IOP Conf. Series: Materials Science and Engineering **735** (2020) 012044 doi:10.1088/1757-899X/735/1/012044

Effect of Repeated Cutting on Low-frequency Torsional Vibration Tapping Torque

Wenzhao Li[1], Zhizun Li[1,*] and Fengqi Han[2]

1 Shijiazhuang Campus, Army Engineering University of PLA, Shijiazhuang 050003, China
2 College of Mechanical Engineering, Shijiazhuang Tiedao University, Shijiazhuang 050003, China
E-mail address: jxxylzz@163.com

Abstract. Low-frequency torsional vibration tapping can significantly reduce the tapping torque, which is an effective method to solve the problem of precision machining of small and deep threaded holes on difficult-to-cut materials. In this paper, the mechanism of repeated cutting of low-frequency torsional vibration tapping is studied by comparing continuous tapping with low-frequency torsional vibration tapping on titanium alloy, and the influence law and mechanism of the process parameters such as repeated cutting times and net cutting angle on the tapping torque are studied through the vibration tapping experiments on different materials. The research results show that under the premise of ensuring the processing efficiency, smaller net cutting angle and larger repeated cutting times should be selected to obtain a good process effect.

1. Introduction

Vibration tapping is the application of vibration cutting technology in tapping processing. After years of research and application, it is proved that low-frequency torsional vibration tapping can significantly reduce tapping torque, improve tap life and thread quality, and is especially suitable for the precision machining of small and deep threaded holes in difficult-to-cut materials [1-3].

The difficulty of the application of low-frequency torsional vibration tapping is how to choose the right process parameters for different materials. The main parameters of low-frequency torsional vibration tapping are net cutting angle L_T, backoff angle L_G, and spindle speed V [2, 4]. Net cutting angle and backoff angle determine repeated cutting times and the influence on tapping torque is significant.

In this paper, the effects of repeated cutting on tapping torque and its internal mechanism were studied by vibration tapping experiments of different materials, which provide basis and reference for engineering application of low-frequency torsional vibration tapping.

2. Experiments

2.1. Experiment System

The experiment system is shown in Fig. 1. The torsional vibration of the spindle is realized by the servo motor driven by the control system, and the vibration parameters can be adjusted arbitrarily. The spindle can float freely in the axial direction, and the axial feed is realized by the self-guiding of the tap during the tapping process. Tapping torque is collected by dynamometer.

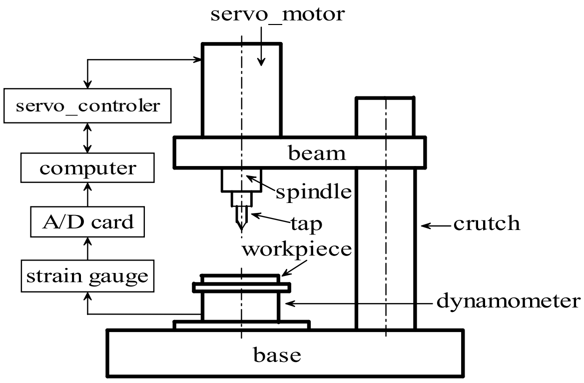

Figure 1. Experiment System

2.2. Experimental Conditions
In order to verify the influence of parameter changes on the tapping torque, difficult-to-cut materials with different processing characteristics were selected as the workpiece. Specific experimental conditions are shown in Table 1.

Table 1. Experimental Conditions

Tap	High speed steel standard machine tap
Workpiece material	High strength steel 30CrMnSi, titanium alloy TC4, superalloy GH4169
Bottom hole	Through hole, depth 15mm
Cutting fluid	Castor oil

2.3. Tapping experiments
In order to study the effect of repeated cutting action of low-frequency torsional vibration tapping, and the influence of parameters on tapping torque, the following experiments were carried out:

(1) Continuous tapping and vibration tapping experiments of M3 threaded holes were performed on titanium alloy TC4 to compare their tapping torque characteristics.

(2) Under the condition that the net cutting angle L_T was constant, backoff angke L_G was changed to perform vibration tapping experiments to study the influence of the change of repeated cutting times on tapping torque.

