EFFECT OF LONGITUDINAL AND CROSS FEED ON FLATNESS AND SURFACE ROUGHNESS IN FLAT GRINDING

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Abstract:
This research focuses on analyzing the impact of longitudinal and cross feed on the grinding quality, with particular emphasis on the parameters of surface roughness and flatness of the machined surfaces. The main objective is to examine how different combinations of these parameters affect the surface roughness and flatness. The experimental study is conducted using a surface grinding machine, where roughness (Ra) and flatness are measured under various longitudinal and cross feed settings. A full-factorial experimental design is implemented to systematically analyze the interaction between these factors. Statistical methods, including regression analysis, are used to determine the significance of the variables and their effect on surface characteristics. The results indicate that both longitudinal and cross feed affect the roughness and flatness of the machined surfaces. These findings highlight the need to optimize process parameters to balance surface roughness and flatness for improved machining performance. The insights gained from this research provide valuable guidelines for optimizing grinding operations in industrial applications, ultimately enhancing efficiency and product quality.

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1. INTRODUCTION

Grinding is a machining process used to achieve a precise and smooth surface finish or to remove a small amount of material from a workpiece to achieve the desired shape or dimension tolerances [1]. This process is particularly significant in industries such as automotive, aerospace, and tooling [2,3], where surface flatness and roughness play a crucial role in the functionality and durability of components [4]. A thorough understanding of the grinding process and its parameters is essential for achieving optimal manufacturing quality, productivity, and cost efficiency [5,6].

Surface roughness is one of the most important characteristics of product quality, and it has a direct impact on product performance, aesthetic appearance, fatigue, corrosion resistance, etc. [7]. This product specification is defined in technical drawings by surface roughness annotations, such as *Ra* (arithmetic mean height), *Rt* (total height) or *Rq* (root mean square height). Process planners consider these requirements in order to select the correct machine tool equipment, cutting tools, or cutting parameters [8], and these decisions have a clear impact on machining sustainability [9].

One of the most critical aspects of surface texture that must be ensured after a properly executed machining process is flatness. As obtaining perfect surface flatness in manufacturing conditions is impossible, the notion of flatness deviation is used to quantify the extent of deviation from an ideal plane. Flatness deviation is defined as the maximum vertical distance between the highest and lowest points of the actual surface relative to an adjacent reference plane. In this context, the adjacent plane is a theoretical nominal plane that encloses the real surface from the outside, ensuring that the farthest deviation from this plane within the designated measurement field represents the smallest possible value [10].

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Among the various technological parameters in grinding, feed rates are important factors in determining the surface characteristics of machined components [11,12]. The longitudinal feed regulates the relative motion of the workpiece along the grinding wheel, which significantly influences the grinding process [13], while the cross feed governs the incremental depth of cut across the surface. Both longitudinal and cross feed directly influence the interaction between the abrasive tool and the material, thereby affecting surface roughness and flatness [14,15]. Selecting appropriate feed rates is crucial for balancing surface quality, material removal efficiency, and process stability [16]. An increase in longitudinal feed generally results in higher material removal rates. However, it may also introduce greater surface roughness due to reduced overlap between successive grinding marks and increased chip thickness per abrasive grain [17]. Similarly, cross feed adjustments influence the uniformity of material removal and the distribution of thermal and mechanical stresses across the workpiece, which can impact both surface integrity and dimensional accuracy [18,19].

Furthermore, improper selection of feed parameters can lead to undesirable effects such as excessive thermal loading, microstructural damage, and geometric distortions, particularly in precision machining applications [20]. The interaction between longitudinal and cross feed rates may exhibit complex dependencies influenced by grinding wheel characteristics, workpiece material properties, and coolant application [14,21]. Hence, optimizing feed rates requires a comprehensive understanding of their combined effects on surface roughness (Ra), flatness deviation, and overall process efficiency [22].

This paper investigates the effect of longitudinal and cross feed on surface flatness and roughness during grinding. It explores how variations in these parameters impact the microgeometry of machined surfaces and identifies optimal conditions for achieving high-quality results. The findings of this research provide valuable insights for optimizing grinding operations, contributing to enhanced efficiency and improved product quality in modern manufacturing environments.

