Theoretical Aspects in Designing of Stepped Horn for Ultrasonic Vibration Assisted Turning of AISI 52100 Hardened Steel

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***Abstract*—The futuristic objective of manufacturing sectors is to adopt sustainable machining using modern technologies in light of demanding environmental liabilities. Ultrasonic vibration turning (UVT) seems to be another sustainable precision machining technology in which ultrasonic vibrations are overlaid on traditional turning cutting tools. This hybrid approach is suitable for machining difficult-to-cut materials due to its periodical action. An ultrasonic vibratory tool (UVT) is an important design component since its primary role is to transport high-frequency vibrations from one end to the other. UVT is made up of a piezoelectric transducer, a booster, and a horn that plays a key role in the turning process when ultrasonic vibrations are applied to it. This paper provides a brief overview of the theoretical issues that must be considered when constructing a stepped horn to achieve the highest feasible effectiveness of the process in terms of surface roughness as well as cutting forces.**

Keywords—Conventional turning, ultrasonic turning, ultrasonic vibratory tool (UVT), stepped horn, surface roughness, cutting forces.

I. INTRODUCTION

The recognition of sustainable machining with modern technologies is the sole key to survival in the rising and competitive manufacturing environment for achieving dependability, increased productivity, greater efficiency, and greatest satisfaction of customers with the finest quality product design [1]. Hard turning refers to machining operations performed on a workpiece having a hardness value more than 45 HRC. This results in a significant increase in cutting forces, rapid tool wear, a low-quality surface finish, high temperature generation, and heavy power consumption, all of which are severe operational hindrances [2-3]. The use of coolants to lower the machining temperature aided the contact somewhat, but maintenance and removal remain a substantial impediment.

Thus, dry machining operations are both economically effective and environmentally friendly because they need the reduction of carbon imprints [4, 5]. Ultrasonic falls under the category of 'acoustics,' having applications in NDT (non-destructive testing), ultrasonic vibration aided milling [6], ultrasonic vibration assisted welding [7], ultrasonic vibration assisted drilling [8], and medical approaches, among others. An ultrasound generating and an ultrasonic vibrating tool (UVT) are the basic components of ultrasound assisted turn (UAT) [9-10, 11]. The motion of vibrations in ultrasonic aided turning (UAT) is classified as tangential, radial, or axially.

The reason why ultrasonic assisted turning (UAT) is also referred to as a "periodic method" is due to the fact that both the cutting tool and the workpiece are periodically limited and especially associated with one another. As a direct consequence of this, the total amount of tool-workpiece contact as well as separation is decreased in comparison to the conventional turning process measure. As a direct result of this, the significant accomplishments that can be attributed to the utilisation of this strategy include, amongst other things, decreased cutting forces, decreased tool wear and residual stress, enhanced surface smoothness, and decreased power consumption. [12].

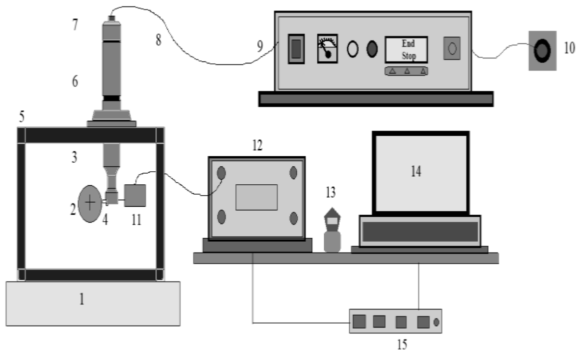


Fig. 1. Following are the parameters shown in this figure . UAT setup 1. Y2K lathe machine, 2. A workpiece, 3. Titanium horn, 4. Cutting tool, 5. Fixture, 6. Booster, 7. Piezoelectric transducer, 8. High-frequency ultrasonic cable, 9. Ultrasonic generator, 10. Manual switch, 11. Dynamometer box, 12. Tool dynamometer, 13. Surface roughness tester, 14. PC, and 15. Power supply)

The UVAT configuration is depicted in Fig. 1, and it comprises solely of a frequency generator, a piezoelectric transducer plus booster assembly, a sonotrode that also functions as a tool holder with an insert connected, an ultrasonic generator, a roughometer, and a dino-lite digital microscope.

