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Dry high speed milling of nickel-based superalloy

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1. Introduction

Nickel-based superalloys are widely employed in the aerospace industry, in particular in the hot sections of gas turbine engines, due to their high-temperature strength and high corrosion resistance. They are known to be among the most difficult-to-cut materials. Attention is focussed on the Inconel 718 family in the following paragraphs [1-2]. A major part of their strength is maintained during machining due to their high-temperature properties. They are very strain rate sensitive and readily works harden, causing further tool wear. The highly abrasive carbide particles contained in the microstructure cause abrasive wear and the poor thermal conductivity leads to high cutting temperatures up to 1200°C at the rake face [3]. Nickel-based superalloys have high chemical affinity for many tool materials leading to diffusion wear also the welding and adhesion of nickel alloys onto the cutting tool frequently occur during machining causing severe notching as well as alteration of the tool rake face due to the consequent pull-out of the tool materials. Due to their high strength, the cutting forces attain high values, excite the machine tool system and may generate vibrations which compromise the surface quality. The difficulty of machining resolves itself into two basic problems: short tool life and severe surface abuse of machined workpiece [4, 5]. The heat generation and the plastic deformation induced during machining affect the machined surface. The heat generated usually alters the microstructure of the alloy and induces residual stresses. Residual stresses are also produced by plastic deformation without heat. Heat and deformation generate cracks and microstructural changes, as well as large microhardness variations [6]. Residual stresses have consequences on the mechanical behaviour, especially on the fatigue life of the workpieces [7, 8]. Residual stresses are also responsible for the dimensional instability phenomenon of the parts which can lead to important difficulties during assembly [9, 10]. Extreme care must be taken therefore to ensure the surface integrity of the component during machining. Most of the major parameters including the choice of tool and coating materials, tool geometry, machining method, cutting speed, feed rate, depth of cut, lubrication, must be controlled in order to achieve adequate tool lives and surface integrity of the machined surface [6, 8].

In this study we are testing the performance of cutting inserts with coatings based on (TiN, TiCN, TiAlN, AlTiN). The determination of the milling system which consumes less power. The study of modes of wear and morphology during dry machining of Inconel 718 [11].

2. Experimental procedure

2.1. Workpiece materials/tool and equipments

2.1.1. Worked materials

The workpiece material used was a rectangular block of Inconel 718 superalloy (220×120×120 mm) with a nominal chemical composition referenced Table 1.

Table 1

Chemical composition (in weight percent)

Ni	Fe	Cr	Nb	Mo	Ti	Al	Ti+Al / Nb	Ti / Al
52.58	20.06	20.10	3.20	1.79	1.13	1.14	0.71	0.99

2.1.2. Cutting tool

Down milling operations were performed, the cutting tool was an end mill of 16 mm diameter with two carbide inserts SandvikCoromant R390 and presented on Fig. 1.

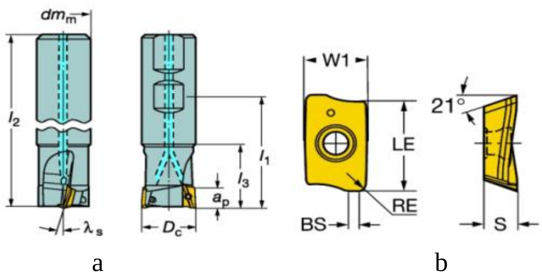

Fig. 1 a) milling cutter Coromill 390 and b) insert geometry [Sandvik coromant]

Machining tests are conducted by down milling mode presented on Fig. 2.

The tree commercial coatings were used on carbide compositions are referenced on Table 2.

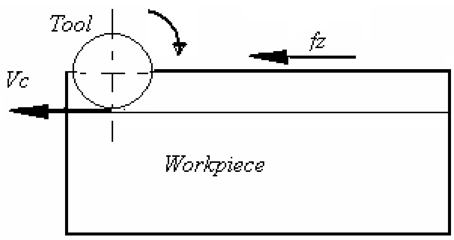

Fig. 2 Experimental setup

Table 2

Commercial coatings inserts testing

C1	Fine grain bicarbide rich in cobalt Multilayer TiN+TiCN, Chemical vapour deposed (CVD)
C2	Fine grain bicarbide High toughness Multilayer TiN+TiCN+TiAlN, Physical vapour deposed (PVD)
C3	Midle grain carbide AlTiNnanocrystalline, (PVD)

Machining tests were realised on a High Speed Machine Röders RP600 instrumented with power controllers Wattpilote™ developed by the society DIGITAL WAY. These controllers allow to record the spindle and the feed motors power consumptions. Power controllers are usually employed to monitor the tool wear and tool breakage. To discuss about the tool wear phenomenon, it is necessary to observe, to measure and to quantify it. Two machines are used.

