Efficient MQL-based Drilling of Inconel 601

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인코넬 601의 효율적인 MQL드릴링 가공

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ABSTRACT

In drilling Inconel 601, which is used for compressor cases in aircraft engines, a lot of cutting oil must be supplied. This prevents tools from wear and fracture due to the heat buildup resulting from the high-temperature resistance and toughness of this alloy. However, the cutting oil supply has compromised the machining environment. This has caused attention to shift to an environmentally friendly cutting fluid supply system called the Minimum Quantity Lubrication(MQL) system. The aim of this study was to find a more efficient drill processing method using MQL and to verify its performance. To that end, the properties of Inconel that make it difficult -to -drill were studied by a comparison with the drilling of SM45C. Specific factors (i.e., cutting force and tool wear) were examined in relation to the conditions in the MQL-based drilling system. Based on these results, a sealed cover and step feed were proposed as measures to increase the effectiveness of the MQL system. The efficiency of the proposed method was established.

1. Introduction

The representative, heat-resistant super alloy Inconel has excellent properties, including high strength and toughness, creep resistance, retained strength at high temperature, and corrosion resistance. It is widely used for aircraft parts, (e.g., aircraft engine compressor cases).[1] However, these excellent properties of Inconel reduce its machinability, leading to problems such as economic loss due to heat-induced wear and breakage of tools during drilling.[2~6] This means that a lot of cutting oil must be applied to minimize heat buildup when machining this alloy. However, the use of large amounts of cutting oil fluids has been shown to have negative effects on working conditions, the environment, and worker health due to scattering and leakage of the cutting oil. Recently, a new approach called MQL (Minimum Quantity Lubrication) was created to solve these problems. MQL is a method of supplying eco-friendly cutting fluid oil in significantly reduced amounts, while maximizing cooling and lubrication.

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Diverse efforts have been made to render MQL viable.[7~13] To date, the MQL system cannot efficiently spray cutting fluid to the cutting points because the oil mist is created using a spray of high-pressure air. This mist easily diffuses into the surrounding air resulting in less effective lubrication than with a wet process. In this work, an improved MQL (IMQL) process was developed to overcome the problems of MQL and conventional drilling process. IMQL is even more practical, efficient, and eco-friendly.

By drilling both SM45C and two forms of Inconel (601 and 718), it was determined during drilling, that the thrust force and drill edge wear was measurably greater for by Inconel than for SM45C. This verified that Inconel was more difficult -to -cut and had poorer drilling properties. In this work, a sealed cover and step feed[14] were added to the MQL process to improve its effectiveness.

2. Apparatus and Method

The machine tool used for the present drilling experiment was a VC630 5AX Machining Center, Doosan Infracore, featuring a 20,000rpm spindle rotation speed. The oil mist provider (MQL device) was a LubriLean Vario UFV10-003 (VOGEL, Germany), and its details are specified in Table 1. For the drilling of Inconel 601, a TiAlN-coated WC drill of 5 mm diameter (DH 423050, YG1) was used. As the workpieces, Inconel 601, Inconel718, and SM45C were used, of which the mechanical properties are specified in Table 2. To measure the axial thrust force in drilling, piezoelectric-element tool dynamometer (7075B, Kistler, Switzerland) was used. To observe the wear and tear of the drill edge, a tool microscope from SOMETECH(South Korea) was used. Fig. 1 showed the schematic diagram of the experimental setup. Table 3 specifies the experimental conditions.

Table 1 Specifications of MQL equipment

Model	Vario UFV10-003
Company	Vogel (Germany)
Oil droplet size (μm)	0.5
Aerosol quantity (ml/h)	0 ~ 260
Air pressure (bar)	0 ~ 7
Lubricants	LubriFluid F100

Table 2 Mechanical properties of the workpieces

	Tensile Strength (Mpa)	Yield Strength (MPa)	Elongation (%)
Inconel601	620	270	51
Inconel718	1280	1030	25
SM45C	569	343	20
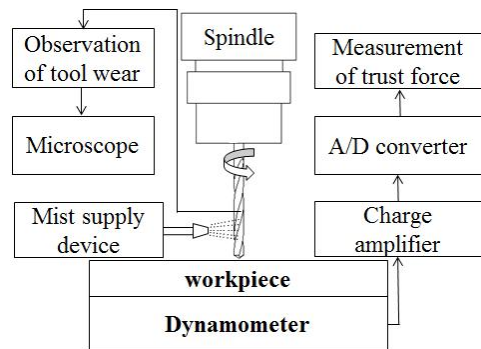
Fig. 1 Experimental setup