(3) In order to further study the influence of the contact condition of the rear face on tapping torque, the experiments were carried out by changing the net cutting angle L_T and backoff angle L_G while keeping the repeated cutting times unchanged.

3. Results and Discussion

3.1. Comparison between Low-frequency Torsional Vibration Tapping and Continuous Tapping
When continuous tapping of M3 threaded hole at a speed of 5 rpm were performed on TC4, tapping torque increased with the increase of the tapping depth, and the twist deformation of the tap became more and more obvious. In order to prevent the tap from breaking, the tapping was stopped timely and the tap was retracted, the tapping torque is shown in Fig. 2. It can be seen from the figure that the tapping torque increases rapidly as the tapping depth increases, especially when the tap starts to retreat, the torque has a large negative value, which is the friction torque on the rear face. The torque waveform indicates that the friction torque on the rear face of the tap accounts for a large proportion of the total tapping torque in the continuous tapping process. Therefore, eliminating the friction torque of the rear face is an effective means to reduce the tapping torque.

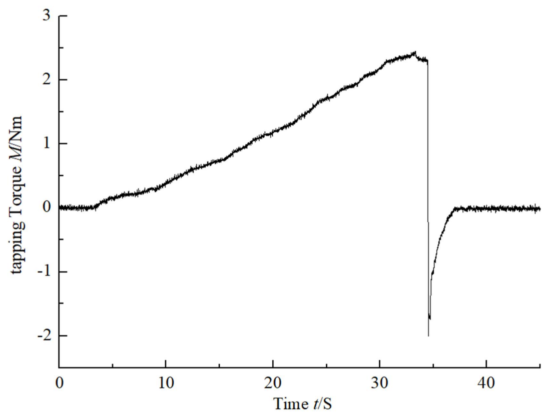

Figure 2. Continuous Tapping Torque Waveform of M3 Threaded Hole of TC4

Low-frequency torsional vibration tapping experiments were carried out on TC4 with different parameters. The experimental results show that during the vibration tapping process, when the cutting part of the tap is completely tapped into the hole, the tapping torque remains basically unchanged, as shown in Fig. 3. The locally amplified vibration tapping torque waveform is shown in Fig. 4. The backoff friction torque directly reflects the friction condition on the rear face of the tap in the tapping process. By comparing Fig. 2 with Fig. 3 and Fig. 4, it can be seen that the peak tapping torque and backoff friction torque of vibration tapping are much smaller than that of continuous tapping.