The optical microscope TESA and it software TESA VISIO is used to observe the tool wear evolution along the cutting tests. It permits to determinate the tool life. The qualification criterion is the degradation of the tetragonal insertions. Classically, in industry, it is considered that acuity tool is degraded after a clearance wear of 0.3 mm [12]. This criterion is used to determinate the test end.

A Veeco NT1100 (Wyko®) Optical Profiler, using the white light interferometry technique presented by Devillez et al [12] is employed to monitor cutting parameters and to generate 3D images of the wear patterns of the cutting tools. This technique was also used with the same objectives [12].

Surface roughness *Ra* was measured using a portable Mitutoyo Surf Test 301.

2.1.3. Identification of optimum cutting conditions

Strategy of experiments.

Machining lengths of 220 mm with C1 insert to determine the cutting conditions to evaluate during the characterization study.

The results of the first tests allow us to choose the following conditions cutting. Thus, three will be tested-coatings, TiN, TiCN, TiAlN and nanocristalin coating AlTiN. Three cutting speeds for having given in phase 01 of good results, 50, 80 and 130 m/min to go beyond what has already been achieved in other studies. Feed per tooth *fz* are 0.05 and 0.1 mm/t, chosen not to ramp up and cause vibrations.

Table 3

Selected conditions of the study

Vc	*fz*	*ap*	*ae*	Remarks
35	0.05	0.5	8	Pronounced wear and vibration
35	0.1	0.5	8	Low vibration and temperature rise
50	0.05	0.5	8	Vibration and ship adhesion
50	0.1	0.5	8	Low vibration and chip adhesion
80	0.05	0.5	8	Vibrations of low amplitude and fast heating
80	0.1	0.5	8	Low Vibration and temperature rise
100	0.05	0.5	8	Vibration and temperature rise
100	0.1	0.5	8	High Vibration and temperature rise
130	0.05	0.5	8	Low vibration and temperature rise
130	0.1	0.5	8	Temperature rise and pronounced wear
150	0.05	0.5	8	Temperature rise
150	0.1	0.5	8	Temperature rise

2.2. Study of type of wear and surface roughness

The second phase relates to the study of flank wear of inserts and surface roughness of machined work piece and power evolution. The experimental design adopted for studying the effect of three cutting speed and two feed per tooth values.

Table 4

Adopted conditions of the study

Vc, m/min	*fz*,mm/t	*ap*, mm	*ae*, mm
50	0.05	0.5	8
50	0.1	0.5	8
80	0.05	0.5	8
80	0.1	0.5	8
130	0.05	0.5	8
130	0.1	0.5	8

3. Results and discussion

Three areas of investigation are studies to characterize the machinability of nickel based superalloy (Inconel 718). In dry high speed milling with multilayer coated carbide inserts, first axis is the monitoring of flank wear *Vbmax* average cutting time. Second axis is a measure of the roughness *Ra* of machined surface and its evolution with cutting time. The third axis is the reports in real time the spindle power consumed to determine the best machining conditions with minimum power consumption.

3.1. Evolution of flank wear *Vbmax* for the tree inserts testing

The first test is made according to the following conditions: Figs. 3-8 show the curves of the flank wear

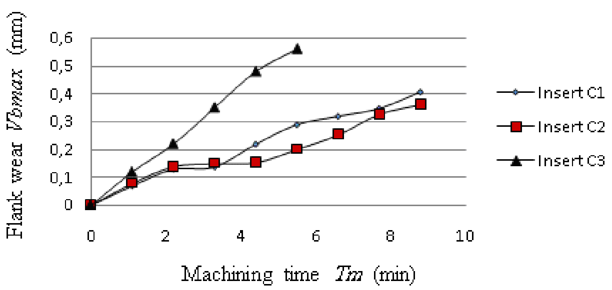

Fig. 3 Dependence flank wear *Vbmax* on machining time *Tm*, when *Vc* = 50 m/min, *fz* = 0.05 mm/t, *ap* = 0.5 mm, *ae* = 8 mm