II. ULTRASONIC HORN

The dependability of the most significant imaginable vibrational amplitude supportability is not just on the characteristics of basic parts of the sonotrode by which it is created, but also on the fundamental state of the sonotrode. Sonotrode are often made from materials such as titanium, aluminium amalgams, mild steel, as well as stainless steel. Titanium has the best acoustical properties of any metal, as well as a substantial fatigue endurance that allows it to sustain fatigue rates at varied progressive intensities. It also has a high hardness as compared to other materials, which helps it to withstand wear conditions. However, titanium horns are typically more expensive than the other materials, owing to the higher cost of the material. Aluminium heat-treated combo has excellent acoustical qualities and is used to build horns that do not require additional vibrational amplitude or strength [13-14].

Stepped, tapered, exponential, cylindrical stepped, and catenoidal ventured forms are the most well-known and simple horn states. The enhancement in machinability in UAT measure is directly related to the proper design of an ultrasonic horn, which ensures the simple conveying of vibration to the cutting tool, resulting in an increase in the rate of undesirable material from the workpiece, i.e. chips. An incorrect sonotrode arrangement will have a negative impact on the entire metal cutting process. The following are the essential things to consider while constructing an ultrasonic vibratory tool [15].

The speed of sound is critical in the construction of a horn. It is mostly determined by the specific specimen's Young's modulus and density. The faster the sound wave travels through the stiffer the material. The slower the sound wave propagate, the thicker the medium, because increased thickness means greater mass per volume, and hence more inertia. As a result, the penetration is a little sleepy. The horns are often made of materials such as aluminium alloys, mild steel, stainless steel, and titanium alloys, as illustrated in Table 1 [16].

TABLE I. VARIOUS MATERIALS FOR DESIGNING OF ULTRASONIC HORN [16]

Name of material Selected	**Young's modulus E (GPa)**	**Density ρ = Kg/m^3**	**Velocity of sound $c = \sqrt{\frac{E}{\rho}}$ (m/s)**
Aluminium	70	2710	5082 m/s
Mild steel	210	7850	5172 m/s
Stainless steel	193	8000	4912 m/s
Titanium	110	4700	4840 m/s

The fatigue strength is one of the important specifications that should be considered while selecting design components. All of these metal parts will be subjected to extremely high cyclic stacking, which can cause fatigue, therefore this critical issue cannot be ignored. As a result, the most well-known horn states include cone-shaped, exponential, Bezier-type, stepped, and cylindrical forms. However, because of its ease of manufacture, the step type horn is featured more in this chapter. Fig. 2 depicts a few of the horn states.

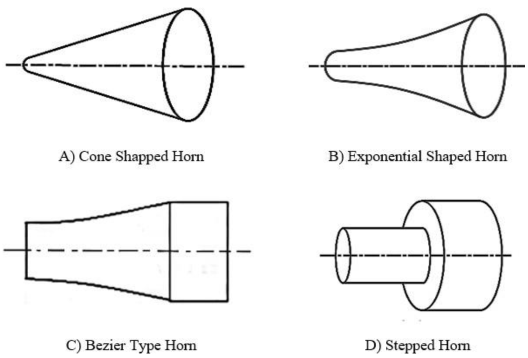


Fig. 2. Types of Ultrasonics Horns [16]

Furthermore, the amplitude of the stepped horn can be estimated as follows by the use of Equation 1.

$$K = \xi_1 / \xi_2 = (d_1/d_2)^2 \quad (1)$$

Where, K = Overall amplitude gain, ξ_1 and ξ_2 = displacements of larger and smaller ends of stepped horn respectively ($\xi_1 < \xi_2$).

III. DESIGN OF AN ULTRASONIC HORN

An ultrasonic vibratory tool is a device that operates in a longitudinal mode and is used to successfully convey energy in the form of vibration from a piezoelectric sensor to a sonotrode. This is accomplished with the help of an ultrasonic transducer, which functions in a transverse mode. This is performed by operating the instrument in a mode known as ultrasonic longitudinal mode. As shown in the figure that follows, in addition to its use as a wave guider or an acoustic horn, an ultrasonic horn can also serve the purpose of a device that holds tools. Fig. 3..

