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Ti6Al4V Titanium Alloy End Milling with Minimum Quantity of Fluid Technique Use

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To reduce the use of cutting fluids in machining operations is a goal that has been searched in the industry due to environmental and human health problems that the cutting fluids cause. However, cutting fluids still promote the longer life of the cutting tool for many machining operations. This is the case of Ti6Al4V titanium milling operation using coated cemented carbide inserts. Therefore, the aim of this work is to study the feasible cutting conditions for use of minimal quantity of fluid (MQF) technique, i.e., conditions that make the tool life in MQF technique closer or higher than those obtained with the cutting without lubrication/cooling and cutting fluid jet without giving up productivity and the average roughness of the parts in the process. To achieve these objectives, several trials at Ti6Al4V end milling were performed by varying the cutting speed and feed rate with MQF application technique using vegetable cutting fluid compared with no lubrication/cooling and cutting with jet fluid to 8% aqueous emulsion. The main conclusion from this study was that the application of the MQF technique in Ti6Al4V end milling process increases the tool life and productivity and reduces the average surface roughness, while maintaining the same cutting conditions originally proposed in machining. Finally, microstructural analysis by scanning electron microscope (SEM) and energy dispersive spectrometry (EDS) was performed from cutting tools, and the main wear mechanisms when varying the lubrication/cooling systems employed were observed.

Keywords Ti6Al4V titanium milling; MQF technique; Optimization of cutting conditions; Minimum quantity of fluid to the Ti6Al4V titanium.

Introduction

Recently, the use of cutting fluids in machining operations has been reduced due to its high operating cost and environmental and human health problems that they cause.

Therefore, so much has been done to minimize the difference between the processes using cutting fluid in abundancy by fluid jet and the technique called minimal quantity of fluid (MQF).

The MQF is the procedure of spraying a small quantity of fluid (50 ml/h on average) in a flow of air directed at the workpiece cutting zone consuming a very small amount of fluid [1].

The Ti6Al4V titanium alloy has been widely used in aviation industry and aerospace and currently represents about 60% of the world's titanium production [2].

Furthermore, titanium has been used in marine, medical, dental, and commercial applications because of their low specific weight, high specific resistance, even at high working temperatures, and excellent corrosion resistance [3].

However, it is a material with poor machinability due to its low thermal conductivity, which increases the cutting temperature and cutting tool wear, which usually leads to higher production costs and a poor surface quality in machining [4].

Therefore, the use of cutting fluid in abundance or fluid jet has been so far the most common strategy for cutting temperature control for Ti6Al4V machining.

To enable the use of the MQF in machining processes, new cutting inserts and coatings have been developed.

The MQF technique is suitable for some machining processes for specific cutting conditions, but it is not correct for other processes, for not achieving acceptable levels of tool life, surface quality, and productivity compared to other lubrication/cooling systems used.

The application of MQF technique has advantages over the fluid jet as it generally reduces problems:

Environmental problems caused by discarding of fluids, when saturated at the environment.

Human health problems caused by the toxic contact of fluids with the skin, respiratory system, and eyes of the operator.

High costs spent for the treatment and reuse of saturated fluids and wash and reuse of chips due to its chemical contamination caused by non-biodegradable fluids and additives [5].

The use of MQF technique, when the cutting is impractical without lubrication application, brings great contribution in sustainable terms, given the huge volume of titanium Ti6Al4V milled in the aerospace and aviation industries, among others.

This work aimed to establish cutting conditions, such as the cutting speed, feed rate, depth of cut, and defined boundary conditions that make the tool life, productivity, and Ti6Al4V surface finish in end milling, suitable for

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MQF use closer or higher to those obtained using conditions of vegetal fluid jet miscible in water at 8% and cutting w/o lubrication.

This work aims to study the main wear mechanisms through SEM/EDS analysis of tool life end and the influence of each condition of employed lubrication/cooling.

The interaction between tool, chips, and workpiece causes not only tool wear, but also leads to chipping and the mechanical and thermal fractures of it, due to actants wear mechanisms that combined with one another vary the tool deterioration forms [6].

Mechanical impacts and vibration are also frequent in milling due to the uninterrupted cutting inherent in the process, which can generate mechanical cracking, chipping, and cutting edge breakage.

Therefore, it is necessary to choose a cutting tool with sufficient hardness and rigid cutting edge with proper positioning in relation to the workpiece to absorb the energy of these impacts without compromising tool life [7].

Due to the high cutting temperatures occurring in the titanium alloy machining, the diffusion is quite often. The cobalt (Co) binder, the carbon and tungsten (W, C) of carbide substrate, the insert coating (C, N, Ti), and titanium alloy material (Ti, Al, V) have a great affinity and can be dissolved in one another.

Wear and mechanical damage has its origin in wear mechanisms, such as cutting built-up edge, abrasion, adhesion, diffusion, oxidation, solubilization, attrition, thermal and mechanical loads variations, impacts between tool and workpiece, etc. [8].

Abrasion is induced, because the Ti6Al4V alloy contains hard particles as vanadium and abrasive particles as aluminum, which rub against tool cutting edge and/or against microparticles torn from the tool itself that are in a sliding zone between the chip and workpiece.

The tool's ability to resist abrasive wear is related to its hardness [6].

The wear zone caused by abrasion usually shows parallel risks to the cutting direction and/or notches [9].

The diffusion in Ti6Al4V involves the transfer of atoms between the workpiece material, substrate, and insert coating with a high solubility between the involved elements and the workpiece primary and secondary shear zone, according to the contact period between these materials and the cutting zone temperature [7].

The adhesion is formed by a Ti6Al4V metallic extract layer combined on tool substrate surface due to the great diffusion in contact between tool and the workpiece with moderate loads and high temperatures [3].

Attrition occurs by the combination of abrasion and adhesion of Ti6Al4V material, usually at low cutting speeds with cyclical adhesion in the tool, where microscopic particles pulled out of the tool and taken with the chip on a sliding area formed between the chip and the workpiece. This mechanism is favored by high temperatures in the cutting zone, by uninterrupted cutting, by irregular thickness chips, and by vibrations and generates very rough surfaces. [10].

The traditional way of reducing the activation of many tool wear mechanisms is the heat reduction generated in the process and the cutting fluid use.

The vegetable cutting fluid used to implement the MQF was also evaluated for its importance in the process yield and their physical and chemical effects that influence the tool wear.

These cutting conditions being met have great productive importance, as will as enable the implementation of the MQF in this process, improving the surface quality, productivity, and economic efficiency and reducing the environmental impact in much of the world's titanium production using processing by milling of Ti6Al4V alloy.

At the level of research, the study of Ti6Al4V finish milling optimization with the use of minimum quantity of fluid technique (MQF) has not yet been consolidated, although several studies emphasize the great importance in increasing the cutting tool life, productivity, and surface quality in the machining of this material with difficult machinability. Investments in technical improvement in the finishing by face milling using the MQF technique operated by CNC machines to industrial operating regime can guarantee in practice largest economy in the productive system with increasing the cutting tool life and increasing the reliability of the produced part surface quality.

Some studies have been conducted on Ti6Al4V machining using the MQF technique here cited to emphasize the evolution, importance, and relevance of the chosen theme; Wakabayashi et al. [11] reported that synthetic ester surpassed vegetal oils in terms of friction coefficient due to the efficiency of oil film formation on the cutting tool and the machined surface.

Sales et al. [5] studied the cooling capacity and lubrication of some cutting fluids used in machining operations. The results showed that the cooling capacity of these fluids was in increasing order of efficiency: synthetic oil 1, pure water, synthetic oil 2, emulsion in water, neat oil, and cutting without lubrication, respectively.

There was little difference in the formulation of two synthetic oils used.

The lubricity capacity of the fluids used in the experiment was in increasing order of efficiency: neat oil, emulsion in water, cutting without lubrication, synthetic oil 2, synthetic oil 1, and pure water, respectively.

Su et al. [12] performed the experimental investigation of lubrication and cooling condition effects of compressed nitrogen-based gas cooled to 0°C and −10°C with and without sprayed oil, cooling by dipping and cutting without lubrication/cooling compared with each other, in the wear of carbide cutting inserts coated on Ti6Al4V finish milling at high-speed machining (HSM).

The main conclusion was a better efficiency of the lubrication/cooling system proposed in nitrogen gas compression-based cooled to −10°C with sprayed oil. The chipping, fracture, wear by diffusion, and thermal fatigue of the inserts side edges were the main mechanisms and failure modes of this process.

Jiang et al. [13] performed various face milling machining experiments using coated carbide inserts with four different cutting speeds, varying the depth of cut, working penetration, and feed rates in Ti6Al4V samples. They used three different lubrication/cooling systems: cutting without lubrication, cutting with vegetable fluid jet miscible in water at 8%, and cutting with the MQF technique.

