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Effect of cutting conditions and thread mill diameter on cutting temperature in internal thread milling of Al7075-T6

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Abstract. Apart from the traditional internal thread-making processes such as thread tapping and thread turning, thread milling comes up with some advantages. Therefore, it has become a good choice among other alternatives in recent years. In this work, the effect of cutting conditions and thread mill diameter on the cutting temperature has been investigated in the internal thread milling of Al7075-T6 alloy. In machining processes, cutting temperature is a measure of machinability, and it is usually a barrier limiting the high-performance cutting. Therefore, cost-effective machining cannot be achieved when excessive cutting temperature occurs. Although the effect of thread mill diameter on the form error in the internal thread milling process has been known, its effect on the cutting temperature has not been investigated. A full factorial design of the experiment was used. Three levels of feed, spindle speed, and thread mill diameter were chosen for M27 thread. According to the results, there is an optimum thread mill diameter that causes the lowest cutting temperature for the possible thread mill diameter interval. In addition, the cutting temperature increases as spindle speed and feed values increase.

Keywords. Thread milling; spindle speed; feed; thread mill diameter; cutting temperature.

1. Introduction

Thread milling is a machining process that can be used to create internal threads as an alternative to other internal thread-making processes such as thread tapping, thread turning, and form tapping. The main advantages of the thread milling process are less dependence on the thread size, reduced tool cost for large diameter holes, local plastic deformation, no need for feed rate-spindle speed synchronization, ability to create threads for inclined surfaces, less torque that the tool experiences, ability to remove a broken tool without damage to the workpiece, better chip removal, left-hand or right-hand threads with the same tool, etc. Some of the limitations in the thread milling process can be counted as follows; thread mill diameter must be less than the hole diameter, the accuracy of the thread depends on both tool geometry and tool path, and thread mills used to machine holes with a high length-to-diameter ratio have low tool stiffness [1].

Al7075-T6 is an aerospace-grade aluminum alloy that has the highest strength among other aluminum alloys. The aerospace industry has its thread standards to fulfill the requirements needed for the high reliability of the structural parts. Different from the standard thread profiles, external threads have higher thread root radii to decrease the stress concentration factors at the roots of the threads, and initial hole diameters of the internal holes are higher to inhibit interferences between the internal and the external threads. Considering the requirements, thread milling is a flexible solution for internal thread requirements.

The thread milling process requires a 3-axis synchronized motion of the cutting tool. Through CNC technology, this requirement can be fulfilled easily. However, special machine tools were required to perform 3-axis synchronized motion in the past. Therefore, thread milling has received more attention in the past few decades. In the literature, Araujo *et al* [2, 3] and Lee *et al* [4] modeled the cutting forces in thread milling. Araujo *et al* [5] investigated the effects of thread geometry, cutting conditions, and tool angles on the cutting forces and torque. Wan and Altintas [6] investigated the dynamics of the thread milling process and stated that the flexibility of the tool, thread mill geometry, tool path, cutting conditions, and material properties determine the dynamics of the process. Fromentin and Poulachon [7–9] investigated the geometric aspects of the thread milling process, such as tool angles, uncut chip thickness, and thread profile. Lee and Nestler [10] introduced a method to design the thread mill geometry by using a simulation-aided approach. Fromentin *et al* [11] introduced an iterative simulation method to determine the appropriate thread mill geometry for non-symmetric thread profiles. Some researchers focused on the penetration strategies and their effects on the form error in the thread milling process. Sharma *et al* [12] investigated the effect of penetration strategy on the cutting forces. The effect of penetration strategy on the dimensional accuracy was investigated by Fromentin *et al* [13]. Fan *et al* [14] developed a correction model for half revolution penetration to prevent overcutting errors. Jun and Araujo developed a mechanistic cutting force model for the thrilling tool which is a combination of a thread mill and a drilling tool [15, 16]. The feasibility of the thread milling process for special thread standards such as API thread [17] and micro threads [18, 19] for dental implants have been investigated. Dong *et al* [20] investigated the tool wear in the internal thread milling process.

