Surface Integrity of Thin-Walled Titanium Parts Machined by Peripheral Milling

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ABSTRACT

Titanium alloys are widely used for aerospace thin–walled parts such as compressor or turbine blades, frames, etc. The main motivation for application of these alloys is their outstanding metallurgical properties such as: hot hardness, high corrosion resistance and wear-resistance. However, in production, titanium alloys are categorized as difficult-to-cut materials. In this study, the surface integrity of thin-walled titanium parts which are produced by milling operations are evaluated against different cutting conditions such as cutting speeds and immersions. Micro-structural analysis is performed and cutting forces are measured using a table dynamometer. Finally the optimum cutting conditions for the process are proposed.

KEYWORDS: Surface integrity, peripheral milling, Thin-walled part

1 INTRODUCTION

The milling operation is vastly used in aerospace industry for production of fuselage flexible parts. In dynamic models of milling process, the tool or workpiece or both of them are assumed to be flexible and as the result of cutting force excitement, the occurrence of vibration is possible.

In low immersion milling when radial depth of cut is a small proportion of tool radius and consequently tool and workpiece are out of cut longer than before, therefore vibrations caused by discontinious engagement of tool and workpiece become more important [1].

Machining of aerospace parts like turbine or compressor blades or frames, encounters many problems as follows:

1. With consideration of periodic variation in amplitude and direction of cutting forces during exert of cutting forces on flexible static and dynamic structures, the machining operation will be complicated.
2. Static displacements cause dimensional errors.
3. The vibrations of part and tool occur that decrease the machining precision and increase the surface roughness.
4. In aerospace industries, production of limited number of parts with high quality and high precision is required that generally the production costs are high, in order to optimize the machining parameters, use of conventional milling which is based on trial and error method is possible.
5. Improving applications of titanium alloys in aerospace industries and production of aero-engines due to high resistance to weight ratio, high corrosion resistance, low density and excellent elevated temperature properties, have influenced the machinability of these alloys and are known as difficult-to-cut materials [2].

Proper prediction of cutting forces in machining operation is so important for selecting the suitable tool and machine tool. For prevention of chatter vibrations and tool damages, first of all the amounts of cutting forces should be predicted correctly [3]. In this study between the ordinary superalloys used in aerospace industry, the properties of titanium alloy (Ti-6AL-4V) and its machinability are investigated. In the next part in order to determine the stable and instable cutting situations, milling forces in different cutting conditions are measured by means of kistler 9255B dynamometer. The other objective of this study is to determine the milling effects on machined surface of Ti-6AL-4V part with different cutting speeds, for researching about this issue, the surface integrity of machined part should be studied.

The investigation about surface integrity of machined surface include metallographic analyses of specimens by means of optical microscopy and measuring variations of micro-structural grain features and also variations of mean values of hardness or size and location of surface defects.

2- SUPERALLOYS APPLIED IN AEROSPACE INDUSTRY

Aerospace superalloys such as nickel base and titanium alloys, as well as other advanced engineering materials like structural ceramics and tantalum are usually employed in manufacture of components for aerospace, electronics and defense,… industries because of their unique combination of properties like high strength at elevated temperatures, resistance to chemical degradation and water resistance. Ability to maintain these properties at elevated temperatures severely hinders the machinability of these alloys, thus they are generally referred to as difficult to cut alloys [4].

The cutting region usually encounters more intense heat generation when machining difficult- to-cut alloys since the machining process requires more energy than that in cutting lower strength materials. The low thermal conductivity of these alloys relative to conventional steels or cast iron, also leads to a significant increase in temperature at the cutting tool and the workpiece during machining [5].

Titanium alloys possess a combination of mechanical properties and corrosion resistance which makes them very attractive for industrial applications. It is better to mention that the main reason for choosing titanium alloys for aero- engines and aero-structures is the high strength to weight ratio [6]. Decreasing weight is frequently one of the main objectives in aerospace applications. Although titanium is more expensive than steel but its main advantage is being lighter than steel (about 1/3 compared with steel) [7]. The main properties of these alloys are as follows:

1- High strength to weight ratio.
2- Low density.
3- High corrosion resistance.
4- High strength at elevated temperatures.

