Optimization of tool geometric parameters for a small fluteless forming tap (FFT)

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Abstract
The small blind internal thread (SBIT) plays a very important role to firmly fastening some functional components on the cover of 3C electronic products. The small internal thread was made in a blind hole using a fluteless forming tap (FFT) without producing chips. However, the four geometric parameters of the FFT (tool width (W), tooth root diameter (D2), front-end diameter (Df), and tooth angle (θ)) will affect the thread filling rate (f) and minimum torque (T) in tapping process. This study reports the Box-Behnken design (BBD), combined with DEFORM-3D (finite element model) and MINITAB (regression analysis) software, to tap 7075-T6 aluminum alloy with small FFT to obtain reliable results of thread filling rate and minimum torque. The experimental results show that the BBD can accurately predict and simulate the thread filling rate of tapping 7075-T6 aluminum alloy. The modeling software and experimental design used in this research are very suitable for the optimal design of the FFT used in industrial production.

Keywords Fluteless forming tap · Tapping · 7075-T6 aluminum alloy · Thread filling rate · Torque

1 Introduction
As 3C electronic products (mobile phone, iPad, laptop, and smart watch, etc.) become thinner and lighter, the manufacturing process of SBITs requires higher geometric and size accuracy to achieve better fastening capabilities. However, traditional taps produce chips during the tapping process, which are not conducive to removal from the small hole-diameter of the workpiece. SBIT tapping is often the last process in machining the cover of 3C electronic products. If the SBIT profile cannot be tapped completely, the fastening failure rate will increase. Therefore, it is a challenging task to manufacture high-quality SBITs required for cover of 3C electronic products. The fluteless forming tap (FFT), which does not produce any chips during the tapping process, can produce a blind internal thread profile through plastic deformation.

Previous studies have determined the influence of hole-diameter, forming speed, cutting fluid, tool hardness, thread filling rate, and tool geometry on tapping torque and force [1–7]. Warrington et al. [8] and Mathurin et al. [9] utilized the finite element model to simulate the influence of the fluteless forming tapping process, various tool design parameters, and tapping conditions on the split crest. The simulation results are verified through experiments. Stéphan et al. [10] used slip line theory to determine the maximum torque of the FFT during the tapping process. Huang et al. [11] established a mathematical model for calculating tapping force and torque of tool and tool geometry parameter design. Carvalho et al. [12] and Filho et al. [13] sectioned an experimental workpieces to determine the surface quality of the internal thread profile using a microscope. Tsao and Kuo [14] used image processing software to study thread filling rate after tapped a SBIT. Pereira et al. [15] showed cutting parameters, tool geometry, or process characteristics effect on torque and temperature during internal tapping. Swissi et al. [16] developed a special experimental setup to identify the intrinsic properties of threads and study the effects of
the tapping process. Ren and Yan [17] used a quasi-static model to predict and simulate the radial pitch diameter difference during tapping for different chamfer lengths and spindle speeds. Brandão et al. [18] provide a detailed review to demonstrate the evolution and the main studies in tapping processes in the last 20 years. However, this researched diameter range for forming and machining taps was between 3 and 10 mm. At present, M1.2×0.25 mm taps are widely used to generate the SBITs for the cover of mobile phones. Therefore, the design/fabrication of FFTs below 3 mm has the ultimate development potential and business opportunities. However, the related literature on FFTs is rarely discussed. Furthermore, the manufacturing characteristic effect of FFT on the thread filling rate and torque has also not yet been thoroughly studied. All these manifest that an in-depth investigation of the SBIT of 7075-T6 aluminum alloy needs to be conducted. The contour of the SBIT is not easy to observe or measure with the naked eye. A computer can be used to quickly establish and measure the area size and tooth profile of the SBIT.