2. EXPERIMENTAL SETUP

2.1 Machining Setup

The TOS Hostivař BPH 300 is a machine for flat grinding designed primarily for precision grinding in light industrial applications. It is part of the BPH series, which is known for its reliability, accuracy, and versatility in handling various grinding tasks. The machine offers high accuracy with a precision of up to 0.001 mm, making it suitable for applications requiring fine surface finishes. It is powered by a 7.5 kW spindle drive, providing sufficient torque for efficient material removal.

The used grinding wheel is a type 1 (straight) wheel with a standardized diameter of 25 cm and thickness of 2 cm.

2.2 Measurement Setup

The Taylor Hobson Surtronic 3+ (Fig. 1) was used to measure the surface roughness in the experiments. It is a surface roughness tester designed for precise and efficient texture measurements. It measures parameters like *Ra, Rz, Rt, Rp*, and *Rv*, compliant with ISO 4287 standards. The device features a diamond-tipped stylus, a motorized traverse mechanism, and a 2.4-inch color LCD screen. It is lightweight, durable, and powered by a rechargeable battery capable of over 10,000 measurements per charge.

Key specifications include ± 5 % accuracy, 2 % repeatability and automatic calibration with traceable standards.

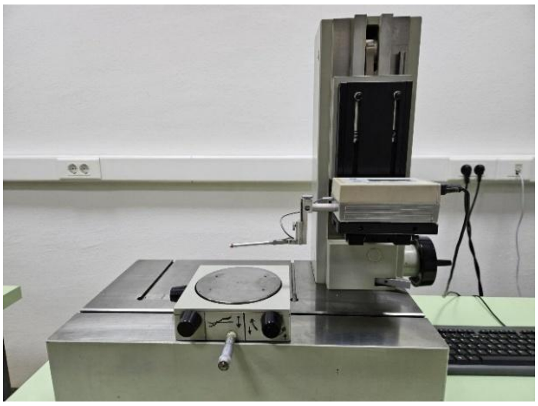

Fig. 1. Taylor Hobson Surtronic 3+ used for measurement of surface roughness

The Mitutoyo Roundtest RA-400 (Fig. 2) is used to measure flatness as a high-precision instrument designed for measuring flatness, roundness, and cylindricity in components.

The system includes auto-focus capabilities, adjustable resolution of up to 65 nanometers, and compatibility with various mask and wafer formats. It can measure parameters like line width, pitch, and defect size while offering automated defect tracking for improved quality control. The RA-400 is powered by a G-Series Ultra-Precision Digital Servo Motor for accurate positioning and alignment, ensuring consistent and reliable results.

This model measures flatness by combining the rotation of its high-precision turntable with the rectilinear motion of the vertical column and horizontal arm. It also allows for spiral scanning of a surface, capturing detailed data to evaluate flatness with high accuracy and repeatability.

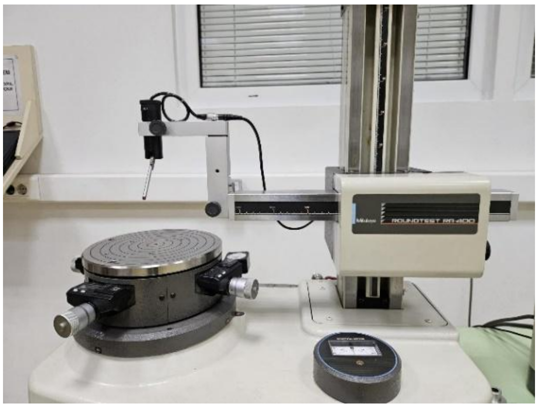

Fig. 2. Mitutoyo Roundtest RA-400 used for measurement of surface flatness

3. EXPERIMENTAL DESIGN

This experiment aims to systematically investigate the effects of two key factors, longitudinal feed and cross feed, on the response variables: surface roughness and flatness. The material used during the grinding process is 42CrMo4 + QT (AISI 4140), a quenched and tempered alloy steel with high mechanical properties, containing chromium and molybdenum as its main alloying elements. This steel is known for its strength, toughness, and excellent machinability, making it suitable for applications in industries requiring high durability and wear resistance.