Its main conclusion was that the implementation of MQF technique in certain cutting conditions improved the roughness of the sample in relation to the fluid jet and cutting without lubrication.

Wins et al. [14] applied the MQF technique in AISI 4340 steel turning. A better roughness with the MQF use was found.

Diniz and Micaroni [15] compared the cutting conditions to approach the life of the cutting tool without lubrication/cooling to those obtained with fluid jet in the 1045 steel finish turning without damaging its roughness. The main conclusion of this work was a good tool life approaching certain cutting conditions such as cutting speed reduction, increase feed rate, and tool nose radius.

Da Silva et al. [16] worked in a comparative study of machining conditions influence without lubrication/cooling and wet during the AISI 1047 steel finishing milling with carbide tools. Cutting fluids were directed to the cutting zone by three different systems: cutting without lubrication/ cooling, fluid jet, fluid reduced rate, and MQF.

The results showed that the major cutting length values and material removed volume were obtained with the application of cutting fluid reduced flow and cutting insert wear mechanisms, and their failure modes have been affected by the machining conditions employed.

Rahim and Sasahara [17] studied the effects of using vegetable fluid (palm oil) in the implementation of MQF technique for Ti6Al4V titanium alloy drilling in high-speed operations.

This research showed that the fluid jet condition can be replaced by MQF technique with the use of synthetic ester or vegetable fluid that showed results close to the tool life.

Anhai et al. [18] presented an experimental study of increasing wear in coated carbide inserts for milling and their failure modes for Ti6Al4V high speed with cutting w/o lubrication/cooling.

The main experimental results showed that the cutting speed is related to the tool failure mechanism progression with different conditions of friction and cutting temperature.

It was observed that the MQF technique application study, the improvement of tool life, productivity, and surface finishing in Ti6Al4V front-end milling are subjects of great research investments.

However, there was still no record of articles dealing with tool life analysis, productivity and surface finish in machining by MQF technique use in Ti6Al4V front-end milling under industrial conditions, and have not been investigated specifically, the influence and effects of the machining conditions variations, appropriate to obtain superior results in relation to fluid jet and cutting w/o lubrication/cooling.

In the works presented above have not been studied the best cutting speed parameters, feed and depth for better production condition and surface quality nor the study of their wear mechanisms, the importance of these factors in the production control even being suggested, which inspired the need to study proposed in this paper.

The use of cutting fluid in abundance or fluid jet has been so far the most common strategy for achieving higher productivity and surface quality in Ti6Al4V finish milling.

In this article, the boundary conditions to obtain cutting speeds, feed rate, and depth of cut in Ti6Al4V finish milling have been determined, resulting in a response set with longer tool life (TL), removed material volume (V), material removal rate (Q), lower average roughness (R_a), and maximum average roughness (R_z) with its cutting yield compared to each other with cutting w/o lubrication (D) and vegetable fluid jet at 8% (J) in relation to MQF w/o vegetable fluid (M).

The cutting inserts used were analyzed by SEM/EDS analysis for the main causes study of wear mechanisms in each lubrication/cooling condition employed.

Materials and methods

For the tests, we used three Ti6Al4V samples (UNS R56400) hot rolled and solubilized (36HRc).

The tests were performed in a Romi D 800 vertical machining center with 6000 rpm maximum engine speed, 22 KW maximum power, 30 tool magazine, and FANUC Series OI-MC command [19].

The fluid jet system (J) is part of a machine lubrication/cooling system with pumping of cutting fluid miscible in water to 8% (Blaser Swisslub Vasco1000) with 2 Bars pressure and flow rate of 20 l/min.

The spray MQF system (M) with air flow rate of 200 l/min with separated supply piping (ITW Chemical Accu-Lub) employed was adapted to the machine lubrication/cooling system where a small amount of vegetable neat fluid (ITW Chemical LB 1100), about 60 ml/h on average, with specific weight of 0.95 g/cm^3, viscosity at 40°C of 48 mm^2/s, viscosity index of 190, and flash point of 312°C was applied in high-pressure fog of 2 Bars, at room temperature at the outlet of two applicators, directed the closest possible of contact between tool cutting edge and piece cutting zone with the tool rotation [1].

In tests the carbide inserts with normal grains of 1.0 μm and ISO S40 classes coated with titanium carbonitride (TiCN) by physical vapor deposition (PVD) process (Taegutec APCT 120430 R Class) were used. The cutter head has a positive axial and radial rake angles (TaeguTec Class TE90AP325-M12-12).

The PVD process was chosen to ensure the same substrate original toughness, which does not occur when using the CVD process, and further it has a thinner layer thickness, allowing more sharp edges, ensuring that the tool tip radius is slightly altered, promoting a better surface finish on the workpiece.

The titanium carbonitride (TiCN) which has very similar properties to TiC, TiN, and TiAlN was chosen by the lower friction coefficient and greater hardness compared to other coatings, avoiding the adhesion of workpiece material on the tool and providing greater resistance to flank wear when dominant the wear mechanism for abrasion, and enabling its use as a single-layer coating.

The choice of normal grains (1.0 microns) to the insert substrate rather than submicrograins (with greater toughness) occurred because it is believed that larger grains on the tool substrate to reduce the solubilization between its elements (Co, W, C, Ti, Ta), coating (C, N, Ti) and workpiece (Ti, Al, V) in the cutting zone with machining temperature increasing, which would cause lower diffusion and adhesion layer with the tool coating wear.

Measurement of the roughness values (R_a and R_z) of each sample after each milling stage was performed by a portable rugosimeter TR100 Time Series High Technology Company [20] with cutoff $\lambda c = 0.8$ mm. Measurement of the cutting insert wear after each milling step was performed by a portable digital optical microscope Capture Micro USB version 2.0 Digimicro Ind. [21]

Microstructure analysis of cutting inserts used in the tests was made using a scanning electron microscope (SEM/EDS) high-definition Zeiss Inca NCAx-act with emission gun for field effect.

The control variables adopted for this experiment were:

i. Cutting speed (V_c)
ii. Feed rate (f)

Conditions of lubrication/cooling:

i. Cutting w/o lubrication/cooling (D)
ii. Fluid jet miscible in water to 8% (J)
iii. MQF w/ vegetable fluid (M)

These variables were those that most influenced the milling process, with the cutting insert wear and the sample finish surface.

The response variables were:

i. Flank wear (V_B)
ii. Cutting length (C_L)
iii. Removed material volume (V)
iv. Material removal rate (Q)
v. Roughness average (R_a)
vi. Maximum average roughness (R_z)

The milling tests were designed in order to provide an accurate and clear comparison of the influence of cutting speed, feed rate, and cutting conditions used in the cutting tool wear and piece surface roughness, through three tests for each experiment, as shown in Table 1, and it was demonstrated if the best responses obtained for the cutting fluid jet (J) and cutting w/o lubricant/cooling (D) would be overcome by obtained responses with MQF technique (M) use with vegetal cutting fluid employed.

TABLE 1.—Test parameter identification.

Test number	Test identification	Machining condition	V_c [m/min]	f [mm/rev]
1	D-70-0.2	D	70	0.2
2	D-90-0.2	D	90	0.2
3	D-110-0.2	D	110	0.2
4	J-70-0.2	J	70	0.2
5	J-90-0.2	J	90	0.2
6	J-110-0.2	J	110	0.2
7	M-110-0.2	M	110	0.2

Some parameters have been recommended by cutting insert manufacturer for fluid jet condition (J) although there are no diagrams of the break chip zone that would indicate a better relationship between depths of cut and feed rates for the used inserts.

For savings and suitability of the available material in carrying out the tests, a depth of cut (a_p) of 0.3 mm considered compatible for this finishing operation was adopted.

For suitability of the sample material, the tests using MQF technique (M) were only performed with a cutting speed (V_c) of 110 m/min since, if the response variables obtained from this machining condition were higher than those obtained under conditions (D) and (J) with cutting conditions of 70, 90, or 110 m/min, this technique would be justified by gain in productivity, cost reduction and cutting fluid used, lower discard and waste pollution treatment, wash and reuse of material removed, use of biodegradable vegetal fluids, and improvement of environmental, ecological and human health associated with MQF use.

Three replicates were performed for the tests identified in Table 1. After four consecutive passes were made the wear measurements of the three inserts of cutting head to determine its arithmetic average (V_B) and simultaneously the measuring of three arithmetic average roughness values (R_a) and (R_z) of the machined sample can be established the standard deviation and the evolution of these measures in each test performed.

The depth of cut (a_p) was the same for all tests, varying only the cutting speed, feed rate, and machining conditions.