Titanium alloys are classified into four main groups:

1- alpha alloy
2- beta alloy
3 - close alpha alloys
4- alpha-beta alloys

In these classifications, alpha-beta alloys are frequently structural alloys and generally are used in production of aero-engine and aero-structural parts. This type of titanium alloy is identified by a microscopic micro-structure of alpha and beta phases and in comparison with aluminum alloys and low-alloyed steels possess higher corrosion resistance and are preferred more in most of the aerospace applications than steels.

Ti-6AL-4V is the most applicable and famous type of titanium alloy which is belonged to alpha-beta group. Some of the physical and mechanical properties of Ti-6AL-4V are presented in table (1).

Density g/cm3 (lb/ cu in)	4.42(0.159)
Melting Range °C±15°C (°F)	1649(3000)
Specific Heat J/kg.°C (BTU/lb/°F)	560(0.134)
Volume Electrical Resistivity ohm.cm (ohm.in)	170(67)
Thermal Conductivity W/m.K (BTU/ft.h.°F)	7.2(67)
Hardness, Rockwell	36
Modulus of Elasticity (GPa)	113.8
Poisson Ratio	0.334
Tensile Strength, Yield (MPa)	880

Table 1: physical and mechanical properties of Ti-6Al-4V [7]

3- MACHINABILITY OF Ti-6AL-4V

In machining the titanium alloys, cutting forces are a little more than cutting forces in machining of steels but the main reason that makes machining of these alloys harder than steels with equal hardness value, is metallurgical properties of titanium alloys. Low thermal conductivity is one of the main problems in machining of titanium alloys. There are some characteristics of titanium that have influenced the machinability of Ti-6AL-4V alloy as follows:[10]

1- Titanium alloy (Ti-6AL-4V) has low thermal conductivity, so heat does not dissipate easily from the tool-chip interface, the tool gets heated quickly due to the resulting high temperature and this leads to lower tool lives. It should be mentioned that thermal conductivity of Ti-6AL-4V alloy is about 8 to 10 times less than thermal conductivity of steels and about 13 times less than aluminum.
2- Titanium has a strong alloying tendency or chemical reactivity with materials in the cutting tools at tool operating temperatures, this causes welding and smearing along with rapid destruction of cutting tool.
3- Titanium has a relatively low modulus of elasticity, thereby having more springness than steel. Work has tendency to move away from the cutting tool unless heavy cuts are maintained or proper backup is employed. Slender parts tend to deflect under tool pressures, causing chatter, tool rubbing and tolerance problems. Rigidity of the entire system is consequently very important, as is the use of sharp, properly shaped cutting tools.

Since milling is a discontinuous machining operation, tool should have higher bending strength or the tool must be harder. The cutting tool used for machining of aero-engine alloys must have high hot hardness in order to endure the elevated temperature during high speed machining [9]. Also it should have high thermal conductivity to decrease the cutting generated temperature. When machining Ti-6AL-4V, conventional tools wear rapidly because poor thermal conductivity of titanium alloys results in higher temperature closer to the cutting edge during machining. There exists strong adhesion between the tool and workpiece material. In addition, titanium alloys are generally difficult to machine at cutting speeds over 30 m/min with high-speed steel (HSS) tools, and over 60 m/min with cemented tungsten carbide (WC) tools, resulting in very low productivity [9]. Coated carbide, ceramic and CBN/BCBN/PCBN tools are the most suitable and applicable tools for machining the aerospace industry alloys. In this study a typical M-grade coated carbide flat end-mill is used for milling operation. Since in milling process, titanium has a tendency to adhere the cutting tool, the method of down-milling is better than up-milling operation. In down-milling, chip is cut away like a comma (,) sign, therefore tool damages as the result of built-up-edge and chip adhesion decrease to a minimum level [11].

