Measurement and analysis of cutting forces when machining nickel superalloys

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Abstract

Presented paper contains a generalization of the number of experiments that were carried out during the last year. These experiments were focused on the analysis of cutting conditions when machining nickel-based superalloys. In this paper main accent is given to the process of measurement and consecutive analysis of cutting forces.

Keywords

Cutting forces, Inconel, milling.

1. Introduction

Milling difficult-to-machine materials, such as nickel-based superalloys, is currently still accountable problem. Properties of these materials cause rapid wear of cutting tools, which leads to high production costs. Another requirement for the machining process is surface quality, which must meet exacting customer requirements. The milling process is accompanied by high cutting forces acting on the tool. Therefore, ensuring constant cutting forces, respectively prevent the occurrence of extremes, leading to increased tool life. On the other hand, low cutting conditions lead to a reduction in the productivity of the manufacturing process and therefore, in terms of productivity is needed to improve conditions.

The number of authors are using adaptive feed control for prevent rapid raise of cutting forces and stabilize them. Researchers apply different tools for prediction output parameters and changing input values as a neural networks and fuzzy logic [1], [3] or genetic algorithms [4]. All mathematical models need to be proceeded by input data, that is why the main target of provided experiments is to receive the maximum possible data that characterize process of milling nickel-based alloy Inconel.

2. Cutting forces measurement

Cutting forces were measured by a piezoelectric rotary dynamometer Kistler 9123C (Figure 1). The dynamometer is equipped with four piezoelectric sensors, on which arises due to the load signal, which is transmitted by cable to the amplifier and A/D converter. This signal is then transmitted to the notebook where the evaluation software DynoWare is installed. The software evaluates the force components in three axes - Fx, Fy, Fz according to the coordinate system of the dynamometer and torque Mz.

During the rotation clamped in the milling dynamometer leads to their natural noise that are unwanted phenomenon. To separate the noise from the signal, it is recommended to use linear low pass filter [2]. This filter does not pass signal of higher frequency than specified. Were used cutoff frequency of 200 Hz and filter order 2. Also used drift compensation tool.

Analysis of cutting forces was performed in software DynoWare 2825, MINITAB® Statistical Software version 14 and MATLAB.

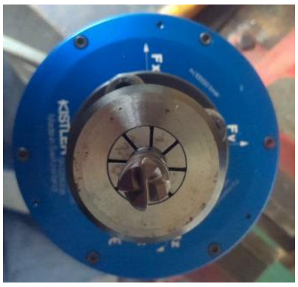

Figure 1. Dynamometr Kistler type 9123C

3. Radial and axial depth of cut experiment

3.1. Experimental procedure

During this experiment, the main attention was given to study cutting forces and surface roughness when radial depth of cut (a_e) and axial depth of cut (a_p) were variable factors. As a material was chosen Inconel 738LC, which is hard-to-machine nickel based alloy. Three levels of radial depth of cut and two levels of axial depth of cut were selected to compare results. Workpiece was clamped in the way that ensure the 14° angle between tool axis and normal to face vector. The experiment was carried out with the following cutting conditions:

Cutting tool	10 mm end milling cutter
Number of edges	4
Radial depth of cut, a_e [mm]	0.5; 1.0; 1.5
Axial depth of cut, a_p [mm]	0.5; 1.0
Cutting force, v_c [m/min]	42
RPM	1337
Feed rate, f_z [mm/rev]	0.07
Feed, v_f [mm/min]	374

3.2. Results of the experiment

In the all experiments were observed higher cutting forces during the first cut when the whole diameter of the cutting tool was loaded. These results were not included to the numerical analysis. Average values of Fa, Fz and Mz were compared with using statistical tools. Force Fa is calculated as square root of sum of squares Fx and Fy, so it is resulting force vector in in the plane XY of rotating dynamometer coordinate system.

ANOVA analysis showed that Fz values were not affected by depths of cut. Resulting cutting force Fa was affected by axial depth of cut value. And Mz was affected by radial depth of cut. These conclusions were made on significant level 0.05. Linear regression models for Fa and Mz are as follow:

$$Fa = 2.5 + 208 * a_p + 59.8 * a_e \tag{1}$$

$$Mz = -0.011 + 0.407 * a_p + 0.421 * a_e \tag{2}$$

Graphically results are presented in Figure 2 and Figure 3.

