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Damping Impact on 1-Dimensional Ultrasonic Vibration-Assisted Turning Machining

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Abstract: In ultrasonic vibration-assisted turning (UVAT), vibration is one of the critical factors that causes noise during machining and affects cutting tool life, machining accuracy and workpiece surface quality. Vibration generated by piezoelectric actuators tends to transmit undesired vibration on the edge of the cutting tool and tool post. This situation hinders the maximization of vibration energy usage in the cutting tool. Thus, this paper investigated the vibration performance in the cutting tool by adding an isolator pad as damping element in the static zone of a tool holder to reduce the resonance generated during the machining process. The static, vibration and surface roughness analysis has been performed to determine the impact of damping on the machining performance. The results revealed a significant improvement in surface roughness where the best R_a for UVAT was 0.38 µm. In addition, vibration and static analysis showed the application of isolator pad capable of reducing 80% of energy loses and a supporter to increase the displacement, respectively. Ultimately this innovative solution can play an important role in improving UVAT performance.

Keywords: Damping, Reduction of Resonance, Ultrasonic Vibration Assisted Turning, Piezoelectric, Vibration Isolation.

1. Introduction

The efficiency of the machining is a critical factor in enhancing the total precise product in the manufacturing industry. In recent decades, there is an increasing demand for the surface quality and machining precision of highly sophisticated products and precision components on the machinery industry such as aerospace, automotive, heavy machinery [1]–[3]. The ultrasonic vibration-assisted turning machining is hybrid machining method which combines ultrasonic vibration with the traditional cutting process. Researchers in this field suggest that a proper selection of the cutting and vibration parameters plays a significant role in having a periodic separation between the tool and workpiece [4]–[6]. Whereas, conventional machining processes are unable to provide that periodic separation which leads to unwanted temperature and surface quality [7]. The gap between the cutting tooltip and the workpiece due to periodic separation (result of vibration and amplitude) during ultrasonic vibration machining process helps to reduce the heat by allowing fluid to enter easily. Despite the positive aspects of UVAT, there are some concerns about UVAT design such as vibration transmission to unnecessary parts of the tool which reduced the maximum performance of the ultrasonic-assisted tool. Therefore, an innovative solution is required by the manufacturers for better machining performance.

The ultrasonic vibration-assisted turning (UVAT) machining provides excellent advantages in the material removing process. Application of high-frequency UVAT in cutting tools could improve machining characteristics of intractable alloys with a cutting force reduction up to 50%, reduction of chatter, cutting tool wear, improvement in surface quality and roundness up to 50% to 80% and smaller chips production compare to conventional turning[3], [8], [17], [9]–[16],[19]. However, structural deformations could affect unusual displacements of the tooltip point (TTP), and this problem would results in undesired deviations and degradations of surface quality during finishing [18]. To avoid such undesirable effects, several requirements should be satisfied by the selected material, such as good dynamic characteristics and dimensional stability, high static stiffness for bending and torsion, a high value of yield strength and elastic modulus [20]. Hence, the main challenge is to define an appropriate material that fulfils the requirements in terms of productivity, accuracy, and efficiency [21].

Vibration damping and excitation avoidance are the most common ways to mitigate the vibration effects on the machine tool. Excitation avoidance refers to the avoidable vibration generated from the vibration source based on the interaction of acceleration [22], by defining a tool path and subsequent velocity profile [23]. On the other hand, there are two types of vibration damping techniques, namely, active and passive. For active damping, an automated control system is used to isolate the vibration, and in passive damping, vibrations are isolated with passive techniques such as rubber pads, foam or similar materials. The good aspects of passive damping are ease of implementation, low cost and non-requirement external energy [24]. Paul et al. [25] investigated the impact of passive damping in turning machining. The study concluded that passive damping could improve cutting performance by reducing the tool vibrations. They also mentioned that damping was simple in construction, low cost, robust and able to work in harsh environments. Similar work was reported in [26] where they used spring damper in the boring process. Thus, passive damping approach may play a key role in vibration isolation in the machining process.

