Journal of Achievements in Materials and Manufacturing Engineering

VOLUME 31
ISSUE 2
December
2008

Study of the milling strategy on the tool life and the surface quality for knee prostheses

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Received 05.09.2008; published in revised form 01.12.2008

Manufacturing and processing

ABSTRACT

Purpose: The aim of this research is to make a study about the influence of the tool trajectory's generation on its tool life and the improvement of the surface quality in multi-axis milling at high speed machining of the knee prostheses. The material used for this study is the titanium alloy Ti-6Al-4V ELI (TA6V ELI) for implant.

Design/methodology/approach: The methodology has consisted on proving a serie of parameters combinations with various machining configurations and various programs of the tool trajectory's generation in three and five axes (the axis of the tool is maintained normal on the machined surface by rotation around Y axis; the axis of the tool is maintained according to axis Z; the axis of the tool is tilted around the Y axis). And determined the influence of the machining strategy over of the tool life.

Findings: The knee prostheses are constructed with important mechanical resistance materials with complex form, which require high performance cutting tools and high cost. The good generation's trajectory of the cutting tool in multi-axes milling permits to minimize flank wear. High speed Machining offers a considerable profit in the capacity of surface quality, duration of the machining and polishing operations and consequently in improvement productivity. But the choice of the cutting speed must be recommended by the couple tool-materials.

Research limitations/implications: A possible future work would be the development of a general the phenomenal of the residual stress of various machining configurations and various programs of the tool trajectory's generation and the knee protheses life. The behaviour of the residual stress studies are planed in the future.

Practical implications: The relationship found between the milling strategy on the tool life and surface quality work piece has an important practical implication since it allows selecting the best cutting condition for knee prostheses. Results are of great importance in the quality of articulation surface so the cartilage in medicine industry.

Originality/value: The paper is original since the bibliographical review has allowed testing that, although works about these themes exist, none approaches the problem like it has been made in this work. This paper could be an interesting source of information for engineers and researchers who work with machining knee prostheses.

Keywords: Machining strategy; Tool life; Surface quality; Knee prostheses; Titanium alloys

1. Introduction

The knee is a complex articulation, at the same time mobile, flexible, solid and resistant which supports the weight of the body and allows multiple activities. In the event of problems, it is always the opinion of a specialist who allows defining the procedure of treatment. The comprehension of the knee operation and the knowledge of its failures made it possible to make important progress in the treatment of various pathologies.

The knee's fractures are dangerous because they interest the articulation surfaces and thus the cartilage. That implies that they must be repaired with the greatest care to give again with the maximum knee of its possibilities and its former functions.

However, the cartilage can be crushed and definitively injured by crushing mechanisms of articulation surfaces at the time of the traumatism. The surgery will as well as possible allow the re-establishment of the anatomy according to the gravity of the initial fracture and in particular to the number of fragments interesting cartilaginous surfaces [1-2].

The radiological assessment of the fractures is essential to plan a treatment. It associates radios and tomography and/or a scanner examination when that proves to be necessary. There is not, often, urgently surgical immediate, except if the fracture is opened, i.e. if there is a wound exposing the knee articulation to the air, or, if there are vascular or nervous complications [3].

The knee prosthesis is not a hinge which would take the place of the articulation. It seeks to replace only the cartilage, where it is worn, while preserving the best possible anatomy of the knee, and in particular its ligaments: this is why there is not only one, but several prostheses which adapt to the various lesions met on the level of knee [2-3].

These prostheses have generally, complex forms which require a very good surface quality and a very good precision of machining in order to preserve the best possible anatomy of each patient. The knee prostheses are out of metallic materials of high mechanical strength, having a low machinability such as titanium alloy, the chromium-cobalt alloy and the stainless steel.

However, to better machining these harder materials and complex surfaces, we use a high speed machining (HSM).

In resents years, high-speed machining HSM has been widely recognized as one of the key processes in fabricating aluminium parts [4-10]. This is due to the several advantages that high-speed machining offers over conventional machining. First, at higher speeds, a single heavy cut is sufficient to produce a good surface finish. The use of heavier cuts along with higher speeds also increases productivity. Second, lower cutting forces generated during high-speed machining of materials compared with conventional machining allows for machining of parts with thin cross-sections. Third, at higher speeds there is no formation of built up edges and burrs, thus helping improve finished part quality. Forth, at higher speeds minimise the residual stresses on all machined surface [4, 9].

The HSM of the complex forms is a technique which appeared following the important innovations implemented during these last years. The joint improvement of materials of the machine tool and, their geometry, cutting tools numerical control unit in general made it possible to widen the range of the applications of this technique. We speak about high speed machining when the values of the operational parameters are much higher than during conventional machining.