A 2^2 full-factorial design is implemented to evaluate all possible combinations of the factor levels, enabling a comprehensive analysis of their interactions. The experiment considers two factors: Longitudinal Feed (Factor A) and Cross Feed (Factor B), each with two levels. For Longitudinal Feed, the employed levels are 3450 mm/min (Level 1) and 6900 mm/min (Level 2). For Cross Feed, the levels are 0.9 mm/stroke (Level 1) and 1.9 mm/stroke (Level 2). The revolutions per minute of the grinding wheel is fixed to 1500 revolutions per minute. Each combination of longitudinal and cross feed is replicated two times to improve reliability and account for variability within the experimental setup. The experiments are randomized to minimize external influences like machine variations or environmental conditions. This ensures reduced bias and improved result reliability.

The roughness parameter *Ra* (average roughness) and the flatness are measured for each experimental sample.

4. RESULTS AND DISCUSSION

The Individual Plots of *Ra* (Fig. 3) and the flatness (Fig. 4) are used to visually represent the distribution of the measured surface roughness (Ra) and flatness values across the different experimental conditions.

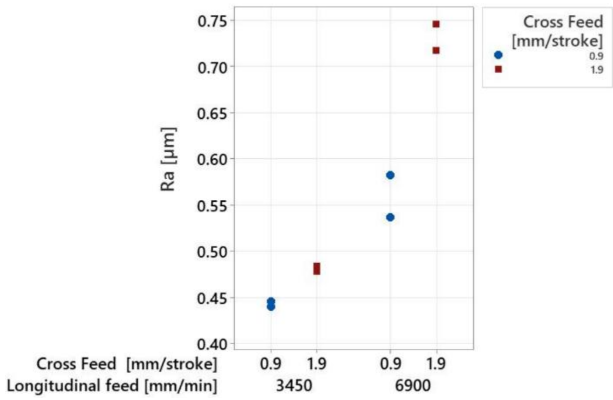

Fig. 3. Individual value plot of Ra values from the experiment

The graph in Fig. 3 shows that *Ra* values range from 0.45 to 0.75 µm, depending on the longitudinal and cross feed. The surface roughness (Ra) is also higher at the higher longitudinal and cross feed levels.

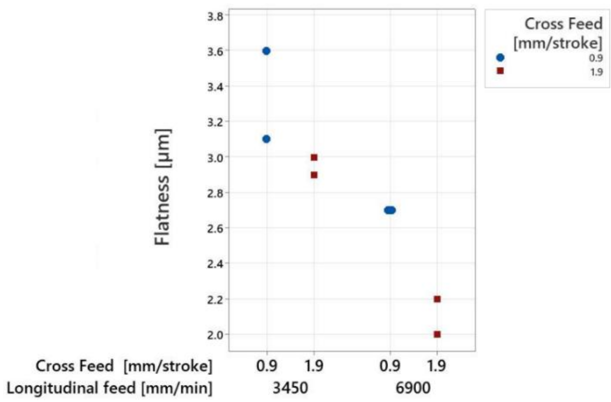

Fig. 4. Individual value plot of flatness values from the experiment

The flatness values vary between 2.0 and 3.6 µm, with different trends compared to roughness, where higher longitudinal and cross feed reduce flatness.

These conclusions are confirmed by the main effects plots, which illustrate the variation of the output parameters as a function of the factor values. As shown in Fig. 5 and Fig. 6 corresponding to *Ra* and flatness, respectively, an increase in the feed rates leads to a higher *Ra* value, indicating deterioration in surface roughness, while simultaneously resulting in a decrease in the flatness value, signifying improved flatness. The increase in *Ra* can be attributed to the higher material removal rate per unit time, which reduces the overlap of abrasive grains on the workpiece surface, leading to more pronounced machining marks and increased roughness. Additionally, higher feed rates introduce greater cutting forces, amplifying micro-vibrations and disrupting uniform material removal, further degrading the surface finish [23]. On the other hand, the observed improvement in flatness with increasing feed rates may be linked to the reduced heat accumulation in the workpiece. At lower feed rates, prolonged contact with the grinding wheel can induce thermal expansion and local distortions, contributing to deviations in flatness [19,24]. In contrast, higher feed rates allow for faster progression of the grinding process, limiting heat build-up and potential thermal deformation, resulting in a more uniform surface profile.

