

An experimental study on cutting forces when machining a CoCrMo alloy

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Abstract. An important property of the metallic biomaterials used in medical applications is their machinability. A good knowledge of this property is a major advantage in terms of the changes that have been made lately in the medical practice due to the shift to value-based healthcare solutions that have led to increased cost-cutting requirements while keeping the same qualitative requirements for this type of products. Having a good biocompatibility and mechanical properties, the Co-Cr alloys are very often used in medical applications such as dentistry and orthopaedics. When talking about machinability, one of the most important technological parameters in machining process is represented by the cutting forces which are used for determining the necessary machining power and dimensioning the cutting tools. The aim of this research paper is to present the experiments conducted in order to determine a cutting force prediction mathematical model when turning a biocompatible CoCrMo alloy by using TiAlN PVD coated inserts.

1. Introduction

Biomaterials are synthetic materials – metallic, ceramic, polymeric or composite – used to replace a part of a living system or to work closely with the living tissue [1-2]. These materials must be corrosion-resistant, biocompatible, bio-adhesive, to have a modulus of elasticity similar to that of human bones, a good fatigue strength, good machinability and availability [1-3]. The first biomaterials used for manufacturing medical implants were the metallic ones [4], and the metallic biomaterials currently used in medical practice are the stainless steels, titanium and titanium alloys, cobalt-chromium alloys, magnesium alloys and tantalum [1-5].

The Cobalt-Chromium based alloys recommended for manufacturing medical implants are: CoCrMo alloys, CoCrWNi alloys, CoNiCrMo alloys and CoNiCrMoWFe alloys [1-2, 4].

CoCrMo alloys used for medical applications are usually casted and, if necessary, machined in order to obtain the required geometry and surface quality [4-7]. This material is a high temperature alloy and it displays a poor machinability – high tool wear, reduced surface integrity [5, 7].



When considering a material machinability, the cutting forces are classified as playing an important role in establishing this characteristic; being used as background for evaluation of the machining power requirements, structural design of machine tool system, tool dimensioning, evaluation of the tool wear evolution, etc. [8-10].

This research paper is intended to provide an insight into the cutting forces developed during the dry longitudinal turning of a CoCrMo alloy and to develop a prediction model for these cutting forces in terms of cutting regime parameters in order to be further used for the evaluation of this material machinability.

The conducted research program consisted of: determining the effective values for some defining characteristics of the CoCrMo alloy, defining the necessary cutting regime parameters, preparation of the CoCrMo samples, performing the physical experiment, experimental data registration, data processing and determination of the mathematical expressions for the cutting forces, drawing the influence charts of each cutting regime parameter upon main cutting force and presenting the conclusions.

2. Physical experiment

In this section, general information regarding the effective characteristics of the CoCrMo material samples, the characteristics of the variables taken into account for the proposed research and the processing experiment in terms of input, technological system elements, process and registration of the experimental data will be presented.

2.1. Material characteristics

Chemical composition and the mechanical properties of the blank – especially its hardness – have a great influence in the cutting process. For this reason, it was decided to determine the effective values of these material characteristics in order to define the cutting parameters within the experimental research program. The CoCrMo alloy standard required and effective chemical composition are shown in table 1 and its effective hardness values are shown in table 2.

Table 1. Chemical composition of CoCrMo alloy [2, 6].

Chemical element	Cr	Mo	Ni	Fe	C	Si	Mn	W	P	S	N	Al	Bo	Co
Standard requirements (%)	27 - 30	5 - 7	max. 2.5	max. 0.75	max. 0.35	max. 1	max. 1	max. 0.2	max. 0.02	max. 0.01	max. 0.25	max. 0.3	max. 0.01	Balance
Effective values (%)	27.8	5.65	2.08	0.39	0.27	0.69	0.75	0.14	0.02	0.01	-	-	-	Bal.

Table 2. Hardness of CoCrMo alloy samples.

Variation range (HRC)	Average value (HRC)
45.3 – 47.3	45.6

2.2. Research variables

In relation to the research objective, the independent and the dependent variables, as well as the machinability functions are adopted.