The application of ultrasonic vibration-assisted turning increasingly improves the efficiency of the cutting process. The abovementioned issues discussed concerning UVAT should be taken into consideration to obtain an optimal solution. The major problem of the ultrasonic-assisted tool is the vibration transmission to unnecessary part of the tool which prevents maximum use of vibration at the edge of the cutting tool. Moreover, this condition is inefficient to achieve better surface roughness and low cutting force. As a result, it affects the performance of the UVAT process. At this stage, an innovative solution is required to allow the vibration to transmit only through the cutting tool. Natural frequency and damping are the two parameters that considered essential in a vibration-related problem. The natural frequency is referred to as the frequency at which the structure will vibrate once displaced and quickly released [27]. As the damping ratio determines the size of amplitude [28], so it is a common consideration for tool designing. Therefore, this research investigated the damping impact on the 1-dimensional (1D) ultrasonic-assisted cutting tool. Al6061 was selected as workpiece material. This paper concluded the analysis and the results of the machining operation output.

2. Materials and Methods

2.1 Ultrasonic Vibration-Assisted Turning

UVAT is the next generation of machining in which ultrasonic vibration with high frequency around 20 kHz is applied to the cutting tool with the operation of the piezoelectric actuator [29], [30]. Fig. 1 shows the principle of the UAT machining process where the cutting tool is in contact with the workpiece (first step). At the second step, the cutting tool moves forward and eliminate the unwanted material, and produce chips. Then the tool moves backwards and returns to the first step. This process is called an intermittent cutting process, where there is no continuous contact between the cutting tool and the workpiece, which provides better surface finish and better tool life [31].

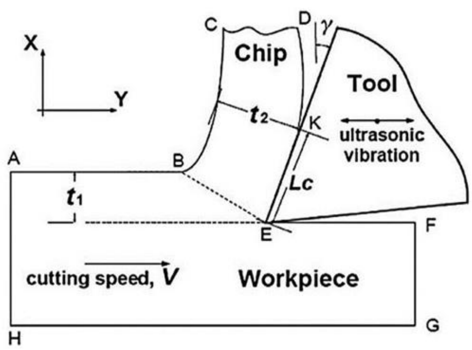

Fig. 1- The principle of UAT machining [32]

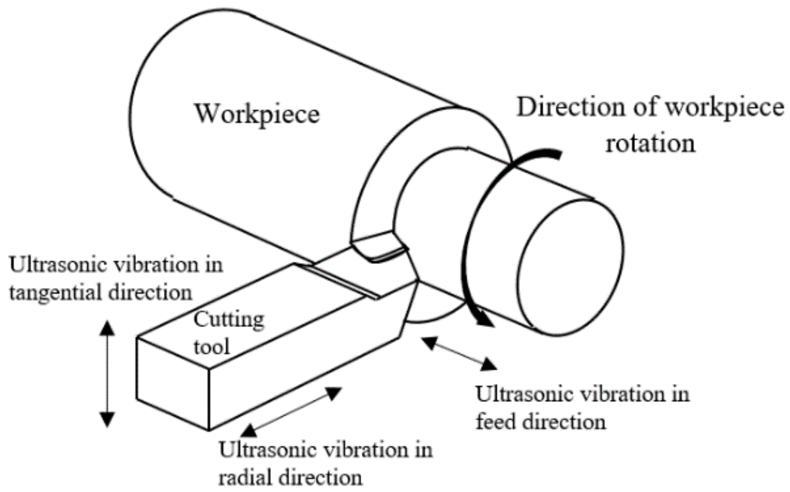

Fig. 2- Vibration direction in UAT machining [33]

