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# GRINDING OF MEDICAL IMPLANTS IN COBALT-CHROMIUM ALLOY

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**ABSTRACT:** The manufacturing of medical implants such as knees or ankles prostheses require surface roughness that milling operations cannot achieve. Thus, polishing operations are mandatory but these operations are mainly carried out manually by skilled workers. As this process is expensive in terms of price and downtime of the parts, automatic finishing on machine tools is an alternate solution to improve quality and productivity. Thus, the aim of this paper is to study the performance of a grinding (or rough polishing) spherical flexible tool for obtaining cobalt-chromium prostheses on 5-axis machine tool. The influence of machining parameters on the machined surfaces quality is achieved using a design of experiments. A range of variation of this pseudo feed, i.e. the relationship between cutting speed and feedrate, is proposed to achieve the quality required by implant manufacturers.

**KEYWORDS:** Grinding, cobalt-chromium, surface roughness, medical implants

## 1 INTRODUCTION

As mentioned in [1], automatic polishing and grinding of free form surfaces is a convenient solution to reduce cost and improve quality. Thus the aim of this paper is to study the performance of a grinding (or rough polishing) spherical flexible tool for the machining of prostheses on 5-axis machine tool. The particularity of this tool compared to a conventional grinding wheel is to be composed of an abrasive cap mounted on a rubber body, which gives it some flexibility.

Recent research works have investigated the use of filleted or ball end tools for grinding and polishing operations. Denkena et al. [2] have developed an analytical model to evaluate the material removal rate in 5-axis grinding of medical implants with a filleted end tool. This approach was conducted in the past in 5-axis milling to evaluate machining strip width as well as scallop heights [3]. Tam et al [4] have proposed a study of the influence of the tool path on the surface roughness with a similar tool (alumina mixed in a binding material of synthetic rubber). The tool contact and removal profiles are computed thanks to the assumptions of Hertzian contact stress leading to elliptical contact. However, modelling is purely geometrical and does not include polishing parameters such as cutting speed and feedrate.

Furthermore, the roughness parameter used to evaluate surface roughness in these works is the theoretical roughness  $R_{th}$ , computed in cross sections, which is well adapted when the scallop left on the part by the tool are predominant. Surface finish is better evaluated by considering surface roughness parameters like  $S_a$  [1,5] or at least, profile measurements in two perpendicular directions. Wang et al [6] have proposed

an innovative use of surface texture parameters to illustrate biomedical functions. However, according to them, a large amount of biomedical experiments would be needed to fully validate this correlation.

The work presented in this paper focus on knee prosthesis machining in cobalt-chromium alloy (KC 28). Surface quality on external surface of knee prosthesis is specified with the arithmetic roughness such as  $0.025\mu\text{m} < R_a < 0.05\mu\text{m}$ . Since mirror effect is also expected, polishing operations are mandatory to finish the part. The aim of this work is to perform experimentations to assess the use of the considered tool and find the grinding process parameters to minimize geometrical deviation and especially  $R_a$  and  $S_a$ .

## 2 EXPERIMENTATION

### 2.1 EXPERIMENTAL SET-UP

The description of the tool as well as the geometrical parameters are illustrated (Figure 1). The most influent factor on the surface roughness is the distance between path  $p$  during grinding which is a well-known result. For the experiments,  $e$  is set to 0.2 mm,  $\alpha$  to 45 degree and  $p$  to 0.1mm.

Thus, the study focuses on two parameters: the cutting speed  $V_c$  and the feedrate  $V_f$ . Two levels are considered for both factors ( $V_{c1} = 50\text{m/min}$ ;  $V_{c2} = 200\text{m/min}$ ;  $V_{f1} = 250\text{mm/min}$ ;  $V_{f2} = 10^3\text{mm/min}$ ). The study is also conducted on a general purpose steel (C10) in order to emphasize the behaviour of the cobalt-chromium alloy. At last, the grit of the abrasive tool is equal to 320 according to ISO standard.

The design of experiment leads to the use of the  $L_8$  Taguchi table (Table 1).