The independent variables taken into account for the experimental research are: the processing type – dry longitudinal turning, the processed material – CoCrMo alloy, the machine tool – precision lathe

SN 320, the cutting tool – PCLNR 2525M-12X-JHP lever lock tool with rhombic CNMG 120404-VL TiAlN PVD coated inserts, the cutting regime parameters – feed, f , depth of cut, a_p , and cutting speed, v_c , and the processing time – approx. 20 s.

The dependent variables taken into account for the experimental research are the components of the turning cutting force in relation to the XYZ reference system associated with the machine tool (see figure 1), as follows: F_x or F_f – the feed cutting force; F_y or F_p – the passive cutting force; F_z or F_c – the main cutting force, called also tangential force and the total cutting force, F , which will be calculated based on the values obtained for its components – F_x , F_y and F_z – as shown in equation (1).

$$F = \sqrt{F_x^2 + F_y^2 + F_z^2} \quad [\text{N}] \quad (1)$$

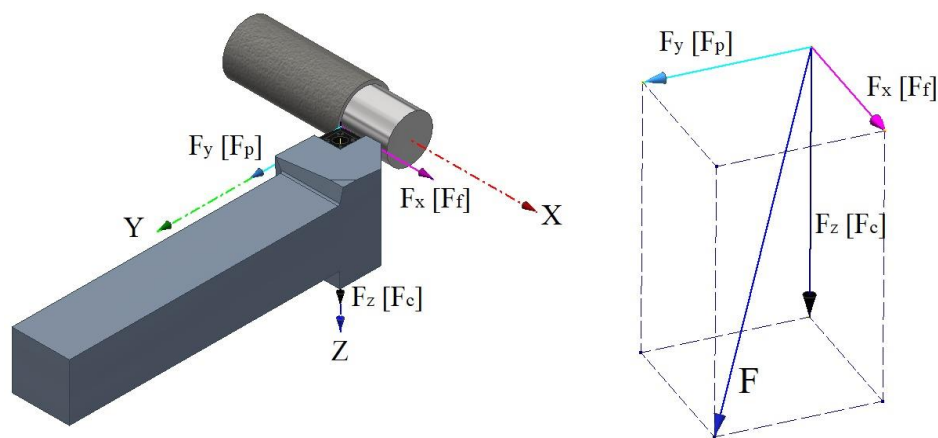


Figure 1. Cutting force components in relation with the machine tool axis system.

2.3. Experiment setup

The main elements of the technological system used for the experiment were: a precision lathe (type SN 320), TiAlN PVD coated cutting inserts ($r = 0,4$ mm), a stationary dynamometer with piezoelectric transducers for measuring the turning cutting forces on which the cutting tool body was fixed with clamps, a signal amplifier and a computer with DynoWare software for data recording (DynoWare Type 2825A-02).

The cutting regime was established by following the recommended ranges given by the experimental researches conducted in this field, the cutting tool manufacturer recommendations and the possibilities of the machine tool, by taking into account the minimum use of material, energy and labour. The ranges of the cutting regime parameters taken into account for the experiment are shown in table 3.

Table 3. Ranges of the cutting regime parameters.

Depth of cut, a_p , (mm)	Feed, f (mm/rev)	Cutting speed, v_c , (m/min)
0.25 – 0.75	0.03 – 0.07	25.1 – 40.2

2.4. Experimental data

Under the presented experimental conditions, thirteen machining experiments were conducted ($E_1 \div E_{13}$). During these experiments, for 20 seconds, graphs and numerical values of the cutting forces components were recorded. It is important to mention that the axis system of the dynamometer was different from the axis system of the machine tool (see figure 2). These differences were given by the way this device was assembled on the lathe carriage and consist of: $F_{x \text{ dynamometer}} = -F_{y \text{ machine}} [-F_p]$,

$F_{y \text{ dynamometer}} = F_{x \text{ machine}} [F_f]$ and $F_{z \text{ dynamometer}} = F_{z \text{ machine}} [F_c]$, a fact which will determine negative values on the software graphs for the passive force.



Figure 2. Dynamometer position on the machine tool.

The variation graph of the cutting force components for E1 experimental case is shown in figure 3 and the cutting data used during machining and the maximum values registered for the cutting force components are shown in table 4.