After experiment, surface roughness was measured. Statistically significant effect on parameter Ra had the factor Radial depth of cut. The larger value of depth of cut the larger value of Ra, so worse surface quality.

Tool wear condition was evaluated on the basis of graphic recording imposed on the optical measuring machine. The minimum tool wear was observed in the number of tools 1 and 2, which correspond to the radial depth of cut of 0.5 mm and 1.0 mm. Machining with radial depth of cut 1.5 mm causes more wear and chipping of teeth.

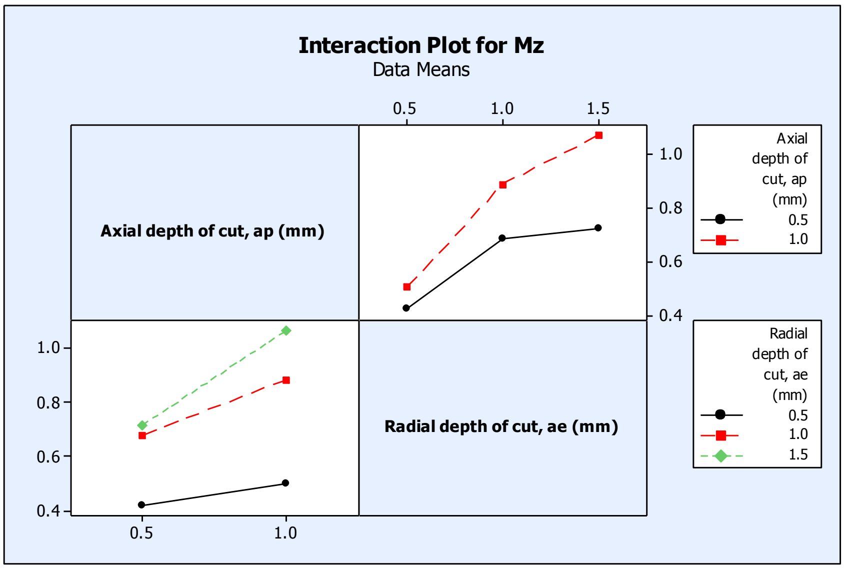

Figure 2. Influence on radial and axial depths of cut on Torque Mz

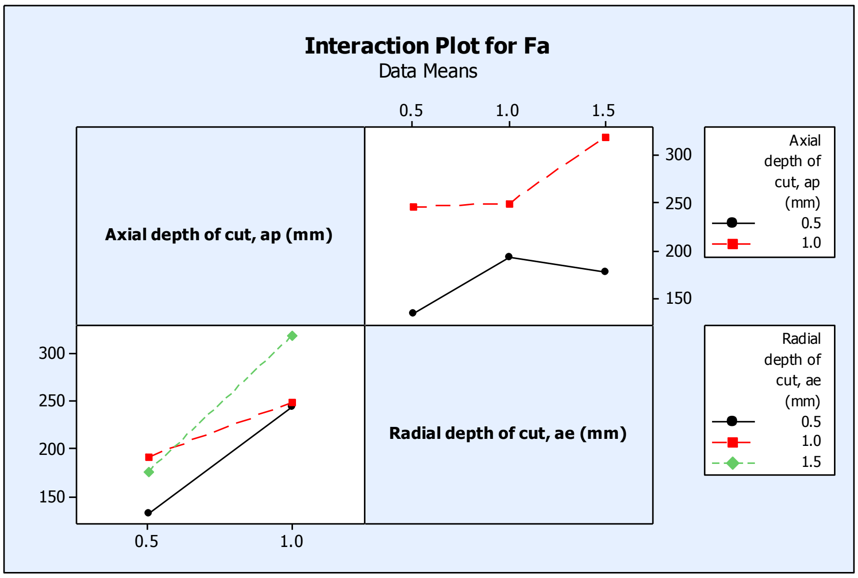

Figure 3. Influence on radial and axial depths of cut on resulting cutting force Fa

4. Entering of the cutting tool

4.1. Experimental procedure

This experiment had two main aims: a) to study a process of entering cutting tool in the material; b) to study changes in cutting forces when feed rate is increasing during a cutting process. During first cut, the tool is usually fully loaded and accordingly to higher cutting forces can be observed. Due to this fact, the first cut is often made of 50% of the normal feed rate, so cutting forces are supposed to be lower. This experiment helped us to study the effect of changing of feed rate when it was changed gradually. For this purpose, three methods of entering were compared.