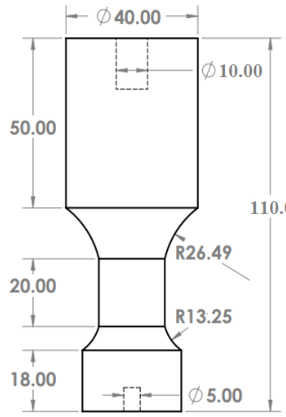


Fig. 3. Structure of UAT [16]

The horn is a solid metallic element that is used to modify the displacement shaking as vibrational amplitude, which is provided by an ultrasonic transducer operating at an ultrasonic repetition range of 16 kHz to 100 kHz. The horn is used to change the amplitude of the vibrational shaking. The horn is used to vary the amplitude of the vibrational shaking. Figure 2 [17], which can be located over here, is an illustration that shows the ultrasonic vibratory tool in its entirety.

IV. SELECTION OF PIEZOELECTRIC MATERIAL

The fundamental notion behind considering a piezoelectric transducer is that it converts electrical energy into mechanical vibrations. As a result, the following piezoelectric material variables must be considered for an efficient system of a ultrasonic transducer [18, 19-20]. The piezoelectric transducer should be able to withstand greater electric voltages as well as mechanical loads. It should have stable features and a strong coupling coefficient among electrical and mechanical coupling, i.e. low temperature and time dependence.

Acoustic characteristics should be coordinated during the design process to provide effective transmission of the respective kind of energy throughout the whole assembly while avoiding its inside impression of vibrations. The Table 2 [18] lists the acoustic impedance of several materials.

TABLE II. ACOUSTICAL IMPEDANCE OF VARIOUS MATERIALS [18]

Material	Acoustical Impedance (Ns/m^3)
Aluminium Alloys	14.25×10^6
Titanium Alloys	39.20×10^6
Steel	41.20×10^6
Aluminium Alloys	14.25×10^6

As a result, compelling use of the acoustical type of an energy of metal components will be directed by collaborating with a large segment of piezoelectric material. Because there is no necessity for energy, the vibrational form of an energy is permitted towards to the main side frontal mass instead of the back mass, which resolves a loss of energy. In a transducer with a longitudinal mode, acoustic energy is generated in the piezoelectric material and transferred to both sides.

To decrease energy misery, the rear side mass should have incremental acoustical resistance relative to the front side mass, causing the majority of the energy to be directed towards to the leading side mass.

V. EXPERIMENTAL SETUP

Prior to the test, a portion of the workpiece was positioned properly in a lathe chuck (Y2K lathe machine model), while the opposite end was held in a tailstock. An ultrasound vibrating tool (UVAT) attachment device was developed and built on the cross slides of the turning machine after the tool post had been taken out of the machine itself. Because of this, the UVAT was able to be installed.. In addition, the UVAT was fastened to the fixture by employing the collar and disc arrangement first, then bolting from the underside of the collar. This was done in order to secure the UVAT in place. Figure 4 provides an illustration of the three-dimensional model of the fixture along with the UVAT that is mounted inside of it.

In order to get an accurate estimate of the cutting parameters for the design of the tests, a comprehensive literature review, the capacity of the machine, a series of preparatory trials, and the instructions provided by the cutting tool manufacturer were used. There were cuts made at speeds of 50, 100, and 150 metres per minute, with feed rates of 0.068 and 0.103 millimetres per revolution, and cut depths of 0.1 and 0.5 millimetres.

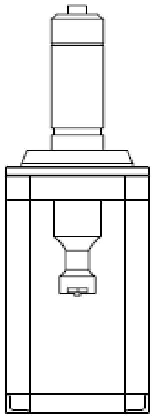


Fig. 4. 3-D model of UVAT mounted on a fixture

In order to make the experimental setup easier to understand, Table 3 provides it to readers. Carbide cut tips were used in the machining process so as to successfully work with AISI 52100 hardened steel. The inserts featured either bare and PVD treated TiAlSiN, and they were coated with a nano laminate. The ISO standard of the cutting tool inserts which was used for the intent of this study is presented in Table 4.