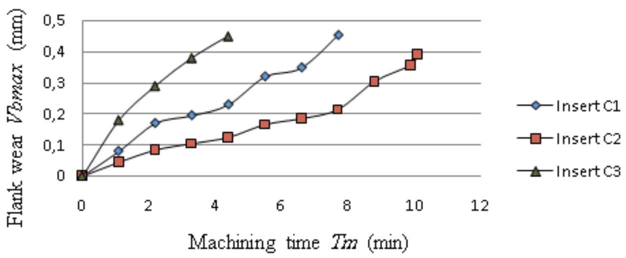

Fig. 4 Dependence flank wear *Vbmax* on machining time *Tm*, when *Vc* = 50 m/min, *fz* = 0.1 mm/t, *ap* = 0.5 mm, *ae* = 8 mm

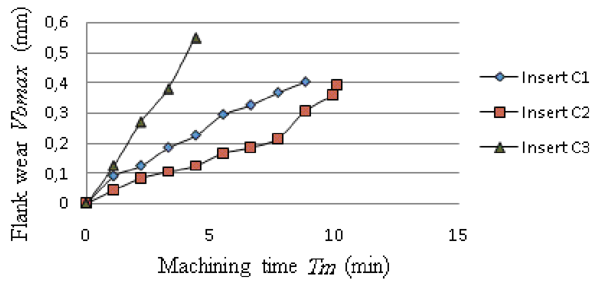

Fig. 5 Dependence flank wear *Vbmax* on machining time *Tm*, when *Vc* = 80 m/min, *fz* = 0.05 mm/t, *ap* = 0.5 mm, *ae* = 8 mm

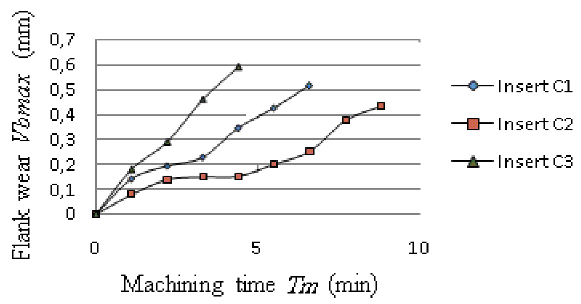

Fig. 6 Dependence flank wear *Vbmax* on machining time *Tm*, when *Vc* = 80 m/min, *fz* = 0.1mm/t, *ap* = 0.5 mm, *ae* = 8 mm

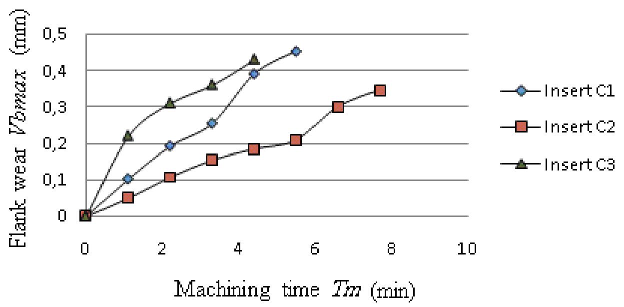

Fig. 7 Dependence flank wear *Vbmax* on machining time *Tm*, when *Vc* = 130 m/min, *fz* = 0.05 mm/t, *ap* = 0.5 mm, *ae* = 8 mm

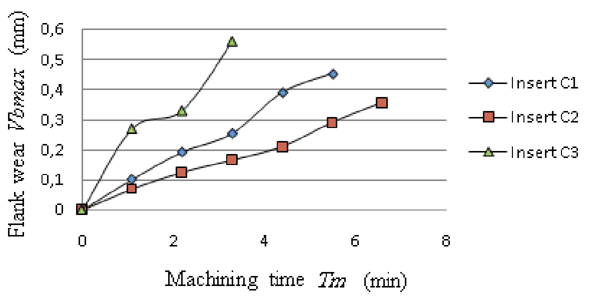

Fig. 8 Dependence flank wear *Vbmax* on machining time *Tm*, when *Vc* = 130 m/min, *fz* = 0.1 mm/t, *ap* = 0.5 mm, *ae* = 8 mm

Vbmax depending on the machining time *Tm*. Each curve represents a test insert and cutting conditions.