Ultrasonic vibrations in turning process can be implemented in the three directions, namely tangential, radial, and longitudinal direction (Fig. 2). Hsu *et al.* [34] observed that the vibration introduced in tangential direction produces better surface quality with less cutting force while increasing cutting tool life. If the cutting tip vibrates in the tangential direction, the vibration velocity should be greater than the cutting velocity as follows:

$$V_c = \left(\frac{\pi\, ND}{60}\right) < V_t(= 2\pi a f) \tag{1}$$

where V_c is the cutting speed (m/min), N is the spindle speed (RPM), D is the diameter of the workpiece, V_t is the tip velocity (m/min), f is the frequency vibration (Hz), and a is the amplitude vibration (μm). The experimental work in [35] shows that the cutting force would be reduced significantly at higher cutting speed, and after exceeding a certain cutting speed ($V_c > V_t$), vibration did not affect the cutting force.

Fig. 3 shows the schematics of the modified turning tool used in this work. The current setup exhibits problem related to energy lost when the tool holder is clamped to the tool post. Vibration induced by the piezoelectric actuator can be transmitted to other parts such as the tool post, hence reducing the efficiency of the cutting process. To overcome such problem, the vibration isolators can be used in the static zone area to break the transmission of vibration to the tool post while focusing the vibration motion to the edge of the cutting tool. However, the level of rigidity is considered as unknown for the isolator. Thus, engineering analysis will be applied to define the force-displacement and maximum load requirement that can bear by the tool holder when attaching with an isolator.

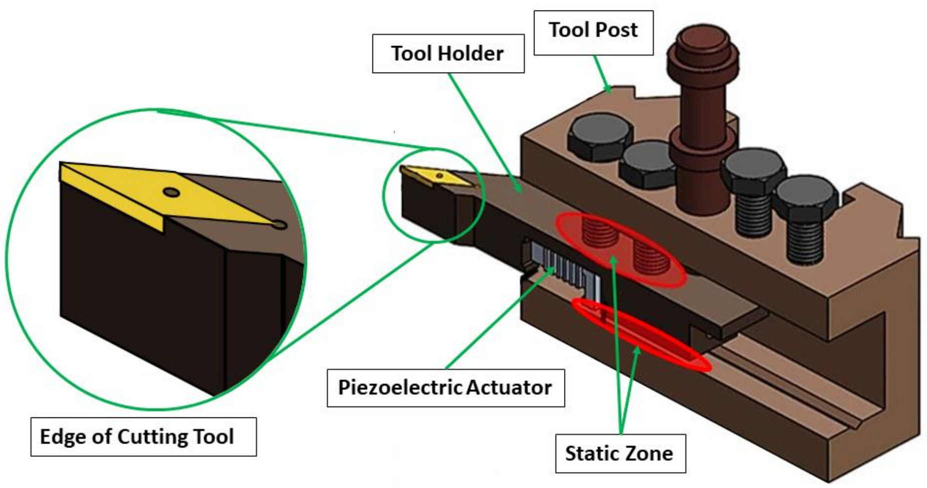

Fig. 3- Modified Turning Tool

2.2 Vibration Isolation Mechanism on UVAT

Vibration isolation of a system of interest from source excitation can be created using separation between vibration source and the device. The work described in this paper will consider a passive vibration isolation system. In this isolation system, the vibration force will be transmitted directly from a vibration source to a supporting structure; i.e. the tool post of the turning machine. At the same time, the vibration is filtered out by an isolator which is referred to as the damping element because of its flexibility [36].