4- IMPORTANCE OF SURFACE INTEGRITY

Dynamic loading is a principal factor in the design of many mechanical structures, but design capabilities are frequently limited by the fatigue characteristics and surface defects. These failure and defect criteria are locations for stress concentration.

Materials like Ti-6AL-4V require improved capabilities because of high hardness and low thermal conductivity in machining, which is needed to pay careful attention to the roughing and finishing of these surfaces. Surface integrity is defined as the inherent condition of a surface produced in a machining or other surface generation. The nature of the surface layer has a strong influence on the mechanical properties of the part. When machining any component it is first necessary to satisfy the surface integrity requirements. Surface integrity produced by a metal removal operation includes the nature of both surface topography as well as surface metallurgy.

Study of surface topography include surface alterations as follows:

1- Formation of notches and defects on the top surface.
2- Plastic deformation of the surface layer.
3- Change in hardness of the surface layer.
4- Microcracking and macrocracking
5- Residual stress distribution in the surface layer.

Metallurgic analyses of machined surface include variations of micro-structural grain features or grain size and comparing the grain size between machined surface and non-machined surface. In following, surface alterations like notches, pits or surface defects and micro-structural grain features of Ti-6AL-4V and comparing these structures between machined edge and non-machined surface will be performed.

5-EQUIPMENTS, MATERIAL AND METHOD OF EXPERIMENTAL TEST

5-1 Test equipments

3-axis CNC milling (Deckel FP4MB) has been used in machining operation, controller of this milling machine is the type of Simense 810-D.

The tool that has been applied is M-grade coated carbide flat end mill with 10 mm diameter and helix angle $(30^\circ)$and the number of flutes is 4.

For experimental test, 6 samples of Ti-6AL-4V material with dimensions of $40\times20\times5$ mm are prepared. It should be mentioned that with consideration of low thermal conductivity of titanium alloy and probability of micro-structural transformation due to overheating, in order to minimize the temperature during sample preparation from the titanium block, the wire-cut EDM has been used for cutting the machining samples from the initial titanium block. The length of 10 mm of the machining sample is clamped in a table-vise which has been fixed on the top surface of the dynamometer. The dynamometer type of Kistler 9255B is used for force measurement. This kind of dynamometer is capable of measuring the force in X and Y orientations in the range of -20 to +20 KN and in Z orientation in the range of -10 to 40 KN. In figure (1) the titanium sample during the milling process is shown.[12]

Figure 1: workpiece during the milling operation

5-2 The method of test

For experimental tests, initially the dynamometer device is calibered. Machining tests are performed using the machining parameters presented in table (2).

Test	DOC (mm)	WOC (mm)	Feed Rate (mm/min)	Spindle Speed(RPM)
1	7	1	10	500
2	7	2	10	500
3	7	1	10	1000
4	7	2	10	1000
5	7	1	10	1500
6	7	2	10	1500
7	7	1	10	2000
8	7	2	10	2000
9	7	1	10	2500
10	7	2	10	2500
11	7	1	10	3000
12	7	2	10	3000

Table 2: machining conditions and performed tests

Milling forces in X and Y orientations for presented conditions in table 2 are measured, The results of 1th , 3th and 9th tests in low radial depth of cut (WOC=1mm) and variable speeds during the time of 5 rotations of cutter are illustrated in figures (2), (3) and (4). By observing the figures of 2,3 and 4 , it is clear that there is a small variation in forces with different spindle speeds. In following the results of Fx and Fy which measured by table dynamometer for 2th, 6th and 12th tests during the time of 5 rotations of cutter are shown in figures (5) , (6) and (7).