Experimentations are carried out on planar samples on a 5-axis Mikron UCP 710 machine tool. Before the grinding operation, the samples are machined with a Ø12 mm ball end mill along parallel planes separated by 0.1 mm. The tilt angle between the tool axis and z-axis is set to 15° to avoid null cutting speed at the tool extremity.

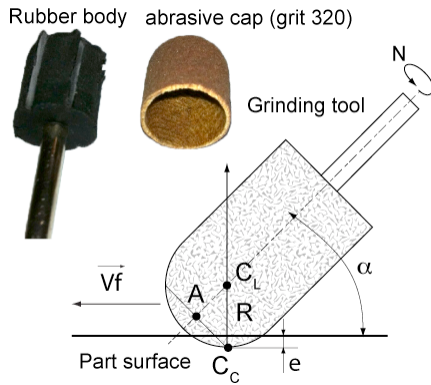


Figure 1: Grinding tool and parameters

## 2.2 EXPERIMENTAL RESULTS

The data analysis procedure consists in a non-contact measurement of surface roughness on a 6 mm by 6 mm patch. The eight surface measurements are illustrated on Figure 2. Surface parameter Sa is evaluated without filtering and thus includes form, waviness and roughness deviations. Figure 2 shows that geometrical deviations are much larger for ( $V_c = 200\text{m/min}$ ;  $V_f = 250\text{ mm/min}$ ). For a small ratio  $V_f/V_c$ , test # 3, the tool does not engage in the material the same way and appears to float on the part much more than in other cases (Figure 2). There are no grinding mark generated by the abrasive particles as test # 1 and # 4.

Five profiles are extracted along and perpendicularly to the grinding tool paths on each sample to evaluate the profile parameters  $Ra_{\perp}$ ,  $Ra_{//}$ ,  $Rt_{\perp}$  and  $Rz_{\perp}$  with a Gaussian filter and a cut-off set to 0.8mm according to ISO 11562. The factor effects are illustrated in Figure 3.

**Material factor effect analysis:** regardless of the roughness parameter, values are lower for the KC28 alloy than for C10 steel. In addition, the effect of this parameter is much more important than the other two.

**Cutting speed factor effect analysis:** increasing the cutting speed  $V_c$  increases the arithmetic mean deviation of the surface Sa but decreases profile parameters  $Ra_{\perp}$  et  $Ra_{//}$ .

**Feedrate factor effect analysis:** increasing the feedrate  $V_f$  decreases the arithmetic mean deviation of the surface Sa but increases creases profile parameters  $Ra_{\perp}$  et  $Ra_{//}$ . The effect of this parameter is in complete opposition to the cutting speed  $V_c$ .

Table 1: experimental results

Mat.	$V_c$ m/min	$V_f$ mm/min	$Ra_{\perp}$ $\mu\text{m}$	$Ra_{//}$ $\mu\text{m}$	$Rt_{\perp}$ $\mu\text{m}$	$Rz_{\perp}$ $\mu\text{m}$	Sa $\mu\text{m}$
KC28	50	250	0.06	0.08	0.59	0.44	0.12
	50	1000	0.12	0.09	0.81	0.62	0.27
	200	250	0.08	0.05	0.74	0.48	0.35
	200	1000	0.06	0.06	0.50	0.38	0.14
C10	50	250	0.13	0.13	1.28	0.76	0.28
	50	1000	0.19	0.15	1.32	0.93	0.32
	200	250	0.12	0.08	1.00	0.69	0.3
	200	1000	0.12	0.16	1.38	0.7	0.3

