Design of experiments to optimize automatic polishing on 5-axis machine tool

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Abstract: Despite the large improvements in the field of high speed machining, manual polishing operations are still necessary to achieve high quality surfaces named mirror for mould and dies or prosthesis parts. This paper deals with the description of a new polishing method performed on a five-axis machine. This method is based on the use of an abrasive discs mounted on a flexible rotating tool describing trochoidal trajectories. Firstly, the influence of each polishing parameter on the surface roughness is highlighted on a conventional polishing machine currently used in material sciences. Based on this knowledge, a specific application concerning the polishing of a stainless medical prosthesis is detailed in order to get a mirror surface roughness which *Ra* is less than to 50 nm.

Keywords: polishing; surface roughness; five-axis machining; abrasion; free form surface.

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1 Introduction

In the bio-medical domain, polishing is a big part of the plan for procedures of medical prosthesis. Indeed, this type of process is indispensable in order to decrease surface roughness of the part. While prosthesis will be set up on a human body, all workpieces have to get a quasi-perfect surface roughness for human safety. Today, the polishing operation is usually performed manually, but this working method is a long time consuming and monotone. Furthermore, in this domain, the demand increases rapidly, so bio-medical companies have to imagine new methods to polish faster than manual polishing. Automation of polishing process on a five-axis milling centre will increase the productivity and decrease the labour intensity.

Many automatic polishing machines using bound abrasives have been investigated. Usually, the polishing is carried out by an anthropomorphic robots (Marquez et al., 2005; Nagata et al., 2007). Robots provide an easy access to any area of complex form due to their number of axes and it is possible to attach a great variety of tools and particularly spindles equipped with polishing force control mechanisms.

A special polishing machine tool has been developed by Wang and Wang (2009), named serial-parallel hybrid polishing machine tool. They proposed to combine a three parallel axis machine tool with a series of rotational mechanisms for degrees of freedom. This type of hybrid machine-tool gets advantage of the two mechanisms without its disadvantage enabling to automatise the polishing operations directly on a machine-tool.

However, to use this kind of machine, the operator must change the machine between the milling and the polishing stages. This action leads to failure in repositioning the workpiece. So it would be better to keep workpiece on the same machine for limiting the duration of the total manufacturing process. The remedy to this problem was suggested by Wu et al. (2007). They developed a new polishing technology of free form surface by grinding centre which was studied also by Ryuh et al. (2006). This type of machine tool is capable of performing milling and polishing without removing the workpiece. On this grinding centre, an elastic ball tool was used. This paper shows that it is possible to make the milling and the polishing operations on the same machine tool. Pessoles and Tournier (2009) and Ahn et al. (2002) have developed this idea on a five-axis milling centre.

For polishing on a machine-tool, scientific research have been done on elastic polishing tools and flexible abrasive tool by Ahn et al. (2001), Cho et al. (2002) and Huissoon et al. (2002). However, the phenomena of material removal by abrasion are not well known. Therefore, further studies seem mandatory to understand this process. The first step that this research will examine is the evolution of the surface roughness parameter *Ra* defined by ISO Standard [ISO 4287 (1997)] as a function of the polishing time to understand what occurs during this super-finish operation. In addition, the influences of various process parameters on the quality of the resulting surface have also been studied. This study will help to understand how abrasive machining could be carried out on a stainless steel provided by a bio-medical company.

2 Experimental set-up

To understand the phenomena which govern the polishing operation, the following experiments will be carried out firstly on flat surfaces before to be applied on free form surfaces. Actually, samples will be polished on an automatic polishing machine shown in Figure 1 using abrasive papers of different grain sizes, and different diamond pastes.

Figure 1 Automatic polishing machine (see online version for colours)

The polished material is a stainless steel (X4 Cr Ni Mn M N 21-9-4-21-10-3) especially machined for biomedical application such as prosthesis. The different steps of the polishing stage are the followings:

1 abrasive paper
   - 240 grains/cm^2
   - 600 grains/cm^2
   - 1,200 grains/cm^2
2 diamond paste applied with polish cloth
   - 9 μm
   - 3 μm.

