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MACHINING OF TOOTH PROFILES ON CNC MACHINES

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ABSTRACT

Conventional methods of tooth machining using worm modular milling cutters, gear wheels and gear combs have common disadvantages - they require specialized equipment, are characterized by complex readjustment and relatively low productivity, which are eliminated in skiving. This paper views the possibilities for machining tooth profiles by means of skiving on CNC turning and milling machines. A new version of the kinematics of the process upon cutting inclined teeth has been implemented, where the feed is in the direction of the tooth, no correction in the angular speed is required and a skiving tool profiled according to the profile of the machined surface is used. Meshing of a tooth pair with crossed axes is reproduced. As a result of the crossing, slipping of the profiles occurs, which is the main cutting motion. The cutting speed, as a determining mode factor, can vary widely and depends on a number of design and technological parameters. Single-factor experiments have been conducted to determine the influence of the conditions of the implementation of the skiving process (the crossing angle of the tool axes and the workpiece, determining the magnitude of the cutting speed, and feed rate) on the quality parameters of the machined surfaces (tooth profile deviation, tooth direction deviation, accumulated pitch error, largest pitch difference and radial runout error) and the corresponding graphical dependencies have been constructed. A 7-12 degree of accuracy of the machined tooth profiles has been ensured.

1. INTRODUCTION

Tooth profiles are formed by periodically repeating complex surfaces and require the application of specialized methods and tools for their manufacture, thus resulting in developing a separate class of specialized machines and tools. The need to concentrate operations demands to look for opportunities to integrate these methods to modern machines of a machining centre type.

As a promising method for machining spur gears, skiving has been promoted by a lot of commercial companies, such as Gleason, Mitsubishi and Prawema [1-3]. Research on the theory and application of skiving has been carried out, focusing on the kinematics of the process and the features of chip formation. Theoretical methods for profiling skiving tools have been established.

A number of papers have presented investigations of the design of the skiving tool, the cutting angle and the force required to slide the gear profiles using numerical methods [4]. Both the preliminary and final machining of induction hardened gears have been investigated [5].

Developments on the skiving process do not sufficiently cover tooth profile modification. In practice, proper tooth modification can help reduce the sensitivity of gears to process errors, which is very important in modern gear manufacturing industry [6, 7].

The aim of the present work is to study the technological possibilities for implementing skiving on turning and milling machining centers and determining the accuracy characteristics of the tooth profiles machined by this method.

2. EXPOSITION

Gear cutting by skiving is based on the centroidal crawling method, realized by meshing a pair of gears with crossed axles. In this method (Fig. 1), the workpiece and the tool perform strictly synchronised rotary movements at speeds of ω_2 and ω_t .

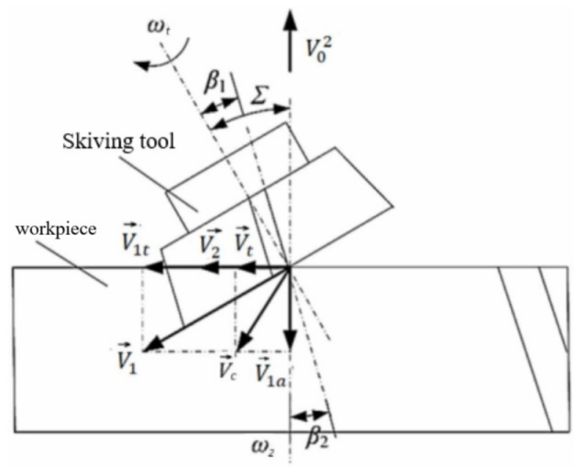

Fig. 1. Scheme of the skiving process

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As a result of the tool and workpiece axes crossing at an angle Σ, there is a relative sliding between the tooth profiles of the tool and workpiece, which is the main motion for the process. The feed motion is typically performed by the tool along the axis of rotation of the workpiece.

The value of the cutting speed V_c is of significant technological importance as it determines the tool life and is dependent on the physical and chemical properties of the material being processed. The determining design factors are known, while very little information is available on the technological factors.

The cutting speed V_c is determined by the following relation:

$$V_c = \omega_t . r_t . \sin\Sigma \quad [m/min],$$

where r_t is the radius of the tool.

