Evaluation of the Environmental Impact of different Lubrorefrigeration Conditions in Milling of -TiAl Alloy

Evaluation of the environmental impact of different lubrorefrigeration conditions in milling of γ-TiAl alloy

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Abstract

Conventional manufacturing techniques have not been subject to much scrutiny by industrial ecologist to date. The implementation of environment-friendly methodologies in metal cutting is, consequently, of considerable direct economic, social and technological importance. This paper aims to analyze the milling operation of a non conventional material such as γ-TiAl alloy from an environmental point of view, taking into account the impact of such material removal process in its various aspects. In particular, three kind of cooling conditions, namely wet, Minimal Quantity of Lubrication (MQL) and dry have been analyzed. Furthermore, for each coolant condition, different process parameters (i.e. cutting speed and feed rate) have been considered during milling operation in order to evaluate their environmental impact.

Keywords: Milling process, Lubricants, Sustainable production.

1 INTRODUCTION

The manufacturing processes were systematically developed and analyzed in order to achieve, through innovation, a maximum efficiency in association with economic manufacturing conditions. Nowadays the economical mass production is not enough to succeed but it is also important to adopt sustainable manufacturing practices like improving energy consumption, waste management, environmental impact, operational safety and personal health.

The faster way to assure sustainability in manufacturing is the analysis of the existing processes and their subsequently modification in order to achieve environmental benefits.

Among manufacturing processes, machining can be wasteful in its use of both materials and energy. In this paper, a preliminary analysis of the environmental impact during a milling process was carried out. In particular, the process has been evaluated through the measurement of the quality of the machined products, the tool life and the energy related to the different lubricant conditions. The measurements have been done at varying of lubrication methods (dry, wet and MQL), on a γ-TiAl sample. This "hard to machine" material was chosen since it is an attractive candidate for structural aerospace applications due to its high-strength, low density and specific weight, and good oxidation resistance. Furthermore, it is well-known that manufacturing process parameters have a significant impact on the performance/life of the final product [1-2]. Hence, the effects of process-level changes have been analyzed in order to truly achieve reduced environmental impact over the integrated product life cycle when γ-TiAl alloy is machined.

2 THE ROLE OF COOLING/LUBRICATION IN MACHINING PROCESS

An individual manufacturing process can be analyzed from the environmental point of view detecting the major factors of influence and the possible alternative design of the process. In machining the most prominent environmental issue is the profligate use of cutting fluids (CFs) or metalworking fluids (MWFs) that have different impacts on the machining process [3 - 4].

One of these concerns the electrical consumption: the absorbed power will increase due to the lubricant supply (pumping system and so on). Therefore, the total energy consumption of the process will increase.

Moreover, lubricants are also considered economic burden since they must be disposed and treated wastes at the end of their life cycle [1]. Furthermore, their use is also characterized by problems in the immediate working environment and hazards for the worker's health in contact with them [1 - 5].

As far as the first problem is concerned, It is known that the cutting fluid is assumed to diverge into four paths during the machining process: vapor waste stream generated through cutting-fluid diffusion into the surrounding environment; liquid waste stream created through fluid coating on the chips generated during the machining process; liquid waste stream resulting from cutting-fluid coating of the workpiece; lubricant flow collected and recirculated through the system. Theoretically speaking, and considering not leakages, the recirculating portion of the cutting-fluid stream is recovered and re-used. A significant portion of the chip-coated fluid may also be recovered through centrifugal or steam-injection methods (energy costly methods) but in this analysis the chip-coated fluid is assumed to be unrecoverable.

Concerning the hazards for human health, some parameters like the relative toxicity and flammability of lubricants have been taken into account as proposed by Munoz and Sheng [4] and resumed in Table 1. The level of toxicity LC_{50} is the Lethal Concentration Value used as one possible indicator of the degree of toxicity of a substance. The ranges of toxicity are indicated by the ranking value W_T. The value W_T = 5 indicates an extreme toxicity level of the substance considered, when W_T = 4 the level of toxicity is high and so on. The best level of W_T is equal to 1 indicating a low level of toxicity so a low level of hazard for human health. Another important indicator, for lubricant environmental evaluation, is the flammability indicated by the melting point Tm or the flash point T_f. A non combustible material presents a value of T_m > 500 °F so a ranking value of W_F equal to 1. A combustible lubricant presents a $T_f > 100$ so a W_F equal to 2 whereas $W_F= 3$ corresponds to a $T_f < 100$ so a flammable lubricant.