The polishing of the samples will be stopped every 10 seconds to measure the surface roughness parameters. When the abrasive paper will be worn, it will be changed to a finer paper. This manipulation will allow plotting the evolution of the surface roughness parameters mentioned above as a function of polishing time. The measurements are performed on a 3D surface roughness device represented on Figure 2.

Figure 2 3D surface roughness device (Wyko) (see online version for colours)

3 Preliminary study

3.1 Arithmetic surface roughness evolution

As shown on Figure 3, it is consistent that the *Ra* value decreases until a limit value as the time of polishing increases. This time limit represents the damage of the abrasive paper meaning that the grains have no more effect on the material removal. When this plateau is reached, the paper must be changed to a finer abrasive paper. It could be noticed a damage of the surface roughness when the abrasive paper is changed, meaning that the following abrasive paper is going to damage the surface roughness obtained previously before to improve it in a second time. In view of this degradation, it is not necessary to go to the limit of the paper. Thus, it is possible to reduce the time of each polishing stage On the other hand, during the use of the diamond paste, there is a continuous improving of the surface roughness, showing that these pastes are well adapted to the polishing operations.

3.2 Influence of the polishing force

To observe the influence of the polishing pressure, two samples having the same surface roughness have been milled with the same parameters during a semi finish operation. Two different polishing forces have been tested; 15 N and 30 N. Then both samples were polished with a 300 rpm constant rotational speed with the paper 600 grains/cm^2. The comparison of those results is given on Figure 4.

Figure 3 Evolution of *Ra* according to the time (s) (see online version for colours)

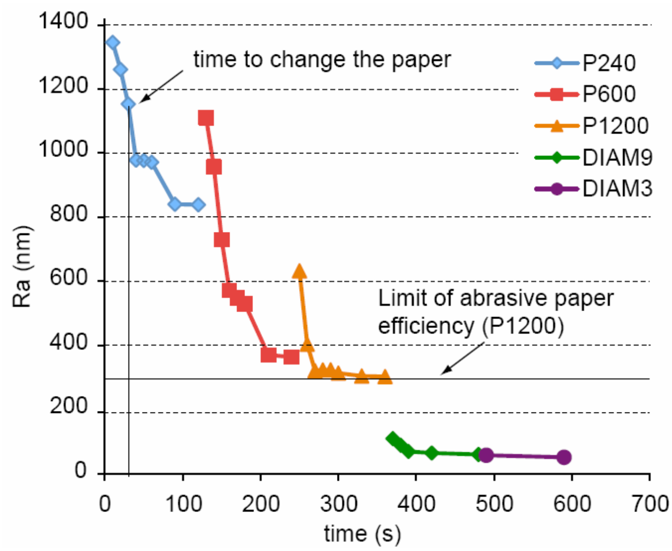
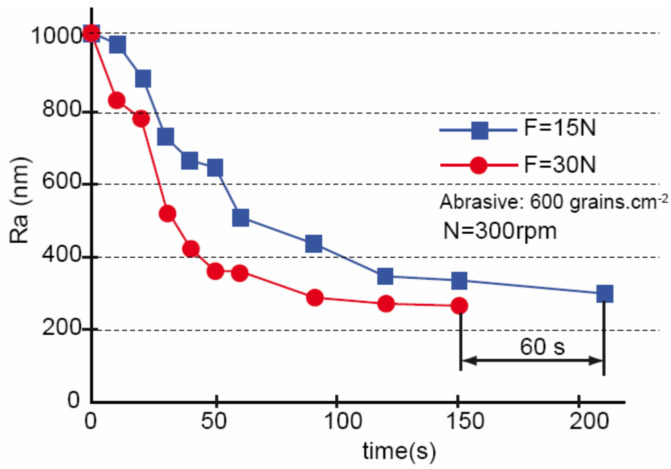


Figure 4 Effect of the polishing force (see online version for colours)