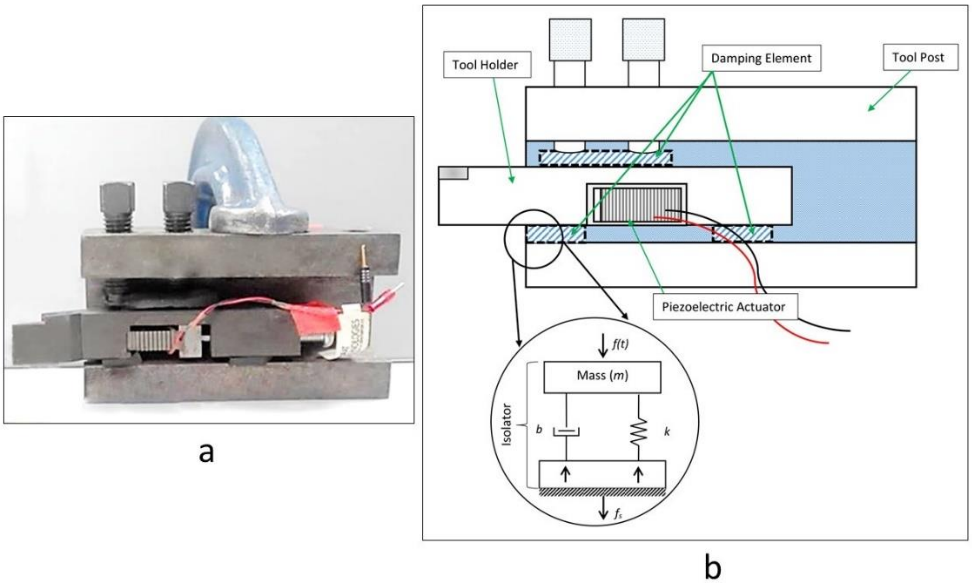

Fig. 4- (a) UVAT tool holder with isolator pad; (b) Schematic model of passive vibration isolation

Fig. 4(a) shows the modified UVAT tool holder with an isolator pad placed in between tool post and top and bottom of the tool holder. Schematic model of passive vibration isolation is shown in Fig. 4(b). The vibration force at the source is $f(t)$, while transmitted vibration force, f_s are transmitted through the isolator pad. If the tool holder mass is denoted as *m* and isolator mass is *s*, then the force transmissibility, T_f can be written as follows:

$$T_f = \frac{f_s}{f} = \frac{s}{m+s} \tag{2}$$

At this point, force directly transmits from the isolator to the tool post for this case. The transmissibility function can be as,

$$T = \frac{k + bj\omega}{(k - m\omega^2 + bj\omega)} \tag{3}$$

where ω is referring to the frequency of vibration. In terms of frequency function ω, the Fourier spectrum can be the representation of general vibration excitation. The multiplication of the transmissibility function and excitation spectrum gives the result of the response vibration spectrum. Then, the selection of appropriate isolator parameters *k* (spring) and *b* (damper) to meet the requirement of isolation. Therefore, Equation (3) could be:

$$T = \frac{\omega_n^2 + 2\zeta\omega_n\omega j}{(\omega_n^2 - \omega^2 + 2\zeta\omega_n\omega j)} \tag{4}$$

The damping ratio is denoted as $\zeta = \frac{b}{2\sqrt{k \times m}}$ and undamped natural frequency as $\omega_n = \sqrt{\frac{k}{m}}$. If the non-dimensional excitation frequency is $r = \frac{\omega}{\omega_n}$, then Equation (4) can be written as below for non-dimensional form:

$$T = \frac{1 + 2\zeta rj}{1 - r^2 + 2\zeta rj} \tag{5}$$

The transmissibility function has a phase angle and magnitude. Transmissibility magnitude can be calculated in the equation below:

$$|T| = \sqrt{\frac{1 + 4\zeta^2 r^2}{(1 - r^2)^2 + 4\zeta^2 r^2}} \tag{6}$$

Therefore, $|T| < 1$ for $r > \sqrt{2}$ which corresponds to the isolation region. It means transmissibility is decreasing while isolation in the system increased. Nevertheless, to achieve the best condition for isolate a system is to obtain a minimum damping ratio, but as it is impossible to make it zero, so we need to have the value of the damping ratio as small as possible [36]. Then, Equation (6) approximated as shown in Equation (7) when $\zeta \cong 0$ and substitute with $r^2 = \omega^2/\omega_n^2 = \omega^2 m/k$.

$$k = \frac{w^2 m T}{(1 + T)} \tag{7}$$

Here, to design stiffness of the isolator of the tool holder for an acceptable level of isolation (1-T), k in the Equation (6) can be used. Moreover, suggested conditions for vibration isolation can be obtained by using higher damping materials such as elastomer, dense foam, rubber or cork as it is needed to minimize resonant vibration. However, a lower damping ratio is required for good vibration isolation. The detail specifications of the isolator pad material can be found in Table 1.

