using dimensional analysis

Govind Ghule[1, a,*], *Sudarshan Sanap*[1, b], *Satish Chinchanikar*[2, c]

[1] MIT-School of Engineering, MIT-ADT University, Pune - 412201, India
[2] Vishwakarma Institute of Information Technology, Pune - 411048, India

[a] https://orcid.org/0000-0003-4331-3501, govindghulemasterofengineering@gmail.com;
[b] https://orcid.org/0000-0002-3788-0692, sudarshan.sanap@mituniversity.edu.in;
[c] https://orcid.org/0000-0002-4175-3098, satish.chinchanikar@viit.ac.in

ARTICLE INFO

Article history:
Received: 03 September 2023
Revised: 17 September 2023
Accepted: 27 September 2023
Available online: 15 December 2023

Keywords:
Ultrasonic vibrations
Hard turning
Dimensional analysis
Buckingham Pi theorem
Tool wear
Power consumption

ABSTRACT

Introduction. Precision machining of hard and brittle materials is difficult, which has led to the development of novel and sustainable techniques such as ultrasonic vibration-assisted turning (*UVAT*) for enhanced removal rates, surface quality, and tool life. **The purpose of the work.** Hard turning using cost-effective coated carbide tools instead of costly to operate ceramic and *CBN* inserts is still not widely accepted due to tool wear and machining limitations. A group of researchers attempted hard turning using carbide tools with different coatings, different cooling techniques, etc., to achieve better machinability. However, very few attempts were made by the researchers on ultrasonic vibration-assisted hard turning (*UVAHT*). Moreover, comparative evaluation of *UVAHT* using dimensional analysis is rarely reported in the open literature. **The methods of investigation.** With this view, this study comparatively evaluates the tool wear and power consumption during conventional turning (*CT*) and ultrasonic vibration-assisted hard turning (*UVAHT*) of *AISI 52100* steel (62 HRC) using a *PVD*-coated *TiAlSiN* carbide tool. Experiments were performed with varying cutting speed, feed, and depth of cut while keeping vibration frequency and amplitude constant at 20 kHz and 20 µm, respectively. Further, a theoretical model was developed to predict the tool wear and power consumption using the concept of *Dimensional analysis*, i.e., the *Buckingham Pi theorem* considering the effect of cutting speed, frequency, and amplitude of vibrations at constant feed and depth of cut of 0.085 mm/rev and 0.4 mm, respectively. Dimensionless groups were created to reveal complex linkages and optimize machining conditions. Tool wear and power consumption were measured experimentally and statistically analyzed using the *Buckingham Pi theorem*. **Results and Discussion.** Using dimensional analysis, the research uncovers substantial insights into the *UVAHT* process. The results show that ultrasonic vibration parameters have a significant impact on tool wear and power consumption. Dimensionless groups provide a methodical foundation for refining machining conditions. The tool wear and the power consumption increase with the cutting speed, depth of cut, and feed. However, this effect is more significant in *CT* than *UVAHT*. The power consumption increases with the cutting speed, vibration frequency, and amplitude. However, the increase in the power consumption is more prominent when the cutting speed changes, followed by vibration frequency and amplitude. The flank wear increases with the cutting speed and vibration amplitude and decreases with the vibration frequency. This study contributes to a better understanding of the underlying dynamics of *UVAHT*, which will help to improve precision machining procedures for hard materials. The paper explores the practical significance of these discoveries for hard material precision machining.

For citation: Ghule G.S., Sanap S., Chinchanikar S. Ultrasonic vibration-assisted hard turning of AISI 52100 steel: comparative evaluation and modeling using dimensional analysis. *Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science*, 2023, vol. 25, no. 4, pp. 136–150. DOI: 10.17212/1994-6309-2023-25.4-136-150. (In Russian).

*** Corresponding author**
Ghule Govind S., M.E. (Design Engineering), Assistant Professor
MIT-School of Engineering, MIT-ADT University,
Pune - 412201, India
Tel.: +91-7020742258, **E-mail:** govindghulemasterofengineering@gmail.com

Introduction

Ultrasonic vibration-assisted hard turning (*UVAHT*) is a potential machining technique that combines the advantages of traditional turning with the use of ultrasonic vibrations to improve hard material machining. *AISI 52100* steel is a commonly used bearing steel that is noted for its excellent hardness, wear resistance, and dimensional stability. *Ultrasonic vibration-assisted turning* (*UVAT*) has demonstrated tremendous potential for improving the machinability of such hard materials, allowing for higher material removal rates, enhanced surface integrity, and reduced tool wear [1–3].

Because of its high strength and hardness, the typical hard turning method sometimes finds difficulties when machining hardened materials such as *AISI 52100* steel. This results in increased cutting forces, higher tool-workpiece interface temperatures, and accelerated tool wear, all of which impair the surface polish and dimensional accuracy of the machined components. *UVAHT* can alleviate these issues and provide various benefits by adding high-frequency ultrasonic vibrations during the turning process.

The underlying dynamics of *UVAHT* involve the propagation of ultrasonic vibrations through the tool and into the workpiece, which results in micro fracturing, lower cutting forces, and enhanced chip removal. These dynamic impacts on the cutting process change the material removal mechanism and affect the tool-workpiece relationship, resulting in better cutting performance. However, to take full advantage of *UVAHT* of *AISI 52100* steel, it is necessary to understand the impact of numerous process factors and its interactions.

Ultrasonic vibration-assisted hard turning (*UVAHT*) has received a lot of attention in recent years as a potential machining technology for hard materials such as *AISI 52100* steel. Several studies have investigated the impact of ultrasonic vibration on hard turning operations and its potential advantages for increasing surface integrity, reducing cutting forces, and extending tool life. The literature study provided here gives an overview of significant research related to *UVAT* and its use in the machining of *AISI 52100* steel. The use of ultrasonic vibrations in machining operations has received a lot of attention. Some studies have focused on ultrasonic-assisted turning of conventional materials, emphasizing the reduced cutting forces and increased surface polish attained with this technology.

