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DEVELOPING OF A MQL VALVE FOR TI-6AL-4V ALLOY MILLING WITH DIFFERENT CUTTING OIL AND GRAPHITE MIXING RATIO

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Abstract. *The use of a minimal quantity lubrication - MQL valve operating with lubricating oil and graphite for machining a Ti-6Al-4V alloy workpiece was the focus of this work. A comparison with different conditions was performed. The oil and oil + graphite conditions were studied The percentage of graphite for lubrication were established in 30%. A factorial design has followed a* 2^3 *model with two central points and one replica for each proportion used. The cutting speed, feed and cutting depth in a milling operation were defined as independent variables and the machining forces were measured with a rotating dynamometer and defined as dependent variables of the experimental planning used. Roughness measurements were performed After the tests. Statistical software was used to obtain the response surfaces. Some interactions were tested, and the feed rate were the variables that most influenced the roughness.*

Keywords: Ti-6Al-4V, milling, MQL, graphite.

1. INTRODUCTION

Titanium is one of the abundantly available materials in nature. In spite of its excellent corrosion resistance, pure titanium is rarely used in engineering applications. Instead, titanium alloys are widely used in the aerospace, structural, biomedical, and defense applications due to their superior properties like high strength-to-weight ratio, biocompatibility, and high corrosion resistance (Revuru et al., 2018).

Although milling is considered the main machining operation for the manufacture of titanium components in the aerospace industry, titanium alloy machining studies are predominantly concentrated in turning operations (Shokrani, 2016). However, milling induced surface integrity, including anisotropic surface roughness, residual stress, surface microstructure alterations and microhardness, has received little attention (Sun, 2009).

Machined surface roughness depends on several factors, such as cutting speed, tool wear, feed, tool materials and geometry (Amin et al., 2007). High-speed machining of titanium alloys generates high cutting temperature in the cutting zone, which decreases tool life rapidly. Thus, the improvement of the tool life in the high-speed machining of titanium alloys very much depends on the effectiveness of the cooling/lubrication provided (Su et al., 2015). Due to the hazards posed by conventional cutting fluids to ecology and health of the workers, there is a greater need to identify eco-friendly and user-friendly alternatives like unconventional methods like dry cutting, cryogenic cooling, minimum quantity lubrication and the use of solid lubricants (Krishna, 2008).

The MQL (Minimum Quantity of Lubrication) approach allows cost reduction by providing precise amounts of cutting fluid mixed with air. In recent years, among various techniques, the researchers have been largely working on MQL/NDM because of its eco-friendly qualities, because the conventional use of coolants during machining creates several techno-environmental problems (Sharma et al., 2016), but this practice shows that MQL-wise techniques are not still widespread in the industry even though the method is well known for decades, because the complex nature of MQL (Gutnichenko et al., 2018 and Muaz; Choudhury, 2019). MQL technique can increase tool life and improve surface quality significantly in many machining processes as a result of lowered temperature and reduced friction at the toolchip interface, however, it is not so effective to the cutting with excessive heat generation (Su et al., 2016). To improve the cooling effect of the MQL techniques two strategies have been recently proposed: one makes use of low-temperature fluids, such as Liquid Nitrogen (LN_2), Carbon Dioxide (CO_2) or cooled air, to provide a hybrid technology in which the tool flank face is lubricated and the rake one cooled simultaneously (techniques named as Minimum Quantity Cooling Lubrication (MQCL), while the other aims at improving the oil heat transfer characteristics thanks to specific additives. The latter solution, named Solid Lubricant (SL)-assisted MQL strategy, is nowadays receiving wider attention since it allows a drastic improvement of the fluid performances by controlling both the heat generation and the friction between the tool and workpiece without significant increase of the process costs, and, at the same time, it also avoids those issues related to the use of cryogenic temperatures as happens when using the aforementioned hybrid techniques (Sartori et al., 2018). The flow rates are typically of the order of 50 to 500 ml / hour (Giasin, 2016) and obtained a significant attention in machining processes to reduce environmental loads caused by usage of conventional cutting fluid (Setti, 2012). A variety of hardware systems have been developed for MQL applications. Depending on the delivery setup to the cutting site, lubricants can be applied with an external nozzle or a through spindle, internal channel. (Tai, 2014). Amrita (2013) notes that MQL process affects the ability to dissipate heat by limiting the provision of adequate lubrication. Hence, the heat-carrying and lubricating ability of soluble oil must be enhanced. According to Marques et al. (2019), the use of solid lubricant in machining has shown satisfactory results regarding to the surface finish, machining forces and tool life in different steels. When solid lubricants are mixed to the oil, the minimal quantity of fluid – MQL technique is normally used for delivering this mixture in the cutting zone. Research studies have shown good results with this technique. The presence of nanoparticles of MoS2 in the tool-workpiece interface improved the quality of the machined surface, and the concentration of 0.5%wt showed the best result. Many other types of solid lubricants, such as graphite, polytetrafluoroethylene (PTFE), hBN, CaF_2, WS_2, boron oxide, etc., have been used in machining with positive results and graphite has better lubricating and cooling properties and hence inclusion of graphite nanoparticles in cutting fluid may help in formulating a better coolant in machining operation.