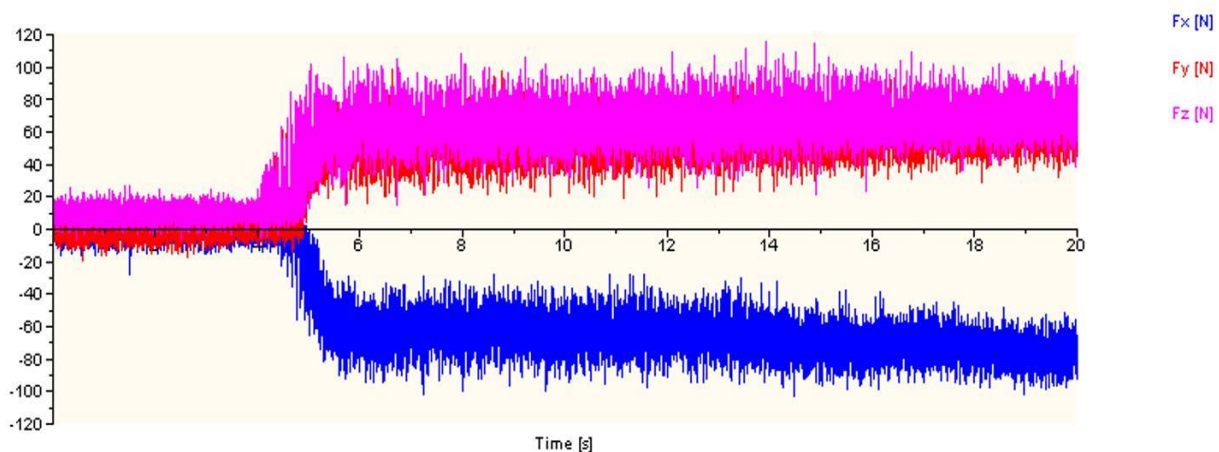


Figure 3. Variation of the turning cutting forces for E1.

Table 4. Cutting regime parameters used during machining and the maximum values registered for the turning cutting forces for E1, E3 and E10.

Exp. no.	Cutting regime parameters			Experimental maximum values of the cutting forces		
	Depth of cut, a_p , (mm)	Feed, f (mm/rev)	Cutting speed, v_c , (m/min)	F_p (N)	F_f (N)	F_c (N)
E1	0.5	0.03	31.4	103.333	98.908	98.9075

3. Results processing and discussion

In this section, the variation of the cutting force components in relation with the cutting regime parameters and the mathematical prediction models for the cutting force components – F_f , F_p and F_c – will be developed; the value of the total cutting force, F , will be calculated – experimental and predicted values – and the its relationship to the considered independent variables will be presented and discussed.

3.1. Cutting forces variation

The variation of the resultant cutting force, F , and its components in relation with the cutting regime parameters considered for the experimental study is shown in figures 4-6.

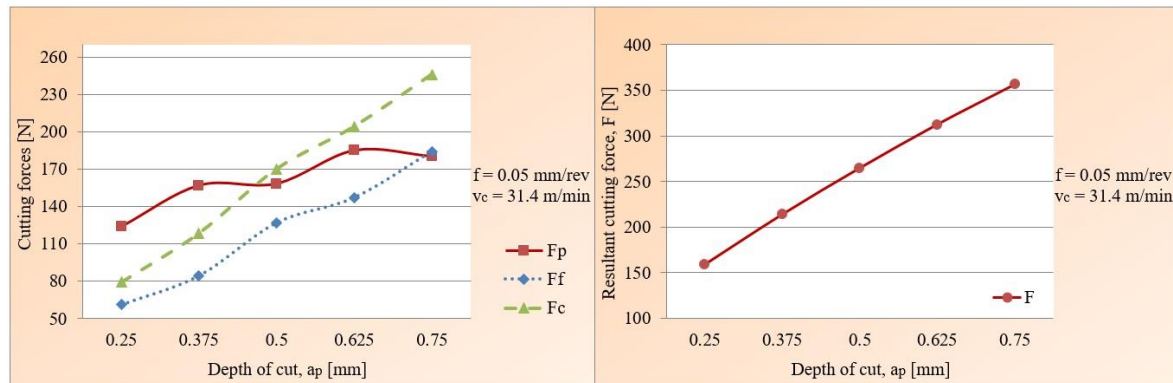


Figure 4. Variation of the turning cutting forces in relation with the depth of cut, a_p .

