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Experimental Study on Cutting Forces Developed during Dry Turning of a CoCrWNi Alloy

M R Dijmărescu

1 University POLITEHNICA of Bucharest, Manufacturing Engineering Department, 313 Splaiul Independentei, 060042 Bucharest, Romania

Abstract. This scientific study focuses on the investigation of the cutting forces developed during dry longitudinal turning with TiAlN PVD coated inserts of a CoCrWNi alloy used in medical applications, especially in orthopaedics. The present paper is organised in two main parts: the first part presents the experimental procedure in terms of material, input data, necessary technological means, physical experiments and data registration while the second part presents the results and their subsequent interpretation. The study reveals the variation of the turning cutting forces in relation to the cutting regime parameters.

1. Introduction

The machinability of metallic materials is one of their most important properties. One of the most important machinability parameters is represented by the cutting forces developed during machining, cutting forces which are instrumental for the optimization of the turning process quality, being a significant factor in determining the necessary machining power, proper dimensioning of the cutting tools, determining the tool wear evolution, etc. [1-3]. Subsequently, an adequate understanding and in-depth knowledge of this parameter is important for choosing a machine tool that complies with the power requirements and can perform the necessary processes while maintaining a low level of energy consumption.

Most studies on metallic biomaterials machinability focus on stainless steels and Titanium alloys, while Co-Cr based alloys still present unexplored areas in this field of research [1, 4-6]. The majority of scientific studies on Co-Cr based alloys used in medical applications focus on the machinability of CoCrMo alloys; no specific studies related to the cutting forces developed during turning CoCrWNi alloys using TiAlN coated inserts were found.

The aim of this research paper is to determine by experimental investigation methods the cutting forces developed during dry turning of a CoCrWNi alloy and to present the influence exerted by the variation of the cutting regime parameters on these forces.

The main steps of the conducted research program were: determination of certain effective characteristics of the analysed alloy and of the cutting regime parameters, preparation of the material samples, physical experiment (dry longitudinal turning and data registration), experimental data processing and analysis of the influence exerted by the variation of the cutting regime parameters on the cutting forces.
2. Experimental procedure
This section provides details on the material and the equipment used to perform the physical experiment. The experimental process is presented in terms of input data (material samples, cutting regime parameters, etc.), technological means, and output data (cutting forces graphs and values).

2.1. Material and methods
CoCrWNi alloy is a Co-Cr based metallic biomaterial with a high resistance to wear, high corrosion resistance and a high degree of hardness used in medical applications, especially for hip and knee implants [7, 8]. The CoCrWNi samples used for the experiment had a 6.5 mm diameter.

The technological equipment used during the experimental process consisted of: a precision lathe (type SN 320), PCLNR 2525M-12X-JHP [9] lever lock tool, rhombic CNMG 120404-VL TiAlN PVD coated inserts [10], a Kistler stationary dynamometer with piezoelectric transducers, a signal amplifier and a computer with DynoWare software (DynoWare Type 2825A-02).

The values of the cutting parameters were established depending on the material characteristics, the cutting tool manufacturer recommendations and the capabilities of the machine tool. The specific range of the values taken into account for the processing experiment are shown in table 1.

The Kistler dynamometer was assembled on the lathe carriage and the cutting tool body was fixed on it with clamps. The machine carriage dimensions prevented the dynamometer from being positioned with its axis system in correspondence with the machine-tool axis system, see figure 1.

Therefore, the relation between these two systems is as follows: $X_{\text{dynamometer}} = -Y_{\text{machine-tool}}$, $Y_{\text{dynamometer}} = X_{\text{machine-tool}}$ and $Z_{\text{dynamometer}} = Z_{\text{machine-tool}}$. This position will determine negative values on the resulted graphs for $F_p$.

| Table 1. Ranges of the cutting regime parameters. |
|---------------------------------|-----------------|-----------------|
| Depth of cut, $a_p$, (mm)      | Feed rate, $f$, (mm/rev) | Cutting speed, $v_c$, (m/min) |
| 0.25 – 0.5                     | 0.03 – 0.07      | 20.4 – 32.7     |

Figure 1. Machine tool /dynamometer axis systems and turning cutting forces.

