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Experimental investigation of ultrasonic vibration-assisted tapping

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Abstract

Vibration-assisted tapping was studied for fabricating internal threads for titanium metal. High frequency imposed on the workpiece, was generated by a piezoelectric actuator. The axial thrust force and the tapping torque were respectively plotted against the tap's traveled distance relative to the workpiece. Each of the plots demonstrated that the entire tapping process could be divided into six characteristic stages. The implication associated with each characteristic stage was discussed for each plot. The stages where there was maximum thrust force and maximum torque located were identified. The frequency, which was adjustable through a control unit, was found to generate the minimum tapping torque when it equalized the resonance frequency of the tapping setup, a significant finding, which could be applied to decrease the tapping torque, and in turn the likelihood of tap breakage. The effect of tap size employed and the role played by cutting oil were also identified and discussed. No adverse effect on the teeth's shapes fabricated by the vibration-assisted tapping was found.

Keywords: Tapping; Internal threads; Piezoelectric actuator

1. Introduction

Employing taps to fabricate internal threads is a widely used machining process. However, the sudden breakage of taps and a residue of broken tap pieces in the hole of the workpiece is one of the most undesirable things that one may encounter during fabricating internal threads. It is particularly true when small size taps (smaller than M6) are used to fabricate internal threads for blind-holes, where breakage of tools occurs the most frequently. The reasons for this occurrence may include: inaccurate tap geometric sizes, blockage of chip material and improper lubrication. In view of this, increasing the life of taps is of the utmost importance. From the knowledge of previous literature, there are three approaches to solving the problem of tap breakage; they are: (1) improving the accuracy of the geometrical shapes of tap, (2) using the attachment for safety taps and (3) introduction of controllable vibration during tapping. Following overall assessment of the preceding three approaches, it is believed that the introduction of control vibrator is the most efficient and effective solution.

As the trend to reduce aircraft weight and increase aircraft speed continues, the use of titanium alloys on aircraft components has rapidly increased. Take the F-15 fighter for example, the use of titanium alloy accounts for 26.5% of the aircraft total components. The steel rivets used on the aircraft, though small in physical volume, are huge in quantity. Normally, an aircraft may have tens to hundreds of thousands of steel rivets in it. If the steel rivets are to be replaced with titanium blind jack nuts, the weight of the aircraft can be considerably reduced. However, the manufacturability of titanium jack nuts is poor because of the difficulty of tapping internal threads for deep holes, particularly the deep holes of M3.5 × 0.6 mm, normally with 10–25 mm hole depth. The reason for this is that the large spring back of the titanium metal due to its low elastic modulus would cause the relief face of the tap to generate a severe frictional torque, which is seven times that of medium carbon steel. The huge torque due to spring-back would in turn lock the tap from rotating and eventually break it in the hole during fabricating internal threads. This problem, which most frequently occurs when smaller size taps are used, cannot be solved even if the relief angle of the tap is enlarged.

The vibration-assisted cutting technology introduced 30 years ago by Kumabe has the potential to bring forth various advantages, such as reducing cutting force, improving surface quality, inhibiting tool wear and so on [1]. Kumabe and Tachibana established an experimental setup and performed vibration-assisted tapping on aluminum, brass and steel, employing frequencies ranging from 59 to 105 Hz [2]. They reported that the torque required for tapping internal threads was considerably diminished, with decreases amounting to 1/4

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to 2/3 of those of the conventional tapping torques. Kim and Lee applied ultrasonic vibration in his study on cutting the carbon-fiber reinforced composite material. Remarkable results were noted in terms of decreased cutting force and improvement of the surface smoothness of teeth of the finished carbon fiber reinforced composite parts [3]. In addition, Zhang and Chen built a vibration-assisted tapping apparatus fit with a stepping motor capable of supplying a vibration frequency of 24 Hz coupled with amplitude of 400 μm. The apparatus has proved successful in tapping internal threads with a much reduced tapping torque, equivalent to only 1/3 of that employed in conventional tapping, in addition to having prolonged the tap's usable lifetime [4]. In a study by Saotoma et al. [5], the advantage of employing vibration-assisted tapping for fabricating internal threads for holes was also demonstrated in that the tap's lifetime was prolonged by up to 10,000 pieces per tool, where a frequency of 20 kHz, coupled with 15 μm amplitude was employed. Patil et al. designed and attached a connector, which was capable of generating vibrations in a controlled manner for vibration-assisted tapping [6]. The study aimed to investigate the influences of the various processing parameters employed on the tapping torque and on the axial thrust of the tapping apparatus. The process parameters employed in the experiments included the size of taps employed, workpiece material and the vibration frequency and amplitude it was coupled with. Suzuki et al. used ultrasonic vibration to assist the tapping of pure aluminum material. The significant findings they reported included the following: the thickness of the aluminum chips produced during tapping was reduced from 250 to 100 μm; the torque was decreased by 20 times, while the cutting ration was increased by three times [7]. Yin and Han built a vibration tapping apparatus for investigating the influence of tapping parameters on the performance of tapping hardened steel [8]; and they drew the conclusion that the inclusion of vibration to assist tapping could enhance the rigidity of torsion torque, while the tapping torque was simultaneously reduced.

