Investigation of Cutting Parameters in Manufacturing of Femoral Heads

Nikolaos I. Galanis and Dimitrios E. Manolakos

Abstract— **In the last years new methods have been investigated for the manufacturing of artificial implants for hip joints. For some parts of these implants, like femoral heads, the method of high speed machining is used to get manufactured. In this paper it was investigated the connection between cutting parameters and forces, in high speed turning of metallic femoral heads. This method is widely used in the industry combined with hard part machining, and leads to having better surface roughness and to decreasing of cutting time. It is also investigated the connection of the surface roughness and this manufacturing method with the measuring of the spheres using Atomic Force Microscopy according to the strict Standards of ISO 7206.**

Index Terms— **Cutting Forces, Femoral Head, High Speed Machining, Roughness.**

I. INTRODUCTION

The mammalian synovial joint is truly a remarkable structure and mechanism. After maturation, guided both by a genetic blueprint and by functionally driven adaptation, its behaviour exceeds that of all simple engineered bearings; it is selflubricating and, to a degree, self-repairing and capable of a service life exceeding *75* years. However, when damaged by trauma, disease or extended use, its repair and replacement has proven to be both one of the most challenging and rewarding of all aspects of human medicine. For when a painful joint, especially in the lower limb, is successfully replaced, the patient has not simply had pain relieved but has been restored to full life, often to such an extent that the permanent presence of an implant is essentially forgotten [1]. During the last decades hip – joint endoprosthetics have been ever more widely used in the world's orthopedic practice; more than 400,000 operations are performed every year and more than 100 types of endoprosthetic construction have been designed [2].

Nowadays, the annual number of prosthesis replacements of hip joints has increased to about 300 000 in the USA, 60 000 in Germany and 20 000 in Russia. At the same time, the amount of operations grows constantly, mainly due to the process of natural aging of the society and the increase in the number of technological and transportation-related accidents. Currently, an industry of the production of implants, instruments and accompanying materials has been developed; in the Western market, this production is estimated to be about US$2.5–3 billion per year [3]. At the manufacture of hip joint prostheses the recent tendency is directed on development and use of new ceramic materials with high physical and mechanical properties for replacement of hirulene, in combination with the metallic ones. For this purpose it is required to solve some scientific and practical problems. There are developments of hip joint construction, a choice of an optimal pair of materials, development of machining technology of internal and external spherical surfaces of metallic and ceramic elements, development of the special diamond tools that allow an excellent surfacing, etc. [4]. In this paper, there will be presented the manufacture of such hip joint implants, especially metallic ones, with the use of ultra high precision techniques in combination with High Speed Machining. The procedure was studied not only during the manufacturing, with the forces that acted to the tool and the specimen, however and after that with the measurement of the final products in order to examine its surface and if the roughness values are close to the restrictions of the International Standards.

II. MANUFACTURING PROCESS

In recent years, high-speed machining (HSM) technology is becoming matured owing to the advance of machine tool and control system. In comparison with the conventional methods, HSM not only exhibits a higher metal removal rate but also results in lower cutting force, better surface finish, no critical heat of the workpiece, etc. HSM has long been applied in die and mold manufacturing [5]. Also it can be combined with hard machining (hard part machining), which is now an accepted method for achieving increased product quality in such leading industrial branches as automotive, roller bearing, hydraulic and die and mold industry. Gear wheels, bearing rings and other transmission parts are typical applications for hard turning, while high-speed hard milling is a leading technology in the die and mold industry [6]. With these parameters, this method can surely be used in the manufacturing of hip joint femoral heads, but of course with better choose of machining parameters in order to optimise the production quality and the productivity. Also with the use of modern machines, like CNC machine tools, which have the ability of accurate movements and precise geometrical constructions the manufacture of such assuming products like femoral heads, which must be constructed under strict standards, can be easy and much more affective. Also with HSM and appropriate choose of the other cutting parameters, like feed rate and cutting depth can achieve excellent surface roughness and also very low cutting forces, which mean less tool wear and better productivity [7], [8].