Table 1- Detail of the isolator pad

Properties	Specifications
Material	Rubber granules
Thickness	0.5 cm
Dimension(Each)	3 cm x 1.5 cm
Elastic in the temperature	-22 °F to 212 °F

3. Results and Discussion

3.1 Vibration Analysis

There are two solutions to solve the problem of energy loses at the tool post, i.e. the first solution to the problem is to place the piezo actuator near to the front end of the cutting tool. The second approach that can be used to reduce the energy losses is by replacing the static zone with vibration isolator pad. The second approach is more practical compared to the first approach as the isolator pad can be used to break the transmission of vibration between the tool holder and the tool post. In order to test the efficiency of the proposed solution, the vibration transmission test was conducted on the tool holder structure with/without isolator pad as shown in Fig. 5.

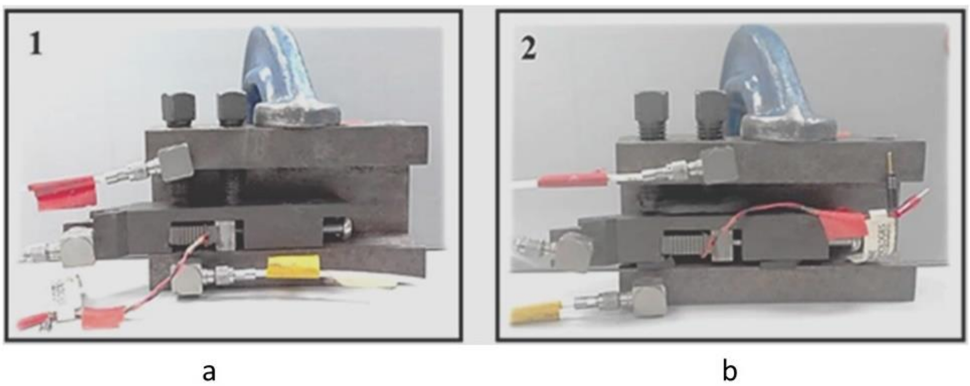

Fig. 5- The vibration transmission test conducted on the UVAT tool holder (a) Without vibration isolator pad; (b) with vibration isolator pad

To compare the level of amplitude, vibration transmission data has been collected through Dytran 3214 single-axis accelerometer sensors. The vibration sensors were placed at three separate locations as shown in Fig. 6(b). A hammer has been used to create a vibration source on the piezo actuator. When the hammer knocked on the piezo actuator, the measured vibration signals will be displayed in the data acquisition system for further analysis (Fig. 6(a)). The amplifier was acting as a power source that generates high voltage to drive the piezoelectric actuator. For this study, a digital oscilloscope was used to measure the output signal voltage strength. The input voltage that can be set in the generator is according to the oscilloscope-simulated data, based on frequency 20 kHz, 40 kHz and 50 kHz.

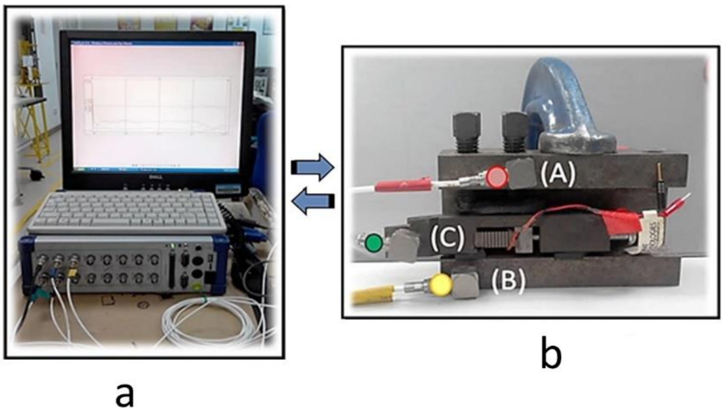

Fig. 6- The data acquisition system used for the UVAT tool holder (a) The signal controller/receiver and (b) The location of the three vibration sensors