Processing results from wear and records the values of roughness have obtained the following Table 5.

Table 5

Experimental values

			Insert C1		Insert C2		Insert C3	
N°	*Vc*, m/min	*fz*, mm/t	*T*, min	*Ra.av*, µm	*T*, min	*Ra.av*, µm	*T*, min	*Ra.av*, µm
1	50	0.05	5.8	0.38	7.5	0.27	3	0.41
2	50	0.1	5.2	0.59	8.4	0.35	2.5	0.52
3	80	0.05	6	0.32	8	0.13	2.5	0.38
4	80	0.1	4	0.42	7.1	0.22	2	0.43
5	130	0.05	3.5	0.26	6.5	0.18	2	0.25
6	130	0.1	3.2	0.49	5.5	0.34	1.5	0.36

Evolution of tool life *T*, min for the tree inserts testing according the adopted cutting conditions.

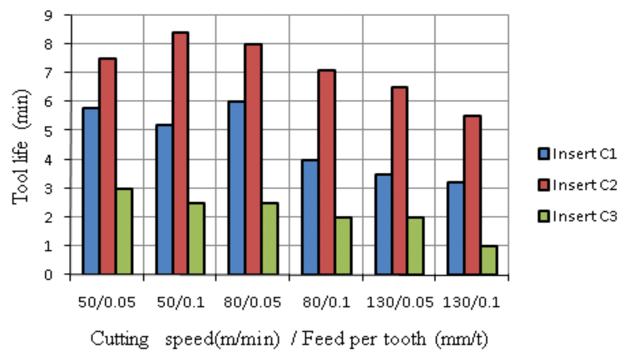

Fig. 9 Dependence tool life *T* on cutting speed *Vc* and feed per tooth *fz* for the three inserts tested

For all tests, the best tool life was obtained by cutting the insert C2. Increasing the cutting speed decreases tool life. It is the same for the feed rate per tooth of the cutter. For the regime (*Vc* = 50 m/min, *fz* = 0.1 mm/t) results are better than those obtained with the feed per tooth (0.05 mm/t) for C1 and C2 inserts. The C3 coated insert (AlTiN nanocrystalline) did not give good results compared to the other two tested inserts.

3.2. Evolution of average roughness for the tree inserts testing according the adopted cutting conditions

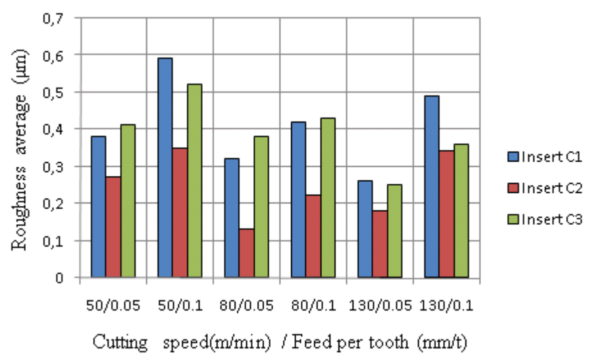

Fig. 10 Evolution of average roughness *Ra* depending cutting speed and feed per tooth for the three inserts tested

The best results of roughness are obtained with insert C2. The value of the smallest roughness is achieved with the cutting regime (*Vc* = 80 m/min; *fz* = 0.05 mm/t) by the C2 insert. The poorer surface roughness was obtained by the C1 insert.

3.3. Evolution of spindle power consumption

Watt pilot sensors are enabled; we can get the evolution of the spindle power according to the machining time.For all tests milling spindle power shave been identified. We show the values obtained for the following conditions (Vc = 80 m/min,fz = 0.1 mm/t, ap = 0.5 mm) and (Vc = 130 m/min, fz = 0.05 mm/t, ap = 0 5 mm) because the results are significant for both cutting conditions;Fig. 11, show the dependence of spindle power evolution on the machining time for three inserts testing.For regime (Vc = 80 m/min, fz = 0.1 mm/t), we notice that the spindle power decreases. This is mainly due to the efficient flow of chips and very favorable cutting conditions. There was not a strong adhesion of the chip.