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A. *Geometry*

It is obvious that the spherical shape should approach to a perfect sphere as much as possible (within the limits of 0.1–0.15 μm). The stated dimensions should be extremely exact (the diameter tolerance is 28±1 μm). Note that the geometrical characteristics are directly dependent on the final stages of processing [3], [9].

B. *Surface Roughness*

The intensity of the wear process of a hip-joint prosthesis ball joint depends on the roughness of the spherical part of the head and the interacting part. According to the standards (from the middle of the 1990s) the roughness, *Ra* must be less than 0.3 μm. Nowadays, these standards seem to be unsatisfactory; almost five years ago, new standards were established: the roughness, *Ra* must lie within 0.02 and 0.03 μm [9]. In order to achieve high sphericity and surface quality, processing techniques that incorporate oscillating or planetary motions are used.

In order to achieve such a surface quality, modern technique of diamond-abrasive lapping of spherical surfaces is related to free abrading, after the manufacturing based on the mutual abrading of the tool and the part as a result of a wear of skew fields during the simultaneous gyration of a leading part, elastically pressed to it through a spherical joint of a led link (cup type tool), the axis of which coincides with the spin axis of the part and is tilted to the axis of a formed or under an angle, see Fig.1.

Table 1: Level independent variables

Factor, coding (unit)	Low (-1)	Centre (0)	High (1)
Cutting speed, Uk (m/min)	264	352	440
Feed, f (mm/rev)	0.06	0.08	0.12
Depth of cut, d (mm)	0.1	0.15	0.2

Thus, the joint fastening and strengthening of the tool ensures the free self-installation of the concave working surface of the part; during the removal of the over-size from the part and the wear of the tool, the profile of the latter is matching the shape and the profile of the part [10].

III. EXPERIMENTAL METHOD AND PROCEDURE

A. *Selection of cutting variables*

The selection of cutting variables was based on the design of experiments methodology [11], [12]. Eight experiments represent 2^3 factorial designs with added ten points in the middle edges of the representation cube, Fig. 2. Taking into account three different levels for each variable, as shown in Table 1, we take the experimental conditions for 18 experiments and also another two experiments were done in order to take more results for roughness comparison, shown in Table 3.

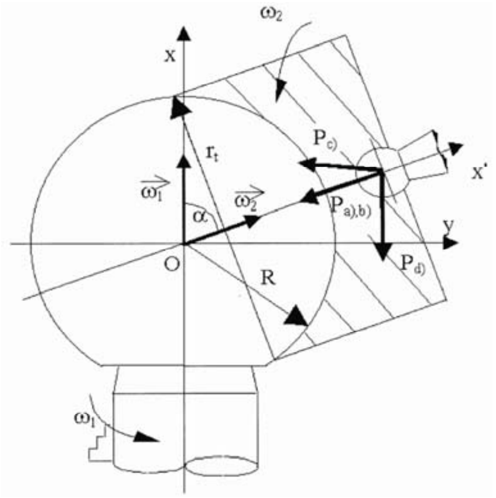

Fig. 1: Variants of diamond lapping control of a head spherical surface [10]