Table 3 Experimental conditions

Items		Conditions
Spindle speed V_s (rpm)		500, 1000, 1500, 2000
Feed f (mm/rev)		0.25, 0.03, 0.05, 0.06, 0.075, 0.1, 0.13, 0.15, 0.2, 0.3, 0.4
Workpiece		Inconel601, Inconel718, SM45C
Drill	Diameter (mm)	5
	Coated material	TiAlN
Cooling type		Dry, Wet, MQL
Oil mist flow rate Q (ml/h)		60, 120, 180, 240

3. Drilling properties of Inconel 601

As seen in Fig. 2, the thrust force F_t varied with increasing feed f(mm/rev) of the drill in drilling of Inconel601, Inconel718 and SM45C when dry (unlubricated). As expected from Table 2, comparing the mechanical properties of the workpiece the F_t for Inconel601 and Inconel718 was greater than that for SM45C. This indicated that Inconel was much more difficult -to -cut than SM45C. In addition, both the variation of thrust force (F_t) and fluctuation width of the thrust force (F_f) were in line with increasing 'f' under dry and wet conditions as seen in Fig. 3. The figure represents the output values of four4 types of tool rotation (V_s) for a drill feed, 'f'. As seen in Fig. 3, the F_t and F_f tended to increase proportionately with increasing 'f', regardless of the variation of V_s. Still, when 'f' exceeded 0.1, the F_f increased in proportion to tool rotation. This finding suggests that a small drill feed should be applied to Inconel. If a large feed is applied, it leads to substantial tool vibration and subsequent damage to the tool. In addition, Fig. 3 indicated no significant difference between wet and dry drilling processes. In Fig. 4, a comparison is presented of the tool life, L_f, or the total drilling length to drill fracture in line with the variation of feed 'f' under different conditions of tool rotation V_s. As seen in Fig.4, L_f was longer under the processing condition where V_s=500 rpm and f=0.05 mm/rev than under any other conditions, which was attributable to the high-temperature strength of the Inconel 601 workpiece.

The surface temperature of Inconel 601 was increased by the friction between the drill and workpiece. This softened the cutting surface, made drilling easy, and reduced heat buildup.[15] Based on the experimental findings in Fig. 4, the most efficient drilling conditions for Inconel601 is where V_s=500 rpm and f=0.05 mm/rev, which is consistent with the drilling conditions widely used in practice.
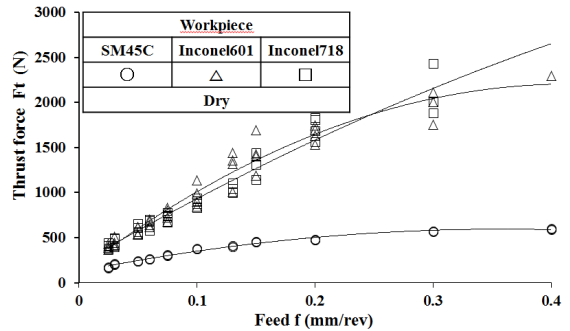

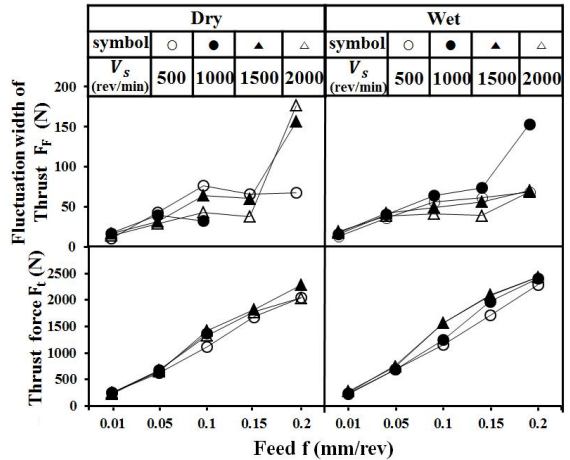**Fig. 2 Comparison of trust forces of workpiece under dry condition**