Investigations about the thread milling process are mostly based on process modeling. The machining performance of the thread milling process is less studied in the literature. This experimental work investigates the effect of cutting conditions on the cutting temperature in internal thread milling of Al7075-T6 since cutting temperature is a measure of the machinability of the workpiece. In addition, this work investigates the effect of thread mill diameter on the cutting temperature. An appropriate diameter for the thread mill should be chosen because it affects the process. In the aspect of produced geometry, a form error occurs in the thread profile in the thread milling process. The form error increases as the thread mill diameter approaches the thread diameter. The form error may cause significant interference if it exceeds the tolerances. One method to prevent the form error may be decreasing the diameter of the thread mill. However, this also decreases the stiffness of the tool. In another aspect, the magnitude of the thread mill diameter may have an effect on the cutting temperature. One of the aims of this work is to reveal this effect.

In the following sections, first, the experimental work was introduced by presenting the design of the experiment and giving detailed information about how the levels of the process variables were determined. In the results and discussion section, experimental results were presented, and the effect of each variable on the cutting temperature was explained by using the main effects and interaction plots. Besides, probable mechanisms were introduced for the variation of cutting temperature with respect to thread mill diameter. Finally, conclusions were given in the last section.

2. Experimental work

The experimental setup is shown in figure 1. Kent KMV-11VC vertical machining center was used for the experiments. The chemical composition and mechanical properties of Al7075-T6 are shown in tables 1 and 2, respectively.

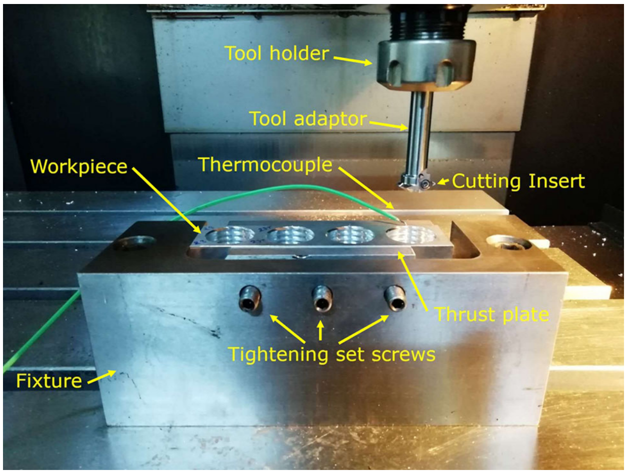

Figure 1. Experimental setup.

Table 1. Chemical composition of Al7075-T6 alloy.

Fe	Si	Mn	Cr	Ti	Cu	Mg	Zn	Al
0.22	0.16	0.02	0.19	0.03	1.32	2.40	5.63	remaining

Table 2. Mechanical properties of Al7075-T6 alloy.

Property	Value
Tensile strength (MPa)	571
Yield strength (MPa)	507
Elongation (%)	12.5

The data given in the tables have been obtained from the material certificate provided by the supplier. The dimensions of the workpieces are 30 mm x 125 mm x 20 mm. M27x3 threads were chosen in the experimental work. The thread milling process was applied to the holes through the thickness of the workpieces. 4 samples were produced per workpiece. Initial holes were created by using a 23 mm drill and a 24 mm boring tool consecutively. Non-standard triangular shape cutting inserts with 5.4 mm inscribed circle diameter were used. The insert has a 1.98 mmthickness, 0.35 mm corner radius, 11° flank angle, and 0° rake angle. The inserts are PVD TiAlN coated. Three different single-point cutting insert adapters shown in figure 2 were designed and produced in-house. The outer diameters of the tools are 15.95 mm, 19.85 mm, and 23.85 mm, respectively. One K-type thermocouple, which has a 1.1 mm head diameter, was used to measure the cutting temperature. The environment temperature was 25°C during the experiments. The thermocouple was aligned to the thread root in advance with a 0.1 mm distance. The thread mill completed one turn

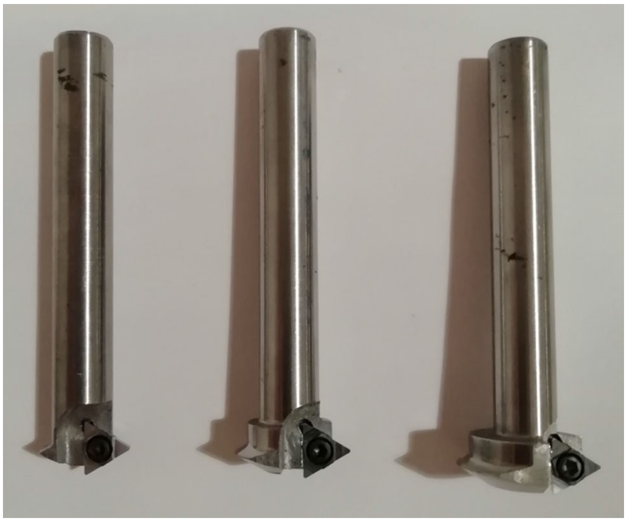

Figure 2. Tool adaptors.