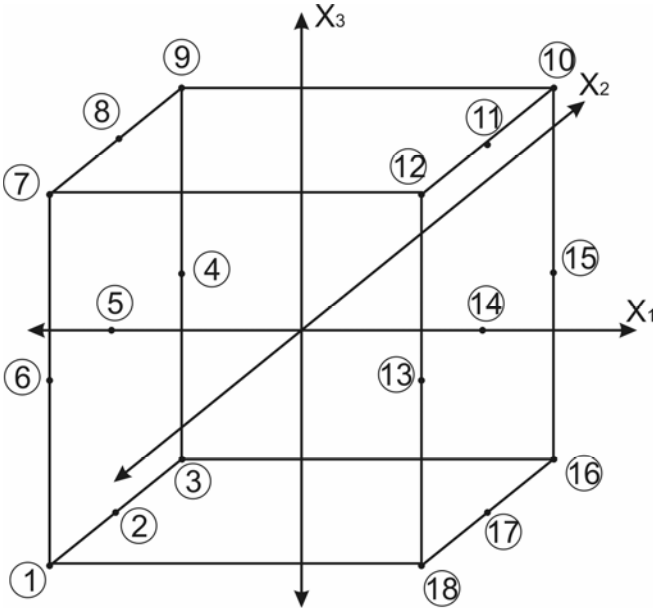

Fig. 2: Representation of a 2^3 factorial design with added parameters

B. *Workpiece and Cutting Tool Material*

The materials, which was manufactured in a CNC lathe OKUMA Lb 10II, see Fig. 3a, with maximum 10000rpm and movement accuracy in both axis 0.1μm, was from AISI 316L steel, which hardness was 79HRB, as shown its properties in Table 2. Coated tool from SECO specification: DNMG 110404 - M3 with TP 2000 coated grade was used for the manufacturing process. The coated grade code means that over the carbide body, there are four coating layers of Ti (C, N), Al_2O_3, Ti (C, N) and TiN.

C. *Measurements*

During the procedure there were measured the forces that acted to the tool. For this reason a special device held a Kistler dynamometer 9257A, as shown in Fig. 3b. This is a three-component piezoelectric dynamometer platform. The force data were recorded by a specifically designed, very

