Determination of the cutting forces regression functions for milling machining of the X105CrMo17 material

T D Popovici¹,² and M R Dijmarescu²
¹University POLITEHNICA of Bucharest, Manufacturing Engineering Department, 313 Splaiul Independentei, 060042 Bucharest, Romania
²Romanian Research & Development Institute for Gas Turbines COMOTI, 220D Iuliu Maniu Bd., 061126 Bucharest, Romania

E-mail: manuela.dijmarescu@imst.pub.ro

Abstract. The aim of the research presented in this paper is to determine a cutting force prediction model for milling machining of the X105CrMo17 stainless steel. The analysed material is a martensitic stainless steel which, due to the high Carbon content (~1%) and Chromium (~17%), has high hardness and good corrosion resistance characteristics. This material is used for the steel structures parts which are subject of wear in corrosive environments, for making valve seats, bearings, various types of cutters, high hardness bushings, casting shells and nozzles, measuring instruments, etc. The paper is structured into three main parts in accordance to the considered research program; they are preceded by an introduction and followed by relevant conclusions. In the first part, for a more detailed knowledge of the material characteristics, a quality and quantity micro-analysis X-ray and a spectral analysis were performed. The second part presents the physical experiment in terms of input, necessary means, process and registration of the experimental data. In the third part, the experimental data is analysed and the cutting force model is developed in terms of the cutting regime parameters such as cutting speed, feed rate, axial depth and radial depth.

1. Introduction
Due to their good mechanical and corrosion resistance characteristics, the usage of stainless steels is increasing day by day in engineering fields; their world consumption showing an annual increase of approximately 6% since the middle of the 20th century [1, 2]. These materials are being used in a multitude of applications, especially in the precision component industries [1]. For this reason, interest in knowing their processing possibilities, especially their cutting processing possibilities for achieving different surfaces has significantly grown.

Knowing the machinability of a certain material has a high level of importance because it determines an advanced assessment of the total cutting processing costs for the pieces made from this material, and, also, it facilitates a rapid choice of the cutting and machine tools and it provides knowledge regarding the operation behaviour [3, 4, 5]. Cutting machinability requires a profound and ample research effort in order to encompass the multitude of factors that influence the cutting process [4]. This process is influenced by variables such as cutting speed, cutting dimensions, tool form and material, cutting fluid, tool fixture rigidity, and the impact level of the tool-workpiece in relation to a constant or an intermittent contact [4, 6, 7, 8]. Due to the high complexity of this process and the lack of a clear methodology for assessing the machinability of a certain material, the
determination of this characteristic compels to an accurate analysis, a concise synthesize and a correct
interpretation of processing experimental data [3, 4, 7].

The experiments which will be presented in this paper have as topic the better knowledge of the
machinability of X105CrMo17 martensitic stainless steel, a material rich in Chromium with high
resistance even in aggressive environments at high temperatures [9].

1.1. Objective
The main objective of the research presented in this paper is the development of a cutting force
prediction model for down end-milling machining of the X105CrMo17 (EN 10088-3:2005)martensitic stainless steel.

1.2. Research program
The main steps taken into consideration for the research program were: making a micro-analysis of the
proposed material in order to achieve some effective defining characteristics (i.e. chemical
composition, metallographic structure, hardness); making the physical experiment and registering the
experimental data; processing the experimental data and determination of the mathematical
expressions for the cutting forces in terms of cutting speed, feed rate, axial depth and radial depth.
These values were established according to the Response Surface methodology.

2. Material micro-analysis
In order to determine the effective characteristics of X105CrMo17 samples which will be used for the
physical experiment, a quality and quantity micro-analysis X-ray and a spectral analysis (analysis
EDAX) were performed. As a result of these performed activities the effective chemical composition
(see table 1), the effective metallographic structure (see figure 1) and the effective hardness of the
material were determined.

| C (%) | Cr (%) | Ni (%) | Cu (%) | Mn (%) | Si (%) | P (%) | S (%) | Mo (%) | Fe (%) |
|-------|--------|--------|--------|--------|--------|-------|-------|--------|--------|
| 0.9-1 | 17-19  | max. 0.5 | max. 0.3 | max. 1 | max. 1 | 0.045 | 0.015-0.03 | max. 0.2 | Rest   |

Figure 1. Effective metallographic structure of X105CrMo17 sample.
A brief analysis of the effective chemical composition and metallographic structure obtained for the X105CrMo17 sample reveals the following: a non-uniform dispersion of the Cr and Fe elements, the fact that the material is an austenitic-martensitic stainless steel with a heterogeneous structure which includes two types of carbides and some areas which are Fe-poor, but rich in Cr.