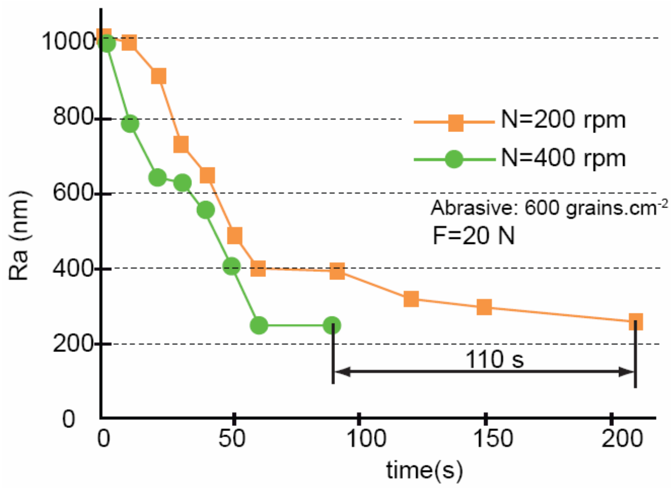


On these two curves which look similar, the time to reach the plateau is quicker for the highest polishing force. In both cases the same final *Ra* is obtained (250 nm). The gain in time to reach the value is close to 60 seconds. In consequence, the increasing in the polishing force enables to save precious time for the operation. From an industrial point of view, in this case the time is reduced of 30% which is significant. The force acting on the paper will be managed directly on the machine-tool by the deformation of the elastic rotating tool.

3.3 *Influence of the rotational speed (rpm)*

The same experimental protocol is also used. Two rotational speeds 200 rpm and 400 rpm, with a 20 N polishing force have been tested. As shown on Figure 5 the rotational speed plays a major role for a polishing operation. The curves underline that more the rotational speed is large more the limit in term of surface roughness is reached. That means the material removal rate is higher. Also, the same final *Ra* is obtained in both cases. On this trial, the saving time is even more important compare to Figure 4. The difference in time between both tests is around 110 seconds, representing a gain of 48%. From the industrial point of view, this parameter is easy to adjust on a CNC machine-tool.

Figure 5 Effect of the rotational speed (see online version for colours)



4 Influence of the primary surface roughness before polishing

To observe this influence, two flat samples were manufactured along parallel planes with two different radial pitches (sample 1: 0.5 mm and sample 2: 0.1 mm). The best finished surface takes 1 minute more as compared to the other. Figure 6 shows the tool path of the milling tool. To observe the influence of this primary surface roughness on the evolution of the final surface roughness obtained by polishing, two samples were polished with an effort of 20 N and a 300 rpm rotation speed. On Figure 7, the sample 1 indicates a longer polishing time to achieve the best surface roughness Ra (500 nm), highlighting that the surface quality before polishing is a significant parameter to take into account.

Thus, in this experiment, the sample 1 possesses an initial arithmetical surface roughness *Ra* = 2,200 nm and the sample 2 *Ra* = 1,250 nm after milling. It is obvious that the paper will have to remove less material for the sample 2 to reach the *Ra* plateau (500 nm). Due to this observation the gain in time for the polishing operation is 1 min and 30 s. Although the milling time is 1 minute more for sample 2, due to the above comment, there is a gain of 30 s for the complete process for these one compared to sample 1. Furthermore, the form defect is better controlled in milling than in polishing, leading to a best geometrical surface for sample 2.

Figure 6 Manufacturing of the primary surface roughness by milling (see online version for colours)

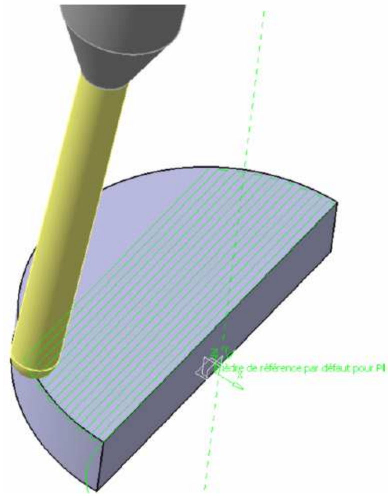
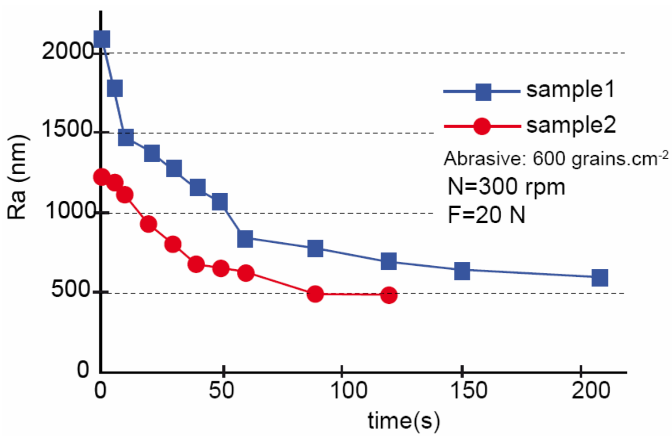


