Physical and Chemical Roles of Metalworking Fluids in a Vibration-Assisted Tapping System*

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Abstract
A vibration-assisted tapping system has been developed in which a piezoelectric-zirconate-titanate (PZT) oscillator applies small-amplitude vibrations to a workpiece and a torque transducer measures the time-evolving torque during the tapping process. To investigate the roles of metalworking fluids, four different metalworking conditions have been examined: without metalworking fluids (dry), with an additive-free fluid (base oil), with an oiliness-agent-containing fluid (fluid A), and with an extreme-pressure-agent-containing fluid (fluid B). The time evolutions of the tapping torque have been obtained for tapping M3 threads in S45C steel with varying vibration amplitudes, vibration frequencies, and tapping speeds. It has been found that the present system decreases the tapping torque; in particular, a decrement of up to 14 % in the tapping torque is obtained for fluid A using 800-Hz vibrations with an amplitude of 5 µm at a tapping speed of 3 rpm. Increments in the vibration amplitude and frequency lead to decrements in the tapping torque, but the effect of the vibration tends to fade with increasing tapping speeds. It appears that vibrations enhance not only the physical effects but also the chemical effects of metalworking fluids.

Key words: Metalworking Fluid, Cutting Fluid, Additive, Oiliness Agent, Extreme-Pressure Agent, Vibration-Assisted Tapping, Tapping Torque, Tapping Speed, Vibration Frequency, Vibration Amplitude, Cutting, Tribology

1. Introduction
Tapping of metals is one of the most difficult cutting operations\(^1\). Small-hole tapping, e.g. below M6, is an especially difficult task and often causes the breakage of taps or the blockage of chips in the hole. Hence, to address these problems, various tapping systems and metalworking fluids have been developed and subsequently improved.

Among these novel systems, vibration-assisted tapping is expected to be one of the potential solutions. In previous studies, two kinds of vibration-assisted tapping have been proposed: One uses torsional vibration of the workpiece\(^2\)\(^-\)\(^4\), and the other, axial vibration of the workpiece\(^5\). The technology of vibration-assisted tapping was introduced in 1978 by Kumabe and Tachibana\(^2\). They applied torsional vibration to M1–M5 tapping of carbon steel, brass, and aluminum under wet conditions and observed reductions in the tapping torque of 1/4–2/3 the conventional value, fewer tap failures, and improvements in the tapping accuracy. Zhang and Chen\(^3\) applied torsional vibration to M6 tapping of titanium alloys under wet conditions and observed reductions in the relief-face friction as well as...
prolonged tool lifetimes. Yin and Han\(^4\) applied torsional vibration to M3 tapping of hardened steel under wet conditions and observed reductions in the tapping torque and the extension of microcracks in chips. Zhang and Yang\(^5\) applied axial vibrations during tapping of 1/4-inch holes in brass under dry conditions and observed reductions of up to 35\% in the tapping torque.

In the present study, axial vibration was applied to M3 tapping of hardened steel under both dry and wet conditions. In order to investigate the roles of metalworking fluids, three kinds of wet conditions were examined, viz. with an additive-free fluid, with an oiliness-agent-containing fluid, and with an extreme-pressure-agent-containing fluid. As a result, reductions in the tapping torque of up to 14\% were observed, and the mechanism of the tapping-torque reduction was discussed.

2. Experimental details

2.1 Apparatus

Figure 1 shows a schematic diagram of the present vibration-assisted tapping system, which measures the time-evolving tapping torque while applying axial vibrations under either dry or wet conditions. The system comprises two units: one vibrates the workpiece and measures the tapping torque (left-hand side in Fig. 1), and the other rotates and translates the tap (right-hand side in Fig. 1).

A cylindrical workpiece with a through-hole is fixed to a workpiece holder, which is, in turn, fixed to the tip of a piezoelectric-zirconate-titanate (PZT) oscillator. The PZT oscillator is mounted on a torque transducer, which is placed coaxially to the workpiece and measures the torque during tapping.

A tap is connected to the spindle of a motor using a tap holder and a flexible coupling. The flexible coupling is of the diaphragm type and is made of polyester, which minimizes not only the misalignment between the tap axis and the spindle axis but also the backlash and vibration from the motor. The motor is placed on the slider of a linear bearing so that the tap can move forward smoothly in the through-hole of the workpiece with the thrust force generated by tapping.

A speed controller determines the rotational speed of the motor spindle, which also corresponds to the tapping speed. A signal from a function generator is amplified and sent to the PZT oscillator, causing the workpiece to vibrate in the axial direction with a specific frequency and amplitude. The signal from the torque transducer, after passing through an amplifier, is stored on a digital data recorder, by which the time-evolving tapping torque is obtained.