2.2. Experimental data
Thirteen dry longitudinal turning experiments were conducted using the aforementioned parameters and conditions. During each experiment, for 20 seconds, graphs and numerical values for $F_x$ ($F_x$ dynamometer), $F_y$ ($F_y$ dynamometer) and $F_p$ ($F_p$ dynamometer) cutting forces were recorded. The cutting forces signal variation graphs for two representative turning experiments are shown in figures 2 and 3. The cutting parameters used and the maximum registered values of the cutting forces for these two experiments are presented in table 2.
3. Results and discussion

Based on the measured values of the turning cutting forces, the resultant cutting force ($F$) was calculated using equation (1).

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

The variation of the turning cutting forces and their resultant force in relation to the cutting regime parameters are shown in figures 4-6.

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**Table 2.** Cutting parameters ranges and measured cutting forces for representative experiments.

| Exp. no. | Cutting regime parameters | Experimental cutting forces maximum values | Observation |
|----------|---------------------------|------------------------------------------|-------------|
|          | $a_p$, (mm) | $f$ (mm/rev) | $v_c$ (m/min) | $F_c$ (N) | $F_p$ (N) | $F_f$ (N) |               |
| 3        | 0.05         | 0.375        | 25.5          | 188.690    | 102.875    | 86.884     | median values of the cutting parameters |
| 10       | 0.05         | 0.5          | 25.5          | 279.388    | 135.620    | 128.510    | largest values of the turning cutting forces |

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**Figure 2.** Turning cutting forces variation for experimental case no. 3.

**Figure 3.** Turning cutting forces variation for experimental case no. 10.
Figure 4. Variation of the (a) turning cutting force components and (b) resultant cutting force in relation to the depth of cut.

Figure 5. Variation of the (a) turning cutting force components and (b) resultant cutting force in relation to the feed rate.

Figure 6. Variation of the (a) turning cutting force components and (b) resultant cutting force in relation to the cutting speed.

Analysing the variation graphs between the turning cutting forces and the cutting parameters, we can ascertain that:

- If \( f = 0.05 \text{ mm/rev} \) and \( v_c = 25.5 \text{ m/min} \), when \( a_p \) increases by 100%: \( F_f \) increases by 68.51%, \( F_p \) increases by 62.90%, \( F_c \) increases by 178.18% and resulted \( F \) increases by 122.43%.
- If \( a_p = 0.375 \text{ mm} \) and \( v_c = 25.5 \text{ m/min} \), when \( f \) increases by 100% – \( F_f \) increases by 51.22%, \( F_p \) increases by 74.86%, \( F_c \) increases by 126.38% and resulted \( F \) increases by 98.82% and
when \( f \) increases by 133. (3) \% – \( F_f \) increases by 56.87\%, \( F_p \) increases by 78.72\%, \( F_c \) increases by 155.45\% and resulted \( F \) increases by 117.90\%.

- If \( f = 0.05 \text{ mm/rev} \) and \( a_p = 0.375 \text{ mm} \), when \( v_c \) increases by 60.29\%: \( F_f \) increases by 18.35\%, \( F_p \) increases by 35.05\%, \( F_c \) increases by 65.62\% and resulted \( F \) increases by 53.14\%.

The cutting parameters have a nonlinear influence on the turning cutting forces, the major influence being exerted by the depth of cut – \( F_c \) increases with 178.18\% and \( F \) increases with 122.43\% when \( a_p \) increases with 100\%; while the lowest influence is exerted by the cutting speed.

The cutting force component that is influenced the most by the variation of the cutting parameters is the main cutting force (\( F_c \)). \( F_c_{\text{max}} = 279.388 \text{ N} \) and \( F_{\text{max}} = 336.103 \text{ N} \), when \( a_p = 0.5 \text{ mm} \), \( f = 0.05 \text{ mm/rev} \) and \( v_c = 25.5 \text{ m/min} \).

Taking into account the aspects presented above, we can ascertain that raising the cutting speed will have a low influence on the cutting forces, but, at the same time, it will result in a shorter processing time.

4. Conclusions
The study focuses on the identification of the most significant parameters that influence the cutting forces during dry longitudinal turning. The results reveal the variation of the turning cutting forces in relation to the cutting regime parameters – depth of cut, feed rate and cutting speed - and expand the knowledge base developed by the existing studies made on Co-Cr alloys, with a particular focus on the CoCrWNi alloy. Subsequently, these results can be used as a basis for the optimization of the turning process quality for this specific alloy, when using TiAlN coated inserts.

Further research will focus on the optimization of the cutting parameters and the development of cutting forces prediction models for dry longitudinal turning of the analysed alloy, models which can be used in research and industrial practice for the evaluation of the machinability of this alloy.

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