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Finite element analysis and process parameters optimization of ultrasonic vibration assisted turning (UVT)

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Abstract

In recent years, there have been many modern engineering materials introduced recently which are hard, brittle and difficult to machine. These materials are very difficult to machine with conventional turning methods. Ultrasonic assisted turning (UAT) is a new non-conventional technique, used to remove an unwanted material to produce a desired product. Ultrasonically assisted turning (UAT) is an advanced machining technique, where a high frequency of vibration (frequency $f \approx 20\pm0.5$ kHz, amplitude around $a \approx 20$ µm) is superimposed on the movement of a cutting tool. In this method, high frequency electrical energy is converted into mechanical vibrations via a transducer or booster combination, which are transmitted through a horn or tool assembly. An ultrasonic vibratory tool (UVT) designed and analyzed using ANSYS® (one of the FE code) for the calculation of its natural frequency and working amplitude of vibration. Taguchi with TOPSIS method is used to optimize both cutting force and surface roughness to find the best possible machining parameters under the used experimental working condition in UAT.

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Key words: *Harmonic analysi; Longitudinal vibration; Modal analysis; Triangular; UAT; UVT;*

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1. Introduction

Ultrasonic vibration has been utilized with considerable benefits for different types of manufacturing processes, for example, ultrasonic emulsification, ultrasonic cleaning, plastic welding, etc. E. C. X. Shamato and T. Morowaki (1999). In typical ultrasonic machining, high frequency electrical energy is converted into mechanical vibrations using a transducer or booster combination, which are transmitted through a horn or tool assembly. Ultrasonic assisted turning is a cutting technique in which a certain frequency (in ultrasonic range) of vibration is applied to the cutting tool or the work-piece (besides the original relative motion between these two) to achieve better cutting performance I. Skiedraite et al. (2007). The Ultrasonic Assisted turning (UAT) is an assisted machining process in which the Cutting edge of the tool vibrates at a high frequency more than 20 kHz. Ultrasonic assisted turning (UAT) is a new technique, used to remove an unwanted material to produce a desired product, In ultrasonic assisted turning (UAT), a high frequency vibration (frequency f ≈20 kHz, amplitude a ≈15μm) is superimposed on the movement of a cutting tool Ainhoa Celaya et al. (2010). It is an advanced non-conventional method, developed for machining tough and brittle materials such as super alloys, ceramics and glass. In ultrasonic assisted turning (UAT) cutting tool is vibrated. During these operations Compared to conventional turning (CT) this technique allows significant improvements in machining intractable materials such as hard metal alloys and brittle plastics. In this process friction is low between tool and workpiece, cutting tool temperature also low and better surface finish. The research includes the design and FEM analysis of ultrasonic vibratory tools, design and development of an ultrasonic assisted vibration turning system, taking the cutting tool as a cantilever beam V.I. Babitsky et al. (2003). Turning stainless steel work-piece material (a general purpose engineering material) using both conventional and ultrasonic assisted turning and analysing the results. Applying ultrasonic vibration on the horn in a Tangential direction while during the machining is shown in Fig. 1.

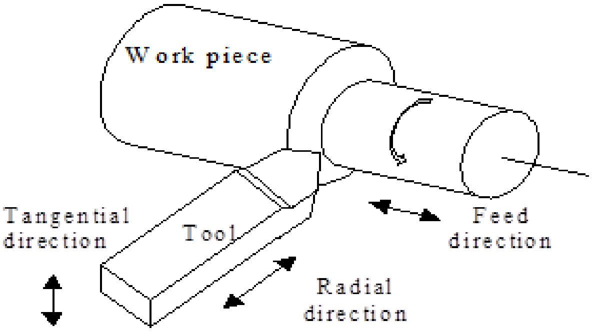

Fig. 1. Principal vibration directions during ultrasonically assisted turning. A. V. Mitrofanov et al. (2003)

When the ultrasonic vibrations applied in tangential direction the following restrictions are imposed:

Tangential direction: $V_c=\pi ND < V_t=2\pi af$

Where Vc is the cutting speed during turning operation, N is the rotational speed of work-piece, V_t is the tip velocity, f is the frequency of vibration and a is the amplitude of vibration.