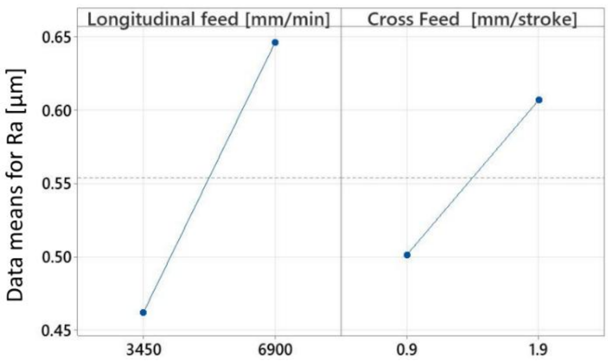

Fig. 5. Main effects plot of Ra

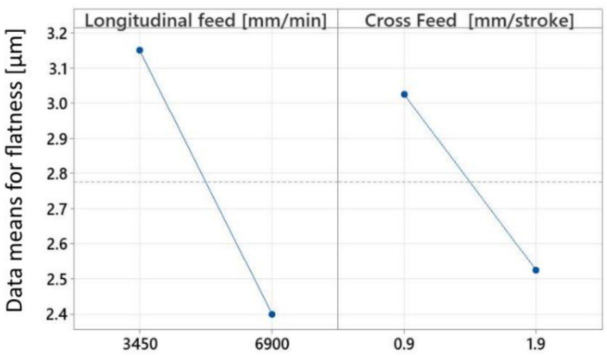

Fig. 6. Main effects plot of flatness

Fig. 7 and Fig. 8 present the contour plots of *Ra* and flatness, respectively, to visualize and assess the interaction between the two factors and their influence on the response variables. These plots help in identifying distinct regions corresponding to different values of *Ra* and flatness as functions of longitudinal and cross feed rates. The contour lines provide insights into whether a potential interaction effect exists. The Ra plot exhibits some curvature, suggesting a possible nonlinear relationship, whereas the flatness plot appears more linear. However, to statistically confirm the significance of this interaction, a detailed ANOVA analysis will be conducted subsequently.

Beyond interaction analysis, these contour plots serve as a tool for process optimization in grinding. By interpreting the plots, it is possible to select optimal combinations of longitudinal and cross feed rates that achieve the desired surface roughness and flatness within the required tolerances. Furthermore, since the choice of feed parameters directly impacts process productivity, these plots enable a strategic trade-off between surface quality and production efficiency.