Liu et al. [4] studied the impact of ultrasonic vibration on the cutting performance of *AISI 1045* steel and found that it improved tool life and surface quality significantly. These investigations laid the groundwork for further research into the use of *UVAHT* for hard materials such as *AISI 52100* steel. Because of its numerous industrial uses, hard turning of *AISI 52100* steel has piqued interest. To improve the machinability of this material, researchers investigated various cutting modes and tool geometries. The authors in [5], for example, investigated the effect of cutting speed and feed rate on tool wear and surface roughness during hard turning of *AISI 52100* steel. These studies revealed the difficulties associated with traditional hard turning and stimulated the study of other methods such as *UVAHT*. The use of ultrasonic vibrations in hard turning has showed significant promise in terms of enhancing machining performance. The effects of various ultrasonic parameters, such as vibration amplitude and frequency, on cutting forces and surface integrity during *UVAHT* have been studied.

In [6] investigated the impact of ultrasonic vibration amplitude on chip formation and surface roughness during hard turning of *AISI 4140* steel, offering important insight into the dynamic effects of ultrasonic vibrations on material removal. In the field of machining, dimensional analysis has been widely employed to investigate the correlations between process parameters and performance indicators. The authors in [7] used dimensional analysis to study the effect of cutting modes on surface roughness in hard turning, laying the groundwork for applying this method to *UVAHT*. Similarly, *Zhang et al.* [8] used dimensional analysis to investigate the impacts of process parameters in ultrasonic vibration-assisted milling, emphasizing its use for optimizing machining processes.

Dimensional analysis is a strong method for studying the *UVAHT* process and identifying the important characteristics that affect its success. This method entails identifying and formulating dimensionless groups that connect the important process variables without necessitating entire experimental research. Dimensional analysis gives important insights into the interactions between numerous process factors and its impact on cutting performance by reducing complicated relationships to dimensionless parameters.

The authors in [9] investigated the *UVAT* method for titanium alloy using dimensional analysis to study the effects of ultrasonic vibration parameters and conventional turning parameters on surface roughness and cutting forces, dimensionless groups were created. The dimensional analysis method was useful in optimizing the *UVAT* parameters for titanium alloy machining. Scientists in [10] presented dimensional analysis which was used in this work to investigate surface integrity during *UVAT*. The research examined how ultrasonic vibration parameters and conventional turning parameters affect surface roughness, residual stress, and micro hardness. The dimensional analysis method assisted in identifying the important parameters affecting surface integrity and gave guidance for enhancing surface quality using *UVAT*.

Scientists in [11] proposed dimensional analysis which was used in this work to investigate surface integrity in *UVAT* of hardened *AISI 4340* steel. Dimensionless groups were formed to investigate the effects of ultrasonic vibration and cutting modes on surface roughness, hardness, and residual stress. The study revealed the use of *UVAT* to improve surface integrity, as well as the utility of dimensional analysis in studying the process. The authors in [12] conducted an experiment which explained the dimensional analysis of ultrasonic vibration-assisted micro-cutting of silicon. Dimensionless groups were created to investigate the impact of ultrasonic vibration parameters and cutting parameters on cutting forces and surface quality. The dimensional analysis technique provided insights into the optimization of the silicon micro-cutting process.

The purpose of this research paper is to comparatively evaluate the conventional hard turning and ultrasonic vibration-assisted hard turning and develop a theoretical model of tool wear and power consumption using dimensional analysis. The model will be developed using *Buckingham Pi theorem* considering cutting speed, density, workpiece hardness, vibrational amplitude, and frequency as the input parameters. The findings of this study will help to optimize the *UVAHT* of *AISI 52100* steel, offering significant guidance for improving machining performance. Furthermore, the findings of the study will provide useful guidance for industry practitioners aimed at improving the efficiency and quality of hard turning operations on *AISI 52100* steel employing ultrasonic vibration support. *UVAHT* has the potential to find widespread use in precision manufacturing sectors requiring hard and difficult-to-cut materials by expanding the understanding of this novel machining process.

The methods of investigation

UVAHT Equipment Configuration

An ultrasonic vibration system is integrated with a conventional lathe in the experimental setup for ultrasonic vibration-assisted hard turning (*UVAHT*). A precision lathe with a motorized spindle and a modified tool holding fixture, specifically designed for mounting an ultrasonic vibratory tool (*UVT*), which is an assembly of a transducer, booster, and a horn that serves as a tool holder for performing hard turning operations conventionally and with ultrasonic vibration assistance. The rotating motion required by the workpiece and cutting tool is provided by the lathe. The total *UVAHT* composition is made up of several components such as a lathe machine, a workpiece, a specifically designed fixture, an ultrasonic frequency generator, and a transducer-booster assembly (fig. 1).

In this sustainable cutting strategy, the cutting tool and w/p are regularly separated and get in contact (intermittent process), resulting in no *BUE* generation. This advanced technique consists of four major stages: 1) approach, 2) touch, 3) immersion, and 4) back off. These four steps of *UVAT* are recreated in fig. 2 for fully understanding this approach [13–15].

However, when vibrations are applied in the cutting velocity direction, a few limitations should be considered, namely $V_c = \pi dn$, $V_t = 2\pi AF$. Where "V_c" is cutting velocity, "n" is rotations per minute, "d" is workpiece diameter, "V_t" is tip velocity, i.e. vibrational speed of cutting, "A" is vibration amplitude, and "F" is frequency. If A = 20 m and F = 20 kHz, then the value for "V_t", i.e., the tip velocity, should be less than 150 m/min. The relative displacements of the cutting tool and the workpiece in ultrasonic-assisted turning (*UVAT*) are depicted in fig. 3 [16].