The purpose of this work is to present a study about high speed machining of titanium alloy used for the knee prostheses. The reasons of this choice of this material were its impressive biocompatibility, its high corrosion resistance and specific mechanical properties. Today, titanium has found increasing application as an implant material.

In this paper, first, we present the models and the shapes of the knee prostheses, and then we introduce some mathematics models of the complex forms in general. And finally, a study about the influence of the machining strategy of over the tool life and on the surface quality milling of the complex forms was presented, followed conclusions of this presentation.

2. Knee prostheses

2.1. Models of the knee prosthesis

The current knee prostheses are characterized by their diversity, related to the complexity of this articulation. The unicompartmental knee prosthesis or half prostheses, which they are femur tibia internal, femur tibia external, replace the cartilage of the injured compartment, without touching the ligaments and nor the other compartments which must so, be healthy (see Figure 1). They are addressed to the osteoarthritides limited to only one compartment, as well as some necroses osseous [3]. Used for more than 20 years, they have involved very little osseous reaction [2]. The femoral prosthesis is metal (titanium alloy), and the support out of polyethylene with the lower part (see Figure 1).

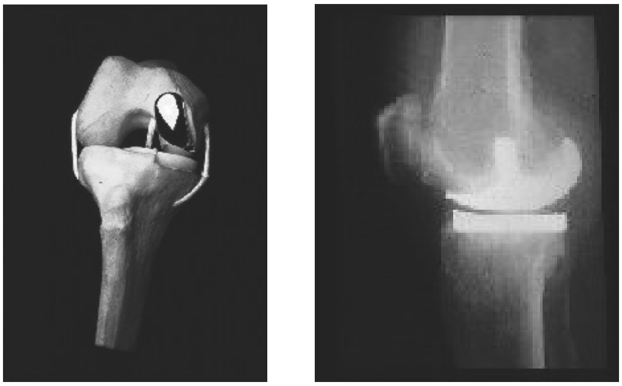


Fig. 1. Position of half prosthesis given in [2]

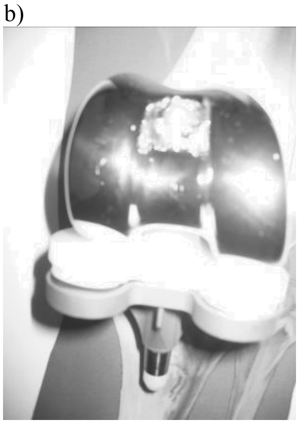
The total prostheses profited from a better knowledge of the physiology of the knee, in particular of the concepts of bearing, slip, and of rotation tibiae: the prostheses with hinges were abandoned with the profit of total slip prostheses, appeared at the beginning of the Seventies, more respecting the knee anatomy and in particular its apparatus ligament [2-3]. Thus, these slip prostheses tend to replace only the cartilage, a little like does it the prosthesis linked for one compartment: they comprise two separated components, a support, partly or entirely out of polyethylene, and a condoyle femoral prosthesis in titanium alloy, which comes to be encased on the lower end of the femur (Figures 2a and 2b).

However, the hinges prostheses, bulkier, they replace completely the knee articulation (Figure 2c). They are rarely necessary. They are reserved for the very important deformations, the ligaments destruction, like for some resumption of prostheses.

Their results, judged on walk and on the disappearance of pains, did not cease improving, and now reach the quality of those of the hip total prostheses. The immediate continuations are rather fast, with absence of immobilization and possibility of early resumption of walk with support. It is the pain which constitutes the fundamental element of the operational indication whose decision belongs to the patient himself [2].

a)

b)



c)

Fig. 2. Different types of slip total prosthesis a), b), and a typical Hinge prosthesis c)

2.2. Cost price of the knee prosthesis

It appears however, interesting to have an idea about the total price of the knee prosthesis paid by the Social security, France, for the installation of the knee prosthesis and to know the share which remains with the load of operated. The total cost of the knee prosthesis is related to several factors: type of prosthesis, but so lasted of the hospitalization, the possible stay in centre of rehabilitation, medical fees, practised complementary examinations etc…

The price estimate in euros of the knee prosthesis dealt with by the “Social Security France”, in officially agreed private clinic in Paris.

These Figures make it possible to have an idea, but they remain very approximate: the durations of hospitalization can vary. Possible a 4 weeks stay in centre of rehabilitation can double the total “operation + hospitalization”. The cost of day in officially agreed clinic private, and the expenses of operating room, is very variable according to the geographical site and, in the same area, classification of the private clinic. This estimation did not take account of possible transport in the ambulance until the centre of rehabilitation or the residence.