The cutting insert geometry and cutting conditions used in the Ti6Al4V experiments were selected and controlled as a boundary condition for optimizing the proposed studies, such as inserts substrate material, deposition process and insert coating material, axial and radial positive angles, lateral incidence angles and positive position angle, long edge inserts with nose radius of 3 mm, head milling with three inserts, axial and radial adjustment control between inserts with a maximum beating of 0.02 mm, involute cutting direction, concordant in the machined route and penetration work with 80% of the head milling diameter, strength in tool settings and in fit between piece-machine, low

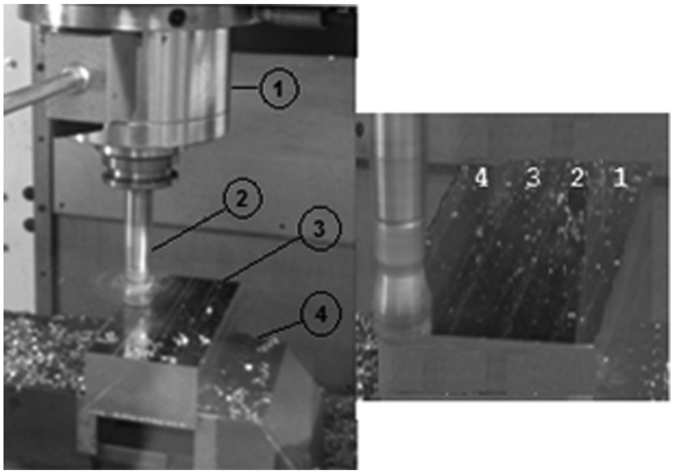

FIGURE 1.—Ti6Al4V front-end milling tests.

finishing cutting forces, continuous cutting with constant removed material thickness, and cutting fluid flow directed between inserts and cutting zone.

All these parameters have a great influence on the final results of the experiments and had their default values controlled both to optimize the process and to ensure that these parameters were compared without outside interference to the previously proposed boundary conditions.

Figure 1 shows the milling transmission shaft (1), head milling and cutting inserts (2), Ti6Al4V machined sample (3), vise for sample attachment (4) in the machine, and the milling operation with a completed pass at every four machined passed on 1, 2, 3, and 4.

At every four passes machined, the cutting tool had the insert flank wear measured.

When the measurement of the average flank wear of the three inserts reached $V_B = 0.30$ mm (insert life end) the passes number applied for performing for each test was added and the final cutting length covered by the tool was calculated.

Figure 2 shows the movement scheme of passed 1, 2, 3, and 4 with the same cutting direction beginning at A, B, C, and D till to be completed each machined pass. The CNC milling machine was programmed to complete four passes with depth of cut (a_p) of 0.3 mm for each pass before the stop for measurements.

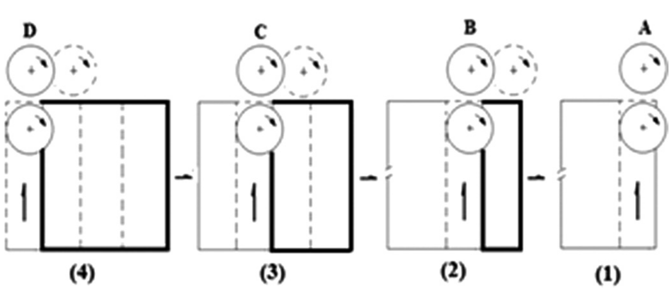

FIGURE 2.—Evolving movement scheme of the tool in each pass.

With this procedure, it was possible to monitor the wear progress of cutting inserts with greater accuracy by the micrographs and measurements performed by optical microscopy.

This procedure was repeated in all test combinations with the count of pass number until it reaches the insert life end.

At the end of each test, the used cutting inserts were properly identified by their position in the cutting head milling and the numbering of the performed test for the further trial in a SEM/EDS.

Aspects involving cutting conditions and measurements of inserts flank wear in milling have been established by ISO 8688-1-2/ 93 [22].

For greater accuracy of the obtained test results, the cutting insert flank wear with long edges were measured by photomicrographs with 0.01 mm resolution and by calculating the cutting length (C_L), removed material volume (V), and material removal rate (Q) considering the sample dimensions and work penetration (a_e) applied to each test.

RESULTS AND DISCUSSION

The results of this work are vanguard since it establishes an unprecedented way a comparative study of MQF technical efficiency with vegetable cutting fluid in relation to cutting condition w/o lubrication/cooling ooling and cutting w/o fluid jet in Ti6Al4V finish milling, which can be applied to much of titanium world production that has in milling w/o fluid jet your primary means of processing.

An efficiency percentage of MQF technique compared to other cutting conditions studied was established, taking into account the process dispersions to a certain cutting speed range, feed rate, and cutting depth resulting in longer tool life, removed material volume, material removal rate, and a lower roughness degree in the sample finishing.

Figure 3 shows the increasing order of the tool life expressed by its cutting length and standard deviation range ($C_L \pm \sigma C_L$).

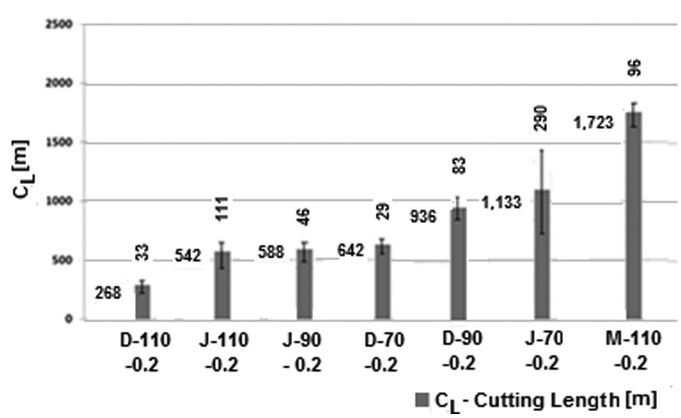

FIGURE 3.—Cutting length (CL) with variation of machining conditions and cutting speeds.

TABLE 2.—Relationship between the tool life (TL) with MQF (M), cutting w/o lubrication/cooling (D), and fluid jet (J) with longer cutting lengths.

Relationship (TL)	TLM110/TLD90	TLM110/TLJ70
Yield	84%>	52%>
Variance	35 to 56%	12 to 57%

For the cutting w/o lubrication/cooling (*D*), the longer tool life (TLD) was at a cutting speed of 90 m/min and a feed rate of 0.2 mm/rev, i.e., D-90-0.2, TLD90.

For cutting w/ fluid jet (*J*), the longer tool life (TLJ) was at a cutting speed of 70 m/min and a feed rate of 0.2 mm/rev., i.e., J-70-0.2, TLJ70.

For the cutting w/MQF (*M*) with vegetable fluid the tool life (TLM) was at a cutting speed of 110 m/min and a feed rate of 0.2 mm/rev, i.e., M-110-0.2, TLM110.

The percentages established in Table 2 demonstrate the highest yield of cutting tool life using the MQF technique with vegetable fluid in relation to the other conditions of lubrication/cooling employed and the feasibility of applying this technique in Ti6Al4V finish milling.

These yield percentages can quantify in each specific application and more effectively, both the productive and economic improvements resulting from the MQF application, for the environmental improvements resulting from their use.

Figure 4 shows the evolution trend of insert flank wear (V_B) as a function of the pass number (*P*) applied in machining w/o cutting fluid use and cutting speed varying of 70, 90, and 110 m/min to the insert life end with $V_B = 0.30$ mm to D-70-0.2, D-90-0.2, and D-110-0.2.

It is noted that the longer tool life for cutting w/o lubrication/cooling use was 936 m or 109 min with cutting speed of $V_c = 90$ m/min. The tool wear variation at each pass occurred more uniformly than in the other cutting speeds studied. It is also apparent that the cutting built-up edge formation did not occur even in a lower cutting speed condition.

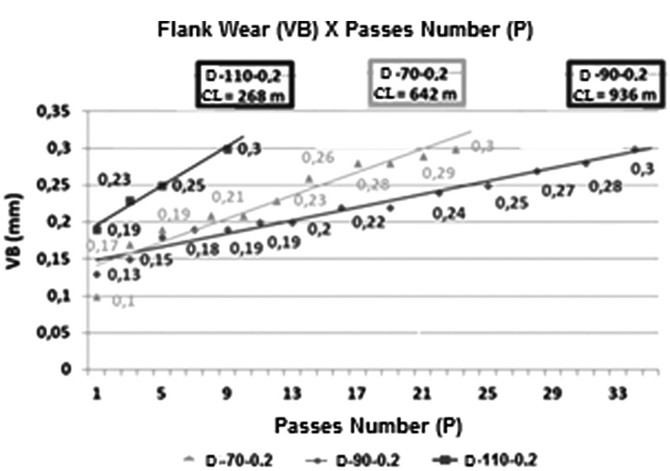

FIGURE 4.—Evolution of flank wear (VB) for cutting w/o lubrication/cooling (*D*).