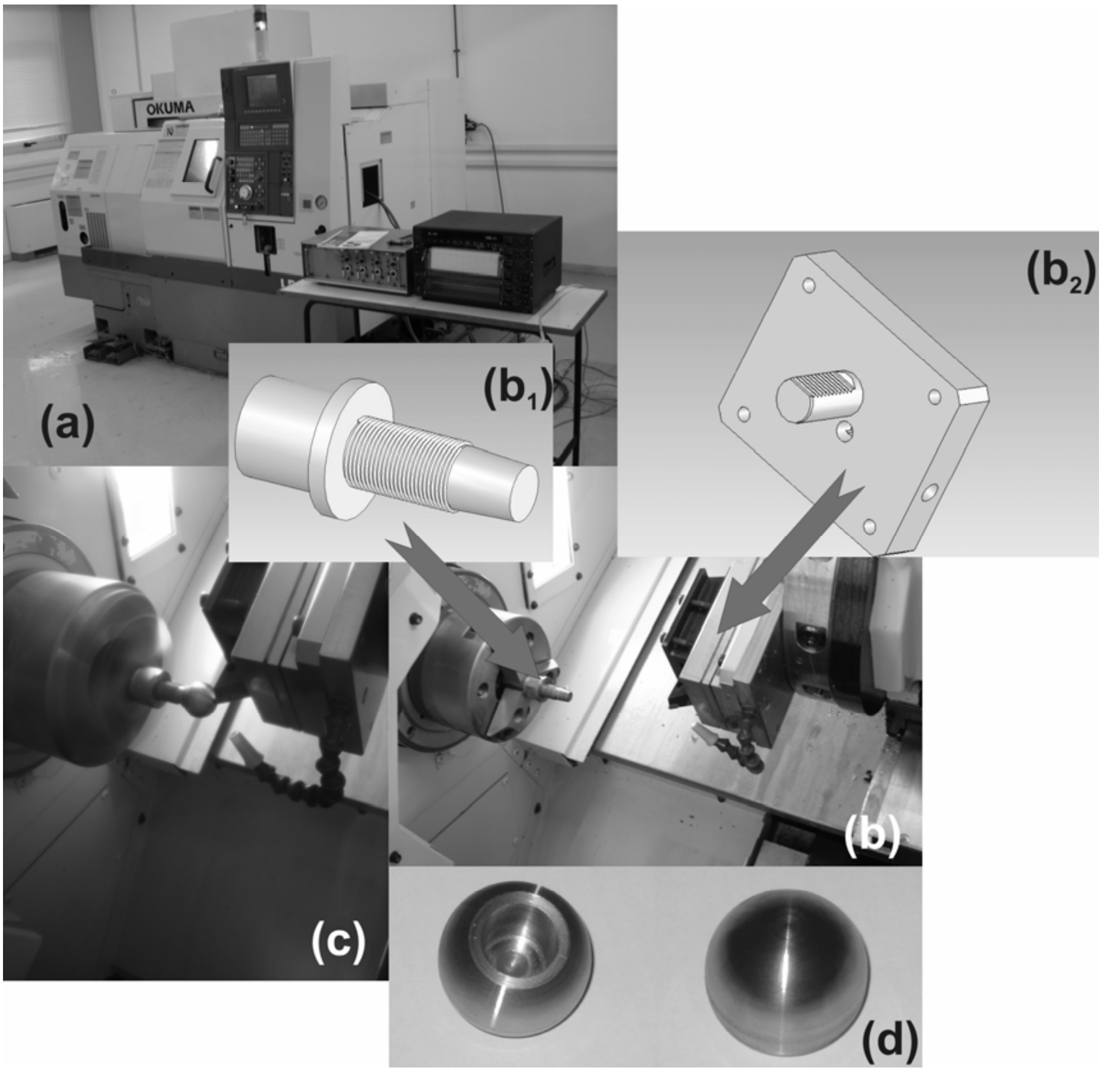

Fig. 3: Experimental procedure (a) the CNC Lathe which was used, (b) inside the cabin where there are the device to support the pre manufacturing material (b1) and the dynamometer (b2), during the procedure (c) and (d) the final femoral head.

compact multi-channel microprocessor controlled data acquisition system with a single A/D converter preceded by a multiplexer.

After the manufacturing, five of these spheres, see Fig. 3d, were measured with an Atomic Force Microscope (A. F. M.). The cantilever is the surface sensor of an AFM. A new cantilever commonly has a tip with a radius of about 10 nm. When the cantilever comes close to the surface of a sample, the tip interacts with the surface atoms, which apply a very weak force to the cantilever. This force is measured by the laser detection system (therefore the microscope is called ‘Atomic Force Microscope’). To measure a surface profile, the cantilever is moved parallel to the surface. At the same time, the controller tries to keep the force on the cantilever tip constant by adjusting the distance between cantilever and sample, therefore moving the cantilever perpendicular to the surface. This movement is recorded and re samples the surface profile. For measuring not only a single profile line but for example a rectangular area, this area is divided into several scan lines which are combined to reproduce a three dimensional surface profile. This operation principle enables the AFM to detect even atomic steps on the surface, while the lateral resolution is directly related to the cantilever-tip radius [13].

Table 2: Material Properties

Material Properties	AISI 316L Stainless Steel
Physical	
Density	8 g/cc
Mechanical	
Hardness, Rockwell B	79
Tensile Strength, Ultimate	560 MPa
Tensile Strength, Yield	290 MPa
Elongation of Break	50%
Modulus of Elasticity	193 GPa
Poisson ‘s Ratio	0.29

This technique was used for two reasons. First it had to be measured very low and accurate values of roughness, and secondly, it is a quite good method for measuring spherical surfaces, as it measures a very small surface, 50 x 50 μm, and this area is like flat one on a sphere. There were naturally several measurements taken all over the surface of the sphere, in order to check the homomorphous surface roughness, and from these ones the average value was taken into account.