The vibration transmission results at the three-point location are shown in Fig. 7 and Fig. 8. where the graph shows the significant changes in amplitude. In the structure without isolator pad (Fig. 7), the highest amplitude recorded on zone B, which is the closest zone from the vibration source. Surprisingly zone C recorded the lowest amplitude, which means the frequencies vibrate is inefficient at the edge of the cutting tool. Structure with isolator pad (Fig. 8) sensed the highest amplitude level on zone C refers to the edge of the cutting tool, which means the frequencies vibrate in the peak at that zone. Whereas in the assumption of the range from 5% to 10% of losses was diffuse to the tool post of the cutting tool holder which is zone A and zone B. Therefore, this test had proven that the vibration isolator pad capable of reducing 80% of energy losses and remarkable for current applications to solve the problem.

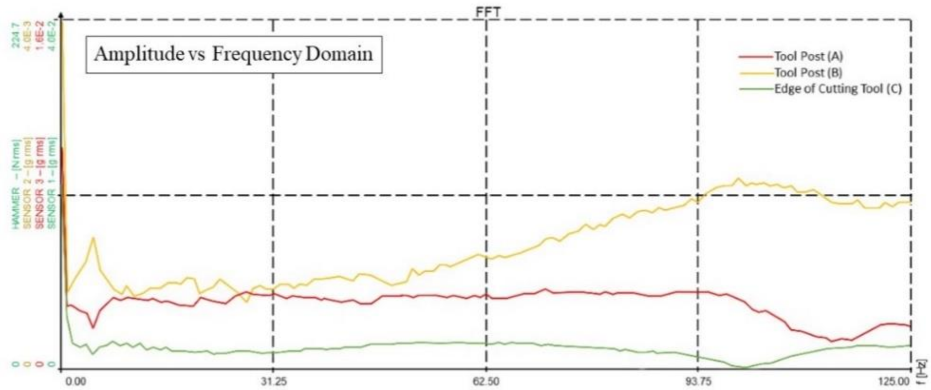

Fig. 7- Graph of the structure without the vibration isolator pad

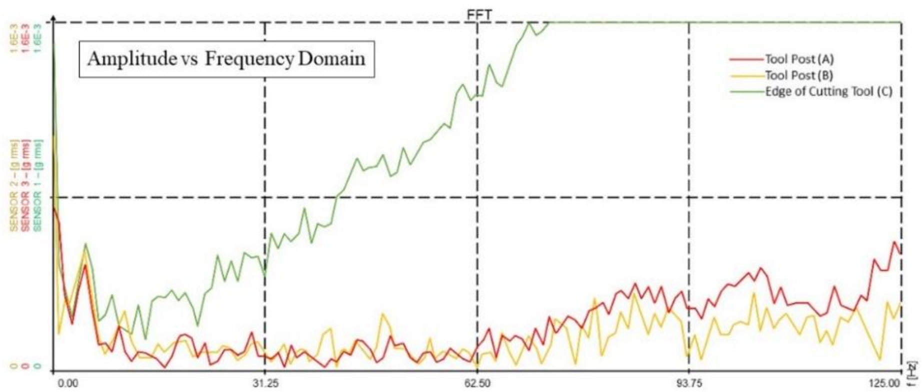

Fig. 8- Graph of the structure with the vibration isolator pad

3.2 Static Analysis

Next, a static analysis is carried out using the SolidWorks simulation program. The parameter data used in the SolidWorks simulation for UVAT tool holder with/without vibration isolation pad cases are shown in Fig. 9. The materials used for the tools and damping elements were assumed as nonlinear, elastic, isotropic and incompressible with a Poisson's ratio ≥ 0.48. The simulation data have shown that the structure with the isolator pad would produce higher cutting displacement at the cutting tip