The increased cutting temperature generated by lubrication lack and lower cooling capacity of Ti6Al4V by thermal conductivity to the workpiece and the chip or by convection between the tool and air with the tool rotation with the uninterrupted cutting milling limits the possibility of cutting speed increasing by high heat retained in tool that can reach 1400°C [12] deteriorating rapidly.

It is believed that the high temperatures generated at the interface between the workpiece and the tool during Ti6Al4V machining w/o lubrication/cooling on one hand facilitates the machined material cutting decreasing the mechanical stress and friction, generated between the tool and workpiece up to a given limit of $V_c = 90$ m/min and on the other hand above this limit, with higher cutting speeds are increased: the mechanical stress with the impact of tool teeth on the workpiece, friction, and temperature leading to a tool premature deterioration.

This phenomena combination explains by hypothesis the obtained results for this machining condition.

Figure 5 shows the evolution trend of insert flank wear (V_B) as a function of the pass number (*P*) applied in machining w/o fluid jet miscible in water to 8% use and varying cutting speeds of 70, 90, and 110 m/min to the insert life end with $V_B = 0.30$ mm to J-70-0.2, J-90-0.2, and J-110-0.2.

It is noted that the longer tool life for the cutting fluid jet miscible in water to 8% use was 1133 m or 203 min with a cutting speed of $V_c = 70$ m/min. The tool wear variation at each pass occurred little uniformly in this condition, but of the more gradual way than in other cutting speeds applied, and yet it was noticed that there was no formation of cutting built-up edge during the machining.

The cutting fluid used based on water in the uninterrupted cutting as the milling, although lubricate the cutting zone and considerably reducing the friction during machining, yet do not avoid the high cutting temperatures generated at the cutting tool due to low titanium thermal conductivity and its high abrasion, but has a

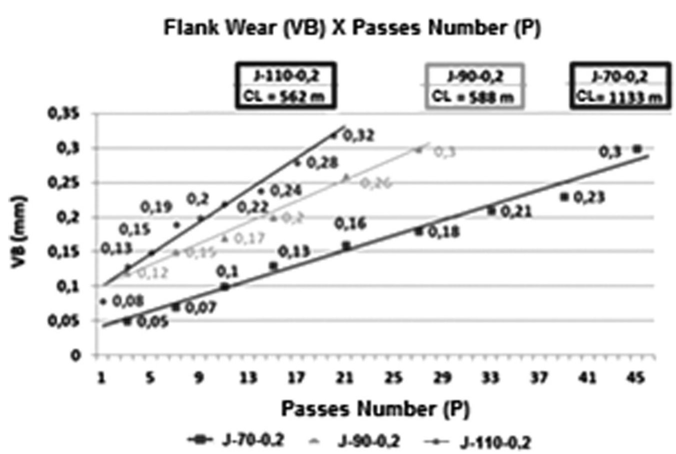

FIGURE 5.—Evolution of flank wear (VB) for cutting w/fluid jet (*J*).

cooling effect which leads to a rapid heating and cooling in your workpiece input and output in each working cycle, weakening it by heat shock action and at the same time the cooling caused by the fluid in the cutting zone makes the workpiece material more resistant leading to an increased cutting stress on the tool edge.

The cutting fluid increases the tool life by reducing friction in the cutting zone up to a given limit of $V_c = 70$ m/min where there are mechanical and thermal shocks supported by the tool, but above this limit, with increasing cutting speed, the mechanical stress with the tool teeth impact on workpiece, the friction, and tool temperature are increased which when cooled at higher temperatures and abruptly cause its thermal fatigue leading to its premature deterioration.

This phenomena combination explains by hypothesis the obtained results for this machining condition.

Figure 6 shows the evolution trend of insert flank wear (V_B) as a function of the pass number (P) applied in machining with MQF technique use w/cutting speed of 110 m/min to the insert life end with $V_B = 0.30$ mm to M-110-0.2 w/ vegetable fluid.

It is noted that the longer tool life in relation to the greater tool life results of the others cutting conditions studied were for the cutting w/MQF w/vegetable fluid with 1723 m or 213 min, with cutting speed of $V_c = 110$ m/min and feed rate of 0.2 mm/rev.

The tool wear increase at each pass occurred in a uniform and gradual way to the MQF w/o vegetable cutting fluid with higher cutting speeds in relation to D-90-0.2 and J-70-0.2, and it is noticed that there was no cutting built-up edge formation during the machining.

It is believed that with the MQF technique application where a small amount of fluid is sprayed onto the contact between the chips and the cutting zone for a better lubrication, a more efficient friction reduction and heat generation avoiding the premature wear of the cutting tool occurred.

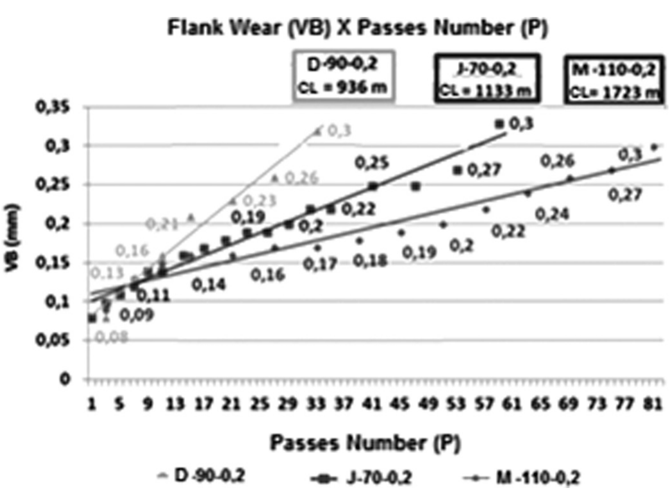

FIGURE 6.—Evolution of flank wear (VB) for cutting with MQF (M) in relation to other studied conditions with longer cutting length.

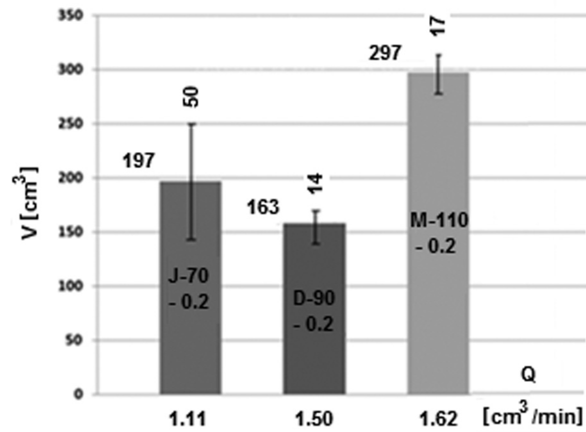

FIGURE 7.—Removed material volume (V) and material removal rate (Q) in the studied conditions with longer cutting lengths.

It was noticed that with the MQF application with vegetable fluid, one can operate with a higher cutting speed $V_c = 110$ m/min, with a smaller tool wear rate in relation to other employed machining conditions. This slowing of flank wear progression can be attributed to the superior lubricating/cooling effect of MQF with vegetable cutting fluid application.

Figure 7 shows the measure of the removed material volume (V) and the material removal rate (Q) for MQF technique application: M-110-0.2 with (VM) and (QM), considering the process dispersion with standard deviation ($\pm\sigma$VM) and the highest obtained values for cutting w/fluid jet J-70-0.2 with (VJ70) and (QJ70) and cutting w/o lubrication/ cooling D-90-0.2 with (VD90) and (QD90) considering the process dispersion with standard deviation ($\pm\sigma$VJ) and ($\pm\sigma$VD), respectively.

To quantify the performance of studied MQF technique, a relationship between M-110-0.2 with VM110 and QM110 and the obtained values for cutting w/fluid jet J-70-0.2 with VJ70, QJ70 and cutting w/o lubrication/cooling D-90-0.2 with VD90, QD90 which reached the highest values of removed material volume (V) and material removal rate (Q) was established, as shown in Table 3.

These yield percentages of the removed material volume and material removal rate were established between the studied machining conditions so that can be quantified in each specific application and more effectively, both the productive and economic improvements resulting from application of this process about the environmental improvements arising from MQF technique use.

TABLE 3.—Relationship between removed material volume (V) and material removal rate (Q) for MQF (M), cutting w/o lubrication/cooling (D), and cutting w/ fluid jet (J) with longer cutting lengths.