The paper should be prepared according to the requirements provided in Table 1. Please pay attention to the fact that the subsection should be not shorter than 0.5 column.

Table 1.
Estimate of the price in euros of the knee prosthesis

	Half prosthesis (Euros €)	Total prosthesis with platform (Euros €)
Stay (15 days on average, 104.07€/jour)	1588	1600
Expenses of operating room	1500	1650
Fees of the surgeon	510	530
Fees of the anaesthetist	230	250
Radio, physiotherapist, laboratory, electrocardiogram	1400	1600
Blood (car-transfusion)	350	350
Prosthesis	1000	3500
Total operation + hospitalization	6570	9480

3. Study of the multiaxis machining of the complex forms

The evolution of the drawing of some implants in full safety allows in theory an inflection until 150° i.e. by increasing the surface of posterior contact between the condoyle and polyethylene in order to limit the early risk of wear [2]. The rotator platform prostheses take part also, with a better mobility. They distribute also better the mechanical constraints of the extension until the inflection supplements in order to decrease the risk of wear of polyethylene.

Additionally, according to the age, the size and also the type of activity of the patient, it is necessary to design and manufacture the femoral prosthesis and polyethylene to ensure the inflection required in each case. However, these prostheses are generally, complex forms, and out of titanium alloy or chromium cobalt alloy [11]. Their manufacture is often released by removal of matters in multi-axis machining. The prostheses must be precise and have a good roughness, i.e. a polished mirror surface to minimize friction (Figure 2a).

The majority of the systems 3D of CAM, Computer Aided Manufacturing treat the complex surfaces conceived by the designer; these surfaces are often modelled by parametric equations such as: polynomial, Bézier, B-Spline, NURBS…

The Bézier surface is defined using a characteristic network on which are located P_{ij} poles. A Bézier surface is written in the form of:

$$S(u,v)=\sum_{i=0}^{n}\sum_{j=0}^{m}P_{ij}B_i^n(u)B_j^m(v) \quad (1)$$

with (Bernstein polynomials)

$$B_i^k=\binom{i}{k}x^i(1-x)^{k-i} \quad (2)$$

The Equation of a B-Spline surface represents the locus of a B-Spline curve when it undergoes simultaneously a translation and a deformation [12]. A surface thus obtained is defined by a network of Pij poles. The Equation is form:

$$S(u,v)=\sum_{i=0}^{p}\sum_{j=0}^{q}P_{ij}N_i^m(u)N_j^n(v) \quad (3)$$

The B-Splines functions $N_i^m(u)$ are polynomials of m degree.

A surface NURBS (Not Uniform Rational B-Spline) is the rational generation of the tensorial product of non rational B-Splines surfaces and is defined by:

$$S(u,v)=\frac{\sum_{i=0}^{p}\sum_{j=0}^{q}w_{ij}P_{ij}N_i^m(u)N_j^n(v)}{\sum_{i=0}^{p}\sum_{j=0}^{q}w_{ij}N_i^m(u)N_j^n(v)} \quad (4)$$

where w_{ij} is the weights assigned respectively to the P_{ij} poles.

This definition includes all surfaces presented previously. Surfaces NURBS, make it possible to model surfaces of revolution (cylinder, torques, sphere…) [13].

4. Influence of machining strategy over the tool life

The machining strategy depends on the multi-axis mode generation of the tool trajectory in particular in milling; it has an important role on the surface quality as over the cutter tool life which is generally with high performance and high cost [14-16].

4.1. Modes of machining and cutting conditions

In order to better optimize the tool wear during the complex forms machining, as it is the case of the knee prostheses manufacture, we did many tests of ellipsoid form milling (who is similar to the shape of the knee prosthesis, Figure 2 with various machining configurations and various programmes of generation of the tool trajectory in three and five axes, as indicated Figures 3 (a), (b) and (c).

The shape of ellipsoid comprises the small and big curves like the case of the femoral prosthesis presented at Figures 1 and 2.