Fig. 3 Relationship of thrust force and fluctuation width of thrust force for (Inconel 601 with Feed) under dry and wet processes
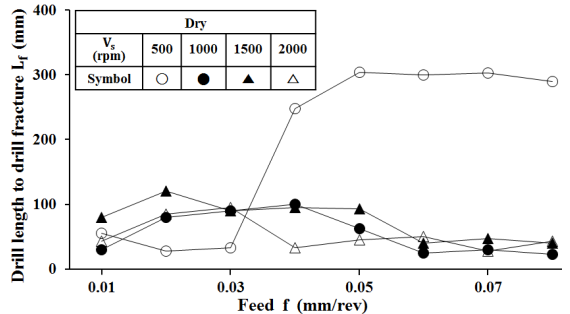

Fig. 4 Relationship between drill length to drill fracture and feed at various rpm for Inconel 601

4. Properties of MQL-based drilling

Fig. 5 shows a schematic diagram of the MQL system used in this study. A certain portion of air in the compressor flows through a manual- slide valve and a pressure control valve, which provide the required amount. At the same time, air enters the mist generator under constant pressure to generate the oil mist. The oil is mist mixed with the rest of the air that has passed through the air conditioner, and is then sprayed through the nozzle in the form of an aerosol (oil mist + air). The oil- mist flow rate depends on the pressures of the oil mist and the air in the aerosol. For accurate measurement of the most sensitive variable oil flow rate Q in the MQL oil supply, an oil mist receiver was attached to the lower part of the MQL unit as seen in Fig. 5. The oil mist receiver has a filter inside that is used, for filtering out the oil mist. When the aerosol enter the oil mist receiver, only the oil mist is filtered out, so only air flow out. Therefore, accurate Q can be determined by weighing the oil mist receiver before and after filtering.

The variation of Q measured with an oil mist detector in line with the variation of the oil mist pressure, P_o, and the air pressure, P_a, is presented in Fig. 6, and shows the lack of relation between P_a and Q. Q tended to rise with increasing P_o, but, when P_o exceeded 3 bar, Q hardly varied. Hence, in this experiment, Q varied within the range 60-240 ml/h. The reason is that above the oil mist pressure of 3 bar, and at the low temperature of the oil mist receiver, the oil mist begins to condense (gas changes to liquid). Fig. 7 showed the behavior of F_t in line with increasing L when drilling was performed varying Q (60, 120, 180 and 240ml/h), at V_s=500rpm and f=0.05mm/rev. These were the most efficient settings under both dry and wet drilling conditions. As seen in Fig. 7, with increasing Q(60-240ml/h) both F_t and L increased. However, the increasing rate of F_t by increasing L decreased, $(\triangle F_t /\triangle L) = -$
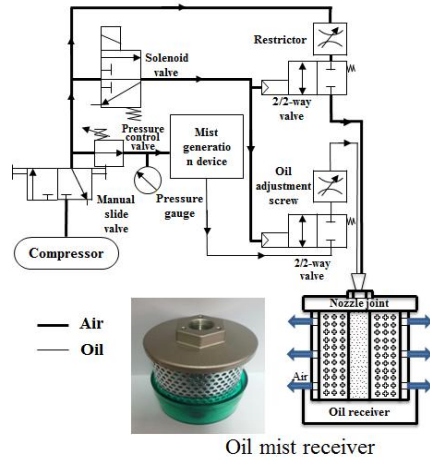

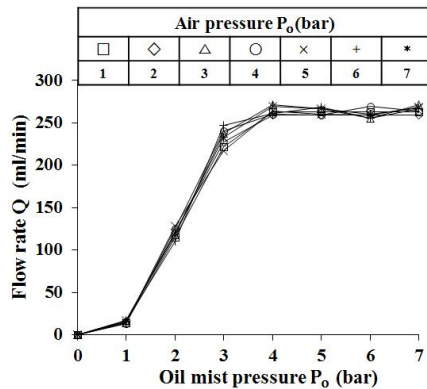**Fig. 5 Schematic diagram of MQL device mounted oil mist receiver**