compared to the structure without the isolator pad. The structure with the isolation pad is capable of producing maximum displacement in the range of 0.6368 μm to 12.74 μm depending on the respective voltage and force settings. The displacement amplitude in UVAM is usually between 1 μm to 15 μm [37]. Thus, the result of static analysis supports the same theory as vibration analysis, which means the effective vibration can be achieved by adding an isolator pad as a supporter to increase the displacement at the cutting tip.

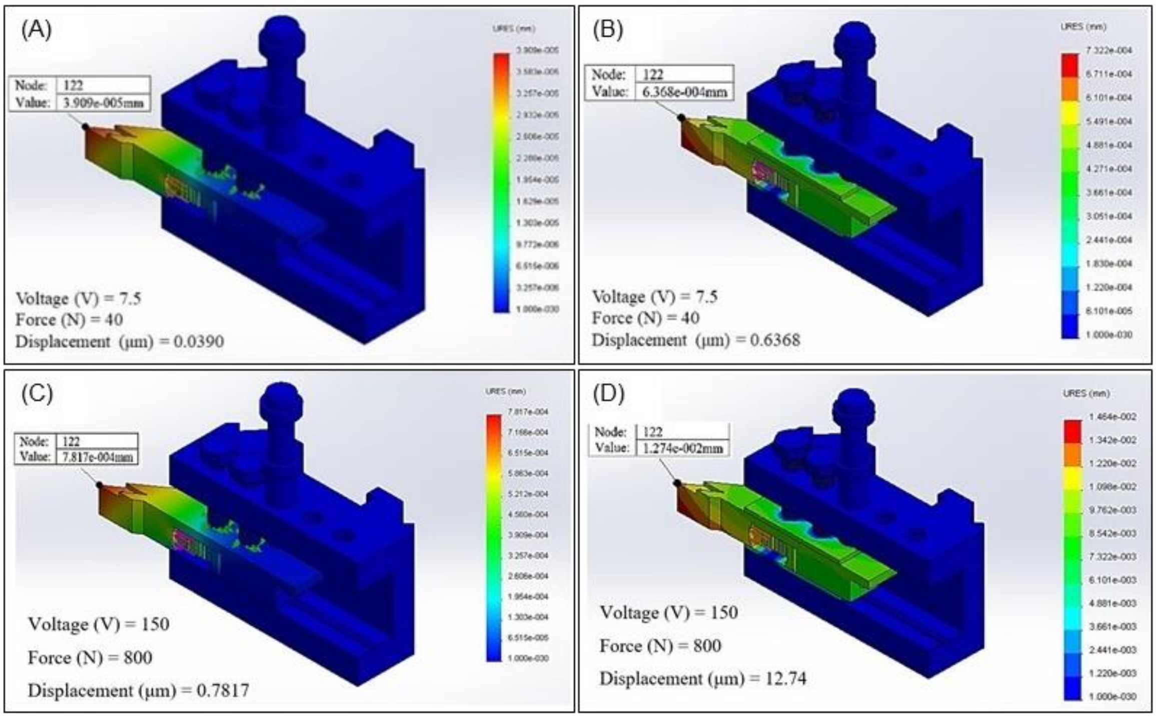

Fig. 9 Simulation Data on Structure with (B) & (D) and without Isolator Pad (A) & (C)

3.3 Surface Roughness, R_a Analysis

The surface roughness results for UAT machining for different vibration source's frequencies and amplitudes are given in Table 2 and Fig. 10. The results show that the average data of surface roughness will gradually rise with the increase in vibration's frequency. The findings from the analysis also show that the best surface finishing can be achieved using the lowest vibration frequency of 20 kHz with 1.0 μm amplitude, whereas the lower amplitude setting (0.5μm) at the same frequency would produce a higher value of surface roughness. A similar trend can be seen in the surface roughness results for different frequencies. This situation also indicates that higher frequency does not provide better surface quality at all the time because of different mechanical properties for each of the material. The findings also show that a higher vibration amplitude helps the cutting tip to vibrate constantly on the workpiece, thus, capable to remove heat faster from the chip.