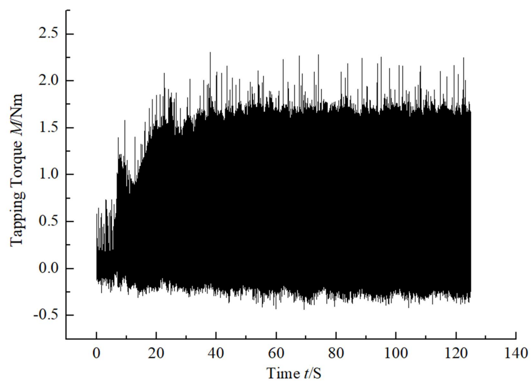

Figure 3. Vibration Tapping Overall Torque Waveform

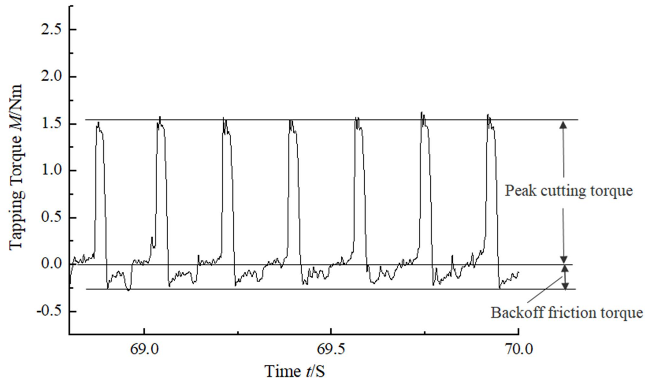

Figure 4. Vibration Tapping Local Torque Waveform

Since the cutting edge is not absolutely sharp, there is always a certain blunt radius, friction is generated in the tool-workpiece contact area, and the springback of the machined surface will also increase the contact area. When the cutting edge and the rear face are worn, the springback amount and contact area will increase, and the rear face may bear the same friction as the rake face [5,6]. Especially when the general tapping method is used to tap on materials with small elastic modulus such as titanium alloy, the amount of springback of the machined surface is large, so the contact area and pressing force between the rear face of the cutter tooth and the workpiece are relatively large, as shown in Fig. 5, the penetration of the cutting fluid into the contact interface between the rear face and the machined surface is very difficult, it is difficult to form an effective boundary lubrication film, so the actual contact area and the cold welding area are large, resulting in a large friction.

Compared with continuous tapping, in the case that the net cutting length is less than the contact length of the rear face and the machined surface, the extrusion of the machined surface to the rear face of the cutter tooth varies in the whole contact range during the cutting stage of the vibration tapping, the amount of springback of the machined surface gradually decreases from the cutting edge to the rear, as shown in Fig. 5, so the extrusion in most areas is relatively light, which is conducive to the penetration of cutting fluid. More importantly, as shown in Fig. 6, after the positive cutting is completed, the machined surface behind the teeth is covered by cutting fluid. In the process of tap retraction, due to the extrusion of the machined surface on the rear face is gradually relieved, the cutting fluid forms a good lubricating film between the rear face and the machined surface under the action of smear and penetration. In addition, the process of tap retraction also provides time for penetration and adsorption of cutting fluid to the newly formed machined surface.