2. OBJECTIVE

The purpose of this study is to compare milling of alloy Ti-6Al-4V with the use of an MQL valve prototype, for two different conditions: oil and oil+graphite (30%). The objective is to study the average surface roughness using the developed MQL device.

For the purposes of this work it was developed an MQL prototype valve mixing proportion of graphite (30%) with the cutting fluid oil Superfluid 3 from the company Quimatic. An analysis of the parameters of the cutting insert chosen and its influence in the roughness, feed force, cutting force, cutting depth force and torque was performed.

Thus, the study intends to contribute to the study and application of cutting fluids in the milling of a Ti-6Al-4V alloy in a sustainable way, providing an alternative condition of mixing fluids using a prototype valve seeking better results of milling on surface roughness.The difference between the existing MQL processes and the one developed consists of the change in the path of the fluids. Commonly, the compressed air travels through side channels and the fluid through an internal channel. The path in the study was altered for improved mixing, resulting in a shorter distance for the fluid to travel to the injection nozzle.

3. EXPERIMENTAL PROCEDURE

In this chapter, is described the methods employed and the materials used for the milling tests.

3.1 MQL device

To study the construction of the device, a pneumatic simulation was carried out in the FluidSIM 5 software. For its application, a 6-bar power supply, a 5/2-way pneumatic valve with a solenoid actuator and spring return, and a compact hydraulic cylinder were used. from the company Miapro. Figure 1 shows the cylinder simulation performing the valve actuator function.

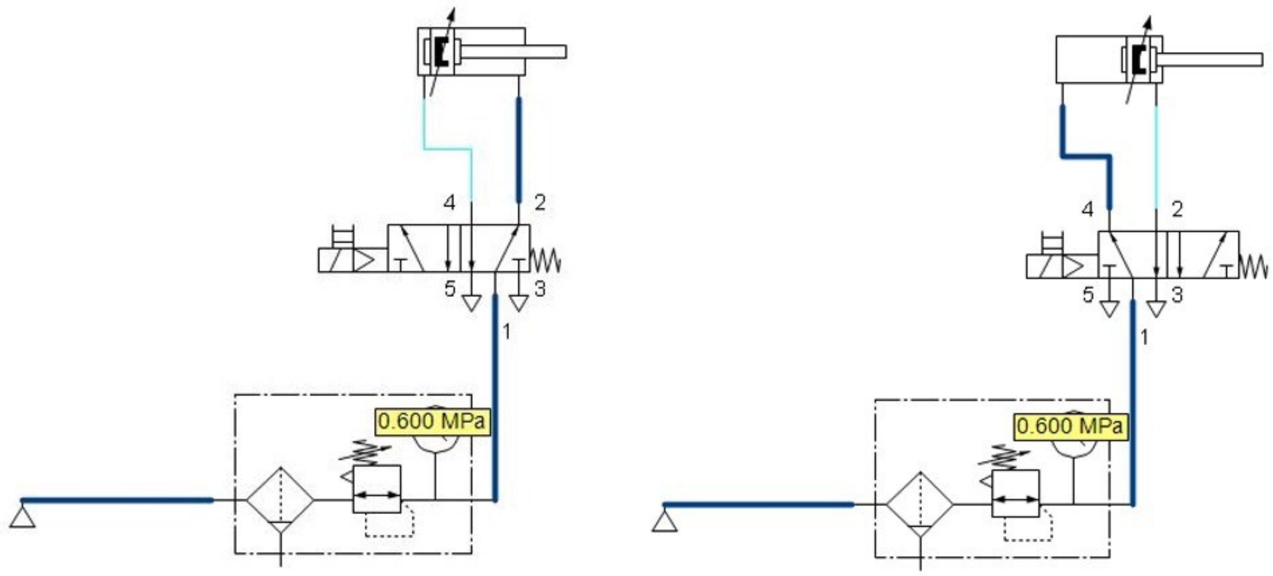

Figure 1. On the left: Solenoid actuation; On the right: return of the cylinder by the spring.