The finite element analysis (FEA) is an effective method that can be used to explain the plastic flow of metal materials. Mathurin et al. [9] also shows that finite element software (DEFORM-3D) can be used to solve the complex plastic forming problems of blind internal threads and give stress, strain, displacement, and velocity. Then obtain the best tool design parameters by design of experiment (DoE). The optimal tool geometry design not only increases the

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Table 1 Tool parameters

| Terms                      | Value     |
|----------------------------|-----------|
| Tool width, W (mm)         | 1.0       |
| Tooth root diameter, D2 (mm)| 0.95     |
| Front-end diameter, Df (mm)| 1.0       |
| Tooth angle, θ (°)         | 60        |
| Outer diameter, D1 (mm)    | 1.245     |
| Inner diameter, D3 (mm)    | 0.84      |
| Tool pitch, P (mm)         | 0.25      |
| Chamfer length (mm)        | 0.25 (1 pitch) |
| Tooth width (mm)           | 0.031     |
| Tooth height (mm)          | 0.1475    |
| Lobe length (mm)           | 0.45      |
| Tool length (mm)           | 3.0       |

![Fig. 1 Geometric characteristics of the FFT (M1.2×0.25 mm)](image1)

![Fig. 2 Production process of the FFT](image2)
thread filling rate but also reduces the minimum torque during tapping. Therefore, this study combines the statistical software (MINITAB) and BBD to establish the regression models of the thread filling rate and the minimum torque. Following, the regression model is used to determine the best tool geometric parameters of the FFT on the thread filling rate and the minimum torque. However, these regression models can be used to design the geometry of the tapping tool, improve thread processing quality, and reduce research and design costs.

2 Methodology

2.1 Tool design

In order to cause plastic deformation of the ductility material and ensure that no chips are generated during the tapping process, the geometric characteristics of the FFT is highly different from that of the traditional tap. From the appearance point of view, the FFT does not require the flute design for chip removal or chip breaking. To reduce the cost and weight, the cover thickness of 3C electronic products is only about 1.5~2.0 mm, and a thickness of about 0.2 mm must be reserved to avoid the appearance of bump defects caused by tapping. In addition, the tapping depth needs to be at least 5~6 teeth to provide 3C electronic product components that can be fastened with the cover screws, which will compress the chamfering length and invalid number of teeth of the front edge of the FFT. The chamfer length of the FFT for this study is about 0.25 mm (1 pitch). Therefore, the quality characteristic of the internal thread produced by the FFT depends on the outer diameter ($D_1$), the tooth root diameter ($D_2$), the tool pitch ($P$), the tool width ($W$), the front-end diameter ($D_f$), and the tooth angle ($\theta$), as shown in Fig. 1. The FFT is made of tungsten carbide in this study. A M1.2×0.25 mm tap must comply with the ISO 68–1 thread profile, and internal threads must comply with the gauge test (CNS533 B6013). In order to meet the aforementioned internal thread inspection specifications, the $D_1$ of the FFT is 1.245 mm, the $D_2$ is 0.95 mm, the inner diameter ($D_3$) is 0.84 mm, and the $D_f$ is 1.0 mm. The inner diameter ($D_3$) is defined as $D_3 = D_2 - 0.11$. Other tool parameters are also shown in Table 1. According to Stéphan et al. [10] report, increasing the number of lobes prevents deviation of the
central axis of the tool during the tapping process, but torque also increases as the contact area increases. Therefore, four lobes are used to maintain stable tool rotation and prevent an excessive torque load. The production process of the FFT used in this paper is shown in Fig. 2, and the production accuracy of the tool can be controlled within ±8 μm.

2.2 Experiments

In this study, the thickness of workpiece (7075-T6 aluminum alloy) is 5.0 mm. All tapping experiments were conducted three times using a Brother S500X1 machining center. The process parameters for the tapping experiment are shown in Table 2. The schematic diagram and photograph of the experimental setup are shown in Fig. 3, which shows that the tapping tool is clamped in the CNC tool holder and controlled using G-code. In Table 2, the rotation speed is 4000 rpm and the tool pitch is 0.25 mm, so the feed rate (F) is 1000 mm/min. When the tool is positioned above the hole, it is fed downward from point (a) and rotates clockwise into the hole. The tool stops when the tapping depth reaches 1.5 mm at point (b). Point (c) marks the retracted stroke when thread processing is complete. The machining center then moves the tool to the next hole, which is marked as point (d). The torques during tapping were measured with a Kistler 9273 piezoelectric dynamometer, which can measure the tapping torque acting on the workpiece by the FFT. The dynamometer will output the tiny voltage generated by the FFT as an analog signal, and then input it to the Kistler 5011 charge amplifier through the BNC line. At this time, the charge amplifier will further amplify the analog signal by a 50X magnification and use the NI-6110S data acquisition (DAQ) card to convert the analog signal into a digital signal and input it to a personal computer hard disk for storage for subsequent data analysis with LabView software.