![Fig. 1  Experimental apparatus: a vibration-assisted tapping system.](image)
The torque transducer utilizes torsional strain to measure the tapping torque; thus, it has compliance in torsional motion. Furthermore, the unit for vibrating the workpiece and measuring the tapping torque has a natural frequency in torsion of 105 Hz.

2.2 Workpiece and tap

The workpiece is cylindrical, with a diameter of 14 mm and a length of 40 mm; it is made of S45C steel with a hardness of 50 HRC. In addition, it has a central through-hole with a diameter of 2.46 mm for M3 tapping.

The tap is a commercial spiral pointed tap for M3 tapping with a pitch of 0.5 mm; it is made of high-speed steel containing a high proportion of vanadium.

2.3 Metalworking fluids

Three kinds of metalworking fluids are used in the present experiment. One is an additive-free metalworking fluid – paraffinic mineral oil with a viscosity of 9.5 cSt at 40 °C – called the base oil in the present paper. The second, called fluid A, is a metalworking fluid consisting of the base oil with 5 wt% of added fat as an oiliness agent. The third, called fluid B, is a metalworking fluid consisting of the base oil again, but with 5 wt% of added sulfurized fat as an extreme-pressure agent.

2.4 Procedure

At first, the through-hole of the workpiece and the teeth of the tap were brushed thoroughly in acetone to minimize contamination. After the workpiece and tap were washed in hexane with an ultrasonic cleaner for 10 min, they were dried in a thermostat chamber at 40 °C for 10 min and subsequently cooled down to ambient temperature (25 °C). Then, they were installed into the apparatus.

After injecting 0.3 ml of one of the metalworking fluids on to the workpiece and tap, the tapping speed was set using a speed controller and the tap was then pushed into the through-hole of the workpiece manually until tapping began. The workpiece was vibrated with the PZT oscillator, which was controlled by the function generator. The torque transducer continually measured the tapping torque during tapping, and this signal was stored on the digital data recorder at a sampling rate of 200 Hz.

In the present study, vibration-assisted tapping was performed at ambient temperature (25 °C). Tapping speeds of up to 48 rpm, vibration frequencies of up to 800 Hz, and vibration amplitudes of up to 5 µm were employed.

3. Results and discussion

3.1 Time evolutions of tapping torque

Figure 2 shows the time-evolving tapping torque at a tapping speed of 3 rpm under dry conditions and the three different wet conditions. Vibration at 800 Hz was applied for durations of 25 s every 50 s, as shown in Fig. 2, where the vibration amplitude was sequentially increased for every period up to 5 µm. Note that the scale of the tapping torque plot for the dry conditions is different from that of the others.

Under all the conditions, the tapping torque starts to increase at 0 s, which corresponds to the moment of contact between the workpiece and tap, and continues to increase until about 75 s, which corresponds to the time when all the teeth of the tap to fully enter the through-hole. Subsequently, the tapping torque tends to increase only under the dry conditions; the tapping torque under the wet conditions becomes stable around each corresponding value. On the whole, the tapping torque under the dry conditions is about two and a half times that under the wet conditions.

A fluctuation in the tapping torque with a period of 20 s appears under all the
conditions, which is based on the tapping speed of 3 rpm. Besides the short-period fluctuation, another fluctuation with a long period is also found to appear, especially with the base oil. As for the effect of vibration on the tapping torque, decrements in the tapping torque are found to occur in the periods in which larger-amplitude vibrations are applied, e.g. in the period of 375–400 s for fluid A; however, the fluctuations in the tapping torque seem to make the effect unclear.

3.2 Changes in mean tapping torque

In order to evaluate the effect of vibration more clearly, the mean tapping torque is introduced, defined as the mean value of the tapping torque in a 25-s period with a constant vibration amplitude. Figure 3 shows the change in the mean tapping torque based on the results shown in Fig. 2, where an open circle denotes the mean tapping torque without vibration, and a solid circle denotes that with vibration.

By using the mean tapping torque, the tapping-torque signal is, in effect, low-pass filtered and the short-period fluctuations disappear, thus allowing the effect of the vibration to be visualized. That is, it is found that vibrations with larger amplitudes, e.g. more than 2 \( \mu \text{m} \), decrease the mean tapping torque independently of the conditions, whether dry or wet. However, similar investigations reveal considerable differences among the results obtained under the different conditions.