Relationship (TL)	VM110/VD90	VM110/VJ70
Yield	82% >	51% >
Variance	77 to 88%	27 to 90%
Relationship (Q)	QM110/QD90	QM110/QJ70
Yield	8%>	46% >

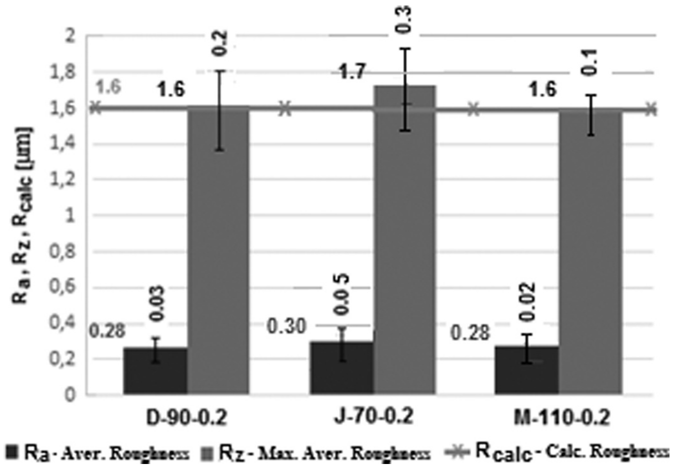

FIGURE 8.—Average roughness (R_a), maximum average roughness (R_z), and calculated roughness (Rcalc.) to the applied machining conditions with longer cutting lengths.

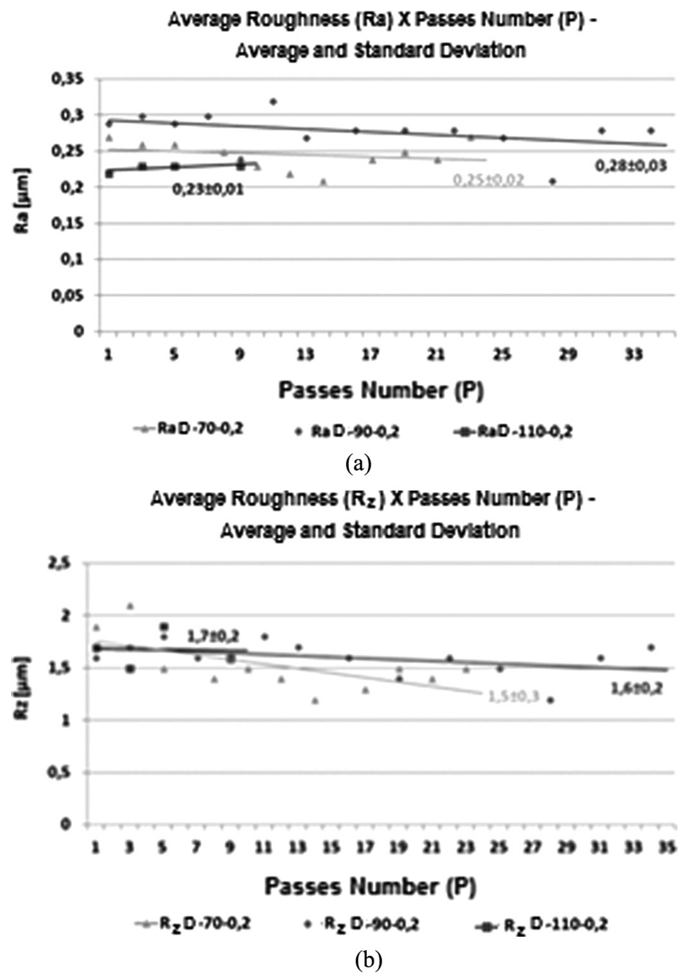

FIGURE 9.—(a).Average roughness (R_a) evolution for cutting w/o lubrication/cooling (D). (b)Maximum average roughness (R_z) evolution for cutting w/o lubrication/cooling (D).

The numbers mentioned above justify the higher yielding of removed material volume and material removal rate using the MQF technique with vegetal fluid M-110-0.2 in relation to the other conditions of lubrication/cooling employed in Ti6Al4V finish machining.

Figure 8 shows the values of average roughness (R_a), maximum average roughness (R_z), calculated roughness (R_{calc}), and their respective standard deviations (σR_a), (σR_z) arranged in increasing order with longer cutting length (C_L).

To quantify the performance of the average roughness (R_a) and maximum average roughness (R_z) to the MQF technique studied M-110-0.2, a relationship w/values R_aM110 and R_zM110 and cutting w/fluid jet J-70-0.2 w/o values R_aJ70 and R_zJ70 and cutting w/lubrication/cooling D-90-0.2 w/o values R_aD90 and R_zD90 which reached the highest cutting length values in machining, as shown in Table 4.

The numbers mentioned above justify the higher yielding and lower average roughness (R_a) and maximum average roughness (R_z) using the MQF technique with vegetal fluid M-110-0.2 in relation to the other conditions of lubrication/cooling employed in Ti6Al4V finish machining. The roughness in the studied machining conditions can be considered statistically similar.

Figure 9(a) shows a little accentuated decreasing trend in evolution of average roughness (R_a) of machined surfaces according to pass number (P) applied to the insert life end w/o use of cutting fluid (D) with cutting speed variation of 70 and 90 m/min and an accentuated increasing trend in evolution of average roughness (R_a) with a cutting speed of 110 m/min.

TABLE 4.—Relationship between average roughness (R_a) and maximum average roughness (R_z) for MQF (M), cutting w/o lubrication/cooling (D), and cutting w/o fluid jet (J) with longer cutting lengths.

Relationship (R_a and R_z)	R_aM110/ R_aD90	R_aM110/ R_aJ70	R_zM110/ R_zD90	R_zM110/ R_zJ70
Yield Variance	0% = Similar	9% < Similar	0% = Similar	9% < Similar

Figure 9(b) shows a little accentuated decreasing trend in evolution of maximum average roughness (R_z) of machined surfaces according to pass number (P) applied to the insert life end w/o use of cutting fluid (D) with a cutting speed variation of 70, 90, and 110 m/min.

It is believed that the insert wear occurring evenly increases its contact area with the workpiece causing a smoothing effect that would justify a decrease in evolution of average roughness (R_a) and maximum average roughness (R_z) with insert wear increase in the cutting speeds of 70 and 90 m/min.

It is assumed that with a cutting speed of 110 m/min a significant increase in friction and cutting temperature occur, leading to a premature and irregular wear of the inserts resulting in tool marks on workpiece surface and to an increase in the evolution of average roughness (R_a) and maximum average roughness (R_z).

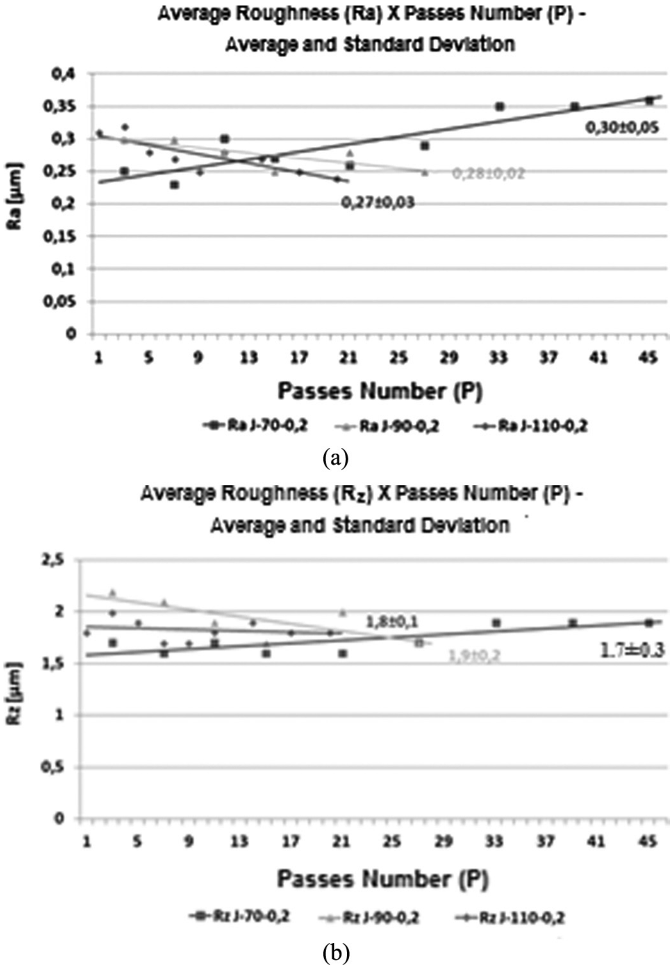

FIGURE 10.—(a) Average roughness (R_a) evolution for cutting w/ fluid jet (*J*). (b) Maximum average roughness (R_z) evolution for cutting w/fluid jet (*J*).

Figure 10(a) and (b) shows an accentuated increasing trend in the evolution of average roughness (R_a) and maximum average roughness (R_z) of machined surfaces according to pass number (P) applied to the insert life end w/use of fluid jet (J) w/o cutting speed of 70 m/min min and a decreasing trend in evolution of average roughness (R_a) and maximum average roughness (R_z) w/ cutting speeds of 90 and 110 m/min.