These trends pushed a number of research to find alternative techniques such as dry machining (cutting without the aid of CFs) as well as minimal quantity of lubrication (MQL) machining. Nevertheless, reach the aim of sustainability is not as simple as just to turn off the cooling/lubricating fluid supply but it is necessary to understand the machining process with cooling/lubricating mechanisms dealt within.

In fact, sometimes the dry process can be detrimental for the characteristics of the final product and can significantly reduce the useful life of the tool. The reason lies in several important functions of cutting fluids, like the reduction of temperature in cutting zone and of friction, the cleaning of tools and workpiece, the transport/evacuation of chips, etc.

An alternative is the MQL lubrication methods that lies on atomizing and delivering of a minute quantities of lubricants to the cutting zone in a compressed air jet.

The media employed, typically oils, are used to reduce friction and adhesion between the chip-tool and tool-workpiece interfaces. Consequently, the heat generated is lower than in completely dry machining case.

Toxicity	***Rank value (W_T)***
$LC_{50} > 450$	1
$350 < LC_{50} < 450$	2
$250 < LC_{50} < 350$	3
$150 < LC_{50} < 250$	4
$LC_{50} < 150$	5

Flash point (F°)	***Rank value (W_F)***
Tm > 500	1
Tf > 100	2
Tf < 100	3

Table 1. Rank value for toxicity and flammability for metalworking fluids.

3 EXPERIMENTAL PLAN

The experimental tests were performed using a three axis CORTINI M500/F1 vertical CNC milling machine, with a maximum power of 3.7 kW and a maximum torque of 24 Nm.

The milling operations were carried out on a γ-TiAl specimen with rectangular shape. It was obtained by electron beam melting process and thermal treated in order to improve the machinability. The chemical composition and the mechanical properties of the material are reported respectively in Table 2 and Table 3. Furthermore, the γ-TiAl specimen presented an average initial hardness of 273 HV30, acquired by a hardness tester *EMCOTEST M4U 025.*

The experimental set-up is shown in Figure 1. Tools used in the experiments were 10 mm diameter *VERGNANO F401 carbide ISO K30/K40* end mills, with 4 uncoated mills. The cutting tool angle was 12° and the helix angle was equal to 30°.The milling tests were executed in dry, MQL and wet conditions in order to verify the power absorption, the cutting forces acting during the process, the environmental impact and the quality of the machined samples (roughness indexes and hardness). The axial and radial depth of cut were fixed equal to 0.3 mm for all the tests. The complete experimental plan is reported in Table 4.

Figure 1: Experimental set-up of the milling tests.

More in detail, the first set of experimental tests was aimed to analyze the effect of the lubricant conditions fixing the process parameters in order to identify the worst case in terms of tool wear. At this stage, the cutting speed was equal to 50 m/min, the feed per tooth equal to 0.08 mm/tooth, and the axial and radial depth of cut were set to 0.3mm.

Then, the analysis was extended with the aim to evaluate the influence of the cutting parameters on tool life, surface quality and power consumption.

In particular, the feed was set to 0.1mm/tooth and three levels of cutting speed were selected. Only dry and MQL conditions were taken into account.

For all the tests reported in Table 4, the electrical power consumption, the roughness of the finished surface, the cutting forces and the tool wear were evaluated.

Elements	**%**
Aluminium	32.0-33.5
Niobium	4.5-5.1
Chromium	2.4-2.7
Oxygen	0.04-0.12
Nitrogen	0.020 Max.
Carbon	0.015 Max.
Iron	0.10 Max.
Hydrogen	0.001 Max.
Total Other Elements	0.05 Max
Titanium	60.0 Max.