![Fig. 5 Scanned SBIT profile](image)

![Fig. 6 Schematic diagram of an ideal tooth shape](image)

Table 3 Selected factors and levels

| No. | W (mm) | D₂ (mm) | D₃ (mm) | θ (°) |
|-----|--------|---------|---------|-------|
| 1   | 1.065  | 0.9714  | 1.0394  | 62.17 |
| 0   | 1.015  | 0.9514  | 0.9994  | 60.17 |
| −1  | 0.965  | 0.9314  | 0.9594  | 58.17 |

Table 4 Table of Box-Behnken design

| No. | W   | D₂  | D₃  | θ   |
|-----|-----|-----|-----|-----|
| 1   | −1  | −1  | 0   | 0   |
| 2   | −1  | 1   | 0   | 0   |
| 3   | 1   | −1  | 0   | 0   |
| 4   | 1   | 1   | 0   | 0   |
| 5   | −1  | 0   | −1  | 0   |
| 6   | −1  | 0   | 1   | 0   |
| 7   | 1   | 0   | −1  | 0   |
| 8   | 1   | 0   | 1   | 0   |
| 9   | −1  | 0   | 0   | −1  |
| 10  | −1  | 0   | 0   | 1   |
| 11  | 1   | 0   | 0   | −1  |
| 12  | 1   | 0   | 0   | 1   |
| 13  | 0   | −1  | −1  | 0   |
| 14  | 0   | −1  | 1   | 0   |
| 15  | 0   | 1   | −1  | 0   |
| 16  | 0   | 1   | 1   | 0   |
| 17  | 0   | −1  | 0   | −1  |
| 18  | 0   | −1  | 0   | 1   |
| 19  | 0   | 1   | 0   | −1  |
| 20  | 0   | 1   | 0   | 1   |
| 21  | 0   | 0   | −1  | −1  |
| 22  | 0   | 0   | −1  | 1   |
| 23  | 0   | 0   | 1   | −1  |
| 24  | 0   | 0   | 1   | 1   |
| Center | 0   | 0   | 0   | 0   |
diameter and depth of the pre-drilled hole are 1.07 mm and 2.0 mm, respectively. The feed rate ($F$) is defined in terms of the tool rotation speed ($\omega$) and the tool pitch ($P$) as follows:

$$F = \omega \times P$$  \hspace{1cm} (1)

The tapped workpiece is then cut in half using a wire-EDM machine. Ignoring the workpiece material that is consumed by the wire-cut diameter, the cut hole in the workpiece can be regarded as a complete semicircle. Figure 4 shows the schematic diagram for the cutting workpiece. After scanning, the cross-section of the hole is shown in Fig. 5, which shows an image of the SBIT profile using a metallographic microscope. The serrated areas on both sides of Fig. 5 are the SBIT profile. The 8 numbered teeth on the top are selected to measure because the first-four threads are the most important for the screw to fasten the component and cover of mobile phone.

### 2.3 Binarization

The image processing software (ImageJ) was used to obtain the SBIT profile after tapped workpiece, which is related to thread filling rate ($f$). Then the binarization method for SBIT profile uses the grayscale threshold to calculate the image area with pixels. The grayscale threshold is manually adjusted or automatically calculated (auto threshold). For this study, the Renyi Entropy algorithm is used to calculate all image areas of the tapped thread [19]. Particle analysis is used to calculate the thread area and the result is given in units of square millimeter. The thread filling rate ($f$) is defined as follows:

$$f = \frac{A_E}{A_I} \times 100\%$$  \hspace{1cm} (2)

where $A_E$ is the experimental thread area and $A_I$ is the ideal thread area. Figure 6 shows a schematic diagram of an ideal thread shape, for which the area is calculated as 0.01974 mm$^2$. The experimental tooth area is measured using the
image processing software and the ideal tooth area refers to the maximum projection range between the workpiece and the tool.