According to the 3 machining strategies, and during the removal of matters, the tool removes the chips with different effective cutting speeds V_{ceff}:

- Mode (1) (Figure 3a):

$$V_{c\text{-}eff}=\frac{\pi.n.\left(2\sqrt{D.a_p-a_p^2}\right)}{1000} \quad (5)$$

- Mode (2) (Figure 3b):

$$\frac{2\pi.n.\sqrt{Da_p-a_p^2}}{1000}\leq V_{c-eff}\leq\frac{2\pi.R.n}{1000} \quad (6)$$

- Mode (3) (Figure 3c):

$$\frac{\pi.n.D\sin\left[\theta_n+\arccos\left(\frac{R-a_p}{R}\right)\right]}{1000}\leq V_{c-eff}\leq\frac{2\pi.R.n}{1000} \quad (7)$$

where $V_{c\text{-}eff}$ denotes effective cutting speed, D, R denotes the nominal diameter, radius of a ball-end cutter, a_p denotes the axial engagement or axial depth of cut and n denotes spindle speed.

The material used for this study is the titanium alloy Ti-6Al-4V ELI (TA6V ELI) for implant which has an excellent mechanical resistance report/ratio/density. Its lightness (4.3 g/cm^3 for titanium alloy, compared to 7.9 g/cm^3 for steel) and its great mechanical properties, high corrosion resistance are also major assets (Tables 2 and 3). Its use is increasingly important and this, in spite of its high cost.

Table 2.
Chemical Composition of titanium alloy Ti6Al4V ELI (%)

Al	V	Fe	O	C	H_2	Ti
5.5 – 6.5	3.5 – 4.5	≤ 0.25	≤ 0.13	≤ 0.08	≤ 0.012	Bal

Table 3.
Mechanical properties of titanium alloy

R (MPa)	Re (MPa)	Elongation A (%)
≥ 860	≥ 780	≥ 10

The machine used is a milling machine with five axes, Gambin 120 CR, with vertical spindle, having a maximum power with the spindle of 14 KW, authorizing rotational frequencies of the spindle 40.000 rev/min. It is controlled by a Telemechanic Numerical Control "Num 1060".

The tool used is a ball end mill with two teeth of carbide base, (94% WC + 6% Co) coated with Ti (CN) of high adherence to the high substrate and hardness.

a) b) c)

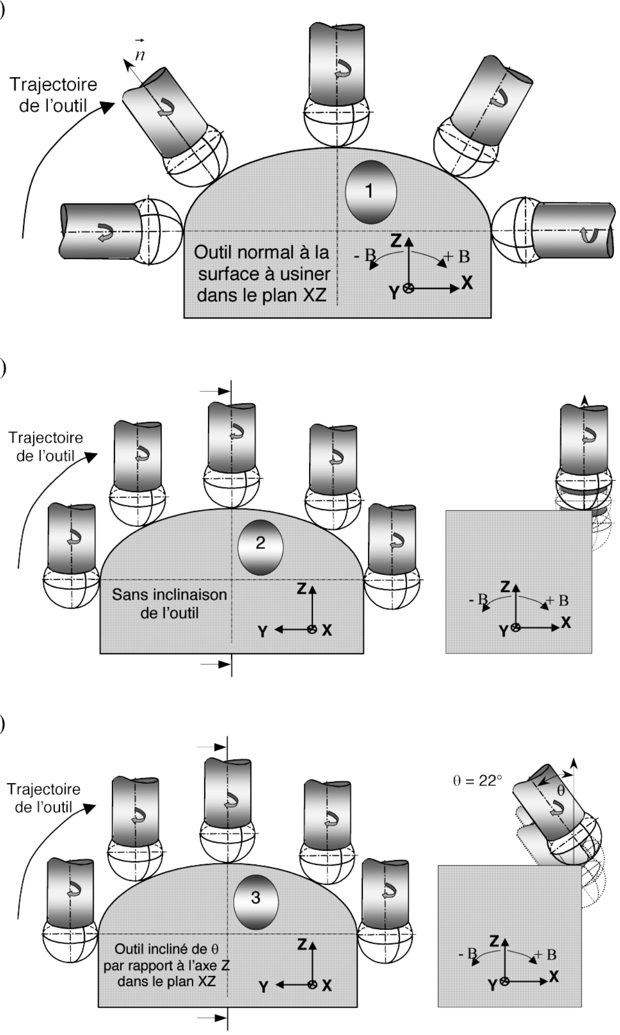


Fig. 3. Machining strategies defined with three different configurations: a) Mode (1): the axis of the tool is maintained normal on the machined surface by rotation around Y axis; b) Mode (2): the axis of the tool is maintained according to axis Z, (reference); and c) Mode (3): the axis of the tool is tilted around the Y axis, in plan XZ, of an angle θ = 22° compared to Z axis

The tests were carried out with the following cutting conditions: diameter of the tool D = 16 mm, feed by tooth f_z = 0.15 mm, number of revolutions n = 2866 rev/min, cutting feed V_f = 860 mm/min, depth of cut axial a_p = 0.4 mm, depth of cut radial a_e = 0.5 mm, dry machining.