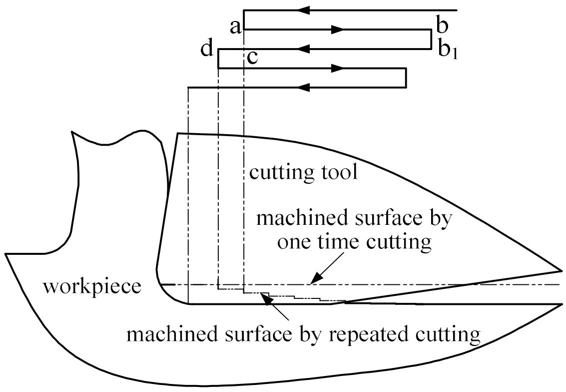

Figure 5. Repeated Cutting Model

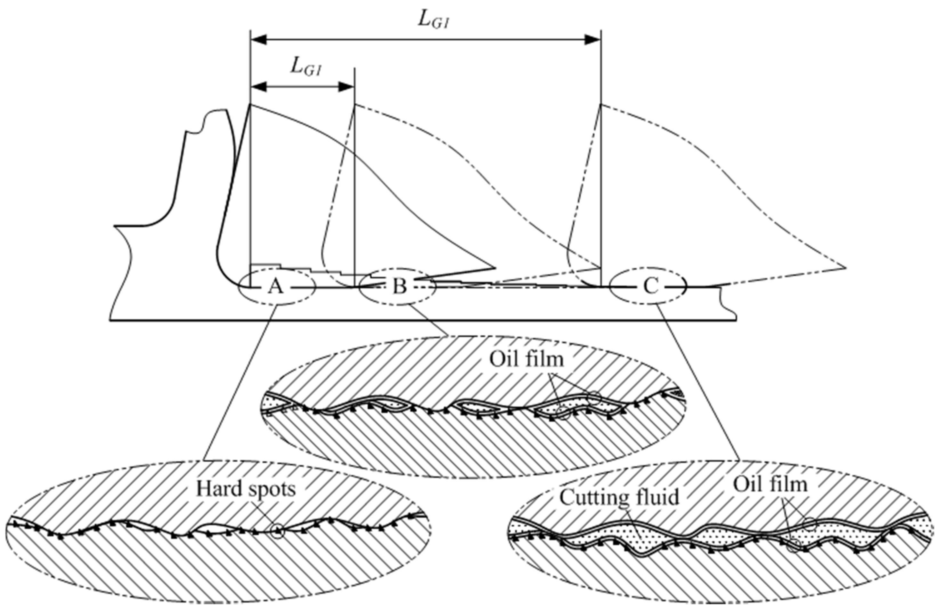

Figure 6. Lubrication of the Rear Face during the Retraction of the Tap

In addition, the formation of thread is a gradual process in the process of tapping, and the shape of any part of thread is formed under the sequential cutting of multiple cutter teeth. If repeated cutting times is enough, the top rear face and side rear face of each cutter tooth can reduce the springback of the machined surface in the current cutting layer to the minimum through sufficient repeated cutting, then the side of the thread is lightly pressed and rubbed against the side rear face of the subsequent teeth, as shown in Fig. 7(a). However, if the repeated cutting times is less, the side rear face of the cuter tooth cannot fully remove the springback of the side of the thread tooth in the current cutting layer, then the newly formed side of the thread will conduct extrusion and friction on the side rear face of the subsequent cutter tooth, and the springback can be gradually removed only after repeated cutting of several subsequent cutter teeth, as shown in Fig. 7(b).

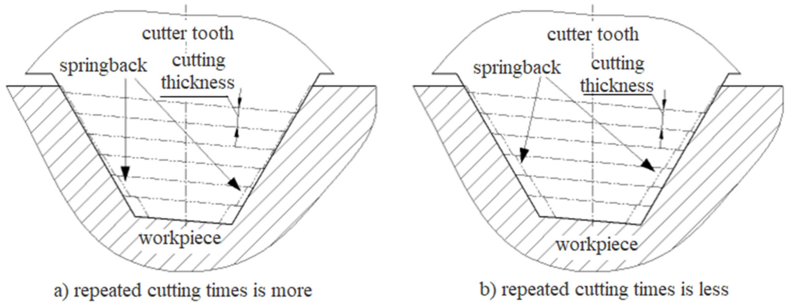

Figure 7. Effect of Repeated Cutting Times on Friction Condition of Side Rear Face of Tap

In a word, under the repeated cutting action of vibration tapping, the contact condition of the rear face has been greatly improved, no matter on the top or both sides of the cutter teeth. On this basis, the periodic tangential separation process between the rear face and the cutting zone greatly improves the boundary lubrication condition of the rear face, which significantly reduces the friction of the rear face during the cutting process, and thus greatly reduces the tapping torque.

3.2. Effect of repeated cutting times on tapping torque

When the spindle speed is 500rpm and the net cutting angle is 1.5°, the law of the backoff friction torque and the peak cutting torque of the M4 threaded holes of the three materials changing with the backoff angle is shown in Fig. 8 and Fig. 9. It can be seen from the figures that the backoff friction torque and the peak cutting torque of the three materials decrease with the increase of the backoff angle. This is because the increase of the bakoff angle increases the repeated cutting times of the machined surface by the cutting edge, thereby reducing the springback of the machined surface and reducing the friction of the rear face. Moreover, since the spindle system, especially the tap, has torsional deformation during the tapping process, the actual reverse angle of the tap cutter teeth is less than the set value. When the backoff angle is small, the separation gap between cutter teeth and workpiece is small, which is not conducive to the smooth entry of castor oil with larger viscosity. The increase of backoff angle can effectively improve this situation. In addition, when the net cutting angle and spindle speed remain unchanged, the increase of backoff angle makes the vibration frequency decrease, and also can fully release the torsional deformation generated by the tap and spindle system during positive and negative rotation, which provides relatively sufficient time and space for castor oil to fully enter the cutting area, which is conducive to reducing tapping torque.