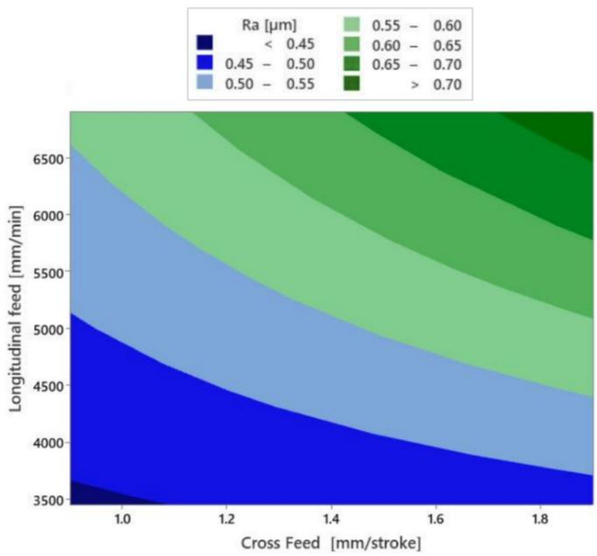

Fig. 7. Contour plot of Ra as a function of longitudinal and cross feed

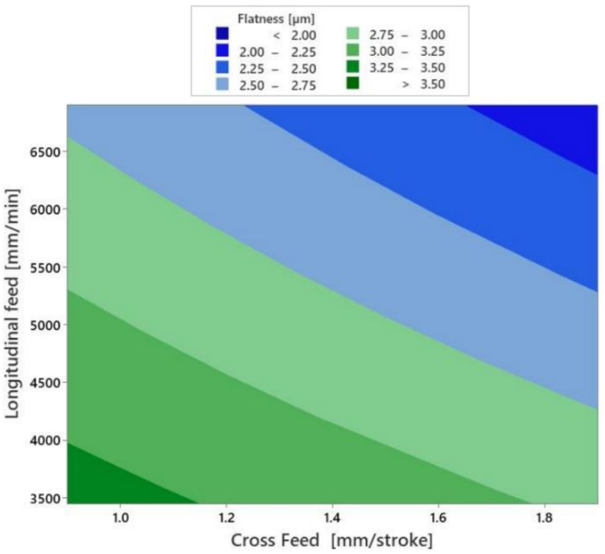

Fig. 8. Contour plot of flatness as a function of longitudinal and cross feed

A regression analysis was conducted for *Ra* and for flatness to evaluate the relationship between the feed rates and the response variables. The Analysis of Variance (ANOVA) test results are summarized in Table 1 for *Ra* and Table 2 for flatness, providing a statistical assessment of factor significance. The ANOVA for *Ra* revealed that only the first-order (linear) terms of the individual factors - longitudinal feed and cross feed - have a statistically significant influence on *Ra*. In contrast, their interaction term does not show a significant effect based on the P-value being higher than the threshold value for statistical significance of 0.05. The high F-values further confirmed the strong influence of these individual factors on the response variable. A similar trend was observed for flatness, where the interaction between the feed rates was also found to be statistically insignificant, reinforcing the conclusion that the relationship between the feed rates and both response variables is primarily linear.

Table 1. Results of ANOVA for Ra

Factor	F-value	P-value
Longitudinal feed (mm/min)	32.30	0.002
Cross feed (mm/stroke)	10.64	0.022

Table 2. Results of ANOVA for flatness

Factor	F-value	P-value
Longitudinal feed (mm/min)	33.09	0.002
Cross feed (mm/stroke)	14.71	0.012

The regression equation for *Ra* is given as:

$$Ra[\mu m] = 0.1308 + 0.000053 \cdot longitudinal\ feed + 0.1054 \cdot cross\ feed \quad (1)$$

where longitudinal feed is given in unit $(\frac{mm}{min})$ and cross feed in $(\frac{mm}{stroke})$.

The resulting R² value of the regression is equal to 89.57%, indicating high predictive accuracy and a well-fitting model for surface roughness.

Similarly, the regression equation for flatness is:

$$flatness\ (\mu m) = 4.60 - 0.000217 \cdot longitudinal\ feed - 0.5 \cdot cross\ feed \quad (2)$$

with an R^2 value of 90.53%, confirming good predictive capability for flatness.

5. CONCLUSION

This study investigated the influence of longitudinal and cross feed rates on the surface roughness parameter Ra and the flatness of machined components in a flat grinding process. The results demonstrated that both feed parameters play a significant role in determining surface quality, with higher feed rates leading to increased *Ra* values while simultaneously reducing flatness deviation. These effects were analyzed using regression models, ANOVA tests, and contour plots, providing a comprehensive understanding of the relationships between feed rates and surface characteristics.

The ANOVA analysis showed that only the individual effects of longitudinal and cross feed rates are statistically significant for both *Ra* and flatness, whereas their interaction does not statistically significantly influence the outputs, indicating that *Ra* and flatness primarily exhibit a linear dependence on feed parameters. The regression models developed for *Ra* and flatness resulted in high R^2 values (89.57% for *Ra* and 90.53% for flatness).

Future research can explore the influence of grinding wheel properties, coolant application, and tool wear progression which would further refine the understanding of process stability and surface integrity in high-precision grinding operations.

Conflicts of Interest
The authors declare no conflict of interest.

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