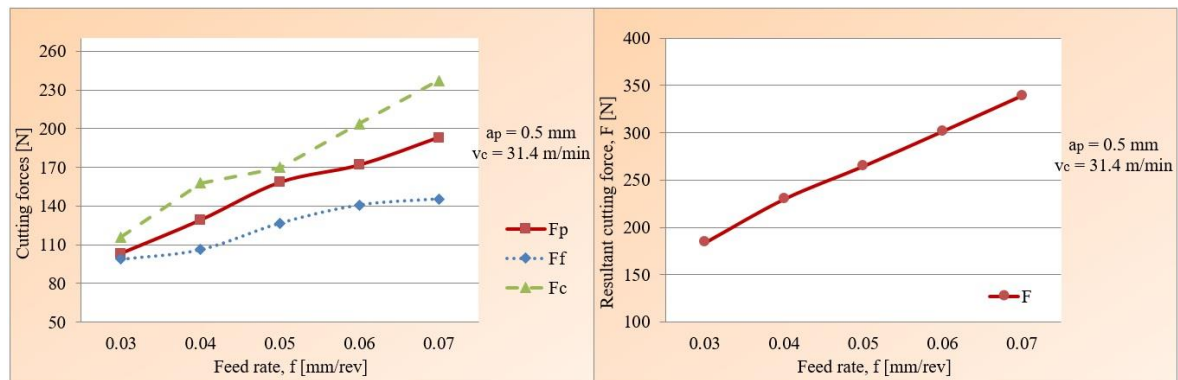


Figure 5. Variation of the turning cutting forces in relation with the feed, f .

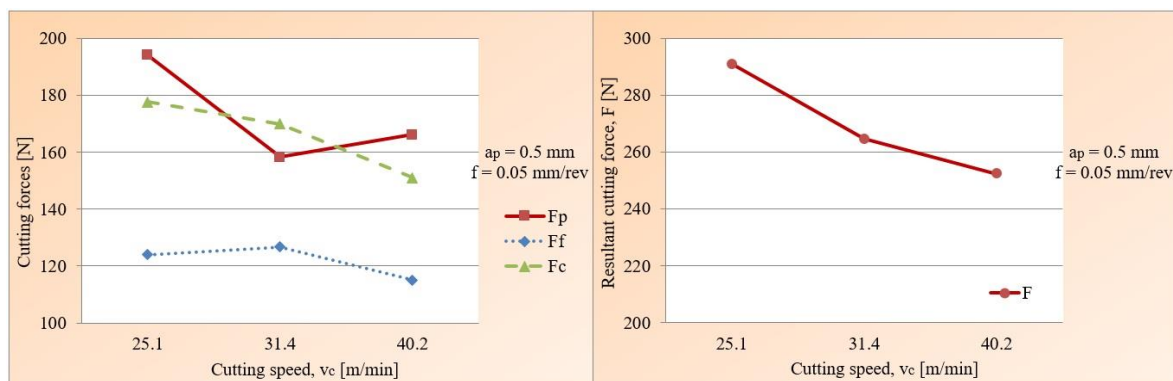


Figure 6. Variation of the turning cutting in relation with the cutting speed, v_c .

After assessing the developed variation graphs of the cutting forces in relation with the cutting parameters, it can be determined that the influence of each cutting parameter on the resultant cutting force value, in terms of average values for the other cutting regime parameters taken into account for the experiment, is as follows: the resultant cutting force, F , increases by 124.14% when the depth of cut, a_p , increases by 200 %; the resultant cutting force, F , increases by 84.12% when the feed, f ,

increases by 133.3(3) %; the resultant cutting force, F , decreases by 13.24% when the cutting speed, v_c , increases by 60.16%.