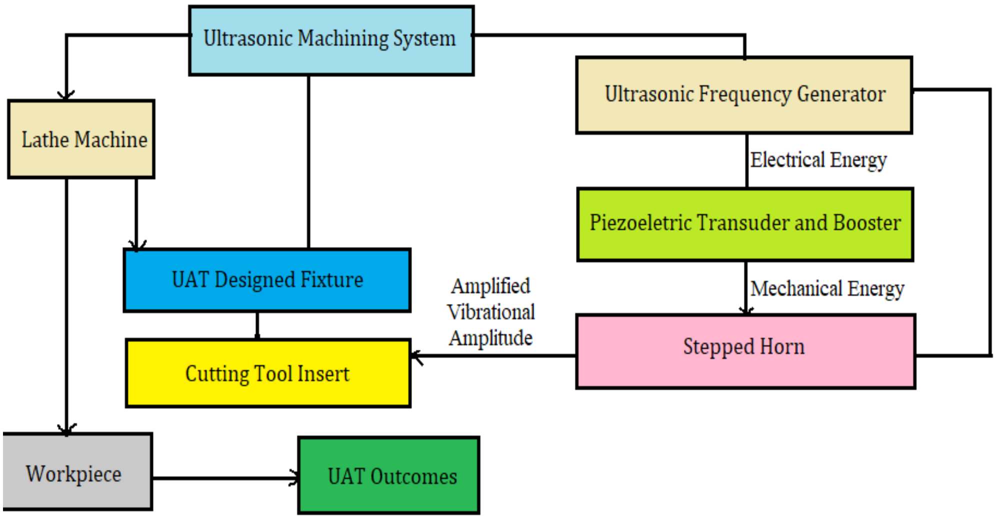

Fig. 1. Schematic diagram of UVAHT systems

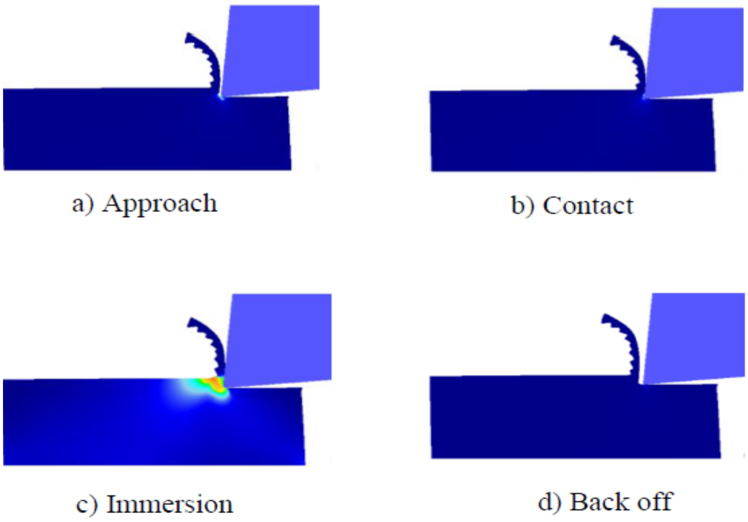

Fig. 2. Four stages of *UVAT*

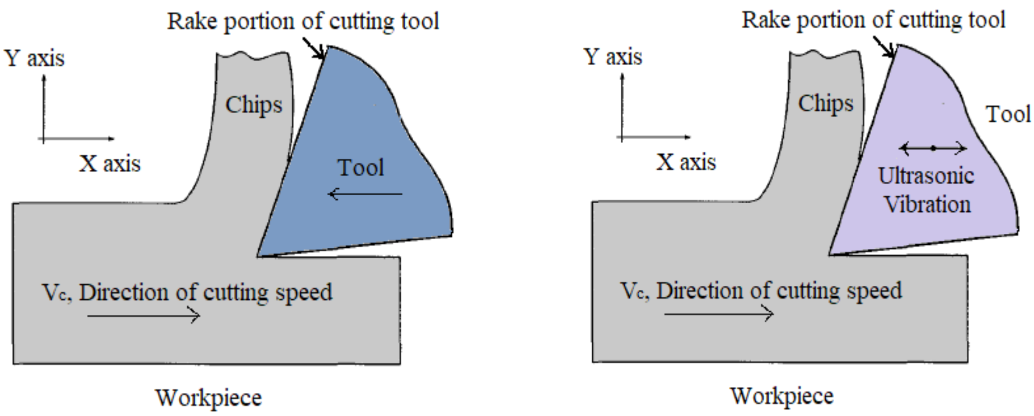

Fig. 3. Relative displacements of the cutting tool and the workpiece in *CT* and *UVAT*

Employing high frequency vibrations, several cycles may be completed in less than a millisecond. During conventional turning (*CT*), the tip of the cutting tool is constantly in contact with the surface of the workpiece. When ultrasonic vibrations are applied to the tip of the cutting tool, the interaction between the tool tip and the workpiece changes completely and becomes discontinuous (i.e., intermittent) [17].

Experimental Setup

The workpiece material used in the experiments is *AISI 52100* steel, common bearing steel known for its high hardness and wear resistance. Because of the severe hardening of the workpieces, the cutting force, required for machining *AISI 52100* hardened steel, is relatively considerable. Accelerated tool wear and chip breakup are challenging tasks, thus the material for the cutting tool should be more abrasion resistant. As a result, selecting the most appropriate cutting tool material, tool form, and cutting modes is critical for enhancing the machinability of *AISI 52100* hardened steel. In this experiment, a *PVD*-coated *TiAlSiN* tool with the geometry *CNMG120408-MF5* was used. Actual photograph of base frame with *UVAHT* mounting is shown in fig. 4. Additionally, table 1 depicts the geometry of the tool insert.

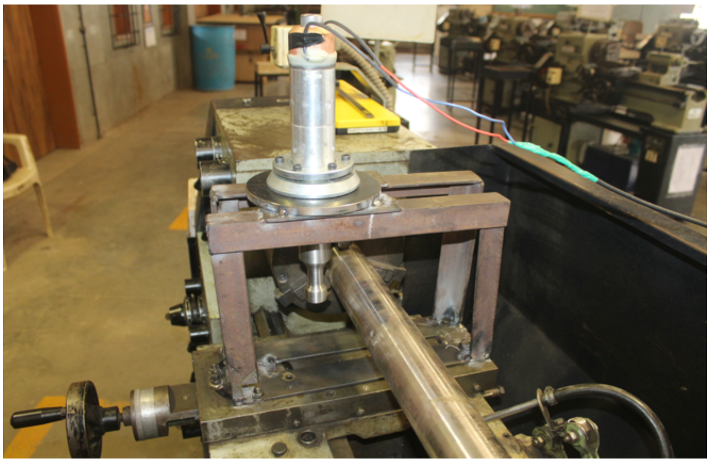

Fig. 4. Actual photograph of base frame with UVAHT mounting

Table 1

Geometry of the cutting insert

Specifications	Values
Insert included angle (degree)	80
Cutting edge length (mm)	12.9
Inscribed circle diameter (mm)	12.7
Insert thickness (mm)	4.76
Weight of item (kg)	0.01
Approach angle (degree)	75
Nose radius (mm)	0.8

Experiments using ultrasonic vibration-assisted hard turning (*UVAHT*) were carried out on a lathe with a maximum spindle speed of 1,145 rpm and a motor power supply of 2.2 kW. The pilot investigations determined the cutting speed, feed, depth of cut, ultrasonic frequency and vibrational amplitude. Experiments were planned using *response surface technology*, namely the central composite rotatable design (*CCRD*). Table 4 shows the selection of cutting modes for turning.