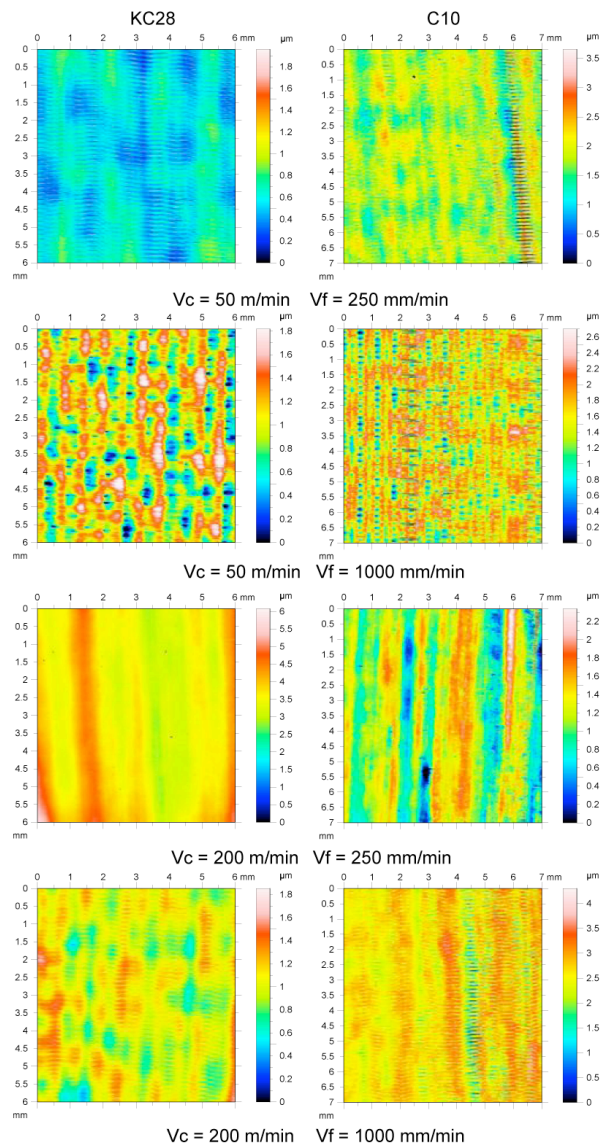


Figure 2: measured surface topology

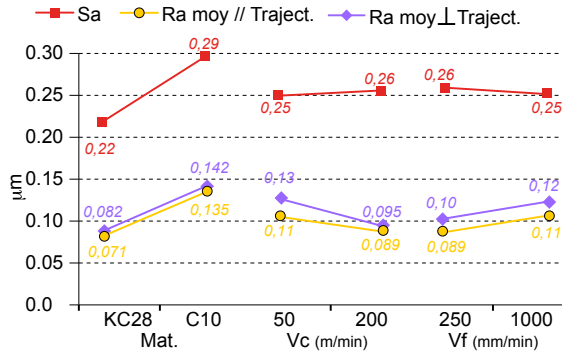


Figure 3: Effects of the three factors

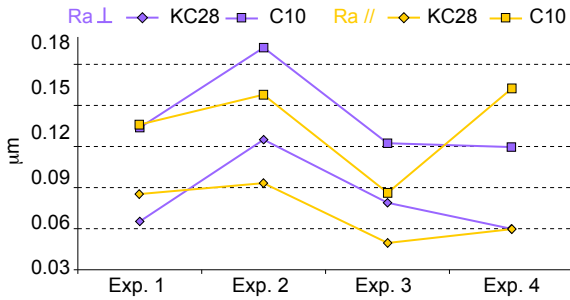


Figure 4: Evolution of Ra⊥ and Ra//

The evolution of the parameters based on the four experimentations for each material is illustrated on Figure 4. Besides the fact that the roughness is always higher for the C10, it can be clearly observed that the evolutions of the parameters Ra⊥ and Ra// are similar, showing that Vc and Vf are key parameters.

Regarding the machining parameters Vc and Vf, the influence of these parameters on the value of Ra// is very close to the one found in conventional milling. The relationship between these two parameters depends on the value of the feed per revolution, which amounts to saying that there exists a pseudo feed per tooth in abrasion. The parameter Ra// decreases as the cutting speed Vc increases and the feedrate Vf decreases, that is to say when Vf/Vc decreases.

### 3 PSEUDO FEED

#### 3.1 PSEUDO FEED MODEL

The aim is to show the existence of a pseudo feed per revolution and its effects on surface quality. The pseudo feed  $f$  is defined by equation (3) and refers to Figure 1 with  $\alpha$  equal to 45.  $R_i$  is the effective radius of the tool  $T_i$  used for each experiment.