TABLE III. THE EXPERIMENTAL DESIGN

Experimental run	Cutting speed (m/min)	Feed (mm/rev)	Depth of cut (mm)	Remark
1	50	0.103	0.5	With alteration of cutting speed
2	150	0.103	0.5	
3	100	0.068	0.5	With alteration of Feed
4	100	0.103	0.5	
5	100	0.103	0.1	With alteration of depth of cut
6	100	0.103	0.5	

TABLE IV. THE EXPERIMENTAL DESIGN

Particulars	Details
ISO Designation of cutting tool insert	CNMG120408
Chip breaker manufacturers designation	MF5
Grade	TH1000
Insert included angle	800
Theoretical cutting-edge length	12.90 mm
Back rake angle	-60
Side rake angle	-60
Nose radius	0.8 mm

The ultrasonic generator has a power output of 2 kW and an input AC voltage of 220-230 volts (mains), and it generates a high frequency in the range of 20 kHz (0.5). The input frequency is 50 Hz. The table that follows, number Table 5, contains the entire list of specifications.

TABLE V. THE EXPERIMENTAL DESIGN

Particulars	Details
Voltage	230 Volts, Single phase AC
Current	6 Amperes
Input frequency	50 Hz
Output frequency	20,000 Hz (i.e., 20 kHz)
Power output	2 kW
Amplitude	20 µm
Tuning mode	Manual/Auto

The cylindrical component faces undergo machining before the tests are run. To eliminate any remaining eccentricity, a final cut is made with the same cutting tool that was used in the experiments, but at a much shallower depth of cut. The accompanying figure, referred to as Fig. 5, shows the real picture of the setup used for testing.

For the purpose of measuring of the response characteristics, including the force of cutting and roughness of the surface, in both conventional (CT) and ultrasonic-assisted (UAT) turning, accurate equipment was employed. UAT refers to ultrasonic-assisted turning, while CT stands for traditional turning.

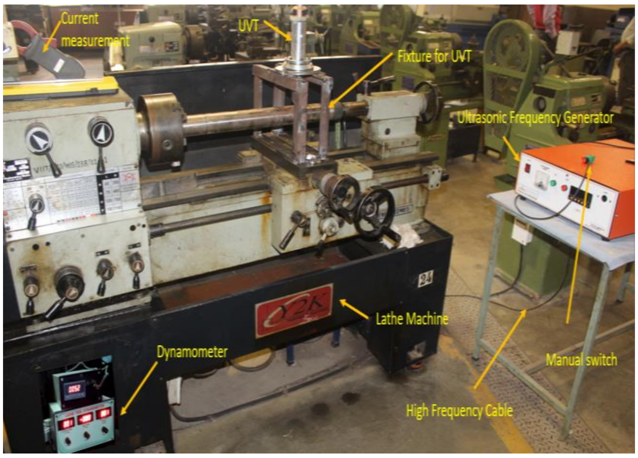
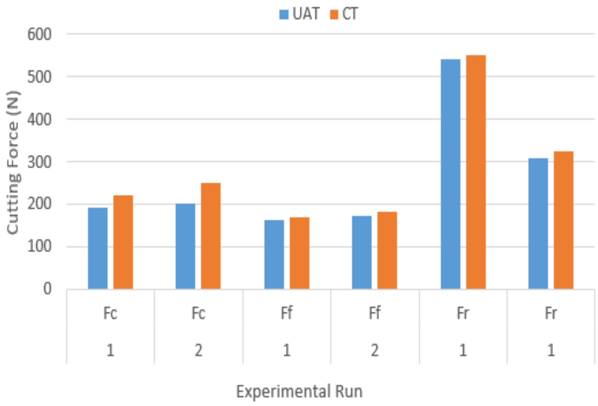