The *CCRD* approach allows selecting a set of experimental runs that thoroughly covers the design space while requiring the fewest number of trials available, hence assisting in the optimization of experimental settings. Based on the pilot experiments, cutting speed, feed, depth of cut, ultrasonic frequency, and vibrational amplitude were selected. Experiments were designed using response surface methodology, specifically the central composite rotatable design.

Two-sets of experiments were performed. First set of experiments comparatively evaluates the machining performance of *CT* and *UVAHT* varying with cutting speed, feed, and depth of cut. In the first set, *UVAHT* experiments are performed using constant frequency of 20 kHz with a vibrational amplitude of 20 μm. To understand *UVAHT* better, a theoretical model for power consumption and flank wear were developed using dimensional analysis. The second set of experiments was performed to calibrate the developed model considering the effect of cutting speed, frequency, and amplitude of vibrations. The cutting conditions used for comparative evaluation and theoretical modeling are depicted in table 2.

Table 2

Values of cutting parameters obtained by *Design Expert*

Run order	Comparative evaluation between CT and UVAHT			Theoretical modelling: UVAHT		
	Cutting speed (V_c) (m/min)	Feed (*f*) (mm/rev)	Depth of cut (*d*) (mm)	Cutting speed (V_c) (m/min)	Frequency (*F*) (kHz)	Amplitude (*A*) (μm)
1	60	0.085	0.4	60	20	20
2	120	0.075	0.35	120	20	20
3	100	0.068	0.4	100	20	20
4	100	0.085	0.5	100	20	20
5	100	0.085	0.4	100	20	20
6	80	0.075	0.35	80	20	20
7	100	0.085	0.3	100	20	20
8	120	0.075	0.45	120	20	20
9	100	0.103	0.4	100	20	20
10	100	0.085	0.4	100	20	20
11	80	0.095	0.45	80	20	20
12	100	0.085	0.4	100	20	20
13	100	0.085	0.4	100	20	20
14	80	0.075	0.45	80	20	20
15	100	0.085	0.4	100	20	20
16	120	0.095	0.35	120	20	20
17	80	0.095	0.35	80	20	20
18	120	0.095	0.45	120	20	20
19	145	0.085	0.4	145	20	20
20	100	0.085	0.4	100	20	20

The focus of the present study was on tool wear and power consumption. A *Dino-Lite* digital microscope with a magnification of up to 240X was used to measure tool wear. A clamp meter, which looks like a clothespin, was used to measure the current carried by a live wire. A clamp meter detects the magnetic field created by a flowing current in a wire. The power consumption during turning is given by the product of voltage and measured current. The actual set of machining conditions as per the design of experiment is shown in table 3. In the case of conventional turning, frequency and amplitude were considered to be zero, and in the case of ultrasonic vibration-assisted turning, frequency and amplitude were kept constant at 20 kHz and 20 μm respectively.

Results and Discussion

Comparative Performance: CT and UVAHT

First set of twenty experiments as depicted in table 2 are performed to comparatively evaluate the power consumption and flank wear under *CT* and *UVAHT*. Experiments were performed varying the cutting speed, feed, and depth of cut and *UVAHT* experiments were performed using constant frequency and amplitude of vibrations of 20 kHz and 20 µm, respectively.

Tool wear is the steady degradation of tool materials which leads the tool to deviate from its original shape during cutting. The wear of tools affects machining efficiency, quality, cutting power, and pricing. Additionally, tool wear has a significant influence on the surface quality of the machined component as well. The three major forms of wear are commonly believed to be abrasion, adhesion and diffusion. A *Dino-Lite* digital microscope with a magnification rate of up to 250X was used to monitor tool wear. *Dino Capture 2.0* recognizes images and stores them in the system memory when installed on a laptop. The digital microscope images of tool wear are given below in varying degrees of detail. As previously defined, conventional turning frequency and amplitude were regarded zero, and in the case of ultrasonic vibration-assisted turning, frequency and amplitude were held constant at 20 kHz and 20 µm, respectively.

Power consumption during cutting provides stability and assists in selecting appropriate modes to reduce energy consumption. Power consumption should be reduced throughout the machining process to encourage sustainable development in the machining process. This section describes how machine tools utilize power during *CT* and *UVAHT* in various cutting conditions. The power required to operate the lathe machine is calculated as the product of voltage and current. Throughout the experiment, the voltage was kept constant at roughly 420 volts (3-phase), and the current was monitored with a clap meter. The power was estimated by multiplying the voltage and current. The changes in experimentally based tool wear and power consumption in *CT* and *UVAHT* are shown in figs. 5 and 6.