2.4 Box-Behnken design

Box-Behnken design, which is experimental design for response surface methodology (RSM), is still considered more convenient and powerful than other designs. However, RSM is an advantageous tool for solving the optimization problem of exact limitations. This study uses RSM to determine the relationship between four explanatory variables \((W, D_2, D_f, \text{ and } \theta)\) and two response variables \((f \text{ and } T)\). The selected factors and levels in this study are shown in Table 3. The factorial experiments were repeated 3 times and one center point are used in the experiment, as shown in Table 4. The result of the factorial experiment by BBD is used to establish the second-order model for optimizing response variables.

3 Finite element method (FEM)

3.1 Modeling

In this study, the solutions of finite element analysis (FEA) are modeled based on the following assumptions: (1) The model is homogeneous, isotropic, and complies with von-Mises yield criterion; (2) the model has plastic incompressibility; (3) tool is regarded as a completely rigid body; (4) the thermal effect of the model is ignored; (5) the rotation process is regarded as quasi-static and the analysis is performed in incremental steps.

To analyze the SBIT for a single hole, the model of the workpiece is simplified as a cylinder with an outer diameter of 2.5 mm, an inner diameter of 1.07 mm, and a workpiece thickness of 2 mm. In order to provide 7075-T6 material model data for FEA, the 7075-T6 tensile test in this study was performed on a 10KN MTS-810 universal testing machine (Fig. 7), and the tensile strain rate was set to 0.2 mm/min and conducts experiments at room temperature to obtain the required plastic flow stress–strain curve data of the 7075-T6 aluminum alloy, as shown in Fig. 8. It can be seen from Fig. 8 that the results obtained from the tensile experiment in this study are in good agreement with the Deform-3D data, so the 7075-T6 material model data of Deform will be used in the FEA in this study. As for the 7075-T6 workpiece specification, the ASTM E8M standard is adopted, as shown in Fig. 9.

The simulation ignores the effects of elastic recovery and temperature. Room temperature is fixed at 20°C for the form tapping analysis model. The tool and workpiece are modeled using SolidWorks software and imported
into Deform-3D as a STL-file. The tool specification is M1.2 × 0.25 mm and the geometric parameters are shown in Sect. 2.1. The initial position of tool and workpiece model for simulation is shown in Fig. 10. The plane of the front-end of the tool and the top of workpiece is considered to be aligned at the same level so that the descending stroke and the processing depth of workpiece are synchronized. This clarifies the relationship between tool stroke and blind internal thread formation. The interface friction between the tool and the workpiece is shear friction. The shear friction factor (m) is 0.1. The feed rate for the tool is 1000 mm/min (16.67 mm/s), the rotation speed is 4000 rpm, and the processing stroke is 1.5 mm.

Fromentin et al. [5] shows that the main deformation region for a FFT is concentrated in the thread surface of the inner hole and other materials are not deformed. The geometry of the blind internal thread profile is more complicated, so the local mesh for the thread deformed area corresponding to the workpiece model must be refined. Figure 11 shows a schematic diagram of the local mesh refinement for the workpiece model. The minimum edge length for the mesh is 0.02 mm. For this study, the number of finite element meshes is determined by convergence analysis. Using the convergence results for thread filling rate and minimum torque, the number of mesh groups is 8. Figures 12 and 13 respectively show the relationship between the thread filling rate and the minimum torque and the number of meshes. The thread filling rate and the minimum torque converge to a stable value when the number of meshes exceeds 80,000. Therefore, this study uses 85,000 meshes to establish a finite element model of the workpiece.

### 3.2 Thread filling rate

The comparison between the simulated and the experimental results is the easiest way to verify whether the blind internal thread profile is correct. Figure 14 shows the overlay of the simulated and experimental results (solid line) on the blind internal thread profile. Nos. 1 ~ 8 in Fig. 14 are the same as the simulated measurements in Fig. 5. Use ImageJ software to scan the image of the microscope to measure the area of each thread in X–Z and Y–Z planes and use these 8 sets of measurement data to obtain the thread filling rate of each thread. In this study, the average simulated thread filling rates were 87.59% and 88.57% in X–Z and Y–Z planes, while the average experimental thread filling rates were