From the simulation, the device was made for use in the milling tests. The construction of this allowed the cycling of the mixture supply, minimizing the losses to the atmosphere with the fluid supply in smaller quantities. Two reservoir heights (5 cm and 10 cm) interchangeable between designs were proposed. In this study, practicality was chosen for the 5cm reservoir. Figure 2 and Figure 3 respectively show the parts for assembling the mixing device using the pneumatic system and the assembled system (1. Body; 2. Nozzle; 3. Piston; 4. Pneumatic cylinder; 5. Cap). With the tests, it was noticed that the cycle system with pneumatic actuation has a delay and is efficient for times of the order of 1.0 seconds. The fluid was introduced into the system through gravity.

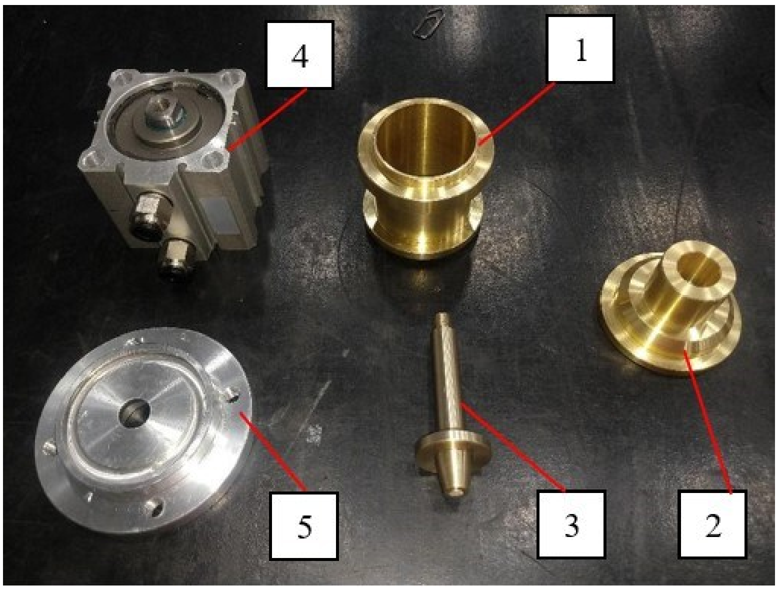

Figure 2. Parts for mounting the pneumatic actuator.

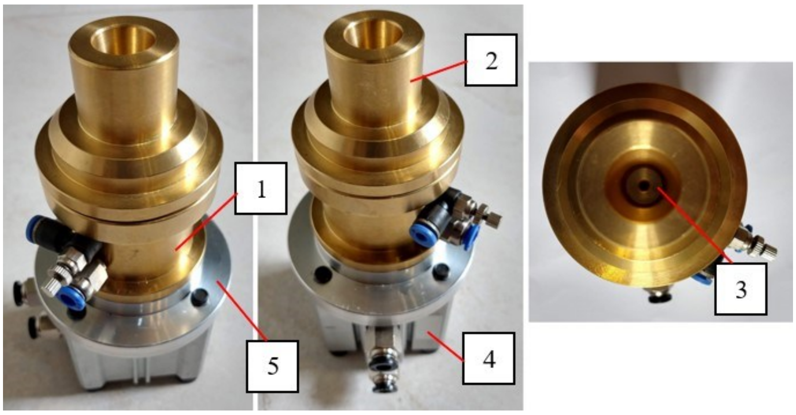

Figure 3. MQL device assembly with the pneumatic approach.

Figure 4 illustrates the components used in the pneumatic circuit of the valve. An air filter with regulation was used at the entrance of the pneumatic circuit (1. Valve; 2. Filter; 3. Pneumatic valve). Figure 5 shows the MQL valve in action.

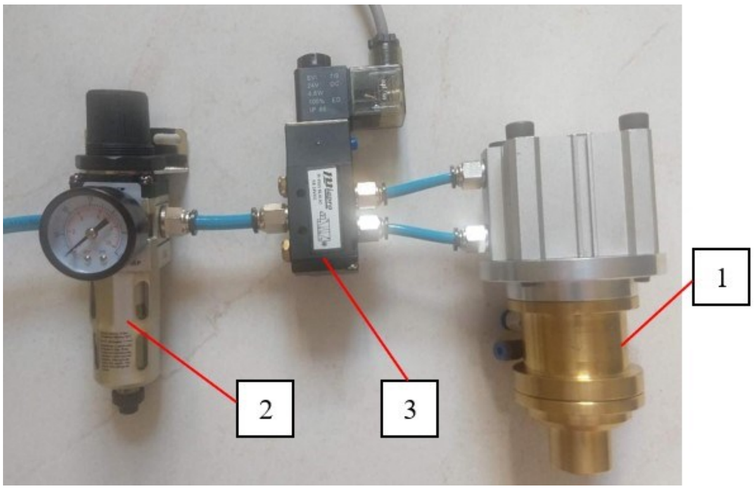

Figure 4. Pneumatic circuit for activating the 5/2-way valve.