Under the dry conditions, the mean tapping torque increases for 300 s, exceeding 0.6 N·m. Vibrations decrease the mean tapping torque, and the effect appears to be reversible, that is, the mean tapping torque after turning the vibration off is equivalent to that before applying the vibration.

When the base oil is used as the metalworking fluid, the mean tapping torque is around 0.25 N·m and a long-period fluctuation is observed. The difference in the mean tapping
Fig. 3 Change in mean tapping torque by vibration under dry conditions, and in the presence of the base oil, fluid A, and fluid B; open circle: without vibration, solid circle: with vibration; tapping speed: 3 rpm, vibration frequency: 800 Hz, vibration amplitude: see Fig. 2.

Fig. 4 Relative tapping torque representing the effect of vibration; open circle: without vibration, solid circle: with vibration.

torque under the dry conditions and with the base oil shows that the physical effects of the base oil drastically decrease the mean tapping torque, for the base oil does not contain any additives. It is conceivable that the base oil plays a role in facilitating the disposal of chips and, thereby, decreasing the cutting drag, and also in penetrating the chip-tool interface, the wear land, or the microcracks on the back of the chips to provide lubrication. Moreover, the effect of vibration on the mean tapping torque is reversible, and the decrement in the torque is more obvious with the base oil than under the dry conditions, indicating that vibration enhances the physical effects of the base oil.

When fluid A is used as the metalworking fluid, the mean tapping torque is around 0.24 N·m; this is equivalent to that obtained with the base oil. However, the long-period fluctuation that appears with the base oil is absent, which must be the effect of the additive included in fluid A, i.e. the chemical effect of the oiliness agent. Generally speaking, oiliness agents, as typified by fatty acids, esters, or fats, act at lower temperatures and create chemical-adsorbed films on metal surfaces under friction. The effect of vibration on the mean tapping torque is reversible, and the decrement in the torque is as obvious as that with the base oil, which indicates that vibration enhances the physical effects of fluid A rather
than its chemical effects.

With fluid B, the mean tapping torque is around 0.25 N·m, which is also equivalent to that with the base oil. However, a distinguishing feature is the discontinuity found at 275 s: The mean tapping torque seems to vary in a continuous fashion until 275 s, although it includes a long-period fluctuation; however, once 800-Hz vibrations with amplitudes of 3 µm are applied at 275 s, the mean tapping torque is decreased drastically and subsequently appears to vary in another continuous fashion with another long-period fluctuation. Moreover, irreversibility is found in the effect of the applied vibrations after 275 s; that is, the mean tapping torque with fluid B is affected by its history.

### 3.3 Quantitative evaluation of the effect of vibration with relative tapping torque

For a quantitative evaluation of the effect of vibration, the relative tapping torque is introduced, as shown in Fig. 4. The relative tapping torque $N_{\text{rel}}$ is defined as the ratio of $N_{\text{on}}$ to $N_{\text{off}}$, where $N_{\text{on}}$ denotes the mean tapping torque in a period with vibration; $N_{\text{off}}$, the mean of $N_{\text{off-1}}$ and $N_{\text{off-2}}$; and $N_{\text{off-1}}$ and $N_{\text{off-2}}$, the mean tapping torques in the periods without vibration just before and after the period of $N_{\text{on}}$, respectively. Therefore, the relative tapping torque reflects the effect of vibration on the mean tapping torque even in a long-period fluctuation, except when irreversibility appears on the application of vibration.

### 3.4 Effect of vibration amplitude on relative tapping torque

The relative tapping torque is plotted against the vibration amplitude based on the results shown in Fig. 3; the results are shown in Fig. 5.

It is found that the relative tapping torque decreases with increasing vibration amplitudes under all the conditions. The effect of vibration appears dominantly for the base oil and fluid A; with 5-µm vibrations, the relative tapping torque for fluid A is 0.86, indicating that the vibrations reduce the tapping torque by up to 14 %.

The minimum value of the relative tapping torque for the base oil is found to be 0.88;
3.5 Effect of vibration frequency on relative tapping torque

As shown above, wet conditions with fluid A produce stable experimental results, which are convenient for evaluating the effect of vibration. Therefore, the effect of the vibration frequency was examined for fluid A. Figure 6 (left) shows the results, where the tapping speed is 3 rpm and the vibration amplitude is 5 µm.

The relative tapping torque decreases with increasing vibration frequencies, with the minimum value appearing at 800 Hz, which is the limitation of the present system and depends on the natural frequency of the PZT oscillator. Moreover, the relative tapping torque below 100 Hz seems to be slightly greater than unity, where the frequency corresponds to the torsional natural frequency, which is determined by the stiffness of the torque transducer and the inertial moment of its payload. Therefore, the frequency dependence of the tapping torque appears to be system-related to some degree.