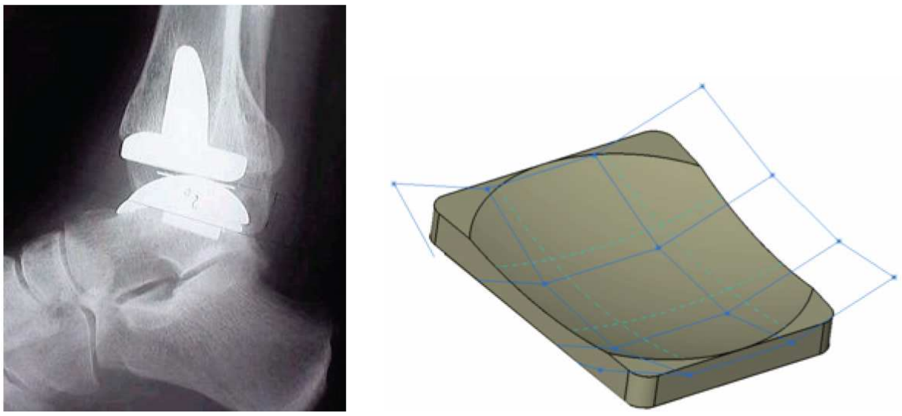
Figure 7 Evolution of the polished surface roughness according to the primary milling surface roughness (see online version for colours)



5 Experimental results and discussions

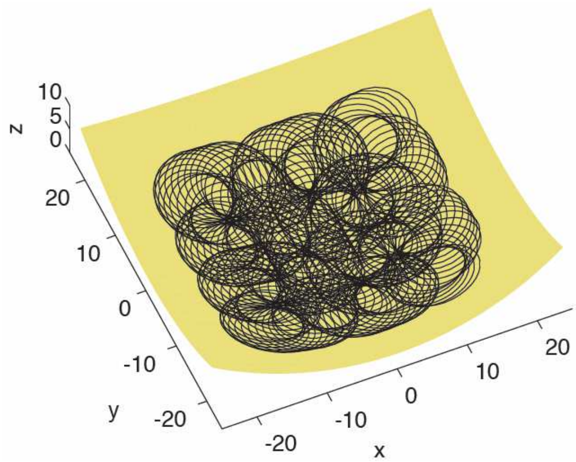
The industrial surface to obtain is a free form surface which is part of an ankle prosthesis as shown in Figure 8. One of the advantages of our approach is to combine the milling and polishing operations on the same five-axis milling centre. The polishing tool path is a combination of a fractal and trochoidal trajectories as shown in Figure 9. It describes the average trajectory of the polishing tool axis to get the most uniform polishing.

Figure 8 (a) Ankle prosthesis (b) free form surface to manufacture (see online version for colours)



(a) (b)

Figure 9 Trochoidal tool path on fractal spine (see online version for colours)



For the polishing on five-axis machine-tool, the flexible tool used and the various papers are represented in Figure 10. Six operations of polishing are then programmed. The first stage of experiments consists in polishing with the two abrasive papers (600 and 1,200 grains/cm^2) and the second stage consists in sliding a felt cardboard with three diamond pastes (8, 3 and 1 μm). The last stage is the sweeping of the surface with the felt cardboard without diamond paste. The initial surface roughness of the milling surface is *Ra* = 1,060 nm. Consequently, the abrasive paper 240 grains/cm^2 will not be used by referring to Figure 3, because it is superfluous.

The different tests have been carried out according to a Taguchi design of experiments. The outputs of these trials will enable to find a model of the polished surface geometrical deviation according to the parameters mentioned in the preliminary study.