4.2. Influence of the machining strategy over of the tool live

The tool wear tests were limited to a maximum value of tool flank wear in VB_{max} = 0.2 mm, see Figure 4a.

The result of the tool life is appreciated in length traversed by the mill axis, indicated machined length. The influence of the mode of machining strategy is really highlighted; indeed, the machined length is 90 m, 360 m, 442 m, according to whether the operation of machining is carried out respectively in mode of program (1), (2), (3) (Figure 4b). (Note: the tool life can also be appreciated in quantity of milled surface).

It is clear that the good optimization of the tool trajectory generation is related to that of the study released out according to the mode of machining (3).

Certainly, the active part of the cut tool edge works in better conditions that in the other cases; the too low cutting speeds (even null) towards the tool centre are avoided, and a better distribution of the pressures on the active part of the tool edge is assured.
When the tool removes materials according to the mode of machining strategy (1) (axis of the normal tool on the machined surface), the surface quality is very bad and the tool live is strongly reduced (until a reduction of - 75%) compared to the reference machining strategy (mode (2)).

a) b)

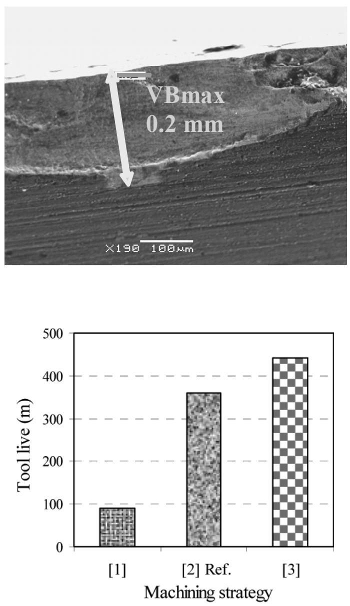


Fig. 4. Typical tool wearing during the function a), and tool life according to the different machining strategies (1), (2), (3) b)

4.3. Influence of high speed machining on the surface quality

In order to study the surface quality of the machined parts, measurements are done with a profilometer Somicronic-Surfascan three-dimensional 3D, equipped with a contact feeler conical with an point angle equal 90° and the point rayon 2 µm.

The analysis of the three-dimensional micro-geometrical surface quality obtained by a sweeping on a rectangle of 3 x 4 mm with a step of 12 µm in X and Y. The analysis shows, clearly, the improvement of the surface quality in high speed machining HSM. The result of parameters of surface quality 3D; the arithmetic mean of surface (Sa), the root mean square deviation of the surface (Sq) and the law of Kurtosis heights distribution (Ek) pass respectively from 1.71 µm, 2.2 µm and 2.9 in conventional machining with 2866 rev/min with values of Sa = 1.29 µm, Sq = 1.6 µm and Ek = 2.6 in machining with 11.900 rev/min (Fig. 5).

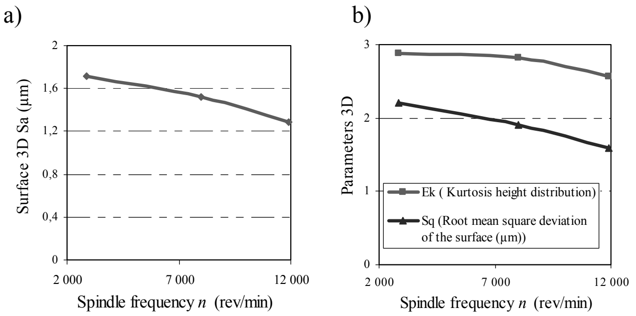


Fig. 5. Improvement surface qualities in high speed milling

5. Conclusions

Titanium alloy is an excellent implant material because of its high corrosion resistance and outstanding biocompatibility. It is known for not causing allergic reactions and it is preferred when infection is a risk.

The knee prostheses are constructed with important mechanical resistance materials of complex form, which require high performance cutting tools and high cost. It is thus necessary to optimize their tool live.

- The good generation's trajectory of the cutting tool in milling multi-axes to minimize flank wear and consequently improve the tool lives.
- High speed Machining offers a considerable gain in the capacity as surface quality, duration of the machining operations and polishing operations and consequently in improvement productivity (gain of 66% in machining of completion). But the choice of the cutting speed must be recommended by the couple tool-materials.
- These results show that a good optimization of the machining by stock removal to four or five axes offers a gain on the manufacturing cost of the prostheses compared to machining with three axes. The profit is due to optimization use of the cutting edge tool which allows improving the surface quality.

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