These methods are shown in Figure 4 and explanation is as follow:

I. Feed rate is increasing from 50% to 100% in the length from start to 100% tool diameter.
II. Cutting tool is entering with a constant feed rate 50%, than is increasing in the length from 50% of tool diameter to 150% of tool diameter.
III. Feed rate is constant 100% during the entering.

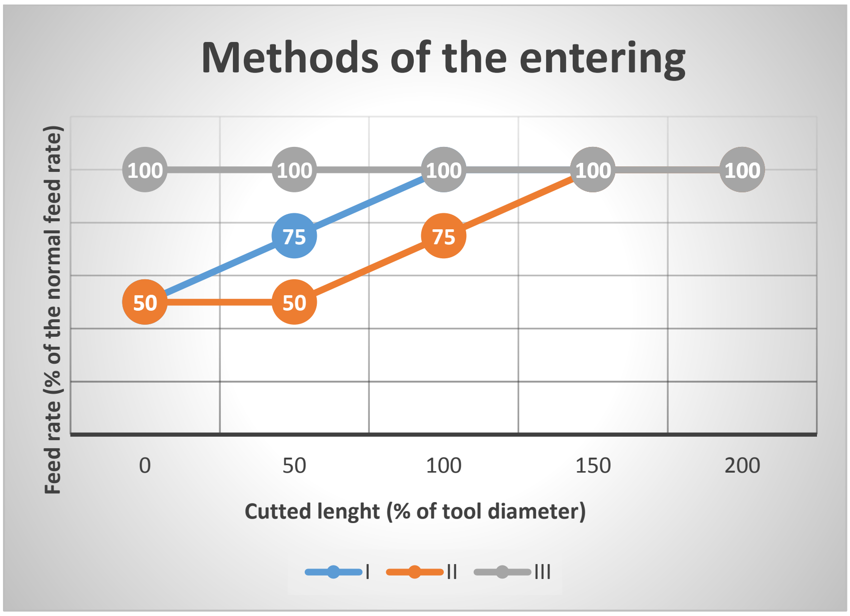

Figure 4. Methods of cutting tool the entering

Gradually changing of feed speed was made by using hand written cycle that changed feed speed 20 times per 10 mm cutting length. The experiment was carried out with the following cutting conditions:

Cutting tool	10 mm end milling cutter
Number of edges	6
Depth of cut, a_p [mm]	0.5
Cutting force, v_c [m/min]	42
RPM	1337
Feed rate, f_z [mm/rev]	0.04; 0.07; 0.10
Feed, V_f [mm/min]	321; 561; 802

4.2. Results of the experiment

First were analyzed graphical results of the experiments. Low-pass filter with frequency 200 Hz was applied to the data. As a representative example, Figure 5 is presented. It is seen the gradually increasing of cutting forces when method I and II were applied. There are no steps in cutting forces due to the changes of the feed rate, which is the good result because sudden change of the feed rate can cause faster cutting tool's wear.