Furthermore, Zhang and Chen applied the elastic–plastic theory to analyze the underlying mechanism that reduces the spring-back of tapped metal surface occurring in the vibration-assisted tapping process, in addition to explaining the reason for the decrease in tapping torque [9]. Rationale was also given for the selection of process parameters to tap threads for titanium alloys. In the meantime, Zhang and Yang also applied a friction couple model to account for the decrease in tapping torque [10]. Zhang and Chen established a metal machining model incorporating the elastic–plastic theory to rationalize the argument that the inclusion of vibration is able to reduce the tapping torque from a theoretical point of view. They employed the process parameters used for tapping the titanium alloy to verify the model [11].

Mezentsev et al. proposed a mechanistic tapping process model, into which effects resulted from misalignment and tap run-out are incorporated. They claimed that the model is able to predict the thread height and pitch size of the tapped hole with an accuracy of within 2% of the actual measured values of the finished pieces [12]. An oblique cutting model proposed by Dogra et al. is capable of calculating the cutting force for taps of different geometrical shapes and inner holes of different features. The cutting force derived from the experiment and that predicted from the model were reported to have less than a 10% difference [13].

From the preceding cited literature, it is can be seen that vibration-assisted tapping not only reduces the tapping torque but also prolongs the tap's usable life. The application of ultrasonic vibration has both beneficial effects in reducing the tapping torque and improving the surface smoothness of the finished teeth. However, few researchers have applied ultrasonic vibration generated by magneto-striction vibrators to assist in internal thread tapping. As such, the present study was motivated to investigate the influence of high frequency vibration on tapping internal threads, utilizing a piezoelectric actuator to generate the high frequency.

The experiment was performed with and without the introduction of cutting fluid. Internal threads tapping for titanium metal were assisted by high frequency vibration aiming at investigating the beneficial effects derived from both the introduction of cutting fluid and vibration. The optimal tapping process parameters were sought after as well.

2. Experimental setup

The apparatus employed in the present study to carry out the ultrasonic vibration-assisted tapping is illustrated in Fig. 1. The device used a voltage actuator embedded in the ultrasonic generator and generated vibrations along the axial direction of the tap, which was clamped by the spindle of a computer numerical control (CNC) machine. Internal threading was performed for a commercially pure titanium cylindrical workpiece, which was screwed tightly onto the ultrasonic generator. During thread tapping, the voltage signals amplified through a dynamometer were fed into a data processor for converting them to torque and axial thrust force.

The ultrasonic control connected to the ultrasonic generator is shown in Fig. 2. It can be used for adjusting the energy of the ultrasonic vibration and the frequency of vibration to near the resonance frequency of the tapping setup, through which the effect of the vibration frequency on the performance of tapping in terms of thrust force and torque can be investigated. The process parameters employed in the experiment are given in Table 1.

3. Results

3.1. The six characteristic stages in the tapping cycle

The axial thrust force and the torque were derived from the dynamometer, and the plots of axial thrust and the vibration frequency versus tapping distance were established separately for investigation. Under the experimental conditions taken by the present study, the shapes of the above two plots both appeared invariable, regardless of whether vibration (with varying or constant amplitude) or lubrication was imposed during tapping or not. The only differences observed were the slopes in the two plots (Fig. 3). In order to elucidate the implications associated with the thrust plot and the torque plot, we divided each plot into six characteristic parts.