It is assumed that the accentuated increasing trend in evolution of the roughness (R_a) and (R_z) with the cutting speed of 70 m/min occurred due to cutting insert chipping by thermal shock that established an irregular and slower insert wear because of lower friction and temperature in contact with workpiece and its smaller smoothing in the wear evolution causing acute tool marks on the workpiece surface.

It is believed that with the cutting speed of 90 and 110 m/min, despite still occur the inserts chipping caused by thermal shock in the cooling performed by the fluid jet, the insert wear increases due to the higher friction and mechanical loads in the cutting, causing a smoothing effect in the same, due to increase in its contact area with the workpiece that would justify a decrease in the evolution of the average roughness (R_a) and maximum average roughness (R_z).

Figure 11(a) and (b) shows a decreasing trend in the evolution of average roughness (R_a) and maximum average roughness (R_z) of machined surfaces according to pass number (P) applied to the inserts life end w/cutting utting speed of 110 m/min and an increasing trend in evolution of roughness (R_a) and (R_z) for the other machining conditions studied.

It is noted that the MQF technique is able to reduce the temperature increase of cutting inserts w/ the heat exchange in cutting fluid evaporation in the inserts with a constant cooling rate, avoiding thermal shocks and reducing the friction more efficiently in the cutting zone.

It is assumed that the MQF use with vegetal fluid causes a more uniform wear in the cutting inserts with a larger lubrication/cooling capacity and lower cutting

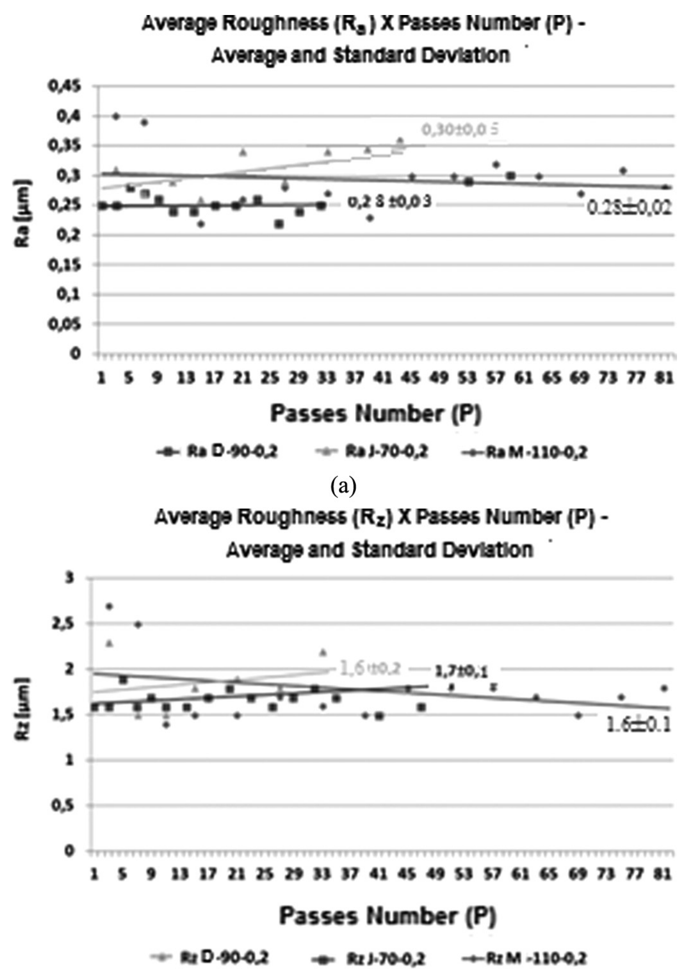

FIGURE 11.—(a) Average roughness (R_a) evolution for cutting w/MQF (*M*) in relation to other studied conditions with longer cutting lengths. (b) Maximum average roughness (R_z) evolution for cutting w/MQF (*M*) in relation to other studied conditions with longer cutting lengths.

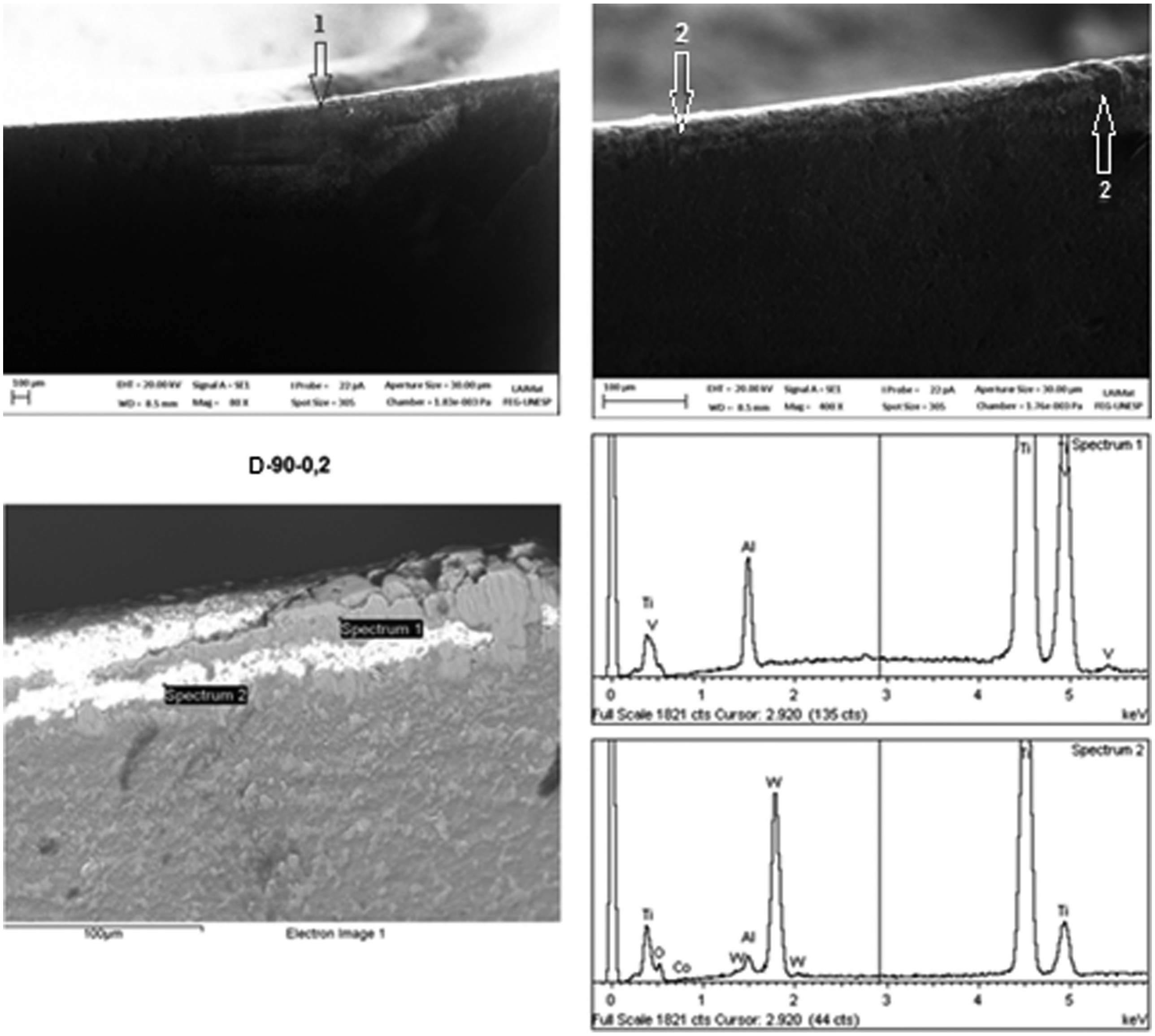

FIGURE 12.—SEM/EDS micrograph w/o lubrication/cooling use.

friction, providing better sample surface finish in relation to other machining conditions studied.

The high viscosity of vegetable fluid has the tendency to adhere further to the workpiece, resist better to the cutting flow, remain in the cutting area longer, and provide more effective lubrication between the chip and workpiece.

The MQF technique was used in this experiment and compared w/ the fluid jet and the cutting w/o lubricant/cooling with the purpose of studying the lubrication and cooling capacity in Ti6Al4V machining through the small amount of cutting oil (60 ml/h) directed by applicators in the region between the cutting zone and tool with the aid of compressed air to be analyzed the main wear mechanisms of tools employed.

The tool wear mechanisms used for machining conditions employed were investigated in this study.

The cutting insert D-90-0.2 shown in Figure 12, refers to the insert of milling head with greater wear in the cutting condition w/o lubrication/cooling and longer tool life.

The fact that high temperatures act close to the cutting edge during titanium machining with the cutting speed increasing is the main reason for the fast tool wear; therefore the increasing tool life in this process depends greatly on the efficiency degree of lubrication/cooling system used.