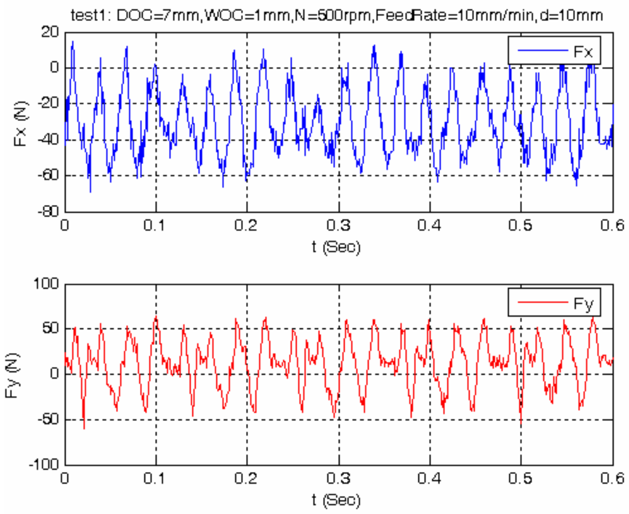

Figure 2: measured forces in spindle speed 500 rpm (test1)

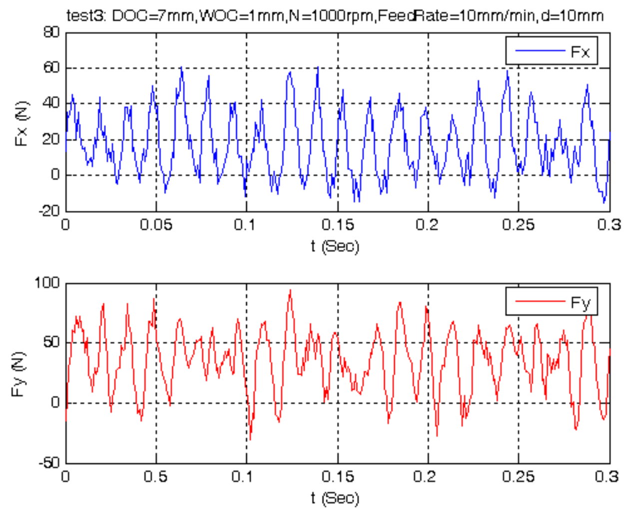

Figure 3 measured forces in spindle speed 1000 rpm (test3)

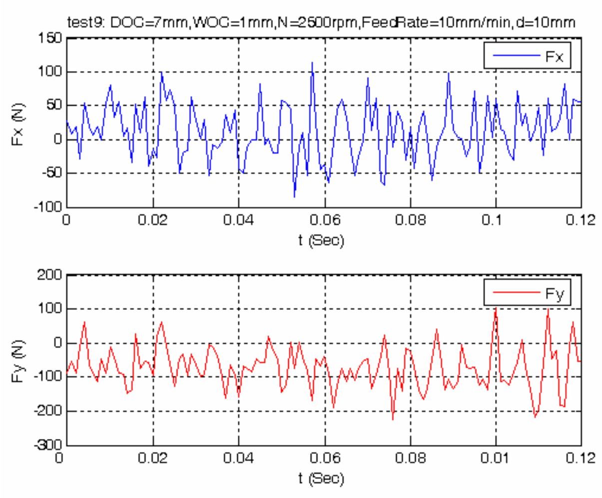

Figure 4: measured forces in spindle speed2500 rpm (test9)

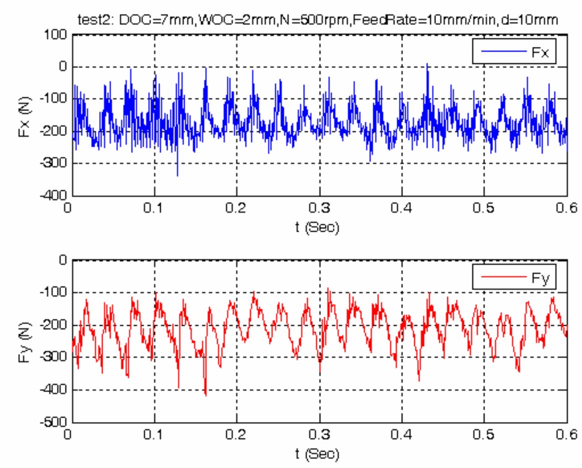

Figure 5: measured forces in spindle speed 500 rpm (test2)