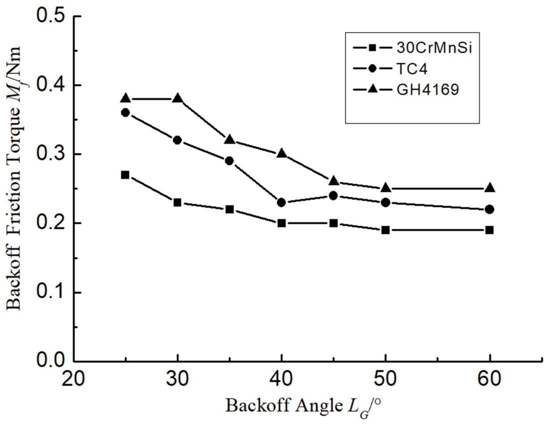

Figure 8. Effect of L_G on Backoff Friction Torque

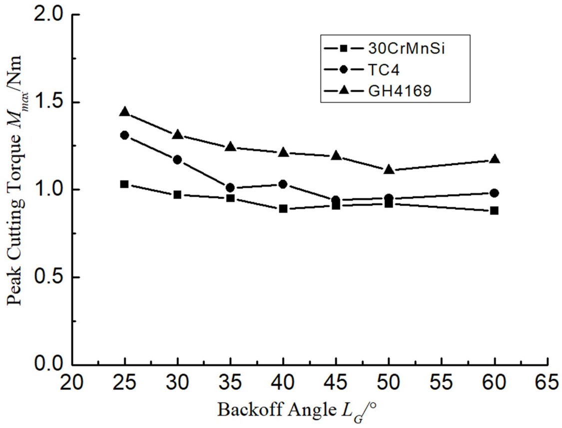

Figure 9. Effect of L_G on Peak Cutting Torque

As can be seen from the above two figures, the vibration tapping torque of the three materials decreases with the increase of backoff angle, and with the increase of backoff angle, its influence on tapping torque gradually weakens. When the backoff angle is greater than 45°, both peak cutting torque and backoff friction torque change slightly with the increase of backoff angle. Especially 30CrMnSi, when the backoff angle is greater than 35°, its influence is not obvious.

In addition, it can be seen from the figures that the increase of backoff angle has the greatest impact on the tapping torque of TC4 and the least impact on that of 30CrMnSi. This is because the elastic modulus of TC4 is the smallest, about 1/2 of 30CrMnSi and GH4169, so the effect of repeated cutting is the most obvious. Compared with GH4169, the work hardening of 30CrMnSi is relatively light, and its springback of machined surface can be easily removed during repeated cutting, which can be judged by the fact that castor oil becomes very black during the vibration tapping process, therefore, repeated cutting times has a relatively small influence on the tapping torque.

Therefore, the smaller the elastic modulus of the material, the more repeated cutting times need to be used in the vibration tapping, in order to remove the springback of the machined surface as far as possible, so as to effectively reduce the tapping torque.

3.3. Effect of net cutting angle on tapping torque when repeated cutting times is constant

In the low-frequency torsional vibration tapping, the repeated cutting times is determined by the net cutting angle and the backoff angle, and the net cutting angle determines the cutting stroke of the tap in each torsional vibration period, which has an important influence on the tapping torque. In order to study the influence of net cutting angle, a series of experiments were carried out with the repeated cutting times Q=20 and the spindle speed V=500rpm unchanged. The results are shown in Fig. 10 and Fig. 11. As can be seen from the figures, the backoff friction torque and the peak cutting torque of all three materials increase with the increase of net cutting angle.