|   | X–Z plane |   | Y–Z plane |   |
|---|-----------|---|-----------|---|
| No. | Simulation | Experiment | Error (%) | Simulation | Experiment | Error (%) |
| 1  | 84.40     | 76.42     | 10.44     | 84.22     | 89.42     | 5.82     |
| 2  | 86.12     | 90.73     | 5.08      | 85.67     | 90.47     | 5.31     |
| 3  | 85.07     | 94.23     | 9.72      | 93.11     | 92.11     | 1.09     |
| 4  | 92.05     | 93.79     | 1.86      | 86.17     | 88.53     | 2.67     |
| 5  | 87.33     | 88.61     | 1.44      | 88.56     | 86.97     | 1.83     |
| 6  | 90.22     | 89.43     | 0.88      | 91.13     | 94.68     | 3.75     |
| 7  | 84.22     | 91.16     | 7.61      | 92.98     | 95.83     | 2.97     |
| 8  | 91.28     | 90.94     | 0.37      | 86.72     | 92.25     | 5.99     |
| Avg | 87.59     | 89.41     | 4.68      | 88.57     | 91.28     | 3.68     |
89.41% and 91.28% in X–Z and Y–Z planes. However, the difference of average thread filling rate between simulation and experiment results in X–Z and Y–Z planes is very small, as shown in Table 5. The circles in Fig. 14 indicate burrs generated during the forming process. The direction of the burr in Fig. 14a, b is different, which is caused by the different initial contact points of the processing. In addition, the arrows in Fig. 14 indicate that different phase angles and different initial contact points cause the thread profile to be mismatched.

3.3 Minimum torque

For a small forming tap, excessive torque will cause damage or breakage of the tool during the tapping process. Figure 15 shows the relationship between time and torque in tapping process with a small forming tap. Zone (a) is the initial advance stroke stage of contact between the tool and the workpiece. The torque increases rapidly from zero with a sharper slope. Zone (b) is the advance stroke stage where the tool continues to enter the hole. The torque increases with the increase of the stroke, and the minimum torque of 87.21 N-mm appears in 0.08755 s. Zone (c) is the advance stroke stage when the tool reaches the bottom of the hole (tool stroke of 1.5 mm), and its processing time is about 0.09 s. At this time, tapping will stop rotating and feeding, so the torque is 0 N-mm. Zone (d) is the retract stroke stage. The difference between its value and the advance stroke is a negative value. In this retract stroke stage, the contact area between the tool and the workpiece gradually decreases, so the torque gradually decreases as time increases until the tool is separated from the workpiece. The torque will be 0 N-mm, and the entire tapping process is completed. In order to simplify the simulation process, this study only considers the minimum torque generated during zones (a) and (b).

4 Results and discussion

4.1 Factorial analysis

The simulation results by DEFORM-3D software are shown in Table 6. In order to understand the relationship between various parameters and quality characteristics of FFTs in 7075-T6 aluminum alloy tapping, the second-order regression model was established using MINITAB software, which can obtain the predict equations of the thread filling rate ($f_1$) and minimum torque ($T_1$). These two second-order regression models can be expressed as follows:

$$f_1 = 88.85 + 11.53W + 1.9708D^2 - 1.8075Df + 2.0717/D^3 - 5.3221W^2 - 3.6358D^2f - 0.4221/D^3 - 1.295WD + 0.3425WDf + 0.2825Wθ + 0.555D^2Df - 1.3175D^2θ - 0.005Df/D^3$$

(3)
Table 7 shows the results of the analysis of variance (ANOVA) for the thread filling rate ($f_1$) and minimum torque ($T_1$). The results of the ANOVA show that the determination coefficients ($R^2$) for the $f_1$ and $T_1$ are 97.0% and 90.6%, which shows the two second-order models are significant. Considering that the factor confidence level is 95%, it can be obtained that the T-value is less than $T(0.05/2,10) = 2.228$ as an insignificant factor item. From Table 7, the $W$, $D_2$, $D_f$, and $\theta$ are the effective parameters for $f_1$, and the $W$, $D_2$, and $\theta$ are important parameters for $T_1$. As the $W$ decreases, the thread filling rate increases and tapping torque decreases. The smaller the $D_2$, the larger is the thread filling rate, and the smaller is the minimum torque. If considering the strength of the FFT during tapping, the $D_2$ of the FFT should not be too small. The $\theta$ also has the same result as $D_2$. However, $D_f$ has insignificant effect on minimum torque because the chamfer length of the FFT for this study is only 0.25 mm (1 pitch). Moreover, it is known from Table 7 that the first-order interaction