Figure 10 Description of the polishing tool (see online version for colours)

Figure 11 indicates the position of the flexible tool during the polishing operation showing the local deformation of the elastic support of the abrasive paper in order to polish the difficult to access surfaces. Furthermore, Figure 11 underlines the polishing parameters which will vary during the experimental tests. The displacement e is a machine parameter which gives the pressure contact between the abrasive disc and the workpiece. According to the contact surface, it gives the polishing force mentioned in Figure 4.

Figure 11 Polishing configuration and parameters to adjust

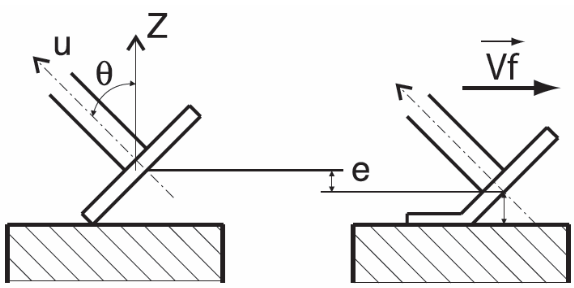


Table 1 lists the polishing parameters and their levels considered in this study. The feedrate V_f, the tilting angle θ and the displacement e are the considered parameters which have a large influence on the surface roughness and the form error of the workpiece. Each factor gets two levels with the hypothesis that there are no interactions between them. The form error after polishing is measured with a three-dimensional coordinate measuring machine. 120 points on the workpiece have been traced to obtain the defect of the surface. The results are written in Table 2.

Table 1 Factors and levels of the Taguchi design of experiments

Factors	*Level 1*	*Level 1*
(F1) Feedrate, V_f (m/min)	2	3
(F2) Displacement, e (mm)	0.5	0.6
(F3) Tilting angle, θ (°)	13	15

Table 2 Taguchi design of experiments $L_4(2^3)$

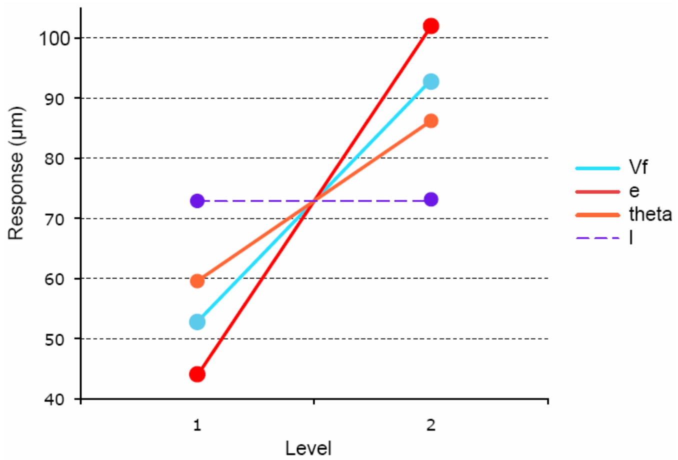
N trial	*(F1) Feedrate V_f (m/min)*	*(F2) Displacement e (mm)*	*(F3) Tilting angle θ (°)*	*Form error (µm)*	*Polishing time (min)*
1	2	0.5	13	10.5	21
2	2	0.6	15	95.2	21
3	3	0.5	15	77.3	18.3
4	3	0.6	13	108.7	18.3

According to those results a model indicating the effect of each parameter is found according to the Taguchi theory [equation (1)].

$$Y_i = l + [a_1, a_2] \cdot F_1 + [b_1, b_2] \cdot F_2 + [c_1, c_2] \cdot F_3 \quad (1)$$

Y_i represents the form defect. a_1 (–20), a_2 (20), b_1 (–29), b_2 (29), c_1 (–13), c_2 (13), are the effects of the polishing parameters. l is the average value of the form error (72.90 µm).