Table 2. Chemical composition of γ-TiAl alloy.

The electrical power consumption was measured using a *Yokogawa* power meter which was clamped onto electricity supply wires to the machine. The evaluation was done by measuring the current in different steps, first of all, after switching the machine on, without activate the spindle or the motors.

After that, the motors were loaded and then the spindle speed turned on. The further step was to measure the current while the spindle was running and when the tool was positioning to the initial point of engagement without any other operation. Subsequently the total current was recorded during machining. Tools were periodically examined, by means of a stereo microscope LEICA MS5 (with 40X magnification), at each cutting passes, corresponding to every 10 minutes until the fixed acceptable wear was reached. The roughness of every milled surfaces were measured by a roughness tester *HOMMEL TESTER T1000*. Finally, the cutting forces acting during the process were measured by means of a four-component KISTLER dynamometer. For the WET process, the flow rate was equal to 10 l/min while for the MQL process was 0.0003 l/min.

Property (at Room Temperature)	
Tensile Strength	344.7 MPa
Yield Strength (0.2% offset)	275.8 MPa
Elongation, percent in 4D	0.50

Table 3. Mechanical properties of γ-TiAl alloy

Process Parameters	**Test 1**	**Test 2**	**Test 3**	**Test 4**	**Test 5**	**Test 6**	**Test 7**	**Test 8**	**Test 9**
Spindle speed [rpm]	1592	1592	1592	1114	1114	1592	1592	2260	2260
Feed rate [mm/min]	509	509	509	446	446	637	637	904	904
Cutting speed [m/min]	50	50	50	35	35	50	50	71	71
Feed per tooth [mm/tooth]	0.08	0.08	0.08	0.1	0.1	0.1	0.1	0.1	0.1
Lubricant condition	DRY	WET	MQL	DRY	MQL	DRY	MQL	DRY	MQL

Table 4: Experimental campaign.

4 RESULTS AND DISCUSSION

4.1 Power distribution

Figures 2-4 show the percentage of the power consumption for the three above-mentioned lubricant conditions, with a cutting speed of 50 m/min and a feed equal to 0.08 mm/tooth.

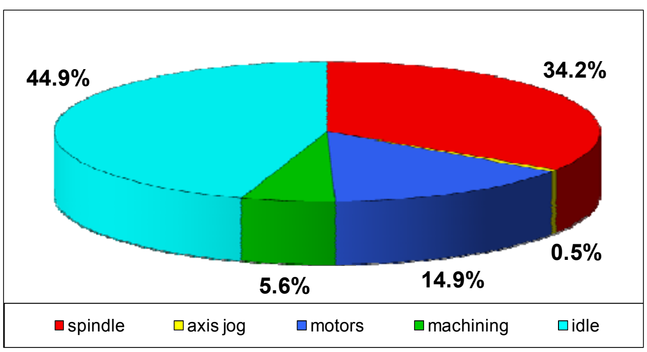

Figure 2: Power distribution in DRY milling .

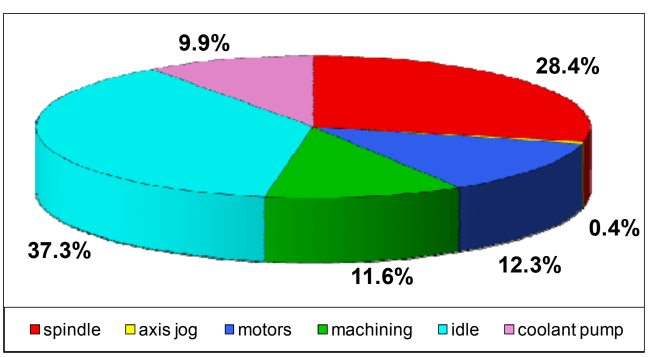

Figure 3: Power distribution in WET milling .