$$T_1 = 89.08 - 6.235W + 6.8958D_2 + 1.0058D_f + 5.5867\theta 
+ 5.0517W^2 + 1.0829D_2^2 - 1.9221D_f^2 + 6.0292\theta^2 
- 0.7975WD_2 + 1.5575WD_f + 0.675W\theta 
- 1.17D_2D_f - 0.245D_2\theta - 2.545D_f\theta$$  \( \text{(4)} \)

Table 7 shows the results of the analysis of variance (ANOVA) for the thread filling rate ($f_1$) and minimum torque ($T_1$). The results of the ANOVA show that the determination coefficients ($R^2$) for the $f_1$ and $T_1$ are 97.0% and 90.6%, which shows the two second-order models are significant. Considering that the factor confidence level is 95%, it can be obtained that the T-value is less than $T(0.05/2,10) = 2.228$ as an insignificant factor item. From Table 7, the $W$, $D_2$, $D_f$, and $\theta$ are the effective parameters for $f_1$, and the $W$, $D_2$, and $\theta$ are important parameters for $T_1$. As the $W$ decreases, the thread filling rate increases and tapping torque decreases. The smaller the $D_2$, the larger is the thread filling rate, and the smaller is the minimum torque. If considering the strength of the FFT during tapping, the $D_2$ of the FFT should not be too small. The $\theta$ also has the same result as $D_2$. However, $D_f$ has insignificant effect on minimum torque because the chamfer length of the FFT for this study is only 0.25 mm (1 pitch). Moreover, it is known from Table 7 that the first-order interaction

| No. | $W$ | $D_2$ | $D_f$ | $\theta$ | $f$ (%) | $T$(N-mm) |
|-----|-----|-------|-------|----------|---------|-----------|
| 1   | −1  | −1    | 0     | 0        | 68.26   | 92.16     |
| 2   | −1  | 1     | 0     | 0        | 72.42   | 108.95    |
| 3   | 1   | −1    | 0     | 0        | 91.80   | 81.54     |
| 4   | 1   | 1     | 0     | 0        | 90.78   | 95.14     |
| 5   | −1  | 0     | −1    | 0        | 69.20   | 99.77     |
| 6   | −1  | 0     | 1     | 0        | 65.29   | 93.49     |
| 7   | 1   | 0     | −1    | 0        | 93.84   | 83.58     |
| 8   | 1   | 0     | 1     | 0        | 91.30   | 83.53     |
| 9   | −1  | 0     | 0     | −1       | 71.06   | 105.80    |
| 10  | −1  | 0     | 0     | 1        | 72.83   | 112.41    |
| 11  | 1   | 0     | 0     | −1       | 93.40   | 92.33     |
| 12  | 1   | 0     | 0     | 1        | 96.30   | 101.64    |
| 13  | 0   | −1    | −1    | 0        | 82.08   | 81.87     |
| 14  | 0   | −1    | 1     | 0        | 77.73   | 85.99     |
| 15  | 0   | 1     | −1    | 0        | 87.36   | 98.60     |
| 16  | 0   | 1     | 1     | 0        | 85.23   | 98.04     |
| 17  | 0   | −1    | 0     | −1       | 76.59   | 80.99     |
| 18  | 0   | −1    | 0     | 1        | 86.70   | 95.37     |
| 19  | 0   | 1     | 0     | −1       | 83.09   | 93.27     |
| 20  | 0   | 1     | 0     | 1        | 87.93   | 106.67    |
| 21  | 0   | 0     | −1    | −1       | 87.82   | 80.33     |
| 22  | 0   | 0     | −1    | 1        | 90.45   | 97.09     |
| 23  | 0   | 0     | 1     | −1       | 83.45   | 92.84     |
| 24  | 0   | 0     | 1     | 1        | 86.06   | 99.42     |
| Center | 0     | 0     | 0     | 0        | 88.85   | 89.08     |
factor has insignificant effect on the thread filling rate and minimum torque. Table 8 shows the compared results between simulation and prediction data for the \( f_1 \) and \( T_1 \). The errors (%) of the \( f_1 \) and \( T_1 \) are below about 6%, which shows the two second-order models are acceptable in this study.

