Effects of tooling unbalance on surface roughness in end milling

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Abstract. The article discusses the issues of surface roughness when milling aluminum alloys. Effects of tooling unbalance are analyzed. The mathematical modeling method was used to calculate residual tooling equipment unbalance values. To assess model adequacy, experiments were conducted according to the fractional three-level four-factor plan. The unbalance effect was determined by regression analysis of the experimental data. Response surfaces were constructed. The experiments were conducted on a modern milling center. The results confirm that the mathematical model is adequate and the degree of surface roughness depends on residual tooling unbalance values.

1. Introduction
The efficiency of technological processes is a key factor in the machine-building industry. The milling technology is one of the most commonly used method that influences the production cost and cycle duration.

End milling is the most common milling technology that is studied by a number of researchers who deal with surface roughness striving to increase the material removal rate or study the finishing technology that allows them to achieve the preset degree of surface roughness and improve productivity. Studies on the end milling technology describe milling quality factors (e.g., vibrations have a negative effect on surface roughness, reduce tool reliability and equipment life).

Regenerative self-oscillations are the most common type of vibrations. Each oscillating cutter tooth creates a wavy surface. Each subsequent tooth cuts off a workpiece layer causing cutting force oscillations and regenerative vibrations.

Along with the regenerative vibrations, there are vibrations of the mechanical system caused by connections and kinematic relations between its elements.

There are two methods for eliminating vibrations. The most effective way is to identify stable cutting areas by modeling the technological system [1-2]. Its effectiveness depends on model adequacy and factors responsible for milling variation. Most authors deal with structural and geometric characteristics of tools, material properties, rigidity of the technological system and ignore the balance factor [4-5]. The balance requirements are formulated in various guides. However, they are based on ISO 1940/1 that contains balance quality requirements for rigid rotors [3] rather than tooling equipment.

The balancing process requires deep studies. When preparing a tool for the high-speed milling process, the permissible residual unbalance value may be very small as far as it depends on the tool rotation frequency and weight.

Therefore, it is necessary to revise the balance requirements in order to reduce tool preparation duration and laboriousness without worsening milling quality or reducing tool durability and spindle life. The revision should be based on empirical results.
Therefore, this article aims to study tooling unbalance effects on the surface quality after end milling.

2. Experiment

The research aims to determine the dependence of surface roughness on the tooling balance quality. The tooling equipment consists of a carbide end mill with a diameter of 16 mm and a shrink-fit chuck Haimer A63.140.16 made for the HSK tool system (Figure 2). The cartridge is able to balance the tooling equipment with balancing screws. Its eccentricity [6] is 0.006 mm which makes it possible to vary residual unbalance values without using the destructive balancing methods.

The study was conducted according to the three-level four-factor Box-Behnken plan. Residual unbalance $U_{res}$ was used to assess the balancing accuracy effect on surface roughness $R_a$. This universal parameter assesses the balance quality regardless of standards applied.

The amplitude of forces and vibrations was measured during the milling process. Cutting modes were chosen following the recommendations and adjusted relying on the experimental results (Table 1.).

The longitudinal ledges were milled in the workpiece (a 1933 alloy block 250*40*40 in size). It was fixed on Kistler 9253B23. HSC 75 linear (Figure 1) was used in the experiment. To measure the degree of surface roughness, Taylor Hobson Form Talysurf i200 was used. To monitor the level of unbalance, Haimer TD2009 Comfort Plus was used. In the research of machining processes, many models of dependencies are traditionally described by equations of the power type [16].

The mathematical roughness model can be described with the power-law regression equation

$$R_a = C_0 U_{res}^{a} f_z^{b} a_p^{c} a_e^{d},$$

where $C_0$, $a$, $b$, $c$, $d$ are model parameters.

Equation (1) reducible to the linear form is

$$\ln(R_a) = \ln(C_0) + a \ln(U_{oct}) + b \ln(f_z) + c \ln(a_p) + d \ln(a_e);$$

After making the following substitution

$$\ln(Ra) = y; \ln(C_0) = b_0; a = b_1; b = b_2; c = b_3; d = b_4;$$

we have

$$y = b_0 + b_1 \ln x_1 + b_2 \ln x_2 + b_3 \ln x_3 + b_4 \ln x_4;$$

The regression equation is
\[ y = b_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 + b_4 x_4 + b_12 x_1 x_2 + b_13 x_1 x_3 + b_14 x_1 x_4 + b_23 x_2 x_3 + b_24 x_2 x_4 + b_34 x_3 x_4 + b_{11} x_1^2 + b_{22} x_2^2 + b_{33} x_3^2 + b_{44} x_4^2. \]

The following expressions are used for coding the variables:

\[
x_1 = \frac{2(\ln U_{res} - \ln U_{res,max})}{\ln U_{res,max} - \ln U_{res,min}} + 1;
\]

\[
x_2 = \frac{2(\ln f_z - \ln f_{z,max})}{\ln f_{z,max} - \ln f_{z,min}} + 1;
\]

\[
x_3 = \frac{2(\ln a_e - \ln a_{e,max})}{\ln a_{e,max} - \ln a_{e,min}} + 1;
\]

\[
x_4 = \frac{2(\ln a_p - \ln a_{p,max})}{\ln a_{p,max} - \ln a_{p,min}} + 1;
\]

Table 2 shows the levels of experimental factors.

| Level of factor | Factors | \( U_{res}, g \times mm \) | \( f_z, \text{mm/tooth} \) | \( a_e, \text{mm} \) | \( a_p, \text{mm} \) |
|-----------------|---------|-----------------|-----------------|-----------------|-----------------|
| \( x_{imax} \)  | +1      | 14,7            | 0,15            | 10              | 2               |
| \( x_{i0} \)    | 0       | 8,9             | 0,10            | 6               | 1,5             |
| \( x_{min} \)   | −1      | 3,7             | 0,05            | 2               | 1               |