along the helical path in cutting before reaching the temperature measurement point. It was considered that the steady-state cutting temperature is achieved after one turn with negligible tool wear. A new cutting edge of the cutting insert was used for each experiment. Tool penetration strategy is also an important factor affecting the process outputs. An additional full revolution was used for tool penetration. This strategy ensures smooth penetration. All experiments were performed under dry cutting conditions.

Factors affecting the process outputs were determined as the spindle speed, feed, and thread mill diameter. In table 3, the levels of each variable are shown. Each experiment was repeated two times. Levels of the spindle speed were selected to include a wide range. Spindle speed was selected as a process variable instead of cutting speed because the thread mill diameter is one of the process variables. If the cutting speed was selected as a process variable, then the spindle speed would change with respect to the level of the thread mill diameter for the same level of the cutting speed. A variation in the spindle speed might result in chatter formation, and it would be difficult to interpret the experimental results. Therefore, spindle speed was chosen as a process variable to ensure the same chatter stability for a level of spindle speed. Of course, the stiffness of the tool is another parameter in the aspect of chatter stability. Since the thread mill diameter has three levels in the experiments, it influences the tool stiffness. In order to provide similar stiffness values for the tools, the shank diameters of the tools were kept constant at 10 mm, and a very limited region in the tools has a slightly different stiffness. On the other hand, choosing spindle speed as a process variable instead of cutting speed causes another problem in interpreting the experimental results. When the effect of thread mill diameter on the process outputs is investigated, a variation in a process output may be attributed to two reasons: cutting speed and instant immersion. For the same spindle speed value, cutting speed increases as the thread mill diameter increases. Therefore, a variation can be related to the cutting speed. On the other hand, a thread mill with a larger diameter brings out a larger instant immersion of the tool for a specific thread such as M27. As a result, a variation in the cutting temperature should be attributed to the combined effect of cutting speed and instant immersion when interpreting the effect of the thread mill diameter. In the results and discussion section, the effects of cutting speed and instant immersion have been investigated separately by choosing appropriate sets of experiments.

Table 3. Levels of the factors.

Factor	1. level	2. level	3. level
Feed (mm/rev)	0.06	0.14	0.22
Spindle speed (rpm)	1,500	2,500	3,500
Thread mill diameter (mm)	15.95	19.85	23.85

Feed value in machining processes influences many process outputs. A high feed value decreases the process time but increases the cutting forces. Feed value also influences the surface roughness and tool wear. Therefore, finding an appropriate feed value is an optimization problem. Control systems of the CNC machine tools usually use the tool center for the entered feed rate (mm/min) values. When the tool path is straight, the contour feed rate value is equal to the center feed rate value. However, it differs when the tool moves on a curved path. Therefore, the contour feed rate value is higher than the center feed rate value in internal thread milling operations. The center feed rate value is calculated by using Eq. (1). The derivation of this equation can be explained as follows. During the internal thread milling operation, the center of the thread mill moves along a helical path. The outer diameter of the thread mill is in contact with the major diameter of the thread. The contact point also moves along another helical path. The diameter of the helix for the center of the thread mill is $D_{th} - D_m$, and the diameter of the helix for the latter is D_{th}. The time interval for both motions is the same. Therefore, the ratio $(D_{th} - D_m)/f$ is equal to the ratio D_{th}/f_c. This calculation is for the contour feed rate of the thread mill. Therefore, the rotational motion of the thread mill about its central axis does not affect the feed rate but affects the cutting speed. The axial feed rate of the thread mill was neglected because its magnitude is low as compared to the contour feed rate.

$$f = \frac{f_c(D_{th} - D_m)}{D_{th}} \tag{1}$$

where D_{th} is major thread diameter, D_m is thread mill diameter, f is center feed rate value, and f_c is contour feed rate value.