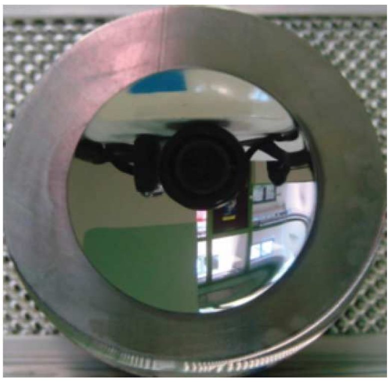
Figure 12 Effect of the polishing parameter on the form deviation (see online version for colours)



On Figure 12, it is possible to notice that the displacement *e* has the major influence on the form error, more than twice as compared to the tilting angle *θ*. Also, it is underlined that the feedrate effect is larger to this tilting angle. This design of experiments allows to classify the factors according to their influence on the considered criterion, i.e., the form error. One important issue of this model is to adjust precisely the polishing parameter in order to reach a given form error and to avoid to manufactured surface with over quality.

Then a test has been performed with the best value of the parameters in order to achieve the best quality surface. This workpiece is showing a mirror surface on Figure 13.

Figure 13 Surface obtained for trial N1 (see online version for colours)



Note: Form error = 10.5 μm and surface roughness *Ra* = 15 nm.

6 Conclusions

This paper has highlighted that milling and polishing are possible on the same machine-tool in order to save time and to avoid the dismounting of the workpiece. Firstly preliminary tests have been carried out on automatic polishing machine to observe the relevant parameters during the polishing operation. The polishing force, the spindle frequency, the density of grains/cm^2 and the initial surface roughness manufactured by milling during the previous stage have been underlined. Based on this knowledge, industrial trials have been performed on a five-axis milling machine according to a Taguchi design experiments. The results of this campaign have shown the effects of the major process parameters, highlighting the displacement of the flexible tool as the major parameter. A model to predict the form error has been found. Related to this model, the best achievable surface indicates a form error less than 10.47 μm and a surface roughness less than 15 nm (named mirror surface).

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References

Ahn, J.H., Lee, M.C., Jeong, H.D., Kim, S.R. and Cho, K.K. (2002) 'Intelligently automated polishing for high quality surface formation of sculptured die', *Journal of Materials Processing Technology*, Vols. 130–131, pp.339–344.

Ahn, J.H., Shen, Y.F., Kim, H.Y., Jeong, H.D. and Cho, K.K. (2001) 'Development of a sensor information integrated expert system for optimizing die polishing', *Robotics and Computer Integrated Manufacturing*, Vol. 17, No. 4, pp.269–276.

Cho, S.S., Ryu, Y.K. and Lee, S.Y. (2002) 'Curved surface finishing with flexible abrasive tool', *International Journal of Machine Tools and Manufacture*, Vol. 42, No. 2, pp.229–236.

Huissoon, J.P., Ismail, F., Jafari, A. and Bedi, S. (2002) 'Automated polishing of die steel surfaces', *International Journal of Advanced Manufacturing Technology*, Vol. 19, No. 4, pp.285–290.

ISO 4287 (1997) 'Geometrical product specifications (GPS) – surface texture: profile method – terms, definitions and surface texture parameters'.

Marquez, J., Perez, J., Rios, J. and Vizan, A. (2005) 'Process modeling for robotic polishing', *Journal of Materials Processing Technology*, Vol. 159, No. 1, pp.69–82.

Nagata, F., Hase, T., Haga, Z., Omoto, M. and Watanabe, K. (2007) 'Cad/cam-based position/force controller for a mold polishing robot', *Mechatronics*, Vol. 17, Nos. 4–5, pp.207–216.

Pessoles, X. and Tournier, C. (2009) 'Automatic polishing process of plastic injection molds on a 5-axis milling center', *Journal of Materials Processing Technology*, Vol. 4209, No. 17, pp.3665–3673.

Ryuh, B.S., Park, S.M. and Pennock, G.R. (2006) 'An automatic tool changer and integrated software for a robotic die polishing station', *Mechanism and Machine Theory*, Vol. 41, No. 4, pp.415–432.

Wang, G. and Wang, Y. (2009) 'Research on polishing process of a special polishing machine tool', *Machining Science and Technology*, Vol. 13, No. 1, pp.106–12.

Wu, X., Kita, Y. and Ikoku, K. (2007) 'New polishing technology of free form surface by GC', *Journal of Materials Processing Technology*, Vols. 187–188, pp.81–84.