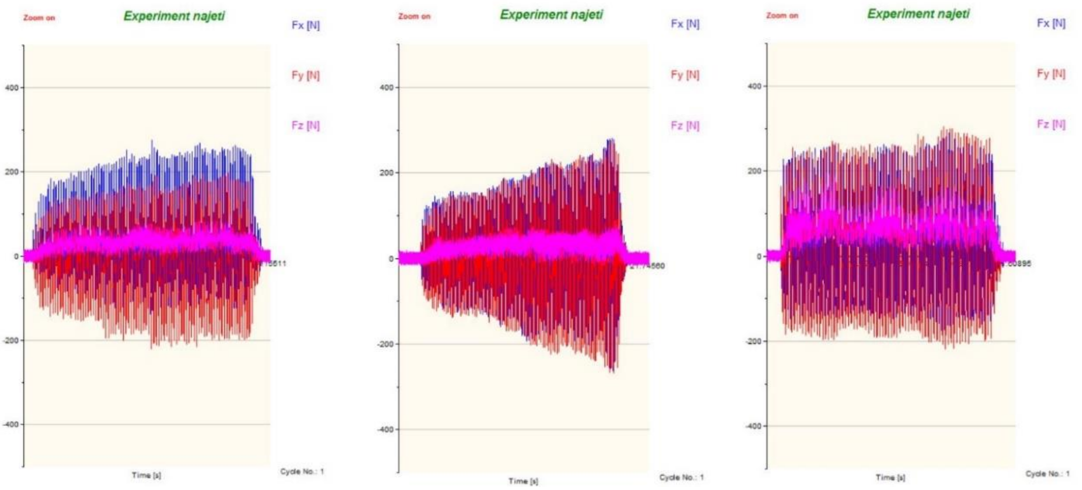

Figure 5. Measured cutting forces during machining with feed rate 0.07 mm/edge. Methods I, II, III

For the numerical analysis, simple mathematical operations were applied. From areas, where the cutting forces were constant, average values of the max values per revolution were taken. Scatter plot (Figure 6) shows values of Fz, Mz and Fa by the vertical axis and feed speed by the horizontal axis with simple linear regression lines. Analysis of variances pointed out that feed speed has a significant effect on the variables Mz and Fa, but has no significant effect on the Fz value. As it can be seen, increasing of feed speed causes raise of cutting forces Fa and torque Mz.

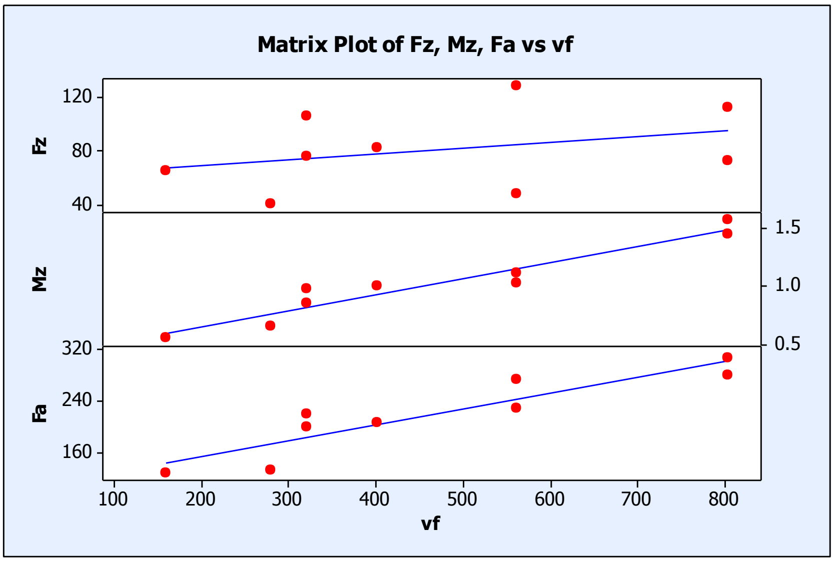

Figure 6. Scatter plot of cutting forces Fz, Mz and Fa versus feed speed v_f

Another part of numerical analysis identified that increasing feed speed by 100% (from 0.02 to 0.04, for example) leads to increasing Fa and Mz by 55-60%. Regression models for Mz and Fa were calculated as follow:

$$M_z = 0.367 + 0.00140 * v_f \tag{3}$$

$$F_a = 103 + .250 * v_f \tag{4}$$

5. Conclusions

This paper experimentally investigates the cutting forces during milling Inconel 738LC. In the different experiments were studied influence of radial depth of cut, axial depth of cut, feed rate and method of entering the cutting tool on cutting forces. The following conclusions can be drawn from this paper:

1. Resulting cutting force Fa is affected primarily by axial depth of cut. Fa is increasing when axial depth of cut is increases.
2. The radial depth of cut affects torque Mz. This factor has also the major effect on surface quality and tool wear. Larger values of Mz leads to worse surface roughness and faster tool wear.
3. Linear regression model were developed and they can be used for further study of Inconel 738LC milling.
4. Method of gradually changing feed rate can be used for corrections in cutting forces during the milling process. An important property is that cutting forces are changing insensibly.
5. Regression model was developed for describing changes in cutting forces when feed rate is changed.

Acknowledgement

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