Nomenclature

A	Amplitude
C	Velocity of sound
f	Frequency
Hz	Hertz
R_a	Surface roughness

2. Dynamic Analysis of UVT

In the present work, an ultrasonic vibrating tool (UVT) is designed and analyzed using ANSYS® for the calculation of its natural frequency and working amplitude of vibration. Finite element analysis is performed by using the commercial package ANSYS® B. C. Behera and S. K. Sahoo (2009-2011).which is one of the most powerful and flexible tools for available for dynamic analysis of structures. The finite element method is very useful in finding the resonant frequency and analyzing the vibration displacement distribution of an acoustic horn with any dimension. In this finite element analysis, the major factors used for modelling a general structural pressure simulation included element type, real constant, material properties, geometry, meshing, boundary conditions, etc.

2.1. Material properties

The titanium is used as the horn material for the analysis with properties, elastic modulus E= 110 GPa, Poisson's ratio, γ=0.33, mass density ρ= 4700 Kg/m^3. Tool steel is used as the single point cutting tool for the analysis with properties, elastic modulus E=210 GPa, Poisson's ratio γ=0.30, mass density ρ=8150kg/m^3.

2.2. Boundary condition

After finalizing settings for the ANSYS® pre-processor, boundary conditions are provided to the solution-finding processor. The output of piezoelectric transducer is applied as input of the tool. 0.01mm displacement uniformly distributed loads is applied at the big end of the ultrasonic vibrating tool.

2.3. Element type selection

Selection of suitable element types according to the material and the design of the UVT are made to ensure the analytical correctness. The UVT is predominantly divided into metallic materials. Element selection varies due to differing features. Considering the special curved surface structure of the vibrating system, solid 92, a tetrahedron with 10 nodes (Fig. 2) is selected as the element. As the tetrahedron element allows the finite element analysis software to grid a complex geometric model easily, it is considered to be suitable for the shape required by the vibrating tool.

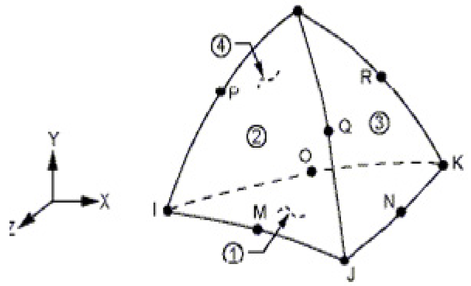

Fig. 2. Solid 92 elements [reproduced from ANSYS 13.0 user guides B. C. Behera and S. K. Sahoo (2009-2011).

2.4 Mesh generation

According to the basic principles of finite element analysis theory, the smaller mesh element size gives more accurate results of an analysis. If the mesh element sizes infinitely small, the theoretical model will approach the optimal solution. However, this is only a speculation. In the analysis process, when elements are too small, element meshing will generate too many elements, nodes and freedom for the model in general. This increases computational intensity, resulting in a model that is either too time-consuming to solve, or potential errors in values. Thus, reasonable mesh element size (number of elements) is a factor that should be considered in a finite element analysis.

In the present analysis 14482 numbers of elements with 21517 nodes are used for the model. Fig. 3 shows the mesh generation modal.

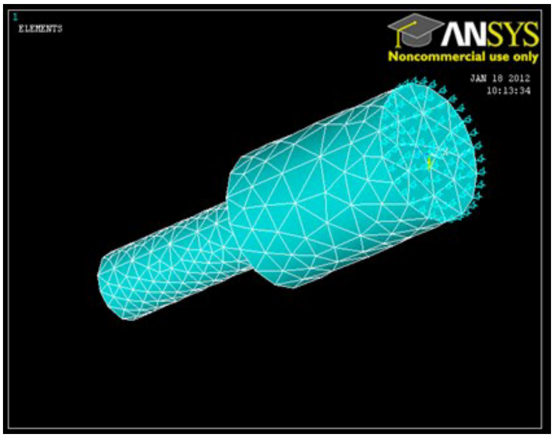

Fig. 3. Mesh generation of horn.