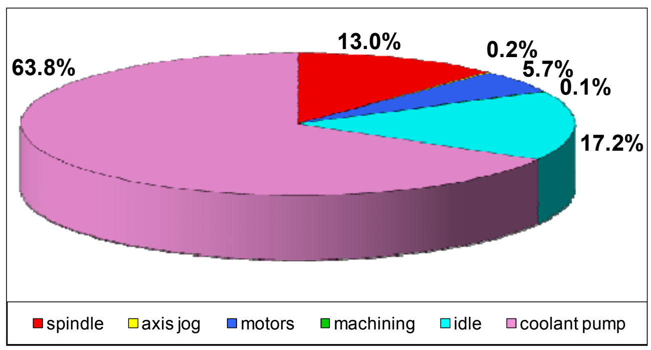

Figure 4: Power distribution in MQL milling .

The total power acquired for each test is the sum of diverse contributions: the idle power, the motors, the spindle, the axis jog and the coolant pump, when it is present.

Lubricant condition	**Total absorbed power**
DRY	1.35 kW
WET	1.46 kW
MQL	3.83 kW

Table 5: Total absorbed power for the three lubricant conditions

Although the machining power depends on material removal rate and workpiece material, the pie chart highlights that the non-cutting operations dominate power use in the machining process. Furthermore, the analysis carried out at the varying of the cutting parameters didn't highlight substantial differences in terms of power consumption. It is worth to pointing out that this trend is also due to the small values and variations of the selected cutting parameters. This precautionary choice was mainly due to the innovative material used in this research and, therefore, due to its unknown behavior under machining. In addition, the most power consuming process is the MQL one, due to the current consumption of the cooling equipment. Thus, the data presented in this study confirms that machine modules are the by far more significantly power consuming than the milling process itself [6].

4.2 Tool wear and tool life measurement

Tool life estimation was conducted using the above mentioned cutting conditions. The tool wear, which takes into account both the flank and the corner wear (Figure 5), was recorded every 10 minutes during machining and for each lubricant condition. The wear limit "TW*" was fixed to 100 µm.

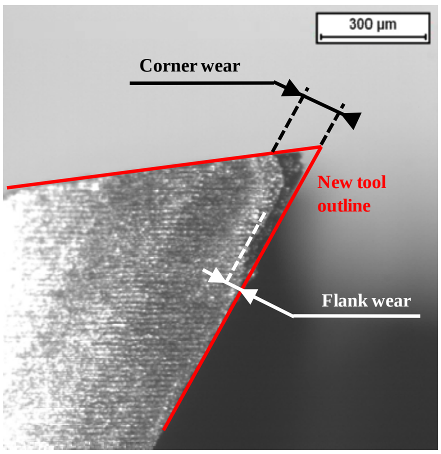

Figure 5: Tool wear measurement.

The results reported in Figure 6, at fixed cutting feed and speed (), highlight that the longer tool life was obtained using MQL cooling condition. In particular, tool life of 5.8 minutes was measured in wet condition, while 24.2 minutes and 145.1 minutes were respectively observed for dry and MQL cooling conditions. In addition, as shown in Figure 7, the tool wear is also influenced by the cutting speed: at the increasing of the cutting speed the tool wear decreases.

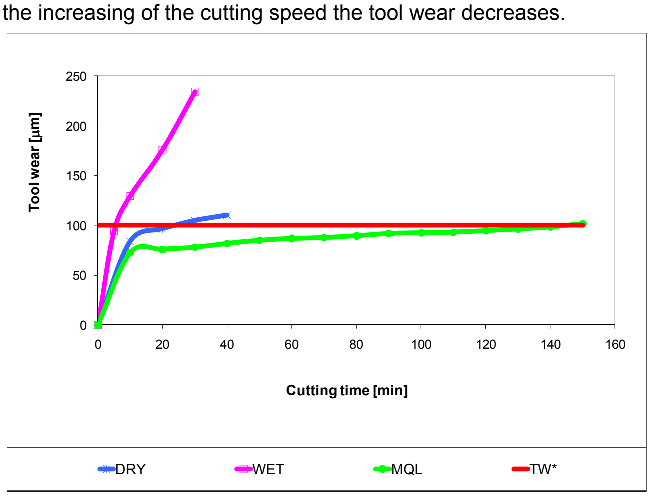

Figure 6: Tool wear for different lubricant conditions.