Processed samples, extracted from the same piece of steel as the samples used for the X-ray and the spectral analyses, were prepared and used for determining the effective hardness of the X105CrMo17 material (see table 2).

| Variation range (HRC) | Average value (HRC) |
|-----------------------|---------------------|
| 19.55 – 20.85         | 20.2                |

3. Physical experiment
In this section, general information regarding the characteristics of the variables taken into account for the proposed research and the experiment details in terms of input, technological means, process and registration of the experimental data will be presented.

3.1. Research variables characteristics
Within the present research, the independent and dependent variables and the machinability functions are adopted in relation to the established objective.

The considered independent variables are: the processed material (X105CrMo17); the processing type (down end-milling); the machine tool (CNC MCV 300); the cutting tool (end-mill cutter); the cutting regime parameters (cutting speed, feed rate, axial depth of cut and radial depth of cut) and the processing time.

The considered dependent variables for this experimental research are the components of the cutting force in relation to the XYZ reference system associated with the cutting movements, respectively, associated with the machine tool, as follows: F_x – the cutting force component parallel to the feed motion; F_y – the cutting force component perpendicular to the feed motion; F_z – the cutting force component parallel to the rotation axis of the main cutting movement. The values of these cutting force components will be determined by measurements, during the milling processing.

3.2. Experiment setup
The physical experiment had as basis two technological systems which worked in parallel: a technological system of processing by down milling and a technological system for measuring the cutting forces. The main elements of the processing technological system are: a CNC milling machine in 3 axes (MCV 300); a solid carbide end-mill cutter type Protostar 45 DIN 6527L (see figure 2); X105CrMo17 samples (see figure 3).

Figure 2. The end-mill cutter Protostar 45 DIN 6527L in working position.

Figure 3. The X105CrMo17 sample used for the experiment.
The main elements of the measuring technological system are: equipment, including a stationary
dynamometer with piezoelectric transducers, for measuring the cutting forces; a signal amplifier and a
computer with special software for data recording (DynoWare Type 2825A-02).

The ranges of the cutting regime parameters and of the kinematic adjustment parameters taken into
account for the experiment are shown in table 3.

**Table 3.** Ranges of the cutting regime parameters and of the kinematic adjustment parameters.

| Axial depth of cut, \( a_p \) (mm) | Radial depth of cut, \( a_e \) (mm) | Feed rate, \( f_z \) (mm/tooth) | Cutting speed, \( v_c \) (m/min) | Spindle speed, \( n \) (rev/min) | Feed speed, \( v_f \) (mm/min) |
|---------------------------------|---------------------------------|-------------------------------|-------------------------|-------------------------|-------------------------|
| 1 – 2.5                         | 0.5 – 2.5                       | 0.01 – 0.1                    | 200 – 300               | 3537 – 5305            | 106 – 1592              |

3.3. **Experimental data**

Under the presented operating conditions, twenty processing experiments were conducted (E1, E2, …, E20). During each processing experiment, for 10 seconds, graphs and numerical values of cutting forces \( F_x \), \( F_y \) and \( F_z \) were recorded. The variation graphs of \( F_x \), \( F_y \) and \( F_z \) cutting forces, for three representative processing experiments, are shown in figures 4-6 and, the cutting regime parameters used during processing and the maximum values registered for the cutting forces for these experiments are shown in table 4.

![a) Variation of \( F_x \)](image1)

![b) Variation of \( F_y \)](image2)

![b) Variation of \( F_z \)](image3)

**Figure 4.** The variation of the \( F_x \), \( F_y \) and \( F_z \) cutting forces for E1.
Figure 5. The variation of the $F_x$, $F_y$ and $F_z$ cutting forces for $E_8$.

Figure 6. The variation of the $F_x$, $F_y$ and $F_z$ cutting forces for $E_{20}$. 
The performed experiments revealed that the values of $F_x$, $F_y$ and $F_z$ cutting forces belong to the following closed intervals: $F_x \in [97.26; 525.25]$ N, $F_y \in [111.31; 495.12]$ N, $F_z \in [54.64; 377.85]$ N.