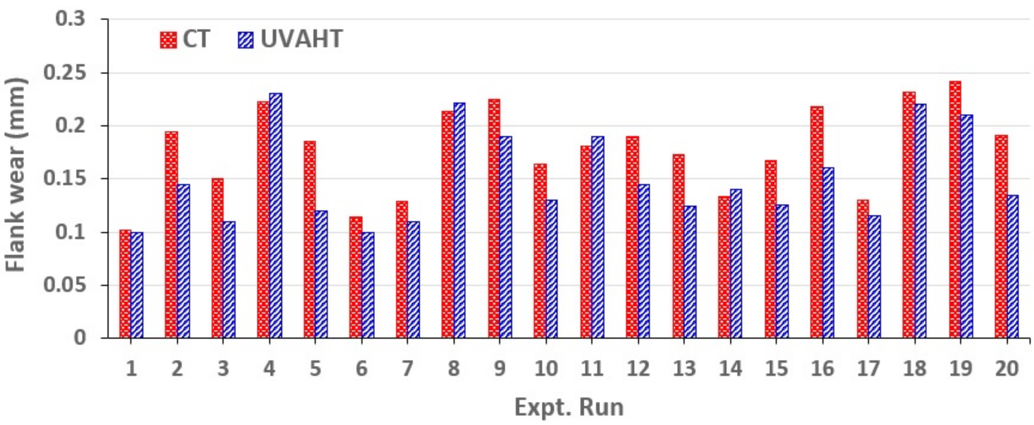

Fig. 5. Comparison of flank wear in *CT* and *UVAHT*

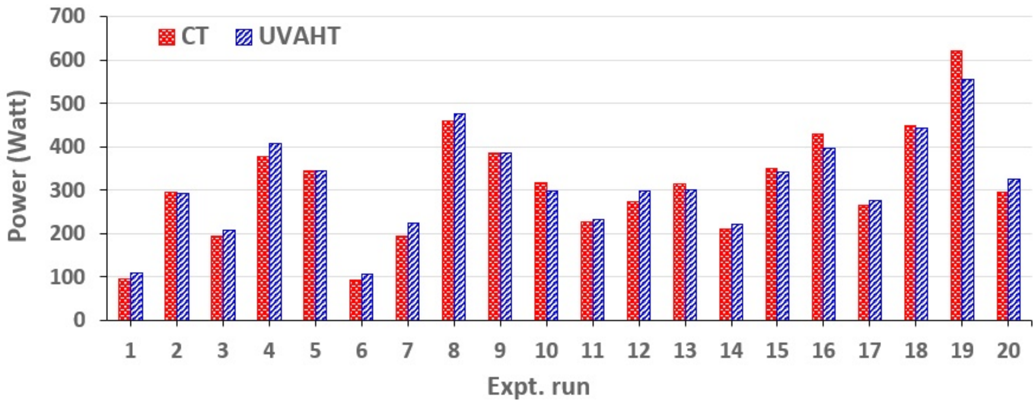

Fig. 6. Comparison of power consumption in *CT* and *UVAHT*

Dimensional Analysis

Second set of twenty experiments as depicted in table 2 are performed to calibrate a theoretically developed flank wear and power consumption models for *UVAHT*. Experiments were performed varying the cutting speed, frequency, and amplitude of vibrations as depicted in table 2 and at constant feed and depth of cut of 0.085 mm/rev and 0.4 mm, respectively.

The *Buckingham Pi Theorem*, named after the physicist *Edgar Buckingham*, is a fundamental principle in dimensional analysis. It states that when a physical problem involves "*n*" variables and "*m*" fundamental dimensions (such as length, time, mass, etc.), the problem can be expressed using *n–m* dimensionless parameters i.e. (*Pi* terms). The *Pi* terms are constructed as products of the original variables raised to appropriate powers such that the resulting expression is dimensionless [18–20]. The process of determining the *Pi* terms involves finding dimensionally independent groups of variables that describe the physical phenomena in the problem. According to *Buckingham Pi theorem*, the equation linking all the variables will have ($n - m$) dimensionless groups if the problem has "*n*" variables and those variables comprise "*m*" fundamental dimensions (for instance, *M*, *L*, and *T*):

$$\pi_1 = f(\pi_2, \pi_3, \ldots\ldots\pi_{n-m}).$$

The resulting equation takes the following form: the groups should not be dependent on one another, and no group should be established by adding the powers of other groups together. This approach has the benefit of being easier to use than the simultaneous equation method for determining the values of the indices (the exponent values of the variables). There are two prerequisites for using this approach to solve the equation. Each of the fundamental dimensions should be represented by one of the "*m*" variables at a minimum. One of the variables in a recurrent set should not be able to be formed into a dimensionless group. A dimensionless group of variables known as a *repeating set*.

Selection of Dimensionless Parameters

The selection of dimensionless parameters (*Pi* terms) involves identifying dimensionally independent groups of variables. These groups are chosen based on the underlying physics of the problem. The goal is to capture the significant interactions and relationships between the variables that govern the behavior of the system. In the context of conventional as well as ultrasonic vibration-assisted hard turning (*UVAHT*) of *AISI 52100* steel, several process variables play a crucial role in influencing the machining performance. This process involves identifying the fundamental dimensions (length [*L*], time [*T*], mass [*M*], etc.) and determining the number of dimensionless parameters (*Pi* terms) required to describe the behavior of the system. By examining the relevant process variables and its corresponding units, one can establish the relationships between the variables and form dimensionless groups.

Modelling of Power Consumption (P_c)

After conducting the dimensional analysis, dimensionless groups were formulated to represent the relationships between the relevant process variables. These dimensionless groups provide valuable insights into the interactions between ultrasonic vibration parameters and conventional turning parameters during the *UVAHT* process. Power consumption is depending on four parameters namely: material removal rate (*MRR*), density of the material (ρ), vibrational amplitude (*A*), and frequency of vibration (*F*). Now by selecting *M* (mass), *L* (length), and *T* (time) as the basic dimensions, the dimensions of the foregoing quantities would then be (table 3).