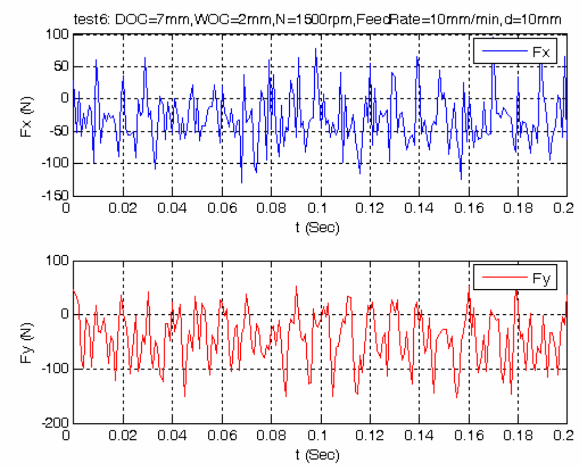

Figure 6: measured forces in spindle speed 1500 rpm (test6)

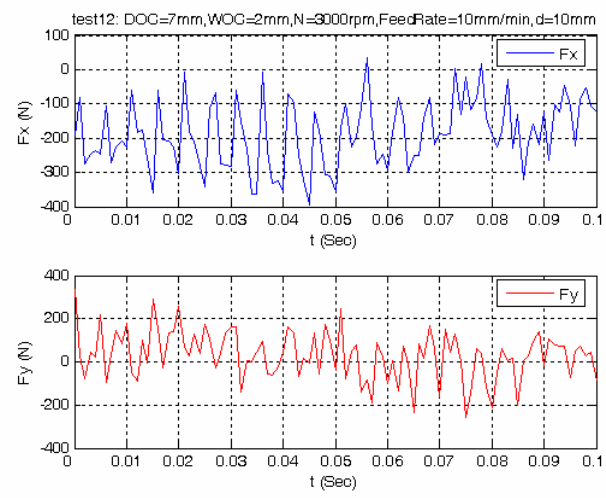

Figure 7: measured forces in spindle speed 3000 rpm (test12)

By increasing the spindle speed from 500 rpm to 1500rpm cutting forces have a little decrease but again with increasing spindle speed to 2000rpm and 2500rpm and 3000prm, the cutting forces are increasing, which result of 3000rpm is illustrated in figure(7).

One of the reasons of force increasing is flexibility of workpiece and being thin-walled part consequently there is an increase in vibrations of tool and workpiece with increase of spindle speed and the other is related to increasing of temperature and therefore friction which lead to more tool wear due to increase of spindle speed.

With consideration of workpiece dimensions (relatively small length) and assurance about proper clamping of workpiece by means of a table-vise during the milling operation, there is not great variation in amplitude of milling forces.

Since the main objective of this paper is to investigate the effects of variation of spindle speed (cutting speed) on the values of cutting forces and surface integrity of the machined part, investigating about dimensional errors has less importance in this paper. Although for measuring the deflections precisely a strain gage should be applied, but in this paper after the machining of thin-walled part, with measuring the axial and radial depth of cut by means of a dial indicator gage and a caliper, It is obvious that there is a trivial difference in depths of cut through the cutting path. Therefore there is a negligible difference between the measured DOC and WOC and given dimensions in written CNC program, so this issue verifies that workpiece has had trivial deflection during the milling process. With comparison of force measurement in tests of 1 and 2 (figures 2 and 5) it is identified that by changing radial depth of cut (from 1mm to 2mm) cutting forces increase and it is because of increasing the tool-workpiece contact face.

6 MICRO-STRUCTURAL ANALYSIS AND PREPARATION OF METALLOGRAPHIC SPECIMENS OF MACHINED PARTS

Observing the microscopic structure of material reveals characteristics that have a tremendous influence on their technological utility. Some of the features that contribute to the strength of materials and virtually all of the features that initiate mechanical failure are resolved by optical microscopy. The objective of preparing metallographic specimens is to reveal the structural features and surface integrity of machined parts.