The relationship between the feed direction and the spindle speed direction gives the milling strategy as up-milling or down-milling. For right-hand internal threads, down-milling is achieved by rotating the tool center counterclockwise when the direction of the spindle speed is clockwise. Therefore, the tool start position is on the bottom side of the hole. In up-milling, the directions are the same, and hence the tool start position is the top side of the workpiece. The main difference between the up-milling and the down-milling is varying chip thickness from the start to the end. In down-milling, the chip thickness decreases from the start to the end until reaching zero at the end. Thus, it ensures less edge rubbing. Considering most of the applications in the industry, the up-milling strategy is used in this work.

Thread mill diameter is another selected parameter. There exist some limitations when selecting a proper thread mill diameter for internal thread milling operations. First of all, form error in the thread profile becomes severe when the thread mill diameter approaches the thread diameter. Therefore, the thread mill diameter should be as small as possible. However, this reduces the tool stiffness due to the fact that as the thread mill diameter is decreased, the shank diameter of the tool must be decreased as well. The use of indexable inserts brings another limitation to the thread mill diameter because they require more gaps to be located on the insert adaptor as compared to the solid carbide tools. Considering the limitations, three levels of the thread mill diameter were chosen.

3. Results and discussion

In table 4, experimental results are shown. According to the measured temperatures, it can be said that the temperatures are low even for low cutting speed. The low temperature can be attributed to the good heat conductivity of the aluminum, moving heat source, and intermittent cutting in milling. In addition, the cutting temperature has been measured on the workpiece side. Although the measured temperatures are not high, they give information about the magnitude of the cutting temperature in the cutting edge of

Table 4. Experimental results.

							Cutting temperature (°C)		
Exp. number	Spindle speed (rpm)	Feed (mm/rev)	Thread mill diameter (mm)	Cutting speed (m/min)	Contour feed rate (mm/min)	Center feed rate (mm/min)	1. Trial	2. Trial	Mean
1	1,500	0.06	15.95	75.2	90	37	48.6	48.4	48.50
2	1,500	0.14	15.95	75.2	210	86	54.0	55.3	54.65
3	1,500	0.22	15.95	75.2	330	135	60.0	56.5	58.25
4	1,500	0.06	19.85	93.5	90	24	47.9	49.6	48.75
5	1,500	0.14	19.85	93.5	210	56	54.4	50.7	52.55
6	1,500	0.22	19.85	93.5	330	87	51.6	54.0	52.80
7	1,500	0.06	23.85	112.4	90	11	57.2	50.5	53.85
8	1,500	0.14	23.85	112.4	210	25	53.0	54.2	53.60
9	1,500	0.22	23.85	112.4	330	39	57.0	55.6	56.30
10	2,500	0.06	15.95	125.3	150	61	53.0	58.1	55.55
11	2,500	0.14	15.95	125.3	350	143	62.1	58.4	60.25
12	2,500	0.22	15.95	125.3	550	225	61.4	58.6	60.00
13	2,500	0.06	19.85	155.9	150	40	60.4	56.0	58.20
14	2,500	0.14	19.85	155.9	350	93	54.4	56.7	55.55
15	2,500	0.22	19.85	155.9	550	146	60.4	55.3	57.85
16	2,500	0.06	23.85	187.3	150	18	54.2	57.9	56.05
17	2,500	0.14	23.85	187.3	350	41	66.0	61.4	63.70
18	2,500	0.22	23.85	187.3	550	64	61.6	63.9	62.75
19	3,500	0.06	15.95	175.4	210	86	59.3	57.4	58.35
20	3,500	0.14	15.95	175.4	490	201	59.5	60.9	60.20
21	3,500	0.22	15.95	175.4	770	315	64.8	61.8	63.30
22	3,500	0.06	19.85	218.3	210	56	55.1	61.4	58.25
23	3,500	0.14	19.85	218.3	490	130	60.4	59.3	59.85
24	3,500	0.22	19.85	218.3	770	204	54.4	58.8	56.60
25	3,500	0.06	23.85	262.2	210	25	61.4	56.5	58.95
26	3,500	0.14	23.85	262.2	490	57	59.1	57.9	58.50
27	3,500	0.22	23.85	262.2	770	90	61.1	59.5	60.30

the tool since the highest cutting temperature occurs in this zone. By using these values, the effect of each experimental variable on the cutting temperature can be revealed.