4. Results processing and discussion

In this section, the experimental data registered during the developed experiments will be processed in order to obtain the mathematical models for the $F_x$, $F_y$ and $F_z$ cutting forces; the value of the total cutting force, $F$, will be calculated and the variation of this force in relation to the considered independent variables will be presented and discussed.

4.1. Machinability regression functions for $F_x$, $F_y$ and $F_z$ cutting forces

The mathematical models for the $F_x$, $F_y$ and $F_z$ cutting forces were determinate as multivariable regression functions having as a general model equation (1).

$$F = e^{A_0 \times X_1^{A_1} \times X_2^{A_2} \times X_3^{A_3} \times X_4^{A_4}}$$

(1)

where: $X_1$ is the axial depth of cut, $a_p$; $X_2$ is the radial depth of cut, $a_c$; $X_3$ is the feed rate, $f_z$; $X_4$ is the cutting speed, $v_c$.

Based on the obtained experimental data and using the DataFit 9.0 software application, the regression coefficients $A_0$-$A_4$ were calculated and the $F_x$, $F_y$ and $F_z$ machinability regression functions were developed, as shown in equations (2), (3) and (4).

$$F_x = e^{7.4699405358 \times X_1^{0.6905168448} \times X_2^{-0.0440181594} \times X_3^{0.4838469996} \times X_4^{-0.1429055508}}$$

(2)

$$F_y = e^{5.7795192499 \times X_1^{0.3754127448} \times X_2^{0.2888017614} \times X_3^{0.3707452094} \times X_4^{0.1110397587}}$$

(3)

$$F_z = e^{-2.2227026380 \times X_1^{0.5856054992} \times X_2^{0.3388157799} \times X_3^{0.4319756159} \times X_4^{0.6701005386}}$$

(4)

4.2. Calculation of the cutting force

As previously stated, the total cutting force, $F$, is a dependent variable and can be calculated based on the values obtained for its components – $F_x$, $F_y$ and $F_z$ – as shown in equation (5).

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

(5)

The values obtained for the total cutting force, as a resultant of the measured functions components, belong to the following closed interval $F \in [165.09; 760.05]$ N.
The values obtained for the total cutting force, as a resultant of its machinability regression functions components, belong to the following closed interval $F \in [130.56; 723.53]$ N.

The variation of the total calculated cutting force in relation with the cutting regime parameters – axial depth of cut, $a_p$, radial depth of cut, $a_e$, feed rate per tooth, $f_z$, and cutting speed, $v_c$, – is shown in figures 7, 8, 9 and 10.

![Figure 7](image1.png)

**Figure 7.** Variation of cutting force in relation to the axial depth of cut, $a_p$.

![Figure 8](image2.png)

**Figure 8.** Variation of cutting force in relation to the radial depth of cut, $a_e$. 
After assessing the obtained variation graphs, we can determine that the influence of each cutting regime parameter on the total cutting force value, in terms of average values for the other cutting regime parameters taken into account, is as follows: the total cutting force, $F$, increases by 64.21% when the axial depth of cut, $a_p$, increases by 150%; the total cutting force, $F$, increases by 27.07% when the radial depth of cut, $a_r$, increases by 400%; the total cutting force, $F$, increases by 168.14%...
when the feed rate per tooth, \( f_z \), increases by 900%; the total cutting force, \( F \), increases by 3.05% when the cutting speed, \( v_c \), increases by 50%.

5. Conclusions
The research presented in this paper was performed in order to enrich the existing studies regarding the materials cutting machinability, with a particular focus on the X105CrMo17 stainless steel.

The relevant conclusions associated with this research are:
- Based on the experimental data, the \( F_x \), \( F_y \) and \( F_z \) machinability regression functions were developed in terms of axial depth of cut, radial depth of cut, feed rate and cutting speed; for each regression coefficient, 10 decimals being taken into account.
- The total cutting force, \( F \), was calculated as a resultant of the \( F_x \), \( F_y \) and \( F_z \) components and variation graphs were drawn to reveal the relation between the calculated \( F \) values and the cutting regime parameters.
- Based on the analysis of the relation between the total cutting force, \( F \), and the cutting regime parameters taken into account for its definition, we can conclude that the greatest influence is exercised by the feed rate, \( f_z \), and the smallest influence by the cutting speed, \( v_c \).
- The axial and radial depths of cut variation have nonlinear influence on the cutting force and this fact requires a higher degree of attention on the produced phenomenon, more studies for other intervals being required.

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