First of all for metallographic analyses the machined parts are cut by means of a Struers cutter device to smaller samples using coolant fluid during the cutting process, in the next step these samples will be mounted in a way that top surface of mounted sample or the surface that will be ground and polished in following steps, be at right angle to the machined surface, In order to observe the influence of surface defects at the edge of machined surface. Mounted sample is illustrated in figure 8.

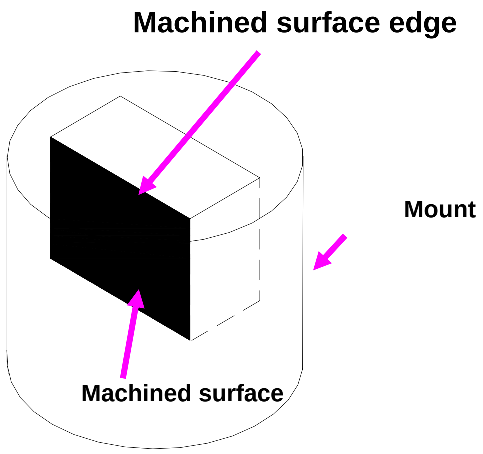

Figure 8: the location of machined surface in mounted sample

In order to observe the surface defects of machined parts those are located at the edge of top surface of mounted sample, the grinding process is applied on the specimens by means of grinding papers, the grit sizes that are used for grinding process are p180,p320,p500,p800,p1000,p1200 respectively. During the grinding process a modest flow of water is passed to carry away the metal flakes ground off the surface. By proceeding through a series of successively finer grits, the scratched and damaged layers left by each grit size are removed by the next one, when changing to a finer grit size, the specimen is rotated 90° from the scratch orientation left by the previous step and ground until all previous scratches are gone. After the grinding process, in order to observe the surface defects that caused by machining process in different cutting speeds, the machined samples are analyzed and investigated by means of a Struers optical microscope. The 9,10,11,12 and 13 Figures show the surface integrity of the machined edge of mounted sample in different cutting situations which are mentioned in table 2 at magnification of 500X. With regarding the figures it is identified that the machined surface in lower spindle speeds (rpm) possess less surface defects (pit, notch, crack) than machined surface in higher spindle speeds (rpm).

During the machining process, the obvious characteristics of chatter vibration like loud and annoying Sounds, intensive vibrations of table-vise, workpiece and tool have not been observed, and also there were not chatter feed marks on the surface of machined part, in addition to, By observing the cutting forces diagrams, it is identified that there is not sensible change in amplitude of cutting forces during the rotations of cutter. Therefore it is clear that there has not been chatter vibration during the milling operation and machined edge destruction is due to increasing of spindle speed (cutting speed).

But with considering that, these defects range in a trivial depth of machined samples from the top of the surface, and for increasing the material removal rate and consequently productivity, it is better to carry out the machining passes in the highest practical spindle speed (rpm) that simultaneously ensure the stable cutting conditions to avoid chatter vibrations and damages that caused by instable cutting conditions. Finally the last machining pass is performed in a low spindle speed in order to eliminate the surface defects left by previous machining passes in higher spindle speeds, however the selection of suitable low spindle speed that simultaneously eliminate the surface defects and provide the acceptable surface roughness is an important issue.

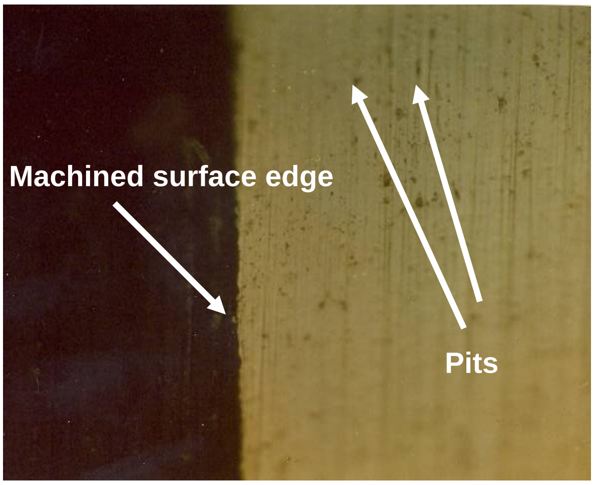

Figure 9: surface integrity of machined sample in 500 rpm at magnification 500X (test 2)