The upper level \( U_{res} \) corresponds to the maximum permissible tool unbalance. The lower level \( U_{res} \) corresponds to the minimum permissible tool unbalance. Fig. 3 shows chips. The cutting mode are adequate. After end milling, the surface roughness (Figure 4) meets the finishing requirements (Table 3).
Table 3 shows the experiment planning matrix and experimental results.

| No. of the experiment | $x_1$ code | $U_{res}$, g x mm | $x_2$ code | $f_z$, mm/tooth | $x_3$ code | $a_e$, mm | $x_4$ code | $a_p$, mm | $R_a$, mm |
|-----------------------|------------|-------------------|------------|----------------|------------|---------|------------|---------|---------|
| 1                     | -1         | 3,7               | -1         | 0,05           | 0          | 6       | 0          | 1,5     | 0,09    |
| 2                     | 1          | 14,7              | -1         | 0,05           | 0          | 6       | 0          | 1,5     | 0,13    |
| 3                     | -1         | 3,7               | 1          | 0,15           | 0          | 6       | 0          | 1,5     | 0,32    |
| 4                     | 1          | 14,7              | 1          | 0,15           | 0          | 6       | 0          | 1,5     | 0,43    |
| 5                     | 0          | 8,9               | 0          | 0,1            | -1         | 2       | -1         | 1       | 0,16    |
| 6                     | 0          | 8,9               | 0          | 0,1            | 1          | 10      | -1         | 1       | 0,41    |
| 7                     | 0          | 8,9               | 0          | 0,1            | -1         | 2       | 1          | 2       | 0,35    |
| 8                     | 0          | 8,9               | 0          | 0,1            | 1          | 10      | 1          | 2       | 0,51    |
| 9                     | 0          | 8,9               | 0          | 0,1            | 0          | 6       | 0          | 1,5     | 0,15    |
| 10                    | -1         | 3,7               | 0          | 0,1            | 0          | 6       | -1         | 1       | 0,15    |
| 11                    | 1          | 14,7              | 0          | 0,1            | 0          | 6       | -1         | 1       | 0,34    |
| 12                    | -1         | 3,7               | 0          | 0,1            | 0          | 6       | 1          | 2       | 0,16    |
| 13                    | 1          | 14,7              | 0          | 0,1            | 0          | 6       | 1          | 2       | 0,27    |
| 14                    | 0          | 8,9               | -1         | 0,05           | -1         | 2       | 0          | 1,5     | 0,11    |
| 15                    | 0          | 8,9               | 1          | 0,15           | -1         | 2       | 0          | 1,5     | 0,21    |
| 16                    | 0          | 8,9               | -1         | 0,05           | 1          | 10      | 0          | 1,5     | 0,28    |
| 17                    | 0          | 8,9               | 1          | 0,15           | 1          | 10      | 0          | 1,5     | 0,41    |
| 18                    | 0          | 8,9               | 0          | 0,1            | 0          | 6       | 0          | 1,5     | 0,15    |
| 19                    | -1         | 3,7               | 0          | 0,1            | -1         | 2       | 0          | 1,5     | 0,31    |
| 20                    | 1          | 14,7              | 0          | 0,1            | -1         | 2       | 0          | 1,5     | 0,27    |
| 21                    | -1         | 3,7               | 0          | 0,1            | 1          | 10      | 0          | 1,5     | 0,19    |
| 22                    | 1          | 14,7              | 0          | 0,1            | 1          | 10      | 0          | 1,5     | 0,54    |
| 23                    | 0          | 8,9               | -1         | 0,05           | 0          | 6       | -1         | 1       | 0,18    |
| 24                    | 0          | 8,9               | 1          | 0,15           | 0          | 6       | -1         | 1       | 0,22    |
| 25                    | 0          | 8,9               | -1         | 0,05           | 0          | 6       | 1          | 2       | 0,14    |
| 26                    | 0          | 8,9               | 1          | 0,15           | 0          | 6       | 1          | 2       | 0,63    |
| 27                    | 0          | 8,9               | 0          | 0,1            | 0          | 6       | 0          | 1,5     | 0,15    |

3. Multiple Regression Analysis and Response Surface Construction

Multiple regression analysis is used to identify the best predictor. Figure 5 presents the regression analysis results. The response surfaces (Figures 6-8) were analyzed in STATISTICA 10.
The experimental results allow us to conclude that an increase in feed per tooth increases the degree of surface roughness, while other parameters remain ambiguous. The regression analysis shows that the residual unbalance effect on the degree of surface roughness is insignificant. The same results have been obtained for the response surfaces.
The model is adequate if the significance level coefficient “p” is < 0.05, and the
determination coefficient “R” is > 0.3, i.e. the response is influenced by the factors described by
the model. These coefficients show changes in the response that are caused by all the factors.
Thus, the model is adequate and has a predictive power.

4. Conclusion
The mathematical model that describes residual tooling unbalance effects on the surface quality
has been developed.

Model adequacy was assessed by regression analysis. The calculation and experiment have
shown that the unbalance effect on the surface roughness is insignificant. The surface was
slightly deteriorated with a several-fold increase in the balance quality allowance. Nevertheless,
even at maximum values of factor x1, the surface was similar to the finished one.

An avenue for further research is effects of the cutter thrust on the tooling unbalance quality.
The results can be used for preparing tooling equipment for milling wrought aluminum alloys.

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