Stage I The tap was approaching the workpiece, and after its front touched the workpiece, the amount of cutting gradually increased. During Stage I, the thrust force

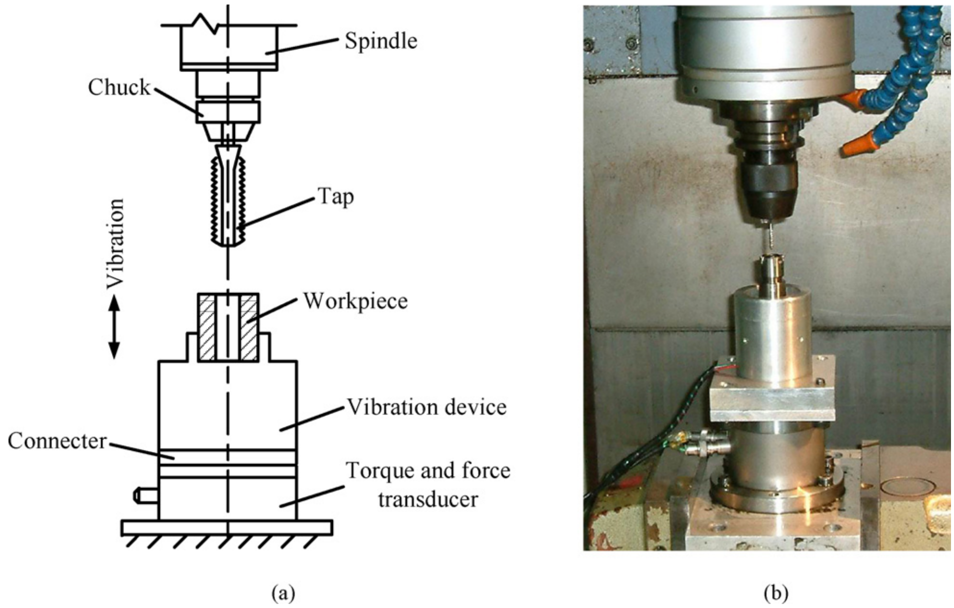

Fig. 1. The apparatus for the ultrasonic vibration-assisted tapping experiments. (a) Schematic view and (b) photographic view.

Fig. 2. The ultrasonic vibration control unit.

increased gradually, while the torque was observed to increase rapidly (Fig. 4).

Stage II During this stage, the tap was moving ahead and increasing its contact length with the workpiece. This is the most critical stage of the entire tapping process, during which the maximum cutting rate is normally taking place. The axial thrust force was increasing steadily, and at the same time the torque was increasing and eventually reached its maximum point as the tap was traveling into the workpiece while making the internal threads concurrently. If the tap were to break, it would most likely occur at this stage when the torque exceeds the tap's maximum resistant value. Hence, the maximum torque reached at this stage can be used for comparing the performance of the tapping process conditions.

Stage III During Stage III, the tap's front portion, i.e. the tap's chamfered area was making its way ahead and was piecing through the opposite side of the workpiece, eventually resulting in the complete immersion of the tap's blades in the workpiece. At this point, thread tapping is basically completed. During Stage III, the thrust force was approaching toward its maximum value, while the torque started decreasing from its maximum value.

Table 1
Experimental parameters employed for the ultrasonic vibration-assisted tapping

Tap size (mm)	M3 × 0.5, M3.5 × 0.6
Workpiece material	Titanium Round Bar TB340C (chemical composition, 99.8 Ti; tensile strength, 447 MPa; yield strength, 327 MPa)
Vibration frequency (Hz), vibration amplitude (μm)	18,000–20,000, 6–24
Vibration wave type	Sine
Spindle speed (rpm)	50
Tapping fluid	Dry, machine oil

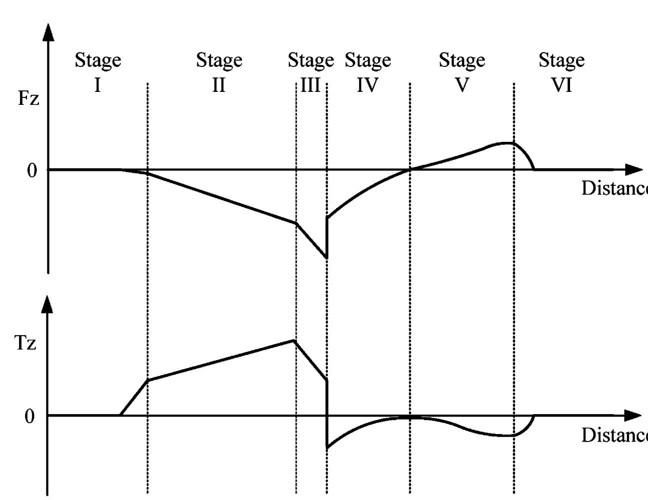

Fig. 3. Showing the entire tapping process, where F_z is the axial thrust force and T_z is the tapping torque.