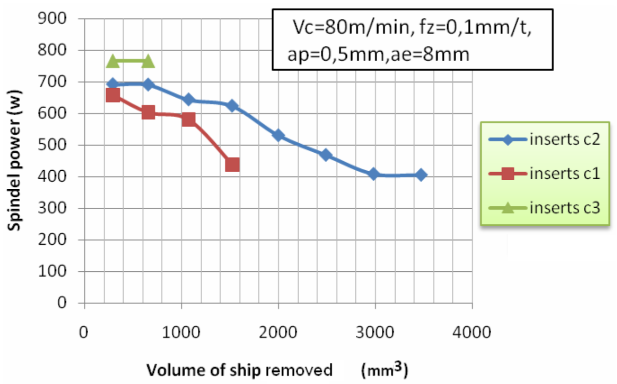

Fig. 11 Dependence Spindle Power consumption on volume of ship removed for three inserts (Vc = 80 m/min, fz = 0.1 mm/t)

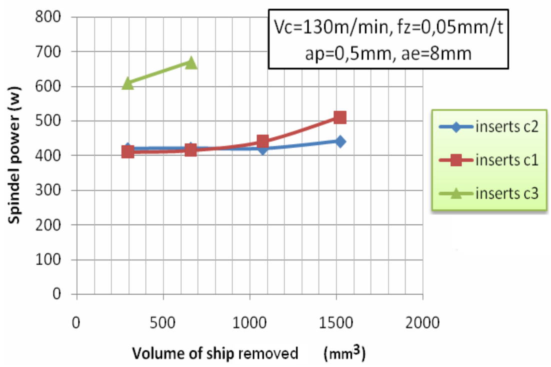

Fig. 12 Dependence Spindle Power consumption on volume of ship removed for three inserts (Vc = 130 m/min, fz = 0.05 mm/t)

For regime (Vc = 130 m/min; fz = 0.05 mm/t, ap = 0.5 mm; ae = 8 mm) we notice an increase in spindle power at the end of machining; this is because of the wear inserts. Cutting speed has reduced the tool life of the inserts. The insert C2 gave the best results. The values of the roughness of the machined surface are low. The best roughness is obtained with the C2 insert.

The roughness value decreases during the running- phase of edge inserts. A small groove is formed by wear, it acts as a scraper, which improves the surface finish. Subsequently, the roughness increases to exceed the originally recorded at the beginning.

For the cutting speed Vc = 130 m/min, for inserts C1 and C3 the value of the roughness starts decreasing and then increasing with the wear evolution of the sharp edge of plates. This is not the case for the C2 insert where the roughness increases with machining. The graph of tool life inserts shows that the C2 insert registered the largest cutting performance. Tool life for C1 inserts has similar values, for C3 insert the tool life has decreased for speed Vc = 130 m/min. Tool life for this insert is very low to be used in industrial applications.

4. Morphological investigation of wear inserts

Fig. 13 show the wear morphology of the C2 inserts tested. Picture of wear have been taken by video microscope for following cuttings conditions: (Vc = 80 m/min; fz = 0.1 mm/t; ap = 0.5 mm; ae = 8 mm). Pictures *1*, *2*, *3*, *4* shows the progression of wear on the rake face and flank face after (1, 4, 7, 9 min) cutting time.

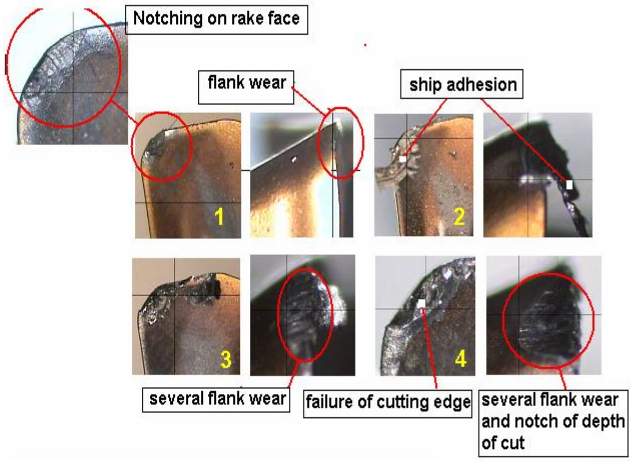

Fig.13 Types of wear pictures (Insert C2)

In Fig. 13 we show the different wear caused by friction and adhesion of the chip. On the picture number *4* we see the breakdown of the spout of the insert .For the other inserts wear occurs in the same way but with a higher speed, especially for the insertC1.