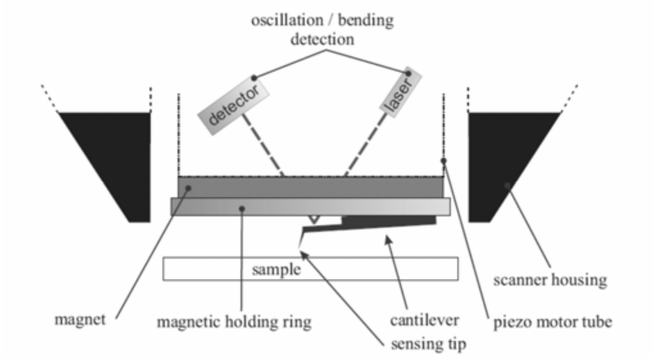

Fig. 4: Schematic drawing of the bottom (sensing) part of an AFM scan head

Table 3: Experimental conditions

No of Cut	Depth (mm)	Speed (m/min)	Feed (mm/rev)	Coding			Cutting Force (N)
				X_1	X_2	X_3	
1.	0.2	264	0.08	1	-1	0	75
2.	0.2	264	0.12	1	-1	1	129
3.	0.2	264	0.06	1	-1	-1	52
4.	0.2	352	0.06	1	0	-1	40
5.	0.2	352	0.08	1	0	0	58
6.	0.2	352	0.12	1	0	1	99
7.	0.2	440	0.12	1	1	1	81
8.	0.2	440	0.08	1	1	0	47
9.	0.2	440	0.06	1	1	-1	32
10.	0.1	440	0.06	-1	1	-1	16
11.	0.1	440	0.08	-1	1	0	24
12.	0.1	440	0.12	-1	1	1	42
13.	0.1	352	0.12	-1	0	1	51
14.	0.1	352	0.08	-1	0	0	30
15.	0.1	352	0.06	-1	0	-1	20
16.	0.1	264	0.06	-1	-1	-1	26
17.	0.1	264	0.08	-1	-1	0	39
18.	0.1	264	0.12	-1	-1	1	68
19.	0.2	115	0.06				
20.	0.2	484	0.06				

IV. RESULTS AND DISCUSSION

After the complete of experiments and measurements, there were taken the results shown in Table 3 for cutting force (Fc) and Table 4 for surface roughness of the five measured spheres. It can be exported that in general by the increasing of the cutting speed and the decreasing of the feed rate speed and the depth of cut; both cutting forces and roughness are decreasing. Also it is noticed that the roughness approaches the strict international standards that have been set in the last years [14]. This is very important, because it fulfills the second requirement of the manufacturing aspects of these implants. For the cutting forces, these affect the wear of simple tool and make it incapable for manufacturing after a small number of cuttings, and also loosing the cutting accuracy of it, which affect the first requirement of the manufacturing aspect.

A. Cutting Forces

In order to examine better the results and to have useful inferences, there are the results separated into groups and plotted on graphs. So for cutting forces there were constructed two 3D graphs, Fig. 5 for cutting forces at 0.2mm cutting depth in regard to cutting speed and feed rate and Fig. 6 for cutting forces at 0.1mm cutting depth. It is obvious from the two graphs that the cutting depth plays a tremendous role in the variation of the force. It is proportional to depth as it becomes the half when the depth is reducing two times. The effect of cutting speed can be attributed to the fact that as speed decreases, the shear angle decreases and the friction coefficient increases. Both effects increase the cutting force. [15]

Also by the decline of the graphs can be seen that the feed rate plays bigger role than the cutting speed as the surface in this axis goes sharply up as the feed rate increases. On the contrary the surface in the axis of cutting speed goes regular down as the cutting speed growths.