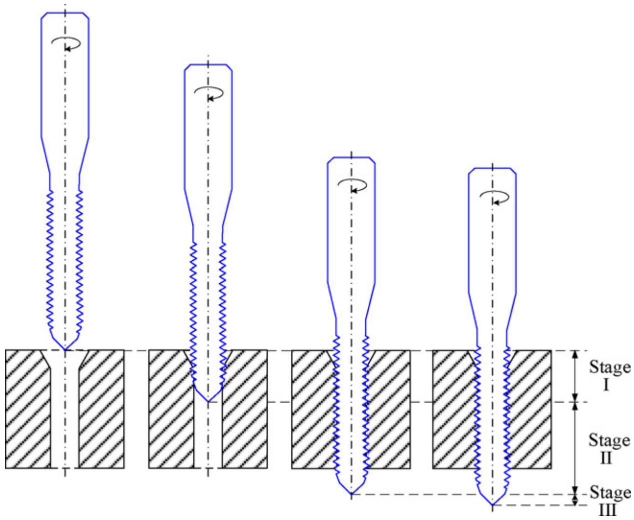

Fig. 4. Showing the relative position of the tap with respect to the workpiece at Stage I to Stage III.

Stage IV Beginning at this stage, the tap started to reverse its rotation and retract from its farthest position, and the tap's chamfer area was gradually returning to the interior of the workpiece. Since the spindle of the tap machine and the tap itself had reversed it rotation at this stage, the axial thrust force responded with an opposite force to counter the original tapping force, resulting in the decrease of the thrust force that eventually becomes zero. Likewise, the torque started reversing and generated the torque in the opposite direction, and decreased steadily and eventually reached a zero value. The decrease of the torque was attributed to the decrease of material spring back, thereby reducing the frictional force between the tap and material (Fig. 5).

Stage V The tap continued retracting, and eventually the cutting blades completely retracted out of the workpiece.

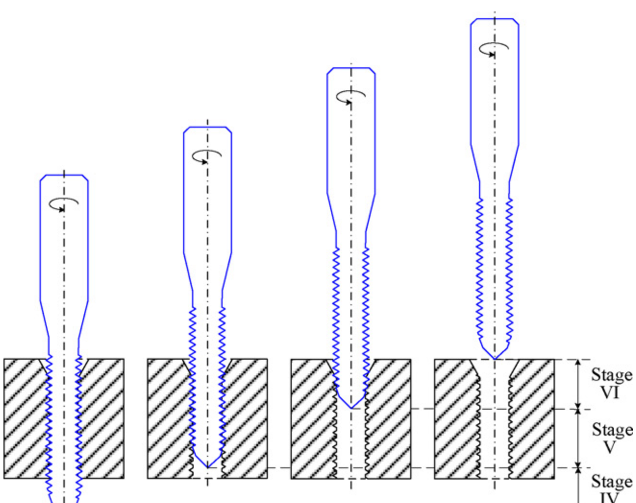

Fig. 5. Showing the relative position of the tap with respect to the workpiece at Stage IV to Stage V.

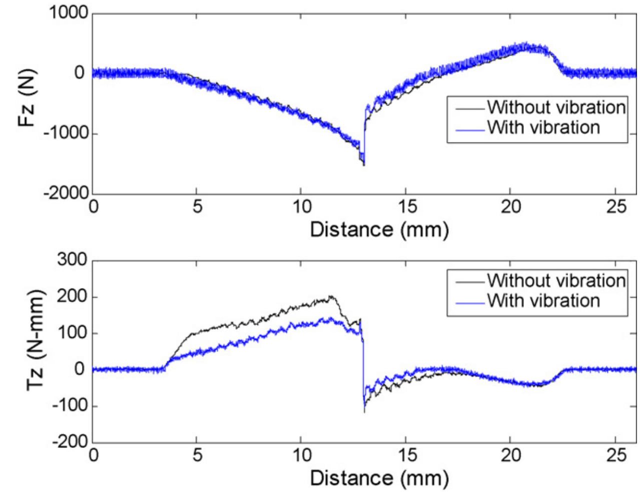

Fig. 6. Showing the variation of axial thrust force F_z and tapping torque T_z with respect to the distance (tap size M3 × 0.5).

During this stage, there existed one point where the net axial thrust force became zero, after which the net axial thrust force began to act in the opposite direction, in response to the retracting tap.

Stage VI The tap kept reversing and retracting until the tap retracted completely out of the workpiece, at which time both the axial force and torque became zero again.