Figure 5. MQL device in action.

3.2 Machining

Machining tests followed complete factorial planning of three factors and two levels with the inclusion of two central points. The procedure uses an unworn insert for each factorial planning test. Table 1 shows the factorial planning used in performing the experiment. The data for v_c, f, and a_p were recommended by the producer of the inserts, and the length produced per test unit was 50 mm. A replication was performed for each cutting condition, totaling 20 tests. From these, the respective averages were calculated.

For end milling was used 1 plate of titanium alloy Ti-6Al-4V (Grade 5), where the dimensions were: 500 mm x 50 mm x 17mm, which had an average hardness of 32.4 HRC. The machine for the production tests was a Production Center ROMI D 600. Figure 6 shows the KYOCERA insert used, named BDMT 11 03 02 ER-JS (CVD). The class of the inserts used in tests was CA6535.

Figure 6. KYOCERA tool used for milling.

Table 1. Factorial planning followed by production.

CP	v_c [m/min]	f [mm/r]	a_p [mm]
1/ 11	80.0	0.06	0.50
2/ 12	100.0	0.06	0.50
3/ 13	80.0	0.10	0.50
4/ 14	100.0	0.10	0.50
5/ 15	80.0	0.06	1.00
6/ 16	100.0	0.06	1.00
7/ 17	80.0	0.10	1.00
8/ 18	100.0	0.10	1.00
9/ 19	90.0	0.08	0.75
10/ 20	90.0	0.08	0.75

3.3 Measures

For the measurements of cutting forces was used a dynamometer type 5223B produced by KISTLER, which allowed to measure the respective forces in the coordinates x (F_x), y (F_y), and z (F_x), and the torque (M_z). To capture the signals was used a data acquisition plate made by *National Instruments*. With this equipment and the software "*LabView Signal Express* version 2.5" provided by the same company, it was possible to control and view the measured data. As configuration was set the data acquisition frequency to 100 kHz. Channels 1 to 4 were used for signals F_x, F_y, F_y, and M_z respectively. The dynamometer's signal conditioner used was type 5223B by KISTLER. To determine the average roughness of the milled surface, it was measured three times at its center. The measurement was taken with the probe placed perpendicular to the direction of feed rate.

3.4 Machining forces

The average results of machining forces and roughness measurements for oil + graphite (30%) and oil condition can be seen in Table 2.

Table 2 Results of dependent variables (oil and oil + graphite 30%).

Oil+Graphite	**F_x (N)**	**F_y (N)**	**F_z (N)**	**M_z (Nm)**	**R_a (µm)**
1	80.00	192.50	52.00	0.55	0.35
2	84.00	217.50	63.00	0.63	0.55
3	127.50	242.50	71.00	0.77	0.55
4	115.00	255.00	81.00	0.78	0.58
5	127.50	375.00	77.00	1.04	0.37
6	142.50	410.00	88.00	1.02	0.45
7	175.00	485.00	112.00	1.34	0.48
8	190.00	465.00	121.00	1.36	0.47
9	130.00	410.00	124.00	1.08	0,37
10	140.00	395.00	116.00	1.06	0.35
Std. Dev.	34.50	107.48	25.95	0.27	0,09
Oil	**F_x (N)**	**F_y (N)**	**F_z (N)**	**M_z (Nm)**	**R_a (µm)**
1	117.00	216.50	84.80	0.59	0.21
2	89.00	260.00	95.20	0.64	0.23
3	107.00	285.00	110.00	0.95	0.26
4	116.00	310.00	113.00	0.93	0.26
5	154.00	365.00	99.40	1.01	0.23
6	116.50	315.00	96.00	1.03	0.24
7	195.00	412.50	124.00	1.25	0.28
8	182.50	435.00	129.00	1.30	0.25
9	125.50	330.00	137.60	0.88	0.19
10	119.00	335.00	125.00	0.91	0.19
Std. Dev.	34.09	66.15	17.31	0.22	0.03

3.5 Statistical results

The analysis of the machining forces and torque for the machining condition (oil and oil + 30% graphite) showed that these forces and torque are dominated by the feed rate and cutting depth. The roughness was influenced by the feed rate. Figure 7 illustrates the result of the factorial design for the feed force for the oil + graphite 30% condition.