Finally, as depicted in Figure 8, the tool life of the MQL process is bigger than the others in all the investigated cases and, as a general trend, it increases by decreasing the cutting speed. Furthermore, the tool wear increases by increasing the feed per tooth.

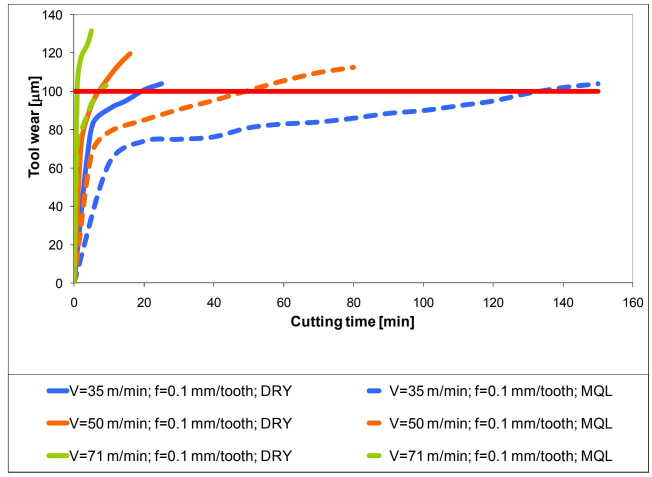

Figure 7: Tool wear measurement.

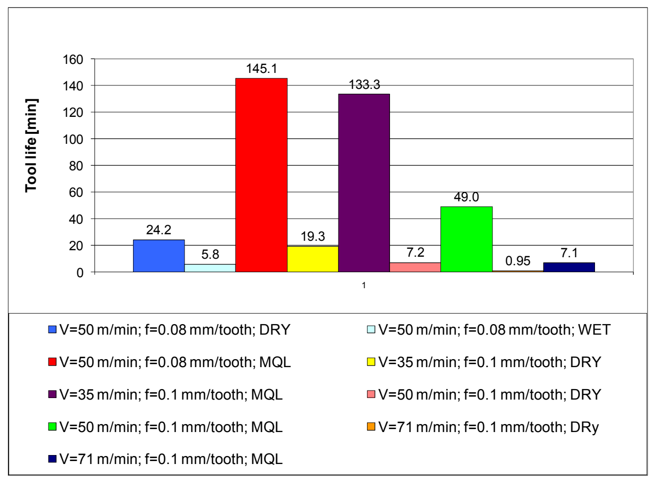

Figure 8: Tool life.

4.3 Roughness estimation

The roughness of the machined sample was measured for each lubricant condition in order to evaluate the characteristic of the machined surface. In particular, mean average, *R*a, the average maximum height of the profile, *R*t, the skewness, *R*sk, and the curtosis roughness, Rku, were measured. It is important to note that *R*sk and *R*ku are important roughness indexes when the machined surface lift needs to be investigated, especially for aerospace applications. The results, as shown in Table 6, demonstrate that each process presents acceptable profiles as far as the surface quality is concerned.

In particular, the maximum height of the profile ranged between 1.66 and 3.03µm while the Ra value varied from 0.22 to 0.32 µm. The skewness resulted to be less than 0µm in all the considered tests while Rku more than 3µm except in Test 8.

4.4 Manufacturing sustainability

Figure 9 reports the results of the different conditions utilized in this research as far as sustainability concepts are regarded. In particular, observing Figures 9-10, it can be noted as MQL process is the best compromise in terms of tool life and surface quality although, as above mentioned, the three cooling processes permit to obtain similar roughness quality indexes and therefore, machined surface quality.