Considering the whole experimental data, main effects plots (figure 3) can be derived to examine the effect of each variable on the cutting temperature. Each graph was constructed by using the mean values of the cutting temperatures for each level of a variable. Referring to figure 3a reveals that the cutting temperature increases as the spindle speed increases. This behavior is expected because spindle speed and cutting speed are directly related. However, the relation between the spindle speed and cutting temperature is not linear, but the cutting temperature tends to settle on an upper limit value. Ming *et al* [21] investigated the cutting temperature in high-speed end milling for an aluminum alloy (AlCuMg) and stated that cutting temperature increases as the spindle speed increases between the spindle speeds 2500-7500 rpm for a 30-mm diameter end mill. They also stated that the heat flux into the workpiece increases as the spindle speed increases, but the rate of change of heat flux is less after a critical spindle speed. The settlement of the cutting temperature to an upper limit value can be attributed to this phenomenon. This observation conforms to the present work. Although they used end milling, similar results can be expected because intermittent cutting occurs in both processes. In figure 3b, the relation between the feed and the cutting temperature is shown. Similar to the effect of spindle speed, cutting temperature increases as the feed increases. This behavior is related to the chip load. As the chip load increases, more energy is consumed for material removal, resulting in higher heat generation. In this case, the relation is said to be more close to a linear relationship. Observations made for the variation of cutting temperature with respect to spindle speed and feed variations conform to the findings reported by Sun *et al* [22]. They carried out experimental work to investigate the effect of cutting parameters on the cutting temperature in milling TiAl4V and stated that cutting temperature increases as cutting speed and feed increase.

A different trend is observed as a result of variation in the thread mill diameter. The cutting temperature reaches its minimum value for the intermediate level of the thread mill diameter. In the section of experimental work, a discussion has been made to investigate the effect of thread mill diameter on the cutting temperature. According to this, a variation in the cutting temperature due to a variation in the thread mill diameter can be attributed to both the cutting speed and instant immersion. As the thread mill diameter increases, the cutting speed and instant immersion of the tool increase. The first one increases the cutting temperature validated by figure 3a, but the second one decreases the cutting temperature because as the instant immersion of the tool increases, the heat is generated in a larger volume, resulting in better heat dissipation. Therefore, an optimum diameter exists for the thread mill in the aspect of cutting temperature by means of these contrary mechanisms. Figure 4 illustrates the instant immersion as the thread mill diameter changes. One may ask that if all the parameters are the same, cutting speed differs as the thread mill diameter changes. However, the effect of the cutting speed has already been assessed and stated that cutting speed cannot be responsible for the trend in figure 3c by referring to figure 3a.

The assumptions made can only be valid when there is not any significant interaction between the thread mill diameter and the other factors. In figure 5, interaction plots are shown. Each graph was constructed by using the mean values of the cutting temperatures for each level of a variable. When the graph consists of parallel lines, it is said

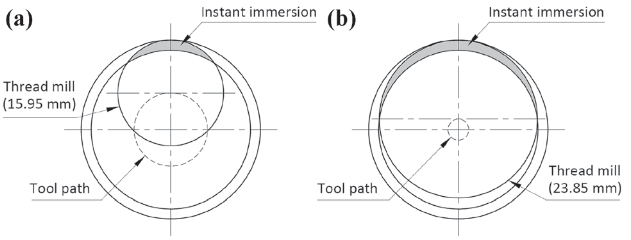

Figure 4. The instant immersion of the thread mill: (**a**) thread mill diameter is 15.95 mm, (**b**) thread mill diameter is 23.85 mm.

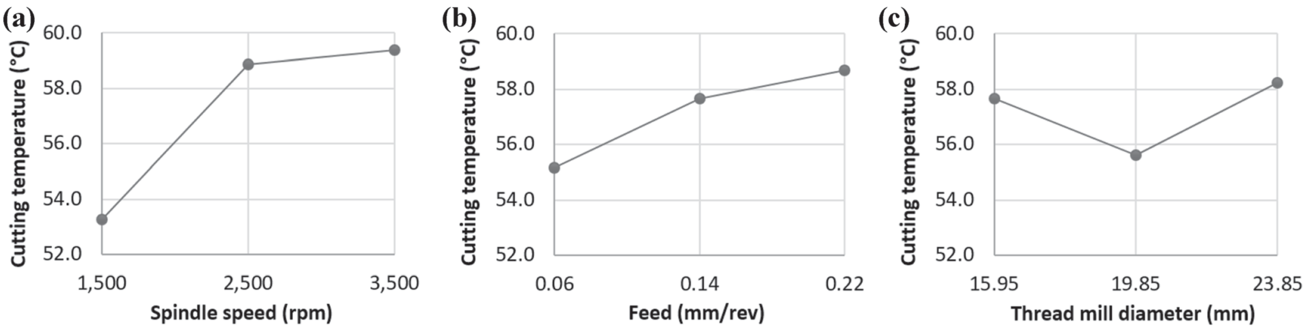

Figure 3. Main effects plots: (**a**) spindle speed, (**b**) feed, and (**c**) thread mill diameter.