Furthermore,

$$P_c = \varphi\,(MRR, \rho, A, F)$$

Table 3

Dimensional analysis

Parameter	Representation
Power consumption (*Pc*) (Watt)	$M^1 L^2 T^{-3}$
Material removal rate (*MRR*) (mm^3/s)	$M^0 L^3 T^{-1}$
Density of the material (ρ) (kg/m^3)	$M^1 L^{-3} T^0$
Vibrational amplitude (*A*) (μm)	$M^0 L^1 T^0$
Frequency of vibration (*F*) (kHz)	$M^0 L^0 T^{-1}$

Here, "*n*" is 5 and "*m*" is 3 and hence in view of the same, ($n-m = 2$) i.e., π_1 and π_2 are the two dimensionless groups that will be obtained. Now, Taking *MRR*, ρ and *A* as the quantities which directly go in π_1, and π_2 respectively, we obtain:

$$\pi_1 = [MRR]^{a_1} \times [\rho]^{b_1} \times [A]^{c_1} \times P_c.$$

Hence,

$$M^0 L^0 T^0 = [M^0 L^3 T^{-1}]^{a_1} \times [M^1 L^{-3} T^0]^{b_1} \times [M^0 L^1 T^0]^{c_1} \times [M^1 L^2 T^{-3}];$$
$$M^0 L^0 T^0 = [L^3 T^{-1}]^{a_1} \times [M^1 L^{-3}]^{b_1} \times [L^1]^{c_1} \times [M^1 L^2 T^{-3}];$$
$$M^0 L^0 T^0 = M^{(1+b_1)} L^{(3a_1-3b_1+c_1+2)} T^{(-a_1-3)}.$$

By equality, it can be found that $a_1 = -3$, $b_1 = -1$, and $c_1 = 4$. Hence, we get,

$$\pi_1 = [MRR]^{-3} \times [\rho]^{-1} \times [A]^4 \times P_c.$$

In similar way,

$$\pi_2 = [MRR]^{a_2} \times [\rho]^{b_2} \times [A]^{c_2} \times F;$$

$$M^0 L^0 T^0 = [M^0 L^3 T^{-1}]^{a_2} \times [M^1 L^{-3} T^0]^{b_2} \times [M^0 L^1 T^0]^{c_2} \times [M^0 L^0 T^{-1}];$$
$$M^0 L^0 T^0 = [L^3 T^{-1}]^{a_2} \times [M^1 L^{-3}]^{b_2} \times [L^1]^{c_2} \times [M^0 L^0 T^{-1}];$$
$$M^0 L^0 T^0 = M^{b_2} L^{(3a_2-3b_2+c_2)} T^{(-a_2-1)}.$$

By equality, it can be found that $a_2 = -1$, $b_2 = 0$, and $c_2 = 3$. Hence, we get,

$$\pi_2 = [MRR]^{-1} \times [\rho]^0 \times [A]^3 \times F.$$

This can now be written as,

$$\pi_1 = k[\pi_2]^n,$$

where *k* and *n* are constants.

$$[MRR]^{-3} \times [\rho]^{-1} \times [A]^4 \times P_c = k\left\{[MRR]^{-1} \times [A]^3 \times F\right\}^n,$$

where *k* and *n* are constants.

The material removal rate (*MRR*) is a product of a cutting speed (*V*), feed (*f*), and depth of cut (*d*). After simplifying the term, the power consumption can be represented as:

$$P_c = (k\rho f d)V^{(3-n)} F^n A^{(3n-4)}.$$

Experiments were performed at constant feed and depth of cut. The density (ρ) of a material is also constant. Therefore, let's define k_1 as a new constant, which is a product of k, ρ, f, and d. Hence, the final model to predict the power consumption under *UVAHT* is shown below.

$$P_c = k_1 V^{(3-n)} F^n A^{(3n-4)}.$$

The constant "n" can be obtained by calibrating the model with the experimental power consumption values under *UVAHT*, obtained at different cutting conditions as depicted in table 2.

$$P_c = 0.00222 V^{1.5987} F^{1.4013} A^{0.2039}. \quad (1)$$

Modelling tool wear (V_b)

Tool wear is determined by four parameters: cutting speed (V), material hardness (H), vibrational amplitude (A), and frequency of vibration (F). Using M (mass), L (length), and T (time) as the fundamental dimensions, the dimensions of the previous values will be as follows: given that $V_b = \varphi\ (V, H, A, F)$, for "$n$" is 5, and "$m$" is 3, and therefore $n–m = 2$. Thus, π_1 and π_2, which are two dimensionless groups, can be defined. Now, taking V, H and A as the quantities that are directly included in π_1 and π_2, respectively, we get

$$\pi_1 = [V]^{a_1} \times [H]^{b1} \times [A]^{c_1} \times Vb.$$

Hence,

$$M^0 L^0 T^0 = [M^0 L^1 T^{-1}]^{a_1} \times [M^1 L^{-1} T^{-2}]^{b_1} \times [M^0 L^1 T^0]^{c_1} \times [M^0 L^1 T^0];$$
$$M^0 L^0 T^0 = [L^1 T^{-1}]^{a_1} \times [M^1 L^{-1} T^{-2}]^{b_1} \times [L^1]^{c_1} \times [L^1];$$
$$M^0 L^0 T^0 = M^{(b_1)} L^{(a_1 - b_1 + c_1 + 1)} T^{(-a_1 - 2b_1)}.$$

By equality, it can be found that $a_1 = 0$, $b_1 = 0$, and $c_1 = -1$.
Hence, we get:

$$\pi_1 = [V]^0 \times [H]^0 \times [A]^{-1} \times Vb.$$

In similar way:

$$\pi_2 = [V]^{a_2} \times [H]^{b_2} \times [A]^{c_2} \times F;$$

$$M^0 L^0 T^0 = [M^0 L^1 T^{-1}]^{a_2} \times [M^1 L^{-1} T^{-2}]^{b_2} \times [M^0 L^1 T^0]^{c_2} \times [M^0 L^0 T^{-1}];$$
$$M^0 L^0 T^0 = [L^1 T^{-1}]^{a_2} \times [M^1 L^{-1} T^{-2}]^{b_2} \times [L^1]^{c_2} \times [T^{-1}];$$
$$M^0 L^0 T^0 = M^{(b_2)} L^{(a_2 - b_2 + c_2)} T^{(-a_2 - 2b_2 - 1)}.$$

By equality, it can be found that $a_2 = -1$, $b_2 = 0$, and $c_2 = 1$. Hence, we get:

$$\pi_1 = [V]^{-1} \times [H]^0 \times [A]^1 \times F.$$

This can now be written as:

$$\pi_1 = k[\pi_2]^n;$$

$$[A]^{-1} \times Vb = k\left\{[V]^{-1} \times [A]^1 \times F\right\}^n.$$

After simplifying the term, it can be represented as:

$$Vb = kV^{-n} A^{(1+n)} F^n;$$

$$Vb = 0.011336 V^{0.1967} A^{0.8033} F^{-0.1967}. \quad (2)$$

The power consumption and flank wear are plotted using the developed theoretical models, Eqs. 1 and 2, varying the cutting speed, vibration frequency, and amplitude. Fig. 7, *a* depicts the variation in the power consumption and flank wear with the cutting speed at constant vibration frequency and amplitude of 20 kHz and 20 μm, respectively.