3.2. Cutting forces variation

The mathematical models for the F_p , F_f and F_c cutting force components were determined as multivariable regression functions having equation (2) as a general model.

$$F = a \times a_p + b \times f + c \times v_c + d \quad (2)$$

Based on the experimental values and using the DataFit 9.0 software application, the regression coefficients a-d were calculated and the F_p , F_f and F_c regression functions were developed, as shown in equations (3), (4) and (5).

$$F_p = 113,231 \times a_p + 2223,49 \times f - 1,371 \times v_c + 35,457 \quad (3)$$

$$F_f = 246,949 \times a_p + 1272,89 \times f - 0,636 \times v_c - 45,010 \quad (4)$$

$$F_c = 335,839 \times a_p + 2891,23 \times f - 1,822 \times v_c - 85,626 \quad (5)$$

As previously stated, the resultant cutting force, F , is a dependent variable and can be calculated based on the values obtained for its components as shown in equation (1). The differences between the experimental and the predicted values of the resultant force are shown in figure 7.

The most dominant factor on the cutting force components value was the feed rate, followed by the depth of cut, while the influence of the cutting speed was almost insignificant.

The average absolute error between the experimental values of the total cutting force F and the predicted ones is 1.794%.

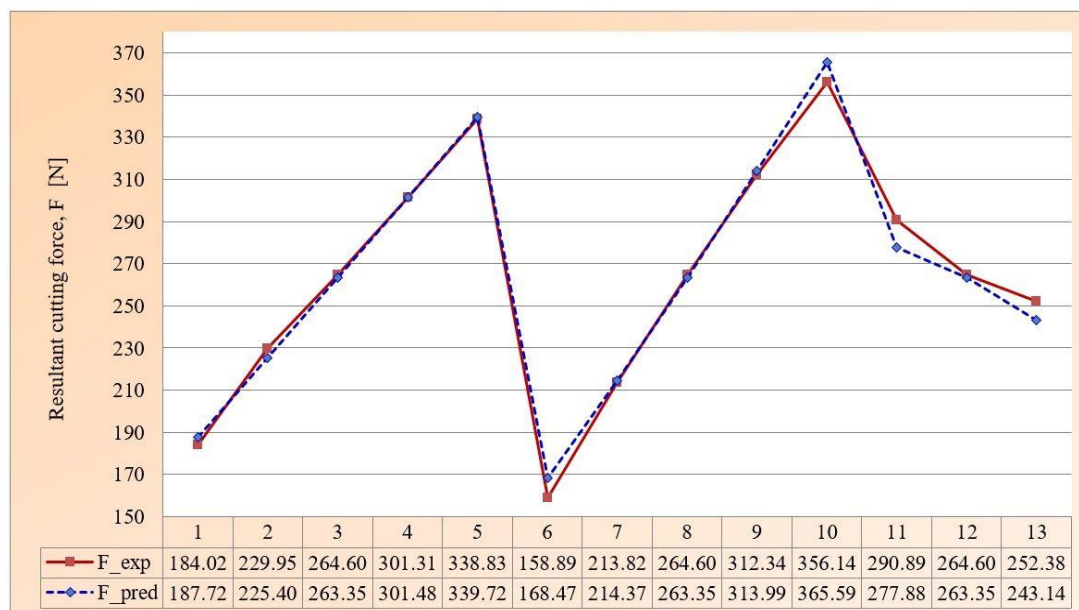


Figure 7. Variation of the experimental and predicted data of the resultant cutting force F .

4. Conclusions

The research presented in this paper shows the results of the turning tests carried out on a CoCrMo alloy used in medical applications in order to determine a prediction model for the cutting forces developed during this machining process.

For the obtained results, the following conclusions can be drawn:

- Based on the experimental data, the total turning cutting force, F , was calculated as a resultant of the F_p , F_f and F_c components and variation graphs were drawn to reveal the relation between these cutting forces and the cutting regime parameters. The analysis of these graphs shows that the total cutting force increases when the feed and the depth of cut increase and it decreases when the cutting speed increases.
- F_p , F_f and F_c cutting forces regression functions were developed in terms of cutting regime parameters – depth of cut, feed and cutting speed – in order to predict these force components for further experiments. Using these components, the values of the resultant cutting force, F , were calculated and compared with the ones obtained from the experimental part. The correlation between these values is a good one, the average absolute error being 1,179%.
- The highest influence on the cutting force components is given by the feed rate, followed by the depth of cut and cutting speed.
- The encountered error is within the acceptable range therefore the developed prediction models can be used for the estimation of cutting forces in turning of CoCrMo alloys.

Acknowledgment

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