However, the milling process favors the cutting temperature reduction through the uninterrupted cutting in which for each milling cutter rotation the heat is reduced by the reducing cutting friction and the convection with heat exchange between the tool and the ambient air, even in cutting condition w/o lubrication.

It is believed that the insert coating material titanium carbonitride (CNTi) despite having high hot hardness

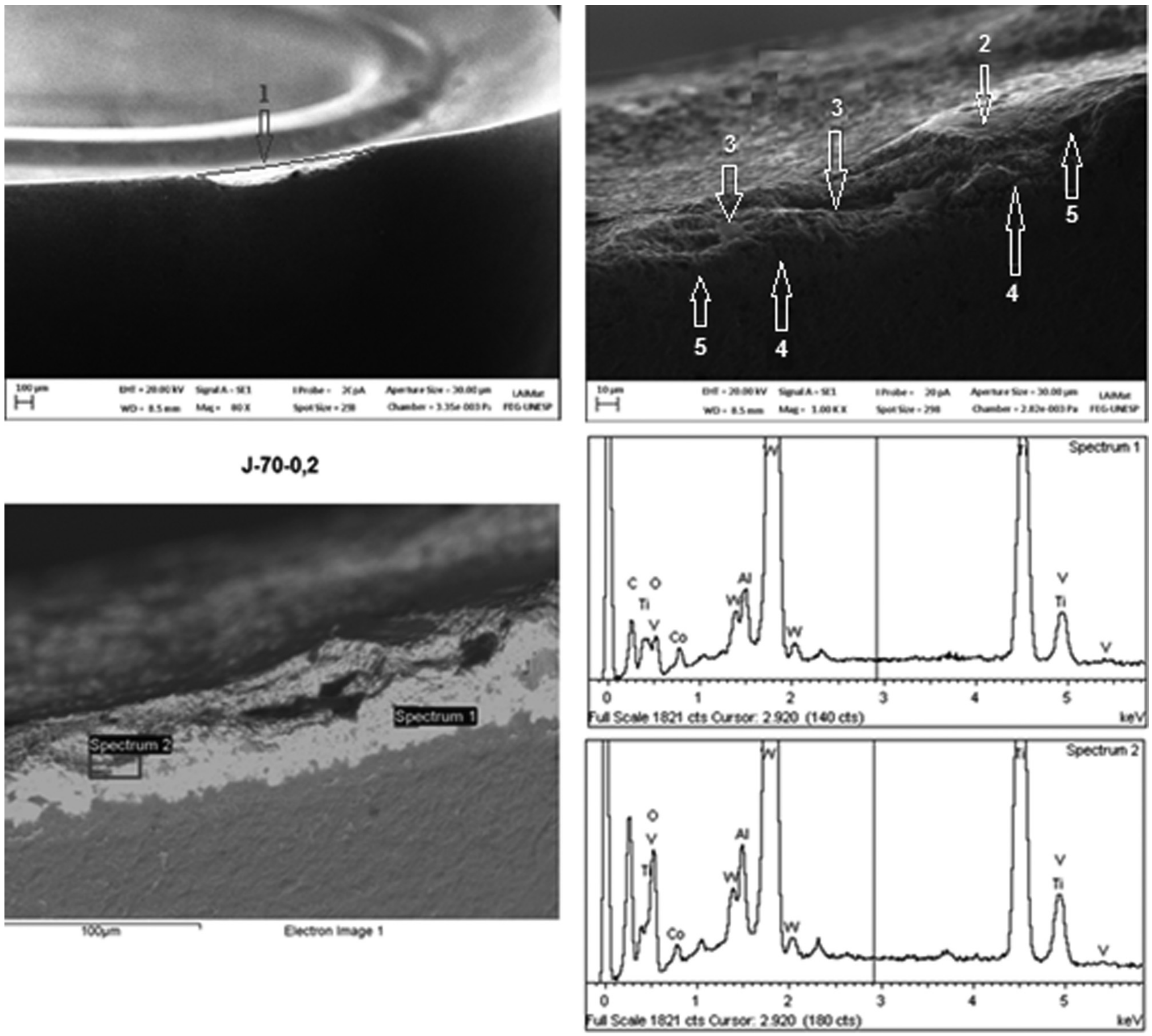

Figure 13.—SEM/EDS micrograph w/fluid jet use.

did not resist to high cutting temperatures imposed in this machining condition.

The abrasion can be verified by the substrate material presence: tungsten and cobalt (Co and W) shown in item 1, present throughout the cutting edge and by the aspect of "sanding" of the same.

The substrate torn from the tool becomes retained in the cutting zone between the tool and workpiece, further increasing the abrasion and friction between the tool flank face and workpiece surface.

With the temperature increase occurs a large increase in diffusion and adhesion that at the same time saturates the tool surface layer with the workpiece material: titanium, aluminum, and vanadium (Ti, Al, V) shown in item 2, avoiding the transfer of tool substrate carbon to the workpiece, which would weaken the tool. This layer is detached cyclically, easily by the dynamics of the milling cutting and for being little resistant in the tool due to the high temperatures generated.

It is noted that the abrasion and accelerated adhesion caused by the diffusion due to high cutting temperatures are the main wear mechanisms in the cutting w/o lubrication/cooling, seen in items 1 and 2.

The nonexistence of attrition where the adhesion layer detachment by abrasion action does not detach the tool substrate by little bonding strength of adherence due to high temperatures is noticed.

It is also believed that the choice of normal grains of 1 microns instead of submicron grains of 0.4 microns for the cutting tool substrate occasioned lower solubility of the atoms that make up the tool and workpiece materials in the cutting zone region with lower diffusion and adhesion rates.

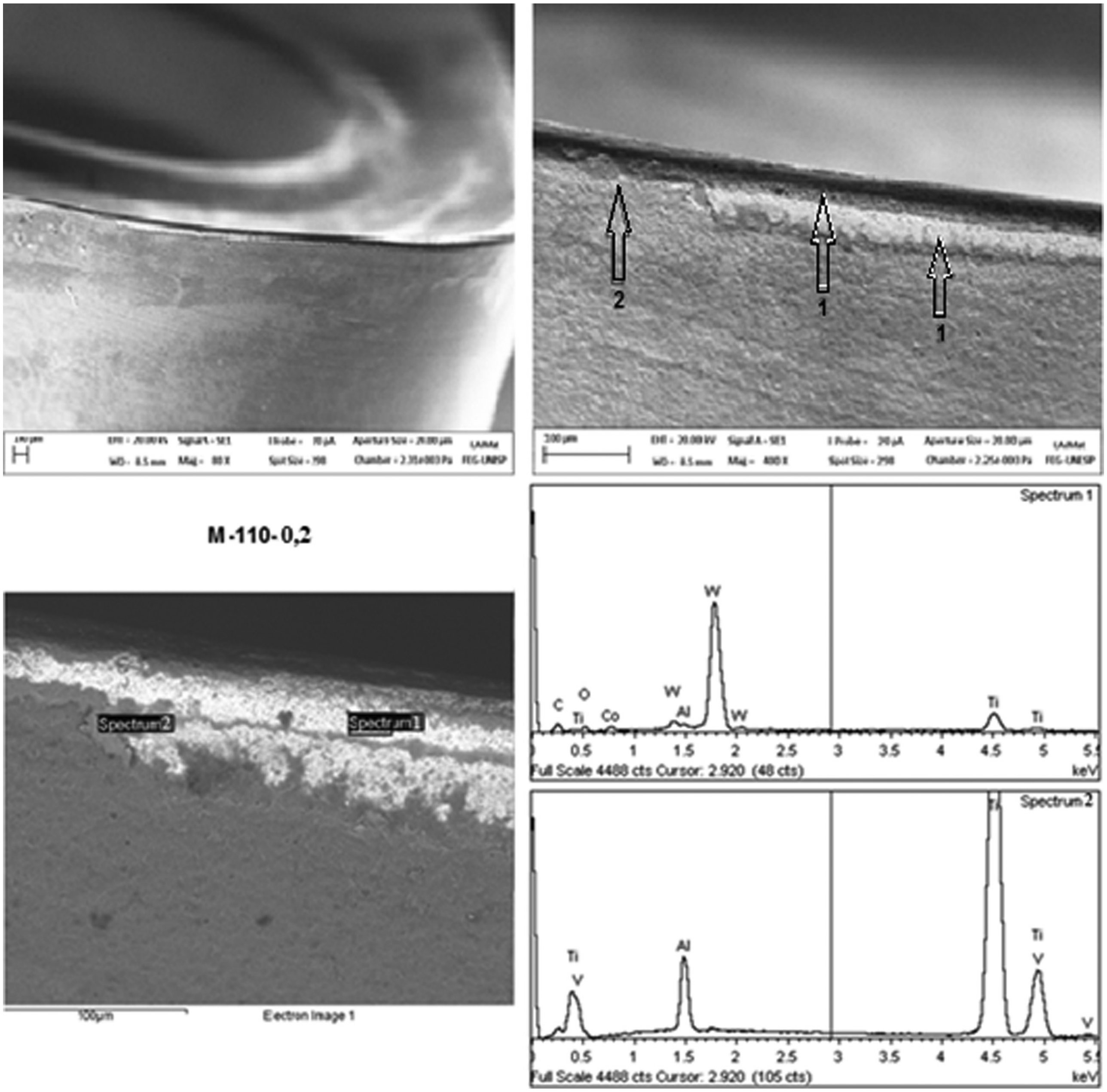

FIGURE 14.—SEM/EDS micrograph w/o MQF use w/vegetable fluid.