3.2. Comparison of conventional tapping and ultrasonic vibration-assisted tapping

Fig. 6 gives plots of the axial thrust force and torque obtained from the ultrasonic-assisted tapping and conventional tapping. It shows that there was no obvious difference in terms of the thrust force whether vibration was imposed or not; whereas, the torque was considerably lower in the case where the vibration was imposed. Fig. 6 also substantiates the beneficial effect of reducing the torque in the case of vibration-assisted tapping. The reason for the breakage of tap is mainly due to too large a torque for the tap to resist. Therefore, through examining the plots shown as such, we can ascertain the variation in tapping torque and judge the performance of the tapping process.

Fig. 7 shows the changes of the maximum torques that occurred under different tapping conditions and with or without vibration imposed. Here, a 28% reduction of the maximum torque could be realized when a tap of M3 × 0.5 was used; only an 8% reduction of torque was observed when a M3.5 × 0.6 was employed. Apparently, the reduction in the torque was more obvious in the case when a smaller sized tap was employed for tapping the internal threads.

3.3. Effect of vibration frequency on maximum tapping torque

The relationship between the vibration frequency and the maximum torque can be investigated by adjusting the ultra-

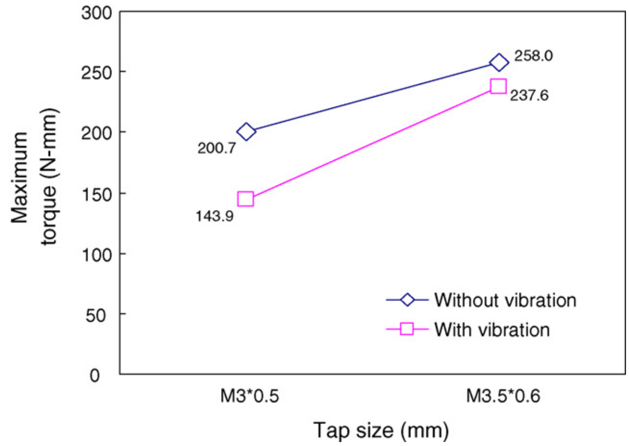

Fig. 7. Showing the effect of tap size employed for tapping with and without the introduction of vibration.

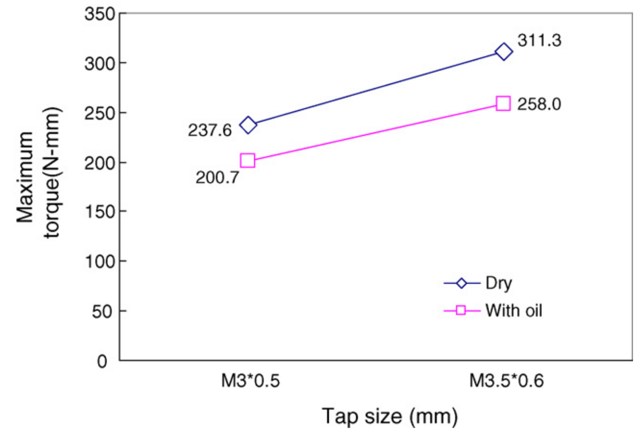

Fig. 9. Showing the effect of tap size employed on maximum tap torque for different tap.

sonic control unit shown in Fig. 2 to match the resonance frequency of the tapping setup. The frequencies were adjusted at intervals of 300 Hz up and down, aiming at investigating the relationship between vibration frequency and maximum torque observed. Fig. 8 shows the tapping performance of two tap sizes employed in this investigation, i.e. M3.0 × 0.5 and M3.5 × 0.6, with no introduction of cutting fluid during tapping. In either case, the magnitude of maximum torques was observed to occur at its resonance frequency, and increased at both ends of the frequency's spectrum. Fig. 8 demonstrated that the best tapping condition was the situation where the assisting vibration frequency matched the resonance frequency. As a result, the vibration frequency adopted in this study was the resonance frequency in all cases.

3.4. Effect of tapping fluid on maximum torque

Ordinary motor oil was used as cutting fluid for investigation of its influence on maximum torque. Fig. 9 shows that there was approximately a 16% reduction of maximum torque; the size of tap used in this investigation did not appear to play any discernable role.