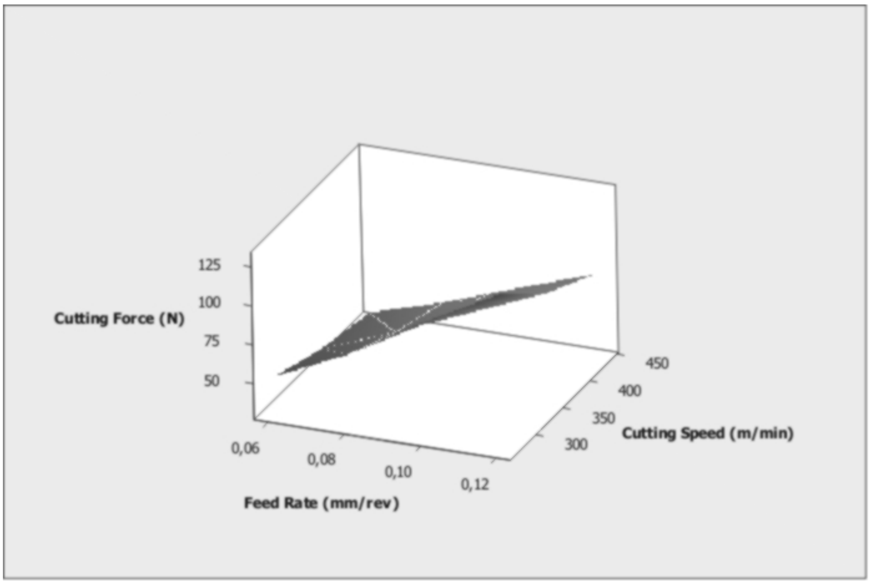

Fig. 5: Graph of Cutting Force at 0.2mm cutting depth

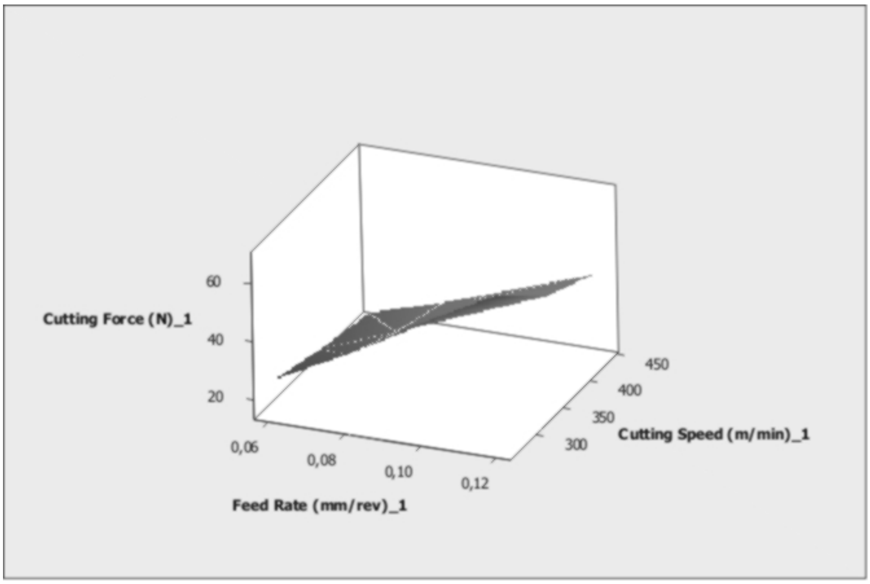

Fig. 6: Graph of Cutting Force at 0.1mm cutting depth

B. Roughness

As it was mentioned above through high speed cutting the forces are lower and the tool wear is less than cuttings with smaller speed values. Also the roughness differs, but not big differences, in the several points on the same spherical surface where the measurements took place. If the graphs, showing these results, are studied, it will be mentioned that the roughness is quite good on all around the surface, but not the same. This will be corrected with the use of special grinding machines, which will make the finishing of the manufactured head [10]. There were measured from five points from each sphere and each measure was revised three times in order to eliminate the fault factor. Below it is shown (Fig. 7) the results of two measures, as they have been taken from the software of the AFM.

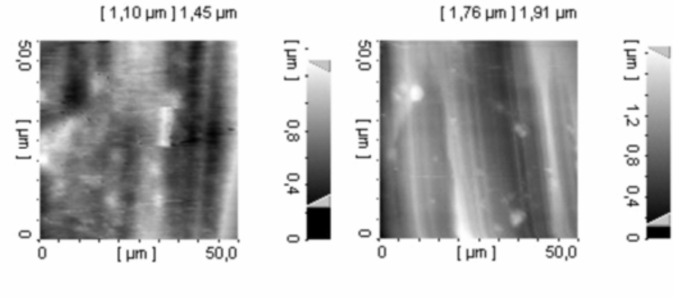

Fig. 7: AFM scanning results of spherical femoral heads

In Table 4, they are listed the measurements at each point and the average measure in each sphere. Out of these results, it can be exported the graph in Fig. 11 that shows the better surface, when the cutting speed increases.