Fig. 6 Behavior of oil flow rate in line with increasing P_o and P_a

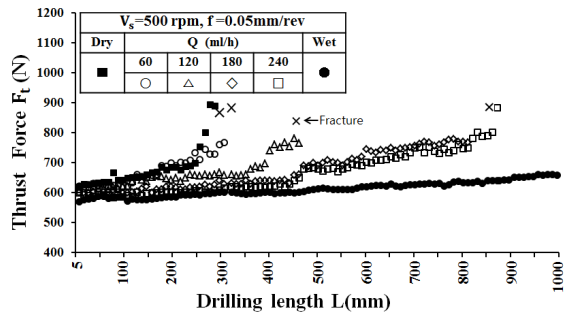**Fig. 7 Relationship between F_t and L atvarious Q under dry and wet conditions**

(negative) when flow rate Q increased from 60ml/h to 240ml/h and wet condition. Therefore, the fracture time (lifetime) of the tool was increased by increasing Q. The effect of the MQL oil supply was small compared to wet drilling, because a large portion of the oil mist sprayed, could not reach the cutting point. To address this issue, a sealed cover and step feed were developed to create an improved MQL(IMQL)
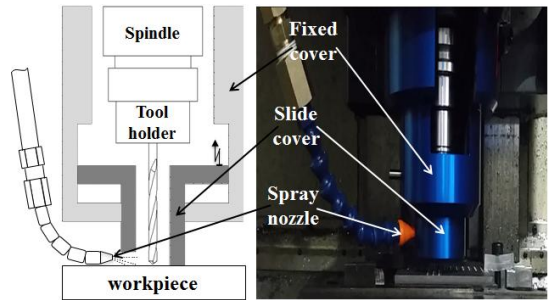
5. Structure and effect of sealed cover

A sealed cover was designed to prevent oil mist from scattering in the air, which was the downside of MQL, and to induce as much oil mist as possible to reach the drilling site by enclosing the cutting point area. Fig. 8 shows the sealed cover composed of a fixed cover sealing the spindle and the tool holder, and the sliding cover working along the movement of the tool. The nozzle is designed to spray oil mist, along the grooves on the sliding cover. In brief, the proposed structure was designed to minimize the oil-mist scattering in the air without interfering in the drilling process. The effects of the sealed cover are shown in Fig. 9. There, the F_t behavior is shown with and without the sealed cover in line with the increasing L, at different flow rates of oil mist, where V_s=500rpm and f=0.05mm/rev. Because a lot of oil mist was applied to the cutting point when a sealed cover was used, the drilling length significantly increased to the fracture point, compared to when the sealed cover was not used. The effects of the sealed cover in creased with in creasing oil mist supply. Moreover, Fig. 10 show microscopic images of the edges of the drills edges used to the brink of fracture, at different flow rates of oil mist, with or without the sealed cover. As seen in the images, the drill edge-wear markedly decreased when the sealed cover was used and the flow-rate of oil mist was high.
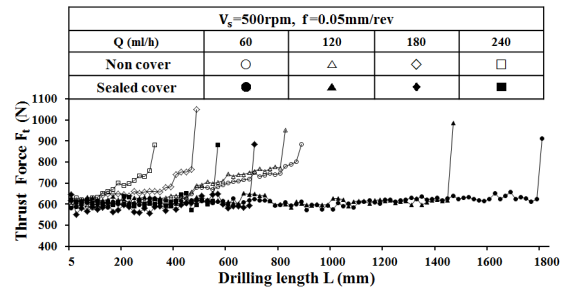

Fig. 8 Structure of a sealed cover

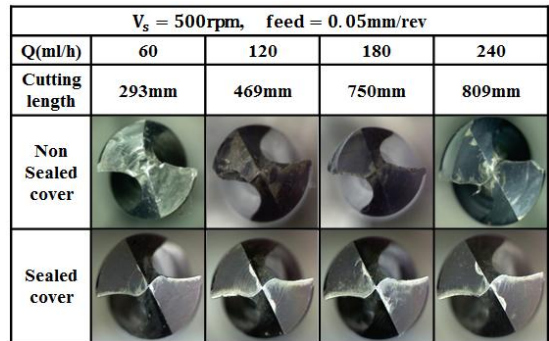Fig. 9 Relationship between F_t and L with or without sealed cover