Fig. 5. Actual photograph of experimental setup

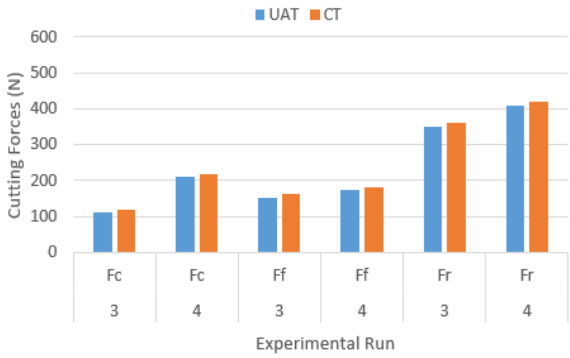
For the purpose of determining the cutting force, a lathe tool dynamometer that featured an LCD display was utilised. The dynamometer's readings in kilogram-force units distinguished between three distinct cutting forces: the radial force, the feed force, and the thrust force. The level of surface roughness was evaluated with the help of Taylor Hobson's Surtronic DUP surface roughness tester. It is needed that the roughness of the surface be measured three times: once at the beginning of the surface, once in the middle part of the surface, and once at the end of the surface. The average of these three measurements is ultimately regarded to be representative of the surface's roughness, hence it is important to keep track of all three.

VI. RESULTS AND DISCUSSION

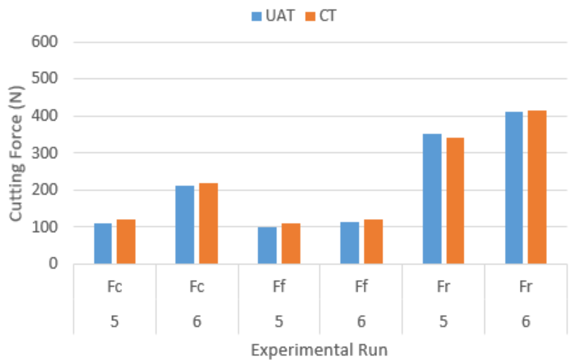
The Hard turning experiments were performed on AISI 52100 steel using a PVD treated TiAlSiN carbide tool in order to evaluate the manufacturing outcomes of traditional turning with ultrasonic vibration-assisted turning, which is additionally referred to as UVAT. The steel had a hardness value of 62 HRC when measured by the HRC scale. The figure 4 is a representation of an analysis of the cutting force elements, such as the principal tangential cut force (Fc), feeding force (Ff), and radially cutting force (Fr), assessed during traditional turning vs ultrasonically vibrating aided turning under a variety of cut scenarios. The events surrounding this cutting are outlined in Table 2.



(a)



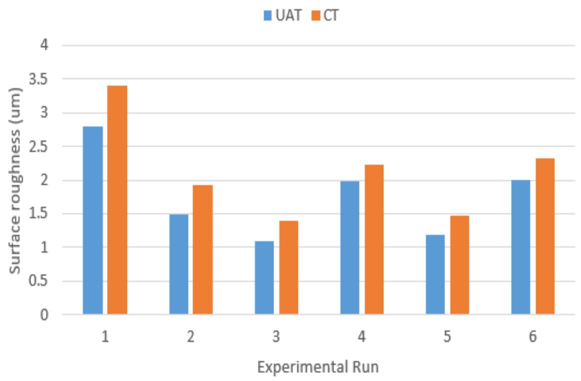
(b)



(c)

The fluctuation in the force that cuts components is illustrated in Figure 4(a), that was made utilising cutting rates of 50 and 150 m/min, in addition to consistent feeding and the depth of cutting measurements of 0.103 mm/rev and 0.5 mm, respectively (Experiment runs 1 and 2, correspondingly). Figure 4(a) illustrates that the forces needed to cut necessary for traditional turning are substantially larger compared to those necessary for UVAT. This is the case because traditional turning utilises a traditional lathe. Both the CT and the UVAT started by concentrating their attention on the radial portion of the force they were measuring. The next step was to determine the tangential cutting force, and then the feed force was analysed after that force.