2.5 Boundary condition

After finalizing settings for the ANSYS® pre-processor, boundary conditions are provided to the solution-finding processor. The output of piezoelectric transducer is applied as input of the tool. 0.01mm displacement uniformly distributed loads is applied at the big end of the ultrasonic vibrating tool.

2.6 Modal analysis

Modal analysis allows the design to avoid resonant vibrations or to vibrate at a specified frequency. It helps in calculating solution controls for other dynamic analyses, because a structure's vibration characteristics determine how it responds to any type of dynamic load; always perform a modal analysis first before trying any other dynamic analysis. Modal analysis is a linear analysis, any nonlinearities such as plasticity and contact elements, are ignored, even if they are defined. Several mode extraction available in the modal analysis but in present case 'BLOCK LANCZOS' extraction method is selected. In modal analysis the frequency is generated 19653Hz and out-put amplitude is 4 times greater than input amplitude.

2.7 Harmonic analyses

The technique to determine the steady state response of a structure to sinusoidal (harmonic) loads of known frequency where the input harmonic loads are forces, pressures, imposed displacements, and imposed voltage of known frequency. The output parameter is harmonic displacement at each DOF, the current flow of piezoelectric elements, stresses and strains. 3. Methods of solving the harmonic equation of motion, but in present case Full method is selected, it is used in full structure and unsymmetrical matrices (ultrasonic stepped horn) shown in Fig. 4.

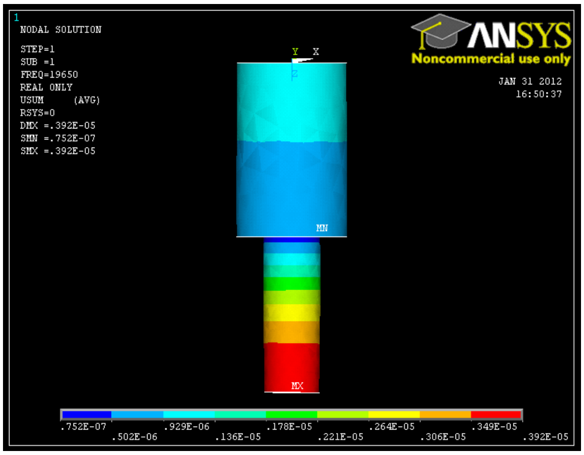

Fig. 4. Harmonic analysis of UVT.

An additional point to be considered when designing UAT setup is that the horn should have at least one natural frequency within the allowable ultrasonic frequency, in this case 19650 Hz (19,500–20,500 Hz). It can be concluded that the geometrical dimension and material properties of UVT used in the analysis of horn can deliver the required frequency. This frequency is matched to another part of the ultrasonic system and the resonance frequency of the horn under the generator frequency and the UVT is amplified 4 times of source amplitude to working amplitude.

3. Experimental Procedure

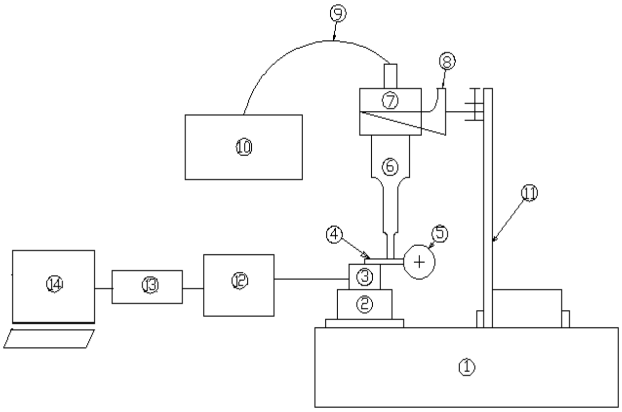

Fig. 5. Schematic Diagram of ultrasonic assisted turning (UAT) set-up

1. HMT Model NH 26 Lathe.
2. Compound plate
3. Dynamometer (Kistler model 9272)
4. Tool (treated as a cantilever)
5. Work-piece
6. Ultrasonic vibratory tool (UVT)
7. Booster/converter
8. Bracket
9. H. F. Cable with 4 pin coaxially (M) to (F) connector connects 20 kHz high voltages to the converter.
10. Generators
11. L-type holder
12. Charge amplifier model 5070A
13. DAQ
14. PC (CONTROL UNIT)