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9
Rt [μm]	1.81	2.38	2.52	2.62	2.46	2.03	2.46	1.66	3.03
Ra [μm]	0.22	0.26	0.28	0.31	0.28	0.24	0.27	0.22	0.32
Rku [μm]	3.31	3.44	3.45	3.28	3.35	3.25	3.38	2.98	3.53
Rsk [μm]	-0.12	-0.36	-0.28	-0.05	-0.20	-0.09	-0.19	-0.05	-0.26

Table 6: Roughness results for the experimental campaign.

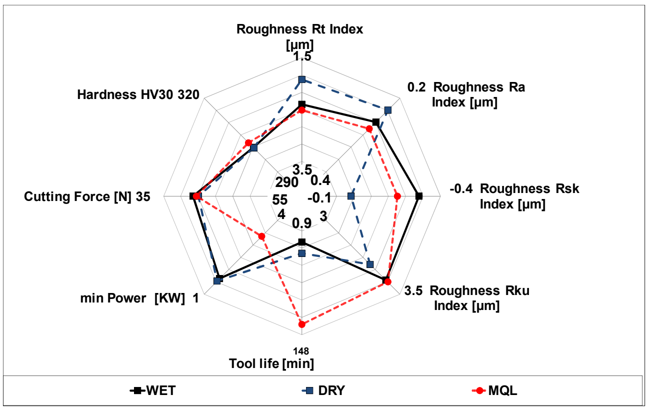

Figure 9 Comparison measured parameters for each lubricant conditions.

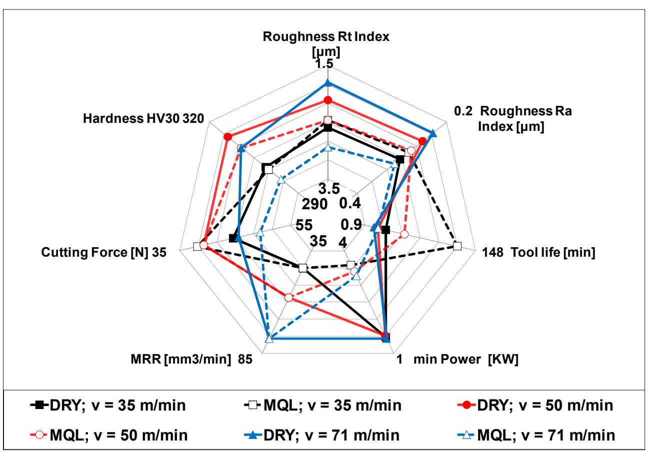

Figure 10 Comparison of measured parameters for each process conditions in dry and MQL conditions.

On the contrary, as far as the power consumption is regarded, it can be highlighted as the MQL cooling process is the most power consuming process compared to the others. On the other hand, it allows to reach longer tool life permitting to limit tool cost and tool replacement. Furthermore, as general trends, each process does not affect very much the current consumption while the machine modules and equipments are the major responsible of the electrical consumption. In fact, MQL condition shows the higher energy consumption due to the use of the coolant pump. Concerning the level of hazard for workers in contact with the lubricants, both the data sheet of the liquids used in MQL and WET didn't show the LC_{50} level. However, the MQL lubricant is completely a vegetable oil, consequently it's level of hazard is lower than that used for WET process (synthetic oil). In addition, the flammability level is also the lowest in the case of MQL (W_F=1) lubrication system. Finally, it is also important to highlight as the quantity of lubricant used during MQL process is significantly low, therefore less pollutant for the environment are produced.

5 CONCLUSIONS

In this paper milling experimental operations on γ-TiAl were carried out. The process was repeated for three different lubricant conditions in order to evaluate the environmental impact and the surface characteristics of each process. The overall results highlight that the MQL process has some benefits in terms of surface quality and especially for the tool life but it also results to be the most expensive process in terms of power consumption. For the considered process parameters, the MQL does not affects very much the roughness of the surface but it allows to save the tool for more than 65 time compared to the dry one and 24 times to the wet lubrication system. Finally, it should be pointed out that further investigations and experimental tests at varying of more severe cutting conditions will be necessary to improve the accuracy of proposed sustainability concept on this new classes of Ti-alloys for aeronautic aerospace industries.

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