Figure 4(b) displays the variance in force of cut elements that takes place if feed speeds of 0.068 and 0.103 mm/rev are employed along with constant values of speed as well as depth of cutting of 100 mm/rev and 0.5 mm, respectively. The variation in force happens if the test runs 3 and 4 are represented. Similarly, the graphs that alter changing cut depth of 0.1 and 0.5 mm are illustrated in Fig. 4(c) with speeds of cutting of 100 m/min and feeding rates of 0.103 mm/rev, respectively. Initially, the force that is radial was determined, then the force that is tangential was determined, and finally, the feeding value was determined in either CT and UVAT settings



(d)

Fig. 6. Experimental outcomes

The Figure 4 depicts the link that exists between the three variables of cut speed, feeding rate, and depth of cutting (d). Surface roughness varies depending on these three factors. Information on the test run is included in Table 3. In every single iteration of the experiment, the surface roughness was measured using UVAT, and the results were substantially better than those obtained using conventional turning.

In contrast to this, the scenario with CT is as follows. It is possible to observe that the surface roughness improves as the cutting speed is made significantly faster. This is something that can be observed. However, it does increase as the feed rate and depth of cut increase, under both the CT and the UVAT, and this occurs in all scenarios. This is the case regardless of whether model is used. It is possible to produce a surface roughness of 1.12 m while simultaneously lowering the force of cut by using feed and depth of cutting numbers that are less than previously thought. The values used are 0.068 mm/rev and 0.1 mm, correspondingly. pressures.

Hard turning AISI 52100 steel by utilising a by ultrasound vibration-assisted turning approach with a PVD covered TiAlSiN carbide tool was found to be a preferred option to conventional hard turn in regards to achieving a reduced force of cutting and roughness of the surface. The results from this investigation were presented in the form of a conclusion that was drawn from the results of the research. It is possible that the enhanced chip breakage and separation of the chip surrounding the tool that occurs throughout UVAT is responsible for the improved smoothness of the surface that can be achieved using UVAT. Contrary with this is the formation of a longer time, curlier pieces in CT, some of that got so stuck on the tool that they could not be removed. These entangled long curled pieces were accountable for the harm done to the surface polish because they caused friction and scratching. On the other hand, there is not a discernable difference between CT and UVAT in terms of the amount of cutting force that is necessary for severe turning. This research broadens the area of investigations into manufacturing through taking into consideration the impact of vibrations that are overlaid on a tool in three different instructions: the feeding direction, the tangential direction, and the radial direction.

The research also made a recommendation for further investigation into the optimisation of the cutting parameters and UVAT variables during hard turning. These parameters include voltage, vibration rate, and vibrating amplitude, among others.

CONCLUSION

In this work, an ecologically sound hybrid UVAT made of AISI 52100 steel with a 62 HRC hardness is investigated. UVAT is accomplished in traditional machining by overlaying sounds with high frequencies and a low intensity on the cutting tool. Hard turning studies were carried out with a PVD-coated TiAlSiN carbide tool in both traditional cutting (CT) and ultraviolet arc turning (UVAT) conditions. Cutting speed, feeding rate, and depth of cutting were subjected to a variety of adjustments. It was noted that the surface finish with UVAT seemed relatively poor, measuring 1.12 m, however it had been possible to attain an improved surface quality. It's possible that the better surface quality reported after UVAT is due to the increased chip breakage and disassociation of the chips all over the tool, as opposed to the long, curly chips created during CT, which were more tangled around the tool. This was in contrast to the fact that the higher surface quality was recorded during UVAT. The surface polish was destroyed as a result of these entangled lengthy curling bits.

The roughness of the surface will improve in proportion to the increase in speed of cutting. On the other hand, it did go up when the CT and UVAT were applied, both when the feed rate and the depth of cut were raised. On the contrary hand, there's not a perceptible variation in the force of cutting when the CT and UVAT are both applied in extreme turn. As a result, the radial part of the pulling force was taken into account first, then the tangent force, and finally the feeding force, while simultaneously taking into consideration the CT and UVAT. This study broadens the scope of machinability exams by taking into account the impact of vibrations that are superimposed on a tool in three different directions: the feed direction, the tangential direction, and the radial direction. This research also advocated evaluating and optimising tool life assessments when subjected to UVAT and CT as a more cost-effective alternative to the costly ceramic and CBN cutting tools that are typically used for hard turning.

A design that is inefficient due to a lack of theoretical considerations would compound problems brought on by the outcomes of the experimental study. In order to build an ultrasonic vibratory instrument, namely a stepped horn, to improve the presentation of system stability, the technique used in this study paper is theoretical in nature.

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