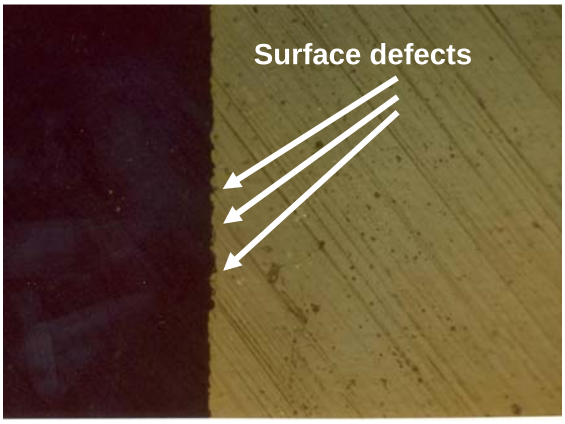

Figure 10: surface integrity of machined sample in 1500 rpm at magnification 500X (test 6)

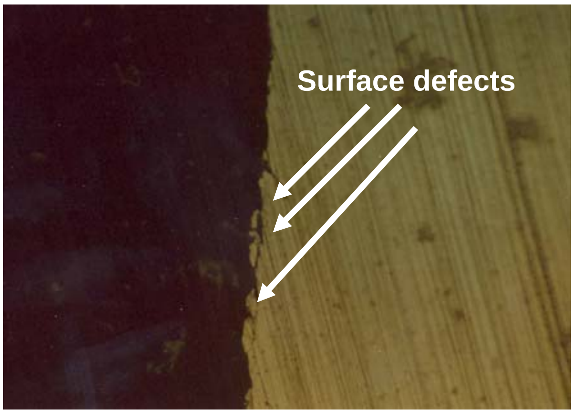

Figure 11: surface integrity of machined sample in 2000 rpm at magnification 500X (test 8)

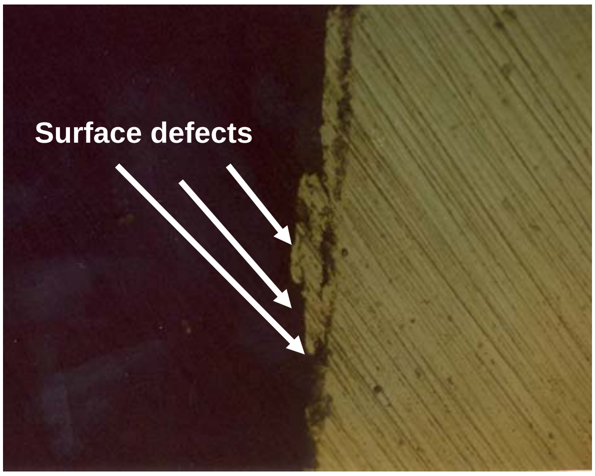

Figure 12: surface integrity of machined sample in 2500 rpm at magnification 500X (test 10)

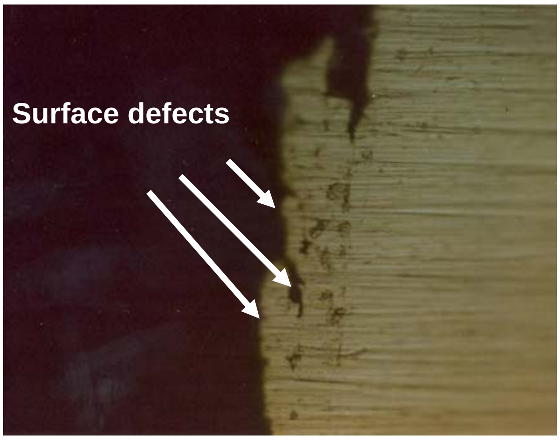

Figure 13: surface integrity of machined sample in 3000 rpm at magnification 500X (test 12)

In the following step in order to observe the micro-structural phases of specimens and comparing the grains in machined and non-machined surface, the specimens should be polished by means of AL2O3 abrasive particles and etched with application of kroll solution.