Fig. 10 Drill edges drilled with or without sealed cover

6. Effects of step feed

Step feed maximizes cooling and lubricating by facilitating chip discharge in processing deep holes or fine holes, and by allowing sufficient application of

fluids to cutting points. According to these experimental findings, because of the low flow-rates of cutting oil mist applied by MQL system, it was difficult for fluid to reach the cutting point effectively, even when the sealed cover was used. To answer this challenge, the effect of the MQL system was improved by applying step feed, after which its effects were verified. As seen in the schematic diagram in Fig. 11, step feed provides a way of processing. For example, a total drilling depth of 6 mm could be divided into 2-mm three steps cycle (2 × 3). Then, when the drill was raised rapidly out of the hole (about 0.5 s) between the first and second steps, room would be left for effective application of the oil mist to the cutting point.

Different conditions needed to be met for effective step feed. Here, for the sake of simplicity, the experiment was conducted at the setting specified in Table 4. Fig. 12 show the variation of tool life, L_f, when an Inconel 601 sheet was drilled with total hole depth of 6 mm, under the step feed condition specified in Table 4 (V_s=500rpm and f=0.05mm/rev). In Fig. 12 dry drilling without the sealed cover was compared to MQL drilling with or without the sealed cover. The step feed hardly affected tool life during dry drilling, whereas IMQL maximized the effectiveness of the sealed cover with the 2 × 3 step feeds. The tool life with step feed processing depended on step depth and step frequency. As seen in Fig. 12, the proper step feed increased tool life 'L_f' because of cooling and lubrication of the drill, and the discharge of chips from the hole. However, the stepping process caused collisions between the tool edges and strain-hardened artifacts, imposing extra loads on the tool. Fig. 13 show microscopic images of drill edges with drill length 302 mm for dry drill, 1182 mm for IMQL(Q=240ml/h) and four-step feeds, with or without MQL. As predicted, the best drilling process was IMQL with 2×3 step feed.
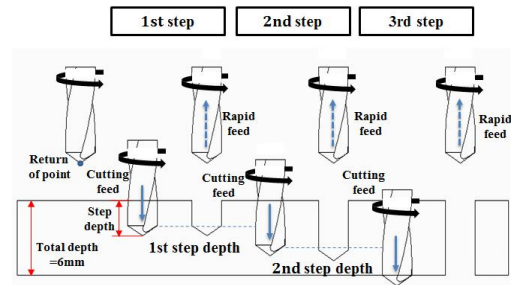

Fig. 11 Schematic diagram of step feed drilling

Table 4 Step feed conditions

step feed (mm × cycle)			
Step depth (mm)	1	2	3
Step cycle	6	3	2
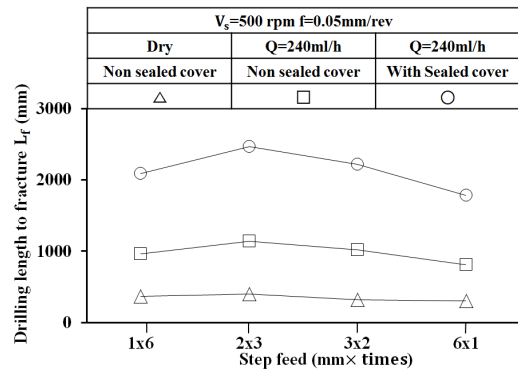
Fig. 12 Relationship between drilling length to fracture and step feeds

Fig. 13 Tool wear under various step feed settings

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7. Conclusion

In this work, MQL was applied to hard-to-cut Inconel with a view to practical, effective and eco-friendly drilling. Based on the results from drilling Inconel, the MQL process was refined (IMQL). The refinements included a sealed cover enclosing the drill area, and step feed. Based on these findings, the following conclusions were drawn.

1. Inconel was characterized by markedly lower machinability than was structural steel S45C. The conditions for most efficient drilling were spindle speed (V_s)=500rpm and feed (f)=0.05mm/rev. These are consistent with the conditions widely used in the field.
2. Although MQL increased the oil-mist flow rate, the effect was negligible in comparison to wet drilling because too little oil mist reached the drill point.
3. Based on the performance tests, the sealed cover improved the effect of MQL, when combined with adequate fluid flow-rate.
4. Step-feed drilling further improved the better results achieved by improved MQL.

Acknowledgement

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