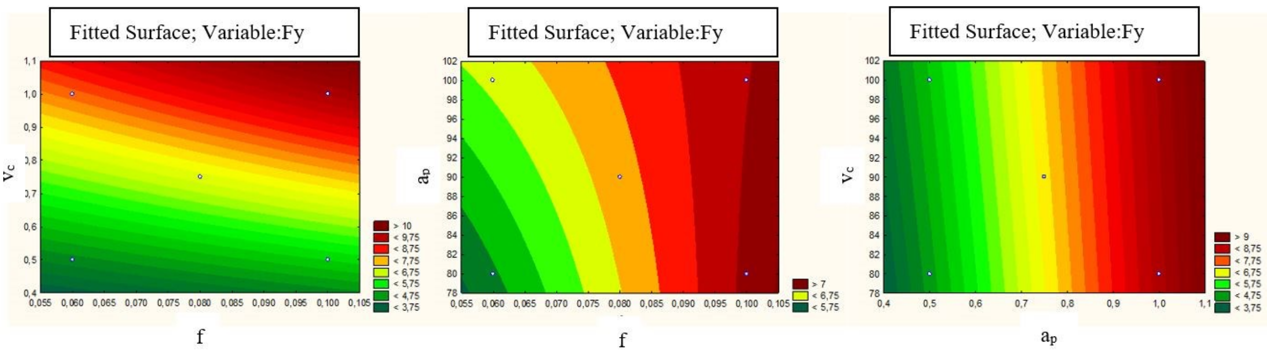

Figure 7. Surface response plots of the fitted model plots: (a) “f x v_c”, (b) “f x a_p” and (c) “a_p x f”.

Table 3 shows the response surface obtained for each dependent variable.

Table 3 - Surface response fitted functions

Model Variables (Graphite - 30%)	Surface response fitted functions
F_y	$=-8.30+0.01*v_c+78.40*f-0.84*f*v_c-0.02*a_p*v_c+38.75*a_p*f+5.40$
F_x	$=0.30-0.007*v_c+34.07*f-0.21*f*v_c+0.04*a_p*v_c+8.25*a_p*f-1.38$
F_z	$=-138.12+3.5*v_c+1218.75*f-9.37*f*v_c-0.25*a_p*v_c+387.0*a_p*f+30.0$ 8*ap*f+30,0
M_z	$=-219.12+3.0*v_c+1468.75*f-9.37*f*v_c-2.25*a_p*v_c+3375.0*a_p*f+330.0$
R_a	$=-1.88+0.02*v_c+18.94*f-0.16*f*v_c-0.01*a_p*v_c-2.42*a_p*f+0.63$
Model Variables (Oil)	**Surface response fitted functions**
F_y	$=-0.82+0.03*v_c-43.37*f+0.67*f*v_c-0.09*a_p*v_c+24.5*a_p*f+8.43$
F_x	$=7.5-0.05*v_c-87.99*f+0.77*f*v_c-0.03*a_p*v_c+45.0*a_p*f+1.03$
F_z	$=68.87+2.90*v_c+1493.75*f+3.125*f*v_c-2.95*a_p*v_c+1825.0*a_p*f+174.75$
M_z	$=275.17+0.77*v_c+6081.25*f-11.87*f*v_c+1.05*a_p*v_c-1825.0*a_p*f+317.25$
R_a	$=0.32+0.01*v_c+5.06*f-0.04*f*v_c-0.01*a_p*v_c-0.25*a_p*f+0.16$

4. CONCLUSIONS

- The use of the prototype of the mixing valve will allow the machining in different conditions of lubrication.
- The parameters that most influence the evolution of the forces F_t and F_f and the moment (M_z) are the cutting depthand the feed rate, being that a significant influence of the pair a_p and f in the evolution of the force F_t is perceived in the tests with graphite 30%.
- In the MQL tests, the feed force Ff showed no influence of feed rate f. In graphite tests, the influence of the advance is very significant, probably because the graphite is a solid lubricant (even in suspension) and has an anti-friction effect. Thus, the efficiency depends on the relative movement between the surfaces in contact and consequently depends on the feed rate f.
- The MQL process that was developed differs from the existing processes in terms of fluid path. Typically, compressed air travels through side channels while the fluid goes through an internal channel. However, in the study, the path was modified, which ultimately reduced the distance the fluid had to travel before being injected by gravity through the nozzle.

5. ACKNOWLEDGEMENTS

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