### 4.2 Optimization analysis

Quality characteristic of machining is one of the most goals pursued by manufacturers, which not only affects the processing costs of manufacturer but also affects the trustworthiness of consumer (or users). Therefore, the geometric parameters of forming tap for \( f_1 \) and \( T_1 \) can be optimized using the two second-order models that are established. Since the thread filling rate is easier to determine than the minimum torque, the thread filling rate is selected for the optimized quality characteristic under the lower torque. The tool geometric \((W, D_2, D_f\text{, and } \theta)\) and tapping process parameters, as shown in Fig. 1 and Table 2, are used to optimize the thread filling rate. However, the optimal solution must satisfy the limiting condition for objective function, which is expressed as follows:

\[
\begin{align*}
\text{Objective function} & : \min T_{s2} \\
\text{Limiting condition} & : f_{s2} - E(f_{s2}) \leq 0
\end{align*}
\]

where \( E(f_{s2}) \) is the expected thread filling rate and its value is 95%. According to Eq. (5), the optimized thread filling rate \( f_{s2} \) must be lower than or equal to 95%. The coded variables for the optimal solution obtained using MINITAB software, as shown in Table 9. It is known from Table 9 that the code values of \( W \) and \( D_2 \) are 1 (1.065 mm) and -1 (0.9594 mm), respectively. The larger the \( W \), the smaller the contact surface (or friction force) between tool and workpiece. In other words, the smaller the contact surface between the tool and workpiece, the smaller the tapping

| No. | Simulation | Prediction | Error (%) | Simulation | Prediction | Error (%) |
|-----|------------|------------|-----------|------------|------------|-----------|
| 1   | 68.26      | 65.10      | 4.63      | 92.16      | 93.76      | 1.73      |
| 2   | 72.42      | 71.63      | 1.09      | 108.95     | 109.14     | 0.18      |
| 3   | 91.80      | 90.75      | 1.15      | 81.54      | 82.88      | 1.64      |
| 4   | 90.78      | 92.10      | 1.45      | 95.14      | 95.08      | 0.07      |
| 5   | 69.20      | 71.74      | 3.67      | 99.77      | 99.00      | 0.78      |
| 6   | 65.29      | 67.44      | 3.30      | 93.49      | 97.89      | 4.71      |
| 7   | 93.84      | 94.12      | 0.30      | 83.58      | 83.41      | 0.20      |
| 8   | 91.30      | 91.19      | 0.12      | 83.53      | 88.54      | 6.00      |
| 9   | 71.06      | 69.79      | 1.79      | 105.80     | 101.48     | 4.08      |
| 10  | 72.83      | 73.37      | 0.73      | 112.41     | 111.31     | 0.98      |
| 11  | 93.40      | 92.28      | 1.20      | 92.33      | 87.66      | 5.05      |
| 12  | 96.30      | 96.99      | 0.72      | 101.64     | 100.19     | 1.43      |
| 13  | 82.08      | 83.20      | 1.36      | 81.87      | 79.17      | 3.30      |
| 14  | 77.73      | 78.48      | 0.96      | 85.99      | 83.52      | 2.87      |
| 15  | 87.36      | 86.03      | 1.52      | 98.60      | 95.30      | 3.35      |
| 16  | 85.23      | 83.53      | 2.00      | 98.04      | 94.97      | 3.13      |
| 17  | 76.59      | 79.43      | 3.71      | 80.99      | 83.47      | 3.06      |
| 18  | 86.70      | 86.21      | 0.56      | 95.37      | 95.13      | 0.25      |
| 19  | 83.09      | 86.01      | 3.51      | 93.27      | 97.75      | 4.80      |
| 20  | 87.93      | 87.52      | 0.47      | 106.67     | 108.43     | 1.65      |
| 21  | 87.82      | 85.75      | 2.35      | 80.33      | 84.05      | 4.63      |
| 22  | 90.45      | 89.91      | 0.60      | 97.09      | 100.31     | 3.32      |
| 23  | 83.45      | 82.15      | 1.56      | 92.84      | 91.15      | 1.82      |
| 24  | 86.06      | 86.28      | 0.26      | 99.42      | 97.24      | 2.20      |
| Center | 88.85    | 88.85      | 0.00      | 89.08      | 89.08      | 0.00      |