3.6 Effect of tapping speed on relative tapping torque

Finally, the effect of the tapping speed on the relative tapping torque was examined for fluid A, as shown in Fig. 6 (right), where the vibration frequency was 800 Hz and the vibration amplitude was 5 µm. The relative tapping torque approaches unity asymptotically, implying that the effect of vibration is weakened by increments in the tapping speed.

3.7 Effect of vibration on tapping accuracy

The tapping accuracy was measured with a screw plug gauge; all of the internal threads were confirmed to be within its reference interval. This indicates not only that vibration decreases the tapping torque but also that it does this without compromising accuracy.

3.8 Physical and chemical roles of metalworking fluids

Through the present experiment, the maximum reduction in the tapping torque was obtained with 800-Hz vibrations with an amplitude of 5 µm at a tapping speed of 3 rpm. In this case, the maximum velocity of the vibration is 25 mm/s, which is about 50 times the peripheral velocity of an M3 tap, and about 1000 times its feed velocity. Therefore, the effect of the velocity produced by the vibration should be the source of the tapping-torque reduction with the present system. Moreover, the vibration velocity increases with both the frequency and amplitude, which is consistent with the results shown in Figs. 5 and 6 (left);
Fig. 7  Effect of metalworking fluids without vibration; tapping torque in the range 3–48 rpm: measured with the present system, tapping torque in the range 420–1340 rpm: measured with a commercial tapping machine.

Furthermore, the peripheral velocity is comparable to the vibration velocity at a tapping speed of 48 rpm, where the vibration effect disappears, as shown in Fig. 6 (right).

Figure 7 shows the tapping torque without vibration under various conditions, where the tapping torque in the range 3–48 rpm is measured with the present system and that in the range 420–1340 rpm is measured with a commercial tapping machine. Note that the difference in the tapping torque under the dry conditions and in the presence of the base oil represents the physical effect of the metalworking fluids, and the difference in that between the base oil and fluid A (or B) represents the chemical effects of the additives. The tapping speed exhibits a kind of severity, which enhances heat generation.

At every tapping speed, the tapping torque with the base oil is lower than that without any fluids, particularly at 3 rpm. Moreover, the tapping torque without any fluids decreases with increasing tapping speeds; this decrement should be caused by a kind of physical effect. Considering that the tapping torque is increased with the tapping speed in the range 3–48 rpm, there should be multiple physical effects on the tapping torque that compete with each other. For example, the softening of the workpiece material by heat generation reduces the cutting drag, but excessive cooling by the fluid hinders the softening. Moreover, the viscosity of the fluid facilitates the disposal of chips, but, at the same time, it also adds to the cutting drag, while the resulting heat generation reduces the viscosity.

At every tapping speed, the tapping torque for fluid A is lower than that for the base oil, that is, fluid A has not only the physical effects possessed by the base oil but also the chemical effects of the oiliness agent. As mentioned earlier, the oiliness agent acts even at lower temperatures, forming chemical-adsorbed films on the metal surfaces under friction. The chemical effect should lead to lower tapping torques and small-amplitude long-period fluctuations, as shown in Fig. 3.

On the other hand, the extreme-pressure agent does not act at lower temperatures, but starts to act above a particularly high temperature at which it forms chemical-reaction films on the metal surfaces under friction. This property appears as the difference in the tapping torque between that obtained with the base oil and that obtained with fluid B, as shown in Fig. 7. Moreover, the work of vibration is converted to heat, and this work is proportional to the square of the vibration amplitude. The discontinuity observed in Fig. 3 indicates the initiation of the chemical effect induced by the heat generation, implying that vibration enhances the chemical effect of the extreme-pressure agent even at low tapping speeds.

4. Conclusions

(1) Axial vibration of a workpiece decreases the torque in M3 tapping of S45C steel. The effect appears independently of the conditions. For example, a decrement in the tapping torque of up to 14 % is obtained under wet conditions including an oiliness agent with 800-
Hz vibrations with 5-µm amplitudes at tapping speeds of 3 rpm.

(2) Increments in the vibration amplitude and frequency cause decrements in the tapping torque, but the effect of vibration tends to fade with increasing tapping speeds. In addition, the effect of the frequency tends to depend on the dynamic properties of the system.

(3) Vibration appears to enhance not only the physical effects but also the chemical effects of metalworking fluids. The former appears as the decrement in the tapping torque under wet conditions with an additive-free fluid, and the latter appears as the decrement under wet conditions including an extreme-pressure agent at low tapping speeds.

References