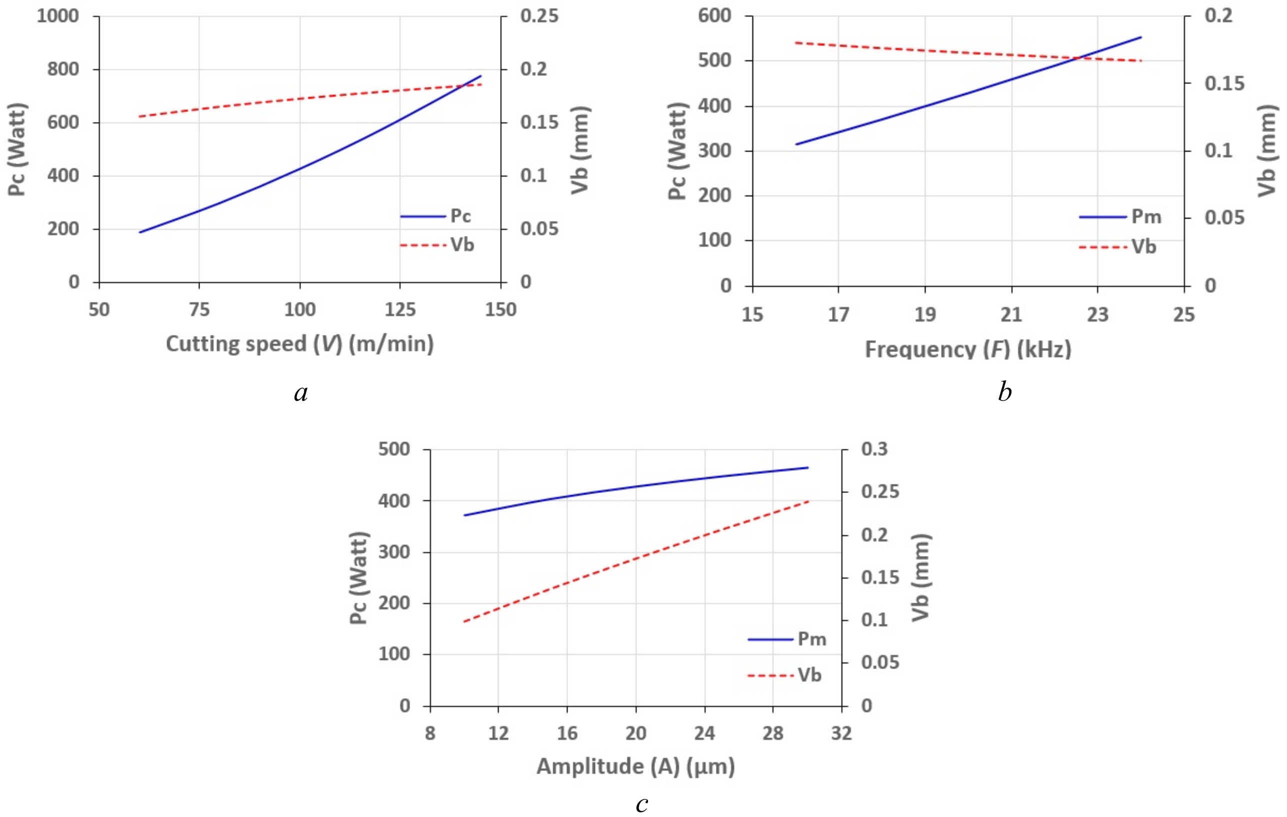

Fig. 7. Power consumption and flank wear varying with cutting speed (*a*), frequency of vibration (*b*), amplitude of vibration (*c*)

Fig. 7, *b* depicts the variation in the power consumption and flank wear with the vibration frequency at constant cutting speed and vibration amplitude of 100 m/min and 20 μm, respectively. Fig. 7, *c* shows the variation in the power consumption and flank wear with the vibration amplitude at constant cutting speed and vibration frequency of 100 m/min and 20 kHz, respectively. The power consumption increases with the cutting speed, vibration frequency, and amplitude. However, an increase in the power consumption can be seen as prominently with the cutting speed followed by vibration frequency, and amplitude. This can be also confirmed from the higher values of the exponent observed for the cutting speed followed by vibration frequency, and amplitude. The flank wear can be seen as increasing with the cutting speed and vibration amplitude and decreasing with the frequency of vibration.

Conclusion

This study comparatively evaluates the tool wear and power consumption during conventional turning (*CT*) and ultrasonic vibration-assisted hard turning (*UVAHT*) of *AISI 52100* steel (62 HRC) using a *PVD*-coated *TiAlSiN* carbide tool. A theoretical model to predict the tool wear and power consumption is developed using the concept of *Dimensional analysis*, i.e., the *Buckingham Pi theorem* considering the effect of cutting speed, frequency, and amplitude of vibrations. Dimensionless groups are created to reveal complex linkages and optimize machining conditions. Tool wear and power consumption are measured experimentally and statistically analysed using the *Buckingham Pi theorem*. The following conclusion can be drawn from the present study.

1. Tool wear is significantly affected by the cutting speed. How, this effect is more prominent with conventional turning (*CT*). This could be attributed to an increase in the cutting temperature during cutting.

However, this effect is less prominent in *UVAHT* due to intermittent contact of the tool with the workpiece, which allows the tool to cool naturally and hence, lowers tool wear.

2. *UVAHT* consumes negligibly higher power than *CT*. Additional power is required in *UVAHT* to drive the ultrasonic generator, which is not necessary in *CT*.

3. The tool wear and the power consumption increase with the cutting speed, depth of cut, and feed. However, this effect is more significant in *CT* than *UVAHT*.

4. The power consumption increases with the cutting speed, vibration frequency, and amplitude. However, an increase in the power consumption is more prominent with the cutting speed followed by vibration frequency, and amplitude.