Table 2- UAT machining surface results

Frequency (Hz)	Amplitude (μm)	R_a, result ($\boldsymbol{\mu m}$)			Average Data	
		1	**2**	**3**		
20000	0.5	0.44	0.38	0.43	0.42	0.40
		0.38	0.37	0.38	0.38	
	1.0	0.38	0.41	0.37	0.39	0.38
		0.34	0.38	0.40	0.37	
40000	0.5	0.48	0.49	0.38	0.45	0.46

		0.40	0.53	0.48	0.47	
	1.0	0.44	0.39	0.40	0.41	0.43
		0.37	0.46	0.49	0.44	
50000	0.5	0.47	0.47	0.40	0.45	0.49
		0.49	0.59	0.50	0.53	
	1.0	0.37	0.44	0.47	0.43	0.45
		0.35	0.38	0.66	0.46	

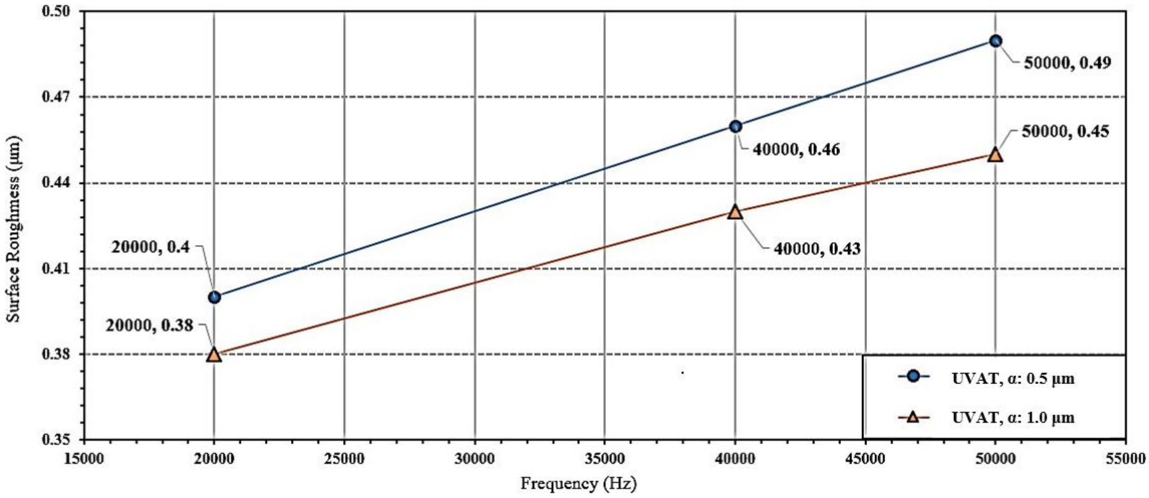

Fig. 10- Graph Surface roughness against frequency

4. Conclusion

This paper deals with the investigation of the damping impact on the 1D ultrasonic-assisted cutting tool machine focusing on static, vibration and surface roughness analysis. The fabricated prototypes represent a modified turning tool with insulator pad as a damping element in the static zone of a tool holder to reduce the resonance generated during the machining process. The application of a vibration isolator pad with the tool holder can reduce vibration transmission to the unnecessary parts of the tool, i.e. the tool post. In this case, the isolator pad worked as a damper element to isolate resonant vibration and maximize vibration transmission only through the edge of the cutting tooltip. The UVAT successfully achieves improvement in surface roughness, where the best R_a for UVAT is 0.38 µm. Finally, this innovative solution shows a significant impact on improving the machining performance which refers to the result of damping in the one-dimensional ultrasonic vibration-assisted machining process.

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