The work-piece (SS-304) is clamped by the three jaw chuck of "HMT model NH 26" lathe. The commercial piezoelectric transducer (unloaded 20±0.5 kHz frequency) provides vibration to the ultrasonic vibratory tool (UVT). The tip of UVT is placed vertically on the cutting tool. The cutting tool is treated as a cantilever beam, which is fixed on Kistler model 9272 dynamometer. The UVT placed perpendicularly to the workpiece in the horizontal plane allows the cutting tool to make the ultrasonic vibration movement in the cutting velocity direction. The amplitude of vibration is 16μm at cutting tool tip as calculated, which the working amplitude for all experiments.

The ultrasonic transducer is clamped at its nodal point by a lightweight bracket and the bracket is fixed by sliding mechanism with special designed L-shape holder. This L-shaped holder maintained the height of the ultrasonic transducer, which is fixed on cross slide of the lathe. The UVT is connected to a generator by H.F. Cable with 4 pin coaxially (M) to (F). The generator is generating high frequency around 20±0.5kHz with 2.0kW (max) power from the input mains voltage 230V AC, 50Hz frequency.

3.1. Cutting condition

Table 1. Cutting condition used in the experiment

Work-piece material	S (m/min)	D (mm)	F (mm/rev)	d (mm)
Stainless steel (SS304)	57	45	0.04	0.1
	74	45	0.05	0.15
	96	45	0.06	0.2
	125	45	0.07	0.25

3.2. Work piece preparation and processing

The work-piece is cylindrical and faces are machined prior to the experiments. A finishing cut with a very small depth of cut is performed using the same cutting tool to be used in the experiments, in order to eliminate any leftover eccentricity. In the experimental run, first cut is made conventional and as soon as the tool travelled by 10mm (depends upon the time) the vibration is switched on thus allowing the second cut to proceed under same cutting condition but with ultrasonic vibration.

Table 2. Composition of work-piece (Stainless steel 304)

Composed of stainless steel 304	Fe	Cr	Ni	Mn	N	S	C	Si	P
Percentage	64.99-74%	18%	8%	2%	0.10%	0.03%	0.08%	0.75%	0.045%

Fig. 6. Work piece preparation in UAT using lathe (HMT Model NH 26).

After finishing one experiment as shown in Fig. 6, it is marked for identification. So, every experiment is divided into two parts, the first part is convention turning (CT) and second one is ultrasonic assisted turning (UAT). Each experiment was done at different cutting condition and the same procedure is applied in different experiments shown in Fig. 7.

Fig. 7. Work piece after the experiment.

'TALYSURF' equipment is used to Measure the surface roughness on the Stainless steel Workpiece in Ultrasonic Assisted Turning (UAT) as well as conventional turning (CT) shown in Fig. 8. By using Kistler model 9272 dynamometer and control unit measuring the cutting forces on both CT and UAT.

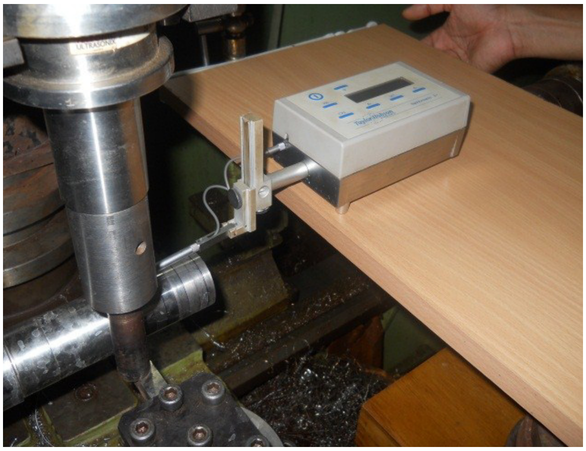

Fig. 8. Measuring the surface roughness of the workpiece using 'TALYSURF' equipment.