Figure 5 shows grinding profiles parallel to the trajectories for  $f^* = 1.25$ ,  $f^* = 5$  and  $f^* = 20$ . So there is a ratio of 4 for the factor  $f^*$  between each experiment. We therefore measured the value of the pseudo feed  $f$  for  $f^* = 1.25$  and  $f^* = 5$  or a mean value for  $f^* = 20$  (Figure 5). Measuring the number of peaks or valleys

per mm shows a pseudo feed per revolution  $f$  of about 0.03mm for  $f^* = 1.25$ , 0.12mm for  $f^* = 5$  and 0.48mm for  $f^* = 20$ . So there is consistency between the picks observed on the profiles and the ratio  $f^*$  which tends to prove the existence of a pseudo feed per revolution. It is possible to calculate the theoretical value of the pseudo feed  $f$  taking into account the effective radius  $R_i$  of the tools and the tilt angle of inclination equal to 45 degrees (equation (3)).

$$Vf = f \cdot N \quad (1)$$

$$N = \frac{10^3 \cdot Vc}{\pi \cdot \sqrt{2} \cdot R_i} \quad (2)$$

$$f = \frac{Vf}{Vc} \cdot \frac{\pi \cdot \sqrt{2} \cdot R_i}{10^3} = f^* \cdot \frac{\pi \cdot \sqrt{2} \cdot R_i}{10^3} \quad (3)$$

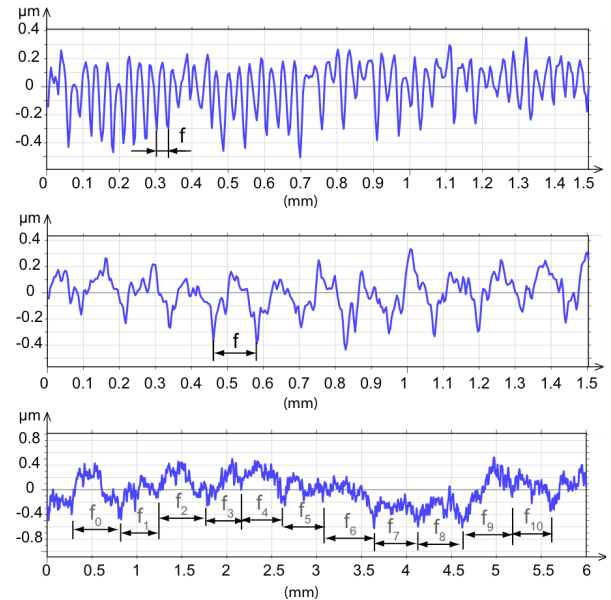


Figure 5: Grinding profiles (Top:  $f^* = 1.25$ ; Middle:  $f^* = 5$ ; Bottom:  $f^* = 20$ )

Table 2: pseudo feed analysis for  $f^* = 5$  in both material

Material	Vc m/min	Vf mm/min	f	Ri mm	f comp. mm	f meas. mm
KC28	50	250	5	5.53	0.123	0.124
	200	1000	5	5.53	0.123	0.125
C10	50	250	5	5.45	0.123	0.122
	200	1000	5	5.51	0.123	0.126

The results are very convincing because there is perfect correspondence between experiments and model, regardless of the material (Table 2). What is also remarkable is that the pseudo advance is the same as we used different caps, so different geometry for each experiment.

### 3.2 EFFECTS OF THE PSEUDO FEED FACTOR

Therefore variations of roughness parameters have been studied according to the ratio  $f^* = Vf/Vc$  which is proportional to the pseudo feed per revolution. Additional tests with ratios of 1 and 4/3 have been conducted.

As for  $Ra_{//}$ , evolution is increasing according to the ratio  $f^* = Vf/Vc$  (Figure 6) which is consistent with the existence of a pseudo feed per revolution. However, if the decrease in the value of  $f^*$  decreases the values of  $Ra_{//}$ , experiments show that other parameters evolve differently.

