Cutting data effect on machine tool vibrational state and surface roughness when machining

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Abstract. The article is devoted to the study of vibration processes of metal-removal equipment. In the course of the study, the dynamic phenomena arising in the metal processing in this complex dynamic system have been investigated for the purpose of further control of cutting modes that minimize the accompanying oscillations and vibrations. This article presents the results of studying the dependence of the roughness parameters on the vibration of the spindle assembly and processing modes in the milling operation. Planning techniques and experimental statistic were used in our investigation. The dependence of vibration acceleration root-mean square parameters (RMS parameters) on cutting set modes was determined. Monitoring of vibration parameters when machining centres operating allows improving the quality of parts processing and preventing expensive machine operating under dangerous dynamic load.

1. Introduction

The elastic system of the machine tool is characterized by static rigidity - the tendency to move the tool relative to the workpiece under the component P action of cutting force, and dynamic admittance – the tendency to move because of disturbing periodic force-induced oscillations [2, 3]. The latter characteristic reflects an important property is that the deformation in the machine tool depends not only on the of applied forces magnitude in the processing, but also on the parameters of its oscillations. Significant and dangerous resonant vibrations occur when the frequencies of these vibrations coincide with the natural frequency of the machine and its components [1]. Accuracy decreases and the bearings service life and the machine tool a whole is reduces, the roughness of processing is increased [4]. Meeting tolerance of processed surfaces roughness is one of the main criteria of their quality. Roughness impacts such product performance properties as a life time, fatigue strength and corrosion resistance of mating parts. The influence of cutting mode on the surface roughness is studied well enough for metal alloys [5]. Nevertheless, the pattern of roughness changes depending on vibration and processing modes is studied less. Some individual experimental studies of vibration and roughness under different processing modes have shown that cutting speed \( V_c \) and feed per tooth \( F_z \) have a significant impact on the response functions. This is most critical in high-speed and high-productivity milling of aluminum alloys, as the cutting process is performed at high spindle speeds with high dynamic loads [6-8]. Therefore, the risk of the above-mentioned resonant vibrations increases [9,10]. The use of expensive machining centers and modern cutting tools in these operations does not solve the problem.
In turn, correctly prescribed processing parameters, providing a stable cutting, allow to reach the maximum process efficiency and to obtain significant economic benefit.

A number of researches are devoted to a study of the vibration generating mechanism during cutting, in particular when milling [11,12]. But they tend to focus on the cutting process and pay insufficient attention to the machine conditions and high vibrations impact evaluation for the condition of equipment.

We carried out the experiments to study these processes and determine the mutual influence of DMG DMC 635V machining center vibration state and the cutting modes with the machined surface roughness parameters.

2. Materials and Methods
In the experimental part of the work the influence of processing modes on the machine vibration state and machined surface roughness were examined. In our experiment we used the planning procedure. The study was conducted according to the fractional four-factor three-level Box-Behnken design [13,14]. Parameters that largely affect the roughness and dynamic behaviour of the machine tool were determined as the studied factors: cutting speed, feed, width and depth of milling.

The experiment included the following stages: factor coding, design of experiment matrix, experiment realization, repeatability checking, determination of regression coefficients significance and model verification. Processing of the wrought aluminium alloy B95 billet was made by Sandvik Coromant R790-032HA06S2-16M cutter with cutting head diameter $D_c=32$ mm.

Passing milling was performed, because in this case the most favourable cutting process and smaller possible displacements of the workpiece take place. Cutting modes, which are presented in table 1, were specified on the recommendations of a tool manufacturer.

The lower and upper levels of rotation frequency correspond to non-resonant sections of amplitude-frequency characteristics (AFC) of the DMC 635V machine tool, and the basic level is in the resonance zone at a frequency of 125 Hz (Fig. 1).