1 – Abrasion—substrate and workpiece material (W, Co, Ti, Al, O)—EDS spectrum 2.

2 – Adhesion—workpiece material (Ti, Al, V)—EDS spectrum 1.

The cutting insert J-70-0.2 shown in Figure 13 refers to the cutting insert with more external position in the milling head with greater wear and beating in the cutting condition w/o fluid jet with longer tool life.

The cutting tool is cooled more quickly with the fluid jet action that causes greater thermal shock, fatigue, and thermal cracks on the cutting edge, shown in item 4; excessive micro chipping and cutting edge fracture, shown in item 1; attrition and abrasion with coating layer oxidation, shown in the items 3, 5, and 2 respectively.

The cutting w/o fluid jet use increased the insert temperature variation by its high cooling capacity causing cracks that were expanded with the higher mechanical load in the beating causing greater abrasion and mechanical and thermal fracture of the insert.

1 – Original cutting edge position.

2 – Adhesion and oxidation—workpiece material (W, Co, Ti, Al, V, C, O)—EDS spectrum 1.

3 – Attrition and oxidation—material of substrate, workpiece, coating, and oxygen (W, Co, Ti, Al, V, C, O)—EDS spectrum 2.

4 – Thermal cracks
5 – Abrasion (W, Co, Ti, Al, V, C, O)—EDS spectrum 1.

The cutting insert M-110-0.2 shown in Figure 14 refers to the insert of milling head with greater wear in the cutting conditions with MQF w/vegetable fluid and longer tool life.

When applying the MQF technique, a compressed air flow mixed with 60 ml/h of vegetable oil was directed and reached the tool and workpiece in the cutting zone evaporating.

It is believed that the low cooling capacity of vegetal fluid in evaporation and generated heat conduction decreased the thermal shock in the tool does not occurring fatigue and mechanical or thermal cracking, while maintaining the heat in the cutting zone that decreased the mechanical strength and increased the tool life.

The lower abrasion on the tool (shown in item 1) due to greater lubrication and contour pellicle adherence with the vegetal fluid evaporation, smaller adhesion layer thickness of workpiece material on the tool (shown in item 2) by lower diffusion due to the lower temperatures, and the vegetable cutting fluid action are noted.

The occurrence of attrition where the adhered layer detachment by abrasion did not wrench the tool substrate by its low thinness was not perceived.

A superior power of vegetal fluid lubrication which had the tendency of adhere further to the workpiece and better able to resist to the dynamic of cutting flow with the reduction of friction and cutting temperature was verified.

1 Abrasion—material of substrate, workpiece, and coating (W, Co, Ti, C, Al, O)—EDS spectrum 1.
2 Adhesion—workpiece material (Ti, Al, V)—EDS spectrum 2.

Conclusions and further work

Based on the results of this work, the following conclusions can be drawn:

The MQF technique with vegetable fluid use obtained longer tool life, volume of material removed, material removal rate and lower surface roughness in relation to the cutting with fluid jet and cutting w/o lubrication/cooling in the boundary conditions established in this experiment and have your application made feasible in this manufacturing process.

Through the yield percentages and their dispersions in cutting speed ranges, feed and depth of cut can be quantified in each specific application on a database and more effectively, both the productive and economic improvements resulting from the MQF application, as the environmental improvements stemming from its use with smaller cutting fluid volume used and its biodegradability.

To use the MQF technique in this process with better cutting performance in relation to the cutting with fluid jet and cutting w/o lubrication/cooling: the vegetal fluid use, the relative increase in the cutting speed, and maintaining of cutting feed applied are required.

The evolution of the sample surface roughness decreases with passes number and with the MQF technique use with vegetable fluid.

The MQF technique increased the tool life due to high molecular thick of lubricant film present in vegetable cutting fluid, its high lubricating capacity with low cooling capacity that decreased thermal shock in the tool and remained the heating in the cutting zone decreasing its mechanical resistance.

Using the level of recommended parameter variations and machining conditions experienced in this work, the roughness will decrease and the material removal rate, the removed material volume, and the tool life will increase by at least 50% with the MQF use.

In future works to obtain more accurate data about the MQF technique application in the Ti6Al4V end milling, other cutting fluids with the MQF use can be used, varying the feed rate and comparing it with the obtained results.

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References

1. Nourredine, B., et al. A technology enabler for green machining: minimum quantity lubrication (MQL). *Journal of Manufacturing Technology Management* **2010**, *21*, 556–566.
2. Boyer, R.; Welsch, G.; Collings, E.W. *Materials Properties Handbook: Titanium Alloys*; ASM International: Materials Park, OH, 1994; 1176.
3. Anhai, L., et al. Wear progression of carbide tool in low-speed end milling of stainless steel. *Wear* **2008**, *265* (1–2), 155–166.
4. Ezugwu, E.O., et al. An overview of the machinability of aeroengine alloys. *Journal of Materials Processing Technology* **2003**, *134* (2), 233–235.
5. Sales, W.F., et al. Cooling ability of cutting fluids and measurement of the chip–tool interface temperatures. *Industrial Lubrication and Tribology* **2002**, *54*, 57–68.
6. Sun, F. et al. Adhering wear mechanism of cemented carbide cutter in the intervallic cutting of stainless steel. *Wear* **1998**, *214*(1), 79–82. DOI: 10.1016/S0043-1648(97)00203-2.
7. Diniz, A.E., Coppini, N.L.; Marcondes F.C. *Materials Machining Technology*; Artliber Editora: São Paulo, 2006.
8. Trent, E.; Wright, P. *Metal Cutting*; Butterworth/Heinemann, 2000.
9. Sandvik Coromant. *Milling Titanium*. Disponível em: http://www.sandvik.coromant,com. (accessed October, 2009).
10. Machado, A.R.; Da Silva, M.B. *Machining of Metals*. Editora da Universidade Federal de Uberlândia: Uberlândia, Brazil, 2003.
11. Wakabayashi, T., et al. Tribological characteristics and cutting performance of lubricant esters for semi-dry machining. *Annals CIRP* **2003**, *52* (1), 61–64.

12. Su, Y., et al. An experimental investigation of effects of cooling/lubrication conditions on tool wear in high-speed end milling of Ti-6Al-4V. *Wear* 2006, *261*, 760–766.
13. Jiang, F., et al. Optimizing end-milling parameters for surface roughness under different cooling/lubrication conditions. *The International Journal of Advanced Manufacturing Technology* **2010**, *51* (10), 841–851.
14. Wings, K.L.D., et.al. *Optimization of Surface Milling of Hardened AISI4340 Steel with Minimal Fluid Application using a High Velocity Narrow Pulsing Jet of Cutting Fluid*. Disponível em: http://www.SciRP.org/journal/eng (accessed October, 2012).
15. Diniz, E.A.; Micaroni, R. Cutting Conditions for finish turning process aiming: the use of dry cutting. *International Journal of Machine Tools & Manufacture* **2002**, *42*, 899–904.
16. Da Silva, R.B., et al. Tool wear analysis in milling of medium carbon steel with coated cemented carbide inserts using different machining lubrication/cooling systems. *18th International Conference on Wear of Materials* **2011**, *271* (9), 2459–2465.
17. Rahim E.A.; Sasahara H. A study of the effect of palm oil as MQL lubricant on high speed drilling of titanium alloys. *Tribology International* **2011**, *44* (3), 309–317.
18. Anhai, L.; Jun, Z.; Hanbing, L.; Zhiqiang, P.; Zeming W. Progressive tool failure in high-speed dry milling of Ti-6Al-4V alloy with coated carbide tools. *The International Journal of Advanced Manufacturing Technology* **2013**, *58*, 465–478.
19. Romi programming and operation manual – D-800 line – CNC Fanuc 0I-MC, 2014.
20. Tr100 Rugosimeter operation manual, 2014.
21. Microcapture microscopy operation manual – Digimicro, 2014.
22. ISO −8688–1/2. Tool life testing in milling, part 1 & 2, End Milling. International Organization for Standardization, ISO −8688–1/2, 1989.