4. Discussion

It is widely recognized that small deep holes are difficult to tap. Breakage of tap frequently occurs because of excessive tapping torque encountered during tapping. However, there are two kinds of force resistance generated between the workpiece and the tap, i.e. the cutting resistance and the frictional resistance. The problem of friction resistance is particularly serious in the case of tapping titanium alloys. This is because titanium has a low modulus of elasticity, which may trigger greater spring-back than other metals of greater elastic modulus. As a result, greater frictional resistance between tap and workpiece may occur. This will result in the rapid increase of resistant torque during tapping.

The application of longitudinal vibration applied on the tap may reduce the instantaneous contact between the tap and the workpiece, leading to less galling between the two materials' surface, and in turn less generated frictional torque. As a result,

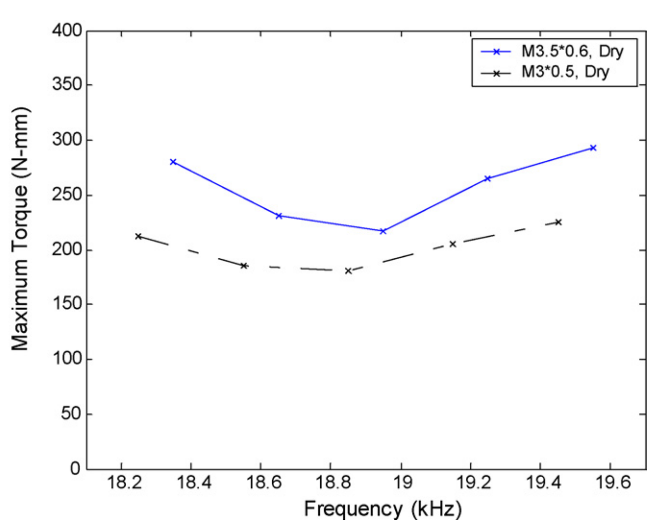

Fig. 8. Showing the influence of tapping frequencies employed on maximum tapping.

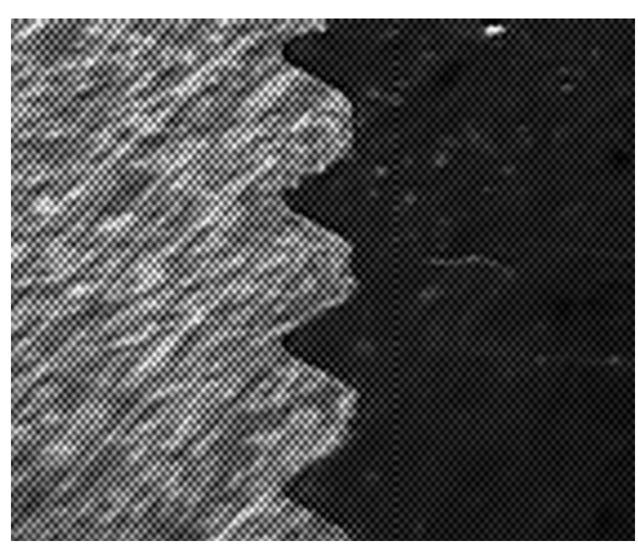

Fig. 10. The image of the 25 times magnification of the internal teeth cut by a M3.5 × 0.6 tap.

breakage of tap may be avoided. In addition, the selection of vibration frequency to assist tapping should take the characteristics of the vibration into consideration. In doing so, the frictional torque and in turn the tapping torque can thus be reduced. As for the concern as to whether the vibration-assisted tapping would affect the thread profiles, this question was addressed and answered in Fig. 10, where the image of the 25 times magnification of the internal threads fabricated by the vibration-assisted tapping is shown. No discernable effect of the vibration was seen. The profile of the threads was noted to be virtually the same as the one obtained under no vibration-assisted tapping, showing the integrity of the entire threads' profile. It is therefore concluded that vibration-assisted tapping would not adversely affect the fabrication of internal threads.

5. Conclusion

The mechanism of fabricating internal threads by means of vibration-assisted tapping was studied. The following points are summarized:

(1) For smaller size tapping of pure titanium metal, imposing an ultrasonic vibration can beneficially affect the tapping process in terms of reducing the tapping torque, and thereby decreasing the likelihood of tap breakage.
(2) Within the adjustable range of the ultrasonic vibration generator, it was verified that vibration-assisted tapping performed at the resonance frequency would have the lowest tapping torque generated.
(3) Introduction of cutting fluid during tapping had a beneficial effect in terms of reducing the tapping torque, though the degree of reduction was less than that realized by vibration.
(4) The smaller the tap size was, the greater the degree of the tapping torque reduction could be.
(5) No adverse effect on the profile of the internal threads was noted when vibration-assisted tapping was employed.

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