The consequent of grinding and polishing process is a mirror-like surface. The specimens will be etched by means of kroll reagent. The chemical composition of this etching solution is as follows:[10]

Dionized water (DI) 100CC , HF (hydrofluoric acid) 3 CC and HNO3 (nitric acid) 6CC.

The etching time is experimentally chosen between 3-15 seconds. Grain boundaries have high energy spots and etching releases all the electrons which are loosely held inside the atoms to reveal the microstructure.

In figure (14) the micro-structural phases of alpha (α) and beta (β) in Ti-6AL-4V after the etching process are identified. The light grains are the alpha grains while dark grains are the beta grains[10]. The reason for this contrast is due to difference in the reflectivity of alpha and beta phases during etching, the reagent selected for etching the specimens is kroll reagent, which selectively attacks only the alpha phase.

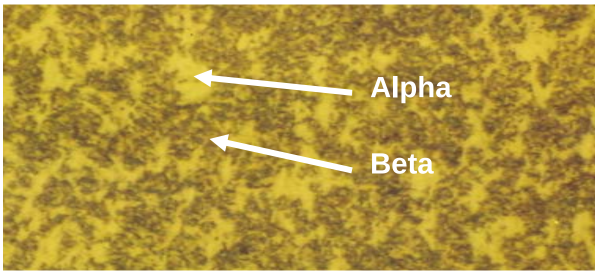

Figure 14: alpha and beta phases in Ti-6Al-4V

Micro-structural grain features at the edge of machined surface and non-machined surface is illustrated in Figure 15.

Figure 15: grain features in machined surface edge and non-machined surface

With consideration of the above figure it is visible that the feature of micro-structural phases at machined edge and non-machined surface is the same and there is no sensible difference between these locations.

The Rockwell (C) hardness test has been done for some specimens, These results are presented in table (3).

	Rockwell C Hardness Test Measurement
Non-machined sample	36.4
Test (4) from table (2)	37.25
Test (10) from table (2)	37.7

Table 3: Rockwell C hardness test measurements for test 4 , test10 and non-machining part

By observing these results, it is determined that hardness values of machined surfaces in higher spindle speeds (rpm) are a little more than hardness values of machined surfaces in a lower spindle speeds and non-machined surface, the reason of this increase in hardness value is work-hardening which has been performed during the machining process on the surface.

7 CONCLUSION

In peripheral milling of thin-walled part Ti-6AL-4V alloy by increasing the radial immersion (radial depth of cut) the milling forces increase, also in low immersion milling there is a small variation in cutting forces by changing spindle speed but by increasing the radial immersion and maintaining it in a constant value and changing the spindle speed, initially cutting forces decrease then in higher speeds they will increase therefore determining the optimum speed is so important. Micro-structural analyses show that in different cutting speeds with increasing speed, surface defects are growing and become more, these surface defects are locations of stress concentration and simplify the growth of early fatigue cracks which decrease the fatigue life strictly. Although changing the cutting speed does not influence the machined surface micro-structural grain features. Hardness test show that hardness value in high speeds is a little more than hardness value in machined surface with lower speed and also non-machined surface. It should be mentioned as a conclusion that, it is better to machine titanium thin-walled part with low immersion (low radial depth of cut). In order to use maximum power of machine tool in a stable machining condition without any chatter, the optimum cutting parameters can be determined. With considering that surface defects range in a trivial depth (less than some microns) and increase of these defects in higher cutting speeds, therefore for obtaining the best condition of surface integrity in machining, it is recommended to use lower spindle speeds in the finishing passes for milling operation. In the current study in order to obtain the best situation of surface integrity and cutting stability it is recommended to machine in 1500 rpm spindle speed and 2 mm radial depth of cut and to finish the workpiece in 500 rpm spindle speed and 1 mm radial depth of cut.

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