5. Conclusion

The experimental study permits to conclude about the machinability of ainconel 718 superalloy.

1. Machinability of this material is hard.

2. The responsible of the major wear is due to its superior properties which conduce to a notch and a cutting face chipping.

3. Thus, the cutting inserts for milling have different kinds of wears: a progressive wear of the flank face characterised by a notch of the part in contact with the top part; and a severe chipping in the cutting face.

4. During the high speed machining of hard metals characterised by a hard machinability, it is recommended to reduce the admissible flank wear criteria *Vbmax* to [*Vb*] = 0.2 mm.

5. The chipping, by it length and it depth can be another criteria to considerate. The experiment allows to say that the most appropriate cutting speed in term of cutting forces is 130 m/min but with a cutting speed of 80 m/min, the tool life begin acceptable. Moreover, the coating C2 is the most efficient with high speed and dry cutting conditions.

6. Practically, the study has confirmed that the implementation of the Wattpilote system to the Röders RP600 for the machining control is efficient. It gives the opportunity to follow the evolution of the cutting process in term of power. Power curves of X, Y and especially Z axes are in phase with the wear curves. The power improving during the milling process is probably linked to the tool wear. Theoretically, it is possible to follow and to control the inserts wear with the power help. The methodology adopted for the tests and the criteria considered to quantify the parameters integrated in the process give a qualification of the tool without incertitude.

7. Thus, two inserts have been awarded with the aim of industrial applications and the coating C2 has proved it particular effectiveness for hard metal machining.

8. The future prospects can be resumed to resolve the problem of the fast coating pull out of the cutting face, it is necessary to develop, on another study, the phenomenon of the chip adhesion and the coating properties. Thus, a local lubrication on the cutting face by an air blow mixed with a freeze and lubricant properties liquid could improve the results.

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NIKELIO SUPERLYDINIO SAUSASIS GREITASIS FREZAVIMAS

R e z i u m ė

Dėl geresnių savybių inkonelis 718 (austenitinis nikelio ir chromo superlydinys) plačiai naudojamas aukštose temperatūrose, esant didelėms apkrovoms ir antikorozinėms sąlygoms. Šis lydinys žinomas kaip sunkiausiai apdirbama medžiaga. Straipsnyje pateikti greitojo frezavimo eksperimento rezultatai susiję su apdirbamumu, apibūdinant inkonelio 718 apdirbimą aštriu įrankiu, nustatant geriausias pjovimo sąlygas, apibrėžiant dilimo tipus ir įrankio patvarumą bei klasifikuojant dangų tipus. Tyrimas atliktas dviem etapais. Pirmajame etape palyginamajai studijai atlikti įvertintos pjovimo sąlygos. Antrajame išanalizuoti dilimo tipai. Apdirbimo metu buvo stebimas dilimo pobūdis, o pjovimo galia didinama ir registruojama. Greitaeigės frezavimo staklės turėjo galios registratorių „Wattpilote“. Buvo siekiama įvertinti superlydinioapdirbamumą, matuojant galią ir įrankio dilimą optiniu mikroskopu ir baltosios šviesos interferometru, esant įvairioms pjovimo sąlygoms ir strategijoms.

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DRY HIGH SPEED MILLING OF NICKEL-BASED SUPERALLOY

S u m m a r y

Inconel 718 Nickel-based superalloy has been applied widely in high temperature, high load and corrosion resistant environments due to its superior properties. They are known to be among the most difficult-to-cut materials. This paper reports some experimentals findings concerning the machinability at high cutting speed in milling process. To characterize the machining of Inconel 718 by tips tools, to identify the best cutting conditions, to define the modes of wear, to determine the tool life, and to classify the types of coatings. The study is conducted according to two phases. Phase one, determination of the cutting conditions for a comparative study. Machining over some lengths with selected tips in order to determine the strategy of milling. Phase two, Study of the types of wear. During machining, the modes of wears are observed and the powers of cut are raised and referred. High speed milling machine equipped by a power consumption recorder Wattpilote. The aim is to show the machinability of the superalloy, measuring the power and the tip wear by optical microscope and white light interferometer, using different strategies and cutting conditions.

Keywords: Machinability; Nickel based superalloy; coating tips; wear; high speed milling; wattpilotes.

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