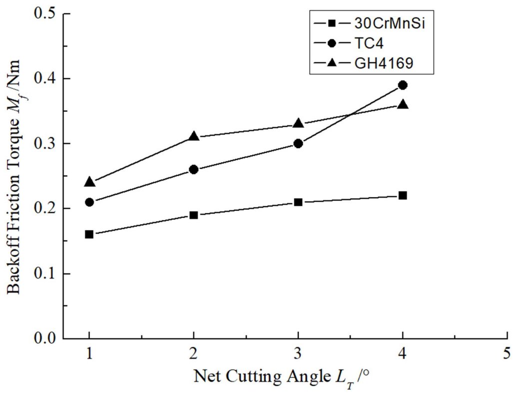

Figure 10. Effect of L_T on Backoff Friction Torque

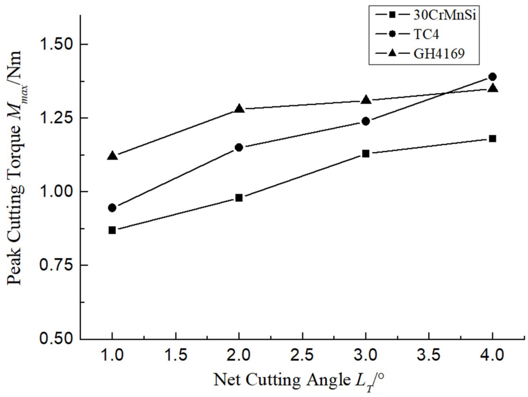

Figure 11. Effect of L_T on Peak Cutting Torque

The extrusion of the machined surface on the rear face of the tap depends on the amount of springback. In the application of vibration tapping, the reverse distance of the tap cutter tooth on the circumference is generally more than 1mm, which is much larger than the width of the wear belt on the rear face of the tap. Therefore, the reverse amount L_G is generally much larger than the contact length between the rear face of the tap cutter tooth and the workpiece in the current cutting layer. In this case, during the cutting stage of each vibration cycle of the tap, the friction condition of the rear face in the current cutting layer of each cutter tooth mainly depends on the net cutting angle L_T, as shown in Fig. 12. The larger the net cutting angle, the greater the length and compressive force of the contact area of the top rear face with the machined surface, and the greater the friction. The friction of the side rear faces in the current cutting layer is equally affected. As mentioned earlier, the magnitude of the effect is related to the properties of the material's elastic modulus and work hardening.

Therefore, in order to reduce tapping torque as far as possible, on the basis of ensuring the necessary repeated cutting times, a smaller net cutting angle should be used.

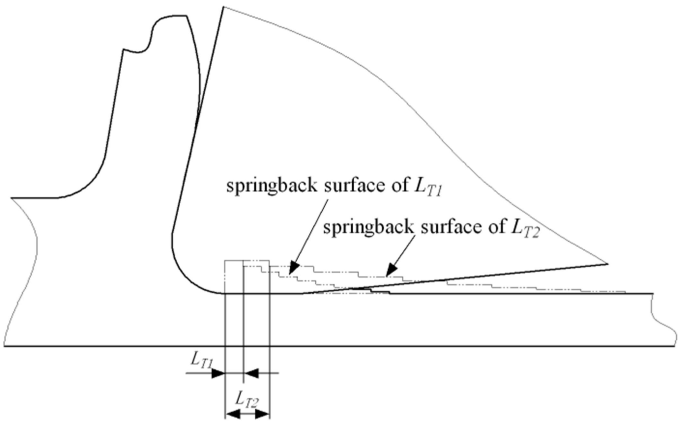

Figure 12. Effect of L_T on the Springback of Machined Surface ($L_{T1}<L_{T2}$)

4. Conclusions

According to the experimental results of low-frequency torsional vibration tapping and the analysis of the friction and lubrication of the rear face, the following conclusions can be drawn:

(1) Low-frequency torsional vibration tapping reduces the extrusion and friction between the machined surface and the rear face of the cutter tooth through repeated cutting, and on this basis, the reciprocating motion of the tap increases the lubrication effect of cutting fluid, effectively reduces the friction torque of the rear face, thus significantly reducing the tapping torque.

(2) Large repeat cutting times should be taken as much as possible to achieve better repeat cutting results.

(3) On the basis of ensuring the machining efficiency, a smaller net cutting angle should be adopted to reduce the extrusion and friction of the machined surface on the rear face of the tap, so as to further improve the technological effect of low-frequency torsional vibration tapping.

5. References

[1] Z.C. Chen: *Studies on the Torsional Vibration Mechanism and Vibration Tapping Technology* (Ph.D. Dissertation, Beijing University of Aeronautics and Astronautics, 2001).

[2] G.J. Li: *Study on the Vibration Tapping and It's Monitoring Technique* (Ph.D. Dissertation, Beijing University of Aeronautics and Astronautics, 2004).

[3] R.D. Han, J. Liu, B. Han 2002 Experiment study of vibration tapping torque of SiCw/Al aluminum composites. *Journal of Harbin Institute of Technology.* **34** 252.

[4] F.Q. Han, Z.Z. Li, D.Y. Zhang 2013 Study on process parameters of low frequency torsional vibration tapping of difficult to cut materials. *Advanced Materials Research*. **712-715** 719.

[5] D.Y. Zhang, D.C. Chen 1998 Relief-face friction in vibration tapping. *Int. J. Mech. Sci.* **40** 1209.

[6] M.S. Shi 1994 *Friction and fluid in cutting*, (China: China railway press) pp 33-97.