Measurement of the machined surface roughness was performed with a profilometer Taylor Hobson Form Talysurf i200.

| Table 1. Cutting modes during the experiment. |
|-----------------------------------------------|
| Factor Code | upper | basic | lower |
| $V_c$, m/min | x1 | 1000 | 750 | 500 |
| $f_z$, mm | x2 | 0.3 | 0.2 | 0.1 |
| $a_e$, mm | x3 | 12.8 | 8 | 3.2 |
| $a_p$, mm | x4 | 4.5 | 3 | 1.5 |

On the basis of experimental design theory (using the software package Statistica 6.0) roughness and vibration state models depending on the processing modes were obtained.

Registration of spatial vibration components was carried out by sensors AR85 using a multi-channel signal converter National Instruments.
The evaluation of the vibration parameters during milling is performed by the averaged vector of the root-mean-square (RMS) values of the vibration acceleration (m/s²) in three mutually perpendicular directions of vibrations of a spindle assembly:

\[
U_A = \sqrt{C_k^2 X + C_k^2 Y + C_k^2 Z}
\]  

(1)

The RMS parameter of vibration acceleration was selected from the time-history after the transition process plot caused by the tool penetration. To exclude the influence of resonance properties of magnetic clamping of the chopper, the initial vibration acceleration signal was filtered by using a digital bandpass filter at a transmission frequency from 10 to 3500 Hz.

3. Results and Discussion

After performing all the necessary substitutions and transformations we obtain the RMS vibration acceleration parameter–milling process studied factors equation (2):

\[
U_A = e^{-188.56 \ln(V_C)} \cdot 57.702 - 4.376 \ln(V_C) \cdot F_z - 0.533 \ln(F_z) - 0.486 \cdot A_c \cdot 0.438 - 0.495 \ln(F_z) - 0.313 \ln(A_c) \cdot A_p \cdot 1.84 - 0.659 \ln(A_p)
\]

(2)

The response surfaces of the vibration acceleration RMS parameter depending on processing modes are shown in figures 2, 3, respectively.

![Figure 2. Dependence of the RMS parameter on vibration acceleration Ua:](image)
a – on the cutting speed Vc and feed to the tooth fz;  
b – on cutting speed Vc and cutting depth of ap
The quality of the machined surface finish was evaluated by the roughness parameter Ra of the machined end surface. Dependence of surface roughness on the milling process factors (3):

\[
R_a = e^{-117.096V_c^{34.831} - 2.657\ln(V_c)F_z^{0.859}A_p^{0.896} + 0.512\ln(F_z)} \cdot A_e^{2.632 - 0.715\ln(A_e) + 0.893\ln(F_z)}.
\] (3)

The roughness parameter response surfaces of the processed surface depending on the machining modes are presented in figures 4, 5 respectively.

The response function of the roughness Ra depending on the cutting parameters (Vc, Fz) and vibration has the following form (4):

\[
Ra = 0.00016 \cdot V_c^2 - 0.2579 \cdot V_c + 340.7249 \cdot F_z^2 - 177.9548 \cdot F_z + U_a + 93.0396.
\] (4)
4. Conclusions

The analysis of the experimental results allows us to conclude that the dependence of processing center vibration state on the processing modes is nonlinear, thereby confirming the presence of stable cutting zones and effectiveness of high-speed processing methods.

The resonance areas that have been identified in the analysis of the amplitude-frequency characteristics (AFC) significantly affect the milling process and lead to increasing in vibration parameters and enhancing the machined surface roughness. Thus, the problem of cutting mode optimization according by processing criterion in non-resonant areas of AFC becomes feasible when monitoring facilities and the vibration state diagnostic of machine spindles are used.

The analysis of predictability self-oscillation excitation during milling on the basis of available information regarding the machine tool parameters, the cutting tool, clamping equipment and the properties of the processed material can be considered as the subject of further research.

Also an important factor is an objective evaluation of the vibrations impact on the equipment and their impact on its operability and service life. In this case, the number of controlled parameters during machining increases. In particular, cutting force is required to be measured. Meanwhile it should be taken into account not only the specific value of the cutting forces projections at a given time, but also the laws of their changes.

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