5. The flank wear increases with the cutting speed and vibration amplitude and decreases with the frequency of vibration.

References

1. Babitsky V.I., Kalashnikov A.N., Meadows A., Wijesundara A.A.H.P. Ultrasonically assisted turning of aviation materials. *Journal of Materials Processing Technology*, 2003, vol. 132, pp. 157–167. DOI: 10.1016/s0924-0136(02)00844-0.

2. Babitsky V.I., Mitrofanov A.V., Silberschmidt V.V. Ultrasonically assisted turning of aviation materials: simulations and experimental study. *Ultrasonics*, 2004, vol. 42, pp. 81–86. DOI: 10.1016/j.ultras.2004.02.001.

3. Vivekananda K., Arka G.N., Sahoo S.K. Design and analysis of ultrasonic vibratory tool (UVT) using FEM, and experimental study on ultrasonic vibration-assisted turning (UAT). *Procedia Engineering*, 2014, vol. 97, pp. 1178–1186. DOI: 10.1016/j.proeng.2014.12.396.

4. Liu Y., Li J., Zhang L. Effects of ultrasonic vibration on cutting forces and machined surface quality in turning of AISI 1045 steel. *International Journal of Advanced Manufacturing Technology*, 2019, vol. 101, pp. 1137–1147. DOI: 10.1038/s41598-022-21236-x.

5. Muhammad R., Maurotto A., Roy A., Silberschmidt V.V. Analysis of forces in vibro-impact and hot vibro-impact turning of advanced alloys. *Applied Mechanics and Materials*, 2011, vol. 70, pp. 315–320. DOI: 10.4028/www.scientific.net/AMM.70.315.

6. Lotfi M., Amini S., Akbari J. Surface integrity and microstructure changes in 3D elliptical ultrasonic assisted turning of Ti–6Al–4V: FEM and experimental examination. *Tribology International*, 2020, vol. 151, p. 106492. DOI: 10.1016/j.triboint.2020.106492.

7. Celaya A., Luis N.N.L., Francisco J.C., Lamikiz A. Ultrasonic Assisted Turning of mild steels. *International Journal of Materials and Product Technology*, 2010, vol. 37. DOI: 10.1504/IJMPT.2010.029459.

8. Jiao F., Liu X., Zhao C., Zhang X. Experimental study on the surface micro-geometrical characteristics of quenched steel in Ultrasonic Assisted Turning. *Advanced Materials Research,* 2011, vol. 189–193, pp. 4059–4063. DOI: 10.4028/www.scientific.net/AMR.189-193.4059.

9. Maurotto A., Muhammad R., Roy A., Babitsky V.I., Silberschmidt V.V. Comparing machinability of Ti-15-3-3-3 and Ni-625 alloys in UAT. *Procedia CIRP*, 2012, vol. 1, pp. 330–335. DOI: 10.1016/j.procir.2012.04.059.

10. Zou P., Xu Y., He Y., Chen M., Wu H. Experimental investigation of ultrasonic vibration assisted turning of 304 austenitic stainless steel. *Shock and Vibration*, 2015, art. 817598. DOI: 10.1155/2015/817598.

11. Kumar J., Khamba J.S. Modelling the material removal rate in ultrasonic machining of titanium using dimensional analysis. *International Journal of Advanced Manufacturing Technology*, 2010, vol. 48, pp. 103–119. DOI: 10.1007/s00170-009-2287-1.

12. Kugaevskii S.S., Ashikhmin V.N. Using local coordinate systems for dimensional analysis in the machining. *Proceedings of the 4th International Conference on Industrial Engineering. ISIE 2018*. Springer, 2018, pp. 301–309. DOI: 10.1007/978-3-319-95630-5_33.

13. Skelton R.C. Turning with an oscillating tool. *International Journal of Machine Tool Design and Research*, 1968, vol. 8, pp. 239–259. DOI: 10.1016/0020-7357(68)90014-0.

14. Mitrofanov A.V., Babitsky V.I., Silberschmidt V.V. Thermomechanical finite element simulations of ultrasonically assisted turning. *Computational Materials Science*, 2005, vol. 32, pp. 463–471. DOI: 10.1016/j.commatsci.2004.09.019.

15. Ghule G.S., Sanap S. Ultrasonic vibrations assisted turning (UAT): A review. *Advances in Engineering Design: Select proceedings of FLAME 2020*. Springer, 2021, pp. 275–285. DOI: 10.1007/978-981-33-4684-0_28.

16. Nath C., Rahman M., Andrew S.S.K. A study on ultrasonic vibration cutting of low alloy steel. *Journal of Materials Processing Technology*, 2007, pp. 159–165. DOI: 10.1016/j.jmatprotec.2007.04.047.

17. Ghule G.S., Sanap S., Adsul S., Chinchanikar S., Gadge M. Experimental investigations on the ultrasonic vibration-assisted hard turning of AISI 52100 steel using coated carbide tool. *Materials Today: Proceedings*, 2022, vol. 68 (6), pp. 2093–2098. DOI: 10.1016/j.matpr.2022.08.368.

18. Zhang G., Sun Y., Xu L., Wang L., Zuo D. Prediction of erosion volume of PDMS by cryogenic micro-abrasive jet machining based on dimensional analysis method and experimental verification. *The International Journal of Advanced Manufacturing Technology*, 2021, vol. 114, pp. 2447–2455. DOI: 10.1007/s00170-021-07020-7.

19. Singh N.K., Sign Y. Experimental investigation and modelling of surface finish in argon-assisted electrical discharge machining using dimensional analysis. *Arabian Journal for Science and Engineering*, 2019, vol. 44, pp. 5839–5850. DOI: 10.1007/s13369-019-03738-5.

20. Airao J., Khanna N., Roy A., Hegab H. Comprehensive experimental analysis and sustainability assessment of machining Nimonic 90 using ultrasonic-assisted turning facility. *The International Journal of Advanced Manufacturing Technology*, 2020, vol. 109, pp. 1447–1462. DOI: 10.1007/s00170-020-05686-z.

Conflicts of Interest

The authors declare no conflict of interest.