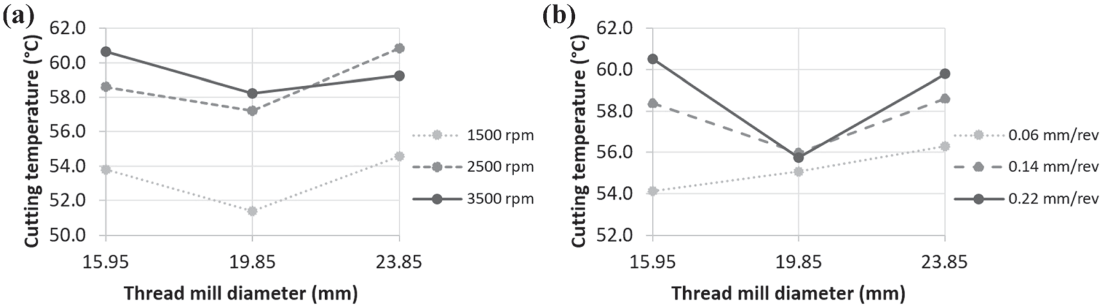

Figure 5. Interaction plots: (**a**) thread mill diameter-spindle speed, (**b**) thread mill diameter-feed.

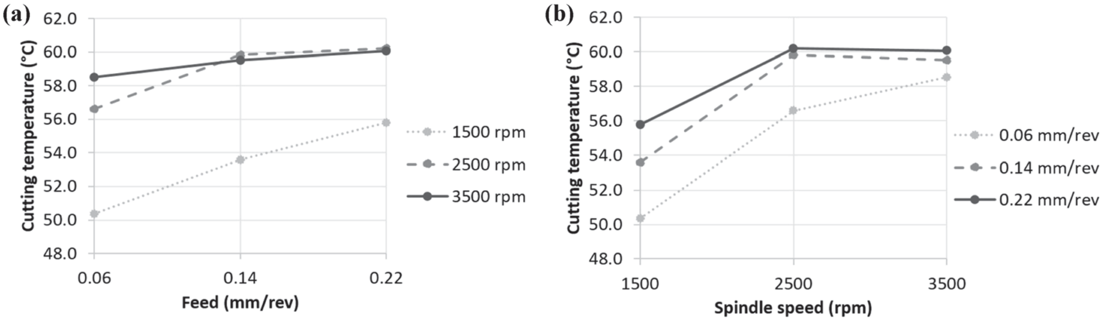

Figure 6. Interaction plots: (**a**) feed-spindle speed, (**b**) spindle speed-feed.

that an interaction does not exist. According to the interaction plots, the lines are mostly parallel. Some non-parallel lines can be attributed to the statistical variations. Therefore, the interaction plots support the assumptions made for the effect of thread mill diameter on the cutting temperature.

Feed-spindle speed and spindle speed-feed interaction plots are shown in figure 6 to verify the assumptions made for the effects of spindle speed and feed on the cutting temperature. It is observed that the graphs mostly consist of parallel lines, and the trends are similar. Therefore, a significant interaction does not exist.

4. Conclusions

Experimental work has been carried out to investigate the effect of spindle speed, feed, and thread mill diameter on the cutting temperature in the internal thread milling of Al7075-T6 alloy. According to the results, the effects of the independent variables are straightforward to interpret: the cutting temperature increases as the spindle speed and feed increase. However, the effect of thread mill diameter on the cutting temperature has been investigated by introducing the mechanisms because it causes more complicated behavior. The trend that occurs in the main effects plot of the thread mill diameter cannot be explained by relating to the cutting speed because the thread mill diameter affects the cutting speed and the effect of the cutting speed is obvious based on the main effects plot of the spindle speed. Therefore, the instant immersion of the tool was considered, and it was concluded that these two phenomena work contrary to each other, resulting in an optimum thread mill diameter to reach the minimum cutting temperature.

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Declarations

Conflict of interests The author declares that there is no conflict of interest.

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