From the graph below (Fig. 8), it can be exported that the surface roughness becomes better as the cutting speed increases. However with the reducing of the feed rate and the cutting depth the roughness improves and the values of the roughness come closer to the ISO 7206 limits for the femoral heads. It is introduced in this graph a new value of the roughness, the pre grinding roughness. It is obvious, that the manufactured heads should finished more, using special grindings machines. But the result of the finishing will be better if the pre grinding heads have a specific roughness. This value comes to 0.5µm and after the grinding should be less than 0.2µm

Table 4: Measurements results of the spherical femoral heads

No Femoral Head	Cutting Speed (m/min)	Feed rate (mm/rev)	Ra (nm)	Average Ra (nm)
1	115	0.06	969	1187.2
			1410	
			1240	
			1450	
			867	
2	264	0.06	955	825.2
			536	
			525	
			1030	
			1080	
3	352	0.06	561	565
			720	
			490	
			430	
			624	
4	440	0.06	536	363.4
			525	
			240	
			331	
			185	
5	484	0.06	485	266.6
			245	
			240	
			193	
			170	

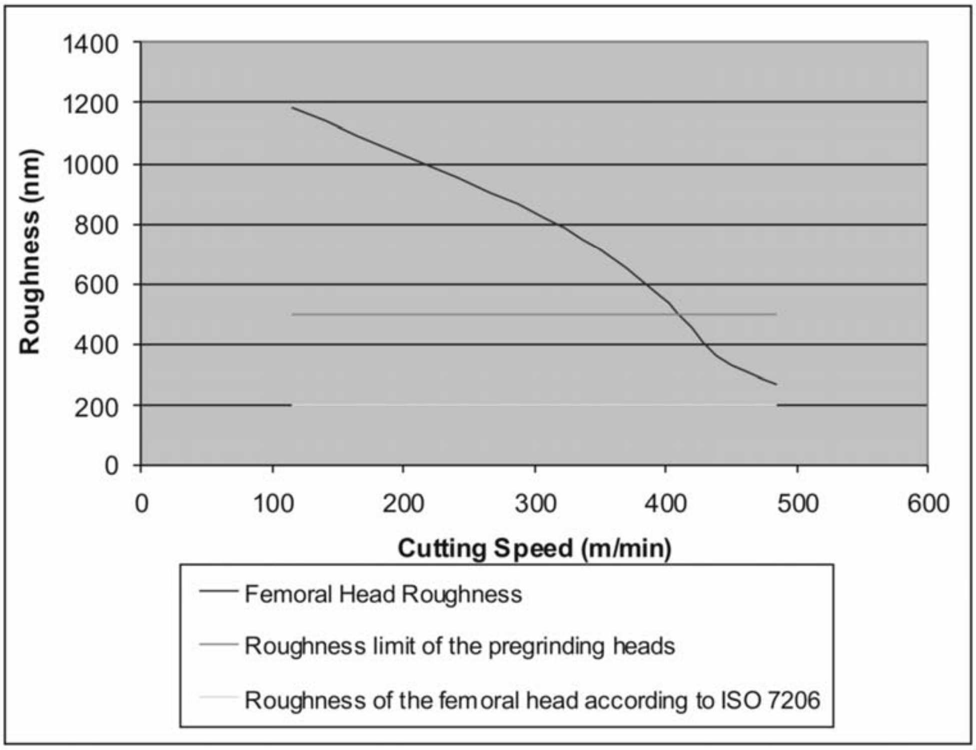

Fig. 8: Graph of surface roughness for the spheres

V. CONCLUSION

This paper summarizes the affect of the cutting parameters during the manufacturing of femoral heads in the cutting forces that act during the procedure and the surface quality of the products. The cutting forces are reducing as the cutting speed increases and feed rate and cutting depth decreases, something very important for the tool wear and the accuracy of the process. On the other hand the surface quality improves as the cutting speed increases and when it takes values bigger than 440m/min it come closer to 0.2μm, a very important border for accepting an implant according to ISO 7206 – 4. By the use of HSM with careful selection of cutting parameters, it can be achieved the production of femoral heads faster and easier, with very good quality after the final finishing.

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