The experimental study has carried out on turning Stainless steel by conventional turning (CT) and ultrasonic assisted turning (UAT). Because of the unstable turning process in CT, the surface can easily produce some defects such as burrs, tearing and so on, so the quality of the surface becomes poor. While the UAT can reduce the influence of deformation and built-up-edge formation because of high frequency reciprocating movement between the contacting surfaces of the tool and the work piece, so as to make the training process more stable. UAT improved the surface roughness by 12.0–40.0%. It proves that UAT can obtain smoother surface. The test results show that the cutting force for the UAT method decreases by 25.0–35.0 % in comparison with CT. As a result, ultrasonic-aided cutting can enhance the cutting quality of Stainless steel.

4. Optimization of Machining Parameters

4.1. Taguchi design experiments in MINITAB

A Taguchi design or an orthogonal array the method is designing the experimental procedure using different types of design like, two, three, four, five, and mixed level. In the study, a three factor four level setup is chosen from a total of sixteen numbers of experiments to be conducted and hence the Orthogonal Array L_{16} was chosen. This design would enable the two factor interactions to be evaluated. As a few more factors are to be added for further study with the same type of material, it was decided to utilize the L_{16} setup, which in turn would reduce the number of experiments at the later stage. In addition, the comparison of the results would be simpler. Machining parameters, depth of cut (d), feed (f), and speed of the spindle (S) are designed (3 factors, 4 levels).

4.2 Topsis

TOPSIS (technique for order preference by similarity to ideal solution) is a simple method which considered that the chosen alternative should have the shortest distance from the ideal solution and the longest distance from the negative ideal solution. Such an approach is both comprehensible and functional (Lee-in Tong and Chao-Ton Su (1997). According to Hwang and Yoon (1981), the ideal solution is a hypothetical solution for which all attribute values correspond to maximum attribute values in the database comprising the satisfying solution; the negative ideal solution is a hypothetical solution for which all attribute values correspond to minimum attribute values in the database. TOPSIS thus gives a solution that is not only closest to hypothetically best, that is also the farthest from hypothetically worst.

Table 3. Response Table for Signal to Noise Ratios

Level1	d	f	S
1	-3.599	-10.423	-10.807
2	-12.326	-7.092	-64.152
3	-63.866	-7.944	-7.873
4	-11.133	-65.465	-8.092
Delta	60.267	58.373	56.279
Rank	1	2	3

4.4 Analysis of responses

In this present optimization, Main effect plot can be generated by using Taguchi techniques and that plot can show the optimal setting of the experiment shown in Fig. 6.

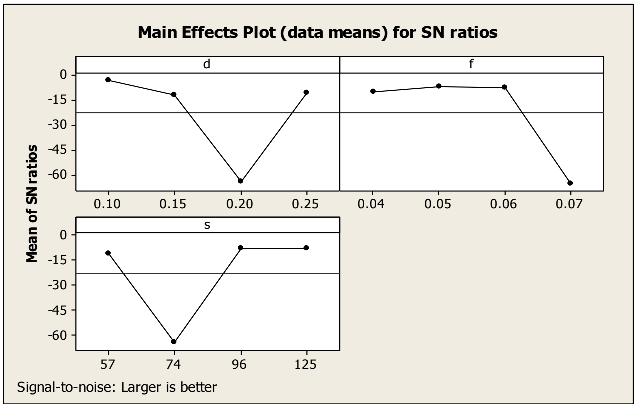

Fig. 9. Main effect plots

In the main effect plot larger is the better criteria is taken, then the optimum Factor levels for predictions d-0.1, f-0.06, S-96. In the 16 experiments, the optimum point is a 3rd experiment wish is shown in table 3. The optimal point have in the experimental design so, no need to take the conformance test.

5. Conclusion

In this present work the experimental study has been carried out to find the difference between UAT and CT. Discuss the experimental set-up and procedure. The results have been compared with Ultrasonic assisted turning (UAT) and conventional turning (CT) process. The UAT method has been found to be a suitable technique to achieve high-quality surfaces finish and lower cutting force requirement not only for hard material but also for general purpose engineering material, like stainless steel etc. Optimum machining parameter combinations for different roughness parameters are also tested through confirmation experiments that show fairly good agreement with prediction of TOPSIS with Taguchi method.

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