It is observed that the evolution of the parameter  $Ra_{\perp}$  has a minimum when  $f^*$  is in the interval [3; 5]. In this interval, the value of  $Ra_{\perp}$  is less than 0.06  $\mu\text{m}$  (Figure 6).

The evolution of the parameters  $Rz_{\perp}$  and  $Rt_{\perp}$  also presents a minimum when  $f^*$  is in the interval [3; 5] (Figure 10). The difference between the two parameters is almost always the same, i.e.  $Rz_{\perp} < Rt_{\perp}$  that is consistent with their definitions. Indeed,  $Rz_{\perp}$  is calculated on lengths corresponding to the wavelength of the cut-off while  $Rt_{\perp}$  is calculated on the total length of evaluation.

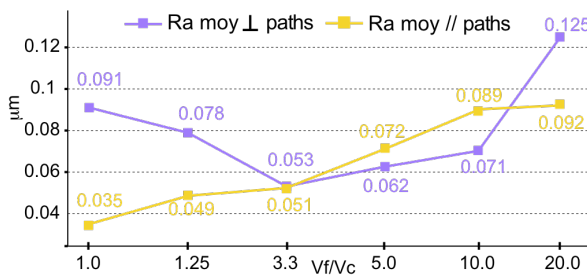


Figure 6: Evolution of  $Ra_{\perp}$  and  $Ra_{//}$  for KC28

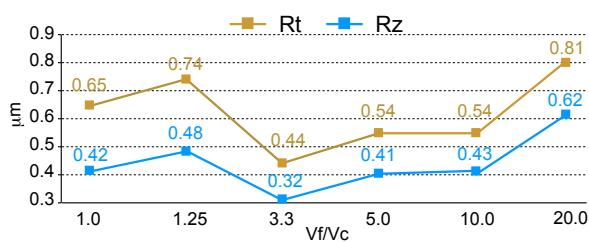


Figure 7: Evolution of  $Rz_{\perp}$  and  $Rt_{\perp}$  for KC28

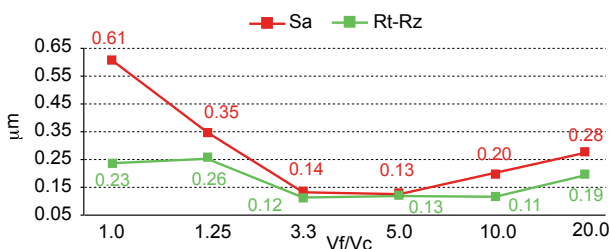


Figure 8: Evolution of  $Sa$  and  $(Rt_{\perp} - Rz_{\perp})$  for KC28

Part of the waviness deviation is not filtered and remains in the value of  $Rt_{\perp}$ , which explains the difference between the values of these two parameters.

The best parameter to evaluate geometrical deviations of the first and second order is the parameter  $Sa$  that was evaluated without filter (Figure 7). The evolution of the parameters  $Sa$  also presents a minimum lower than 0.15  $\mu\text{m}$  when  $f^*$  is in the interval [3; 5].

The evolution of the difference between  $Rz_{\perp}$  and  $Rt_{\perp}$  does vary in the same way that the value of  $Sa$  (Figure 7), which is consistent.

### 4 CONCLUSIONS

The results show that there is an operating point to minimize the geometrical deviation of surfaces when using the considered abrasive tool in Cobalt-Chromium alloy. To minimize  $Ra_{//}$ , the ratio  $Vf/Vc$  must tend to 0 whereas to minimize  $Sa$  and  $Ra_{\perp}$ , the ratio  $Vf/Vc$  must be within the range [3; 5]. Outside this range, the tool should not engage properly in the material and seems to float upon the part while degrading form deviation, waviness and roughness. Moreover, this behaviour occurs in both materials.

To ensure a polishing time as short as possible, it would be better to have high feedrates and therefore high cutting speeds, to maintain the operating point. It would then be necessary to evaluate the wear of the abrasive caps.

Finally given the quality requirements on medical implants, this grinding operation should be followed by fine polishing with diamond paste.

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