### Table 9 The optimal solution with the Box-Behnken design

| W       | D_2      | D_f      | \( \theta \) |
|---------|----------|----------|--------------|
| 1 (1.065 mm) | -0.3279 (0.9448 mm) | -1 (0.9594 mm) | 0.3939 (60.96°) |

Coded variable (real value)
torque and the larger the thread filling rate obtains. The code values of $D_2$ and $\theta$ are $-0.3279$ (0.9448 mm) and 0.3939 (60.96 °), respectively. When the code value of $D_2$ is $-0.3279$, it will cause the tapping torque to decrease, but it has little effect on the thread filling rate (T-value), as shown in Table 7. However, the reason for $\theta$ can be same explained it.

In order to verify the accuracy of the prediction model, the optimal solution is simulated and examined using the finite element model and experiments, respectively. The

Fig. 16 The forming diagram of simulated tapping for the optimal solution at a stroke of 1.5 mm

(a) Forming profile

(b) Effective strain distribution

(c) Effective stress distribution
error results among predicted, simulated, and examined conditions on thread filling rate and minimum torque are shown in Table 10. The results in Table 10 show that the simulation and examination conditions have 93.26% and 91.61% and 88.12 N-mm and 81.07 N-mm for thread filling rate and minimum torque, respectively. Compared to the predicted condition, the error results of the simulated and examined conditions on thread filling rate and minimum torque are 1.54% and 3.28% and 0.58% and 8.53%, respectively. However, this practice is always well and its prediction models have been fully explored. Figure 16 shows the forming diagram of simulated tapping for the optimal solution at an effective stroke of 1.5 mm. From the result of Fig. 16c, it is known that the maximum stress of the FFT is distributed in the zone where the thread is formed. The modeling results agree well with the practical experience in industry.

5 Conclusion

Box-Behnken design (BBD) is a highly experimental method used in industry to solve the optimization problem of exact limitations. The use of SBIT has raised manufacturers of 3C electronic products concern which call for different alternatives. The FFT has been successfully introduced as an acceptable machining tool to generate a SBIT; however, its potential to decrease defect and cost in tapping process are much higher than the one achieved using traditional tap. The optimization of tool geometric parameters ($W, D_2, D_f$, and $\theta$) with DEFORM-3D and MINITAB software for a FFT in tapping 7075-T6 aluminum alloy have been investigated. Based on the obtained results, the following conclusions are drawn as follows:

1. The results of the ANOVA show that the determination coefficients ($R^2$) for the $f_1$ and $T_1$ are 97.0% and 90.6%, which shows the two second-order models are significant. However, the $W$, $D_2$, $D_f$, and $\theta$ are the effective parameters for $f_1$, and the $W$, $D_2$, and $\theta$ are important parameters for $T_1$.
2. Compared to the predicted condition, the simulated and examined conditions can effectively control the error

and its error can be limited by 0.5–9.0% on thread filling rate and minimum torque. Combining DEFORM-3D and MINITAB software, it is feasible to use small FFT to tap 7075-T6 aluminum alloy to obtain reliable results of thread filling rate and minimum torque.

3. The coded level for the explanatory variables using the optimal solution is $W=1.0$ (1.065 mm), $D_2=−0.3279$ (0.9448 mm), $D_f=−1.0$ (0.9594 mm), and $\theta=0.3939$ (60.96°). The simulation and examination results on thread filling rate and minimum torque are 93.26% and 91.61% and 88.12 N-mm and 81.07 N-mm, respectively. In comparison to predicted condition, the error results of simulated and examined conditions were well within acceptable value, which revealed the simulated model and experimental data were a good fit to the Box-Behnken design.

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Data availability All necessary data are shown in the figures and tables within the document. The raw data can be made available upon request.

Declarations

Ethics approval Not applicable.
Consent to participate Not applicable.
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Conflict of interest The authors declare no competing interests.

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