The quality of the machined profiles and the productivity of the skiving process depend on the cutting speed and feed rate. To evaluate the influence of these factors on the accuracy characteristics of tooth profiles produced by skiving on a TM2500 turning and milling center, single-factor experiments were conducted. The tooth profile deviation, tooth direction deviation, accumulated pitch error, largest pitch difference and radial runout error were selected as parameters for accuracy evaluation. The selected control factors are the crossover angle Σ and feed rate.

The crossover angle Σ is formed by the angles of inclination of the workpiece teeth β_2 and the tool β_1 [1-3]. A variation range of 10° to 30° was chosen for the experiments, which corresponds to gears with inclined teeth.

The feed rate range was selected from 100 mm/min to 500 mm/min in order to search for an optimum value ensuring the set accuracy while maintaining smoothness and productivity.

The experimental studies of the skiving process were carried out on an experimental setup (Fig. 2), including a TM2500 turning and milling machining center, the necessary workpiece setting equipment and cutting tools. They were implemented in the conditions of the C1.2. laboratory "CAD/CAM systems for design and production of high-tech products" at the Competence Centre "Intelligent Mechatronic, Eco- and Energy-Saving Systems and Technologies".

Fig. 2. Experimental setup

The cutting tool is a gear generating wheel with a module $m = 0.8\,mm$, number of teeth $z = 60$ and tooth inclination angle $\beta_1 = 0°$.

The machined workpiece is a gear with external teeth of aluminium alloy D16T with a module $m = 0.8\,mm$, number of teeth $z = 32$ and tooth inclination angle $\beta_2 =$ 10°; 15°; 20°; 25° and 30°, respectively. The width of the gear crown is 6 mm and the external diameter D_B is determined by the corresponding relationship according to the tooth inclination angle.

The results of the experiments are presented graphically as a function of the corresponding accuracy parameter from the crossing angle and feed rate (Fig. 3 ÷ Fig. 10). The results obtained are approximated by straight lines.

Fig. 3 shows the influence of the crossover angle on the tooth profile deviation, respectively for the left profile - FAL, for the right profile - FAR and the mean deviation - FA. As the crossing angle increases, the deviation tends to increase and, respectively, the accuracy of the machined profile tends to decrease, and it varies within the range of 9 to 12 degrees of accuracy. It is typical that the deviation increases in different directions for the two sides of the tooth - for the left side, FAL increases in the negative direction and for the right side, FAR increases in the positive direction. The two variations do not compensate, as the mean FA increases by 8 μm over the range studied.

This influence can be explained as follows. On one hand, the increase in the crossover angle leads to an increase in the relative slip rate of the two profiles. On the other hand, the same tool of 0º tooth skew is used at the different angles, therefore its profile does not match the tooth profile.

The nature of the variation of the tooth direction deviation FB depending on the crossover angle is presented in Fig. 4. When the crossover angle increases, an increase in FB is observed. At a minimum angle of 10º the deviation is about 2÷3 μm, at 30º it increases 3÷4 times up to 15 μm. This variation corresponds to 7 - 12 degrees of accuracy. The nature and magnitude of the deviation of the left and right profiles are approximately the same.

The increase in the tooth direction deviation as the crossover angle increases is explained by the fact that the teeth change from an “inclined” type into a helical type, i.e. the tooth generant changes from a straight line into a helical line. When designing the control gear-cutting program, it is assumed that the tool moves in a straight line. As the angle increases, this trajectory diverges from the actual helical line of the tooth. Therefore, when working with crossover angles larger than 20º, it is desirable to change the straight trajectory of the tool into a trajectory corresponding to the actual helical line of the tooth, thus reducing tooth direction deviation.

The parameters characterizing the tooth pitch deviation (cumulative pitch error F_P and largest pitch difference R_P) as a function of the crossover angle are presented in Fig. 5. As the crossover angle increases, an increase in F_P is observed. At a minimum angle of 10º the deviation is about 30 μm, at 30º it increases twice up to 70 μm. The largest R_P pitch difference shows an increasing trend of approximately 60 μm. These variations correspond to 7 - 12 degrees of accuracy.

The variation of the radial runout error depending on the crossing angle is presented in Fig. 6. The resulting values from 67 μm to 89 μm correspond to an accuracy of 8. The radial runout values are mainly formed by workpiece setting errors.

The effect of feed rate on tooth profile deviation (Fig. 7) is pronounced, as the change in rate from 100 to 500 mm/min results in a 4-fold increase in F_a. The results obtained correspond to 8 - 11 degrees of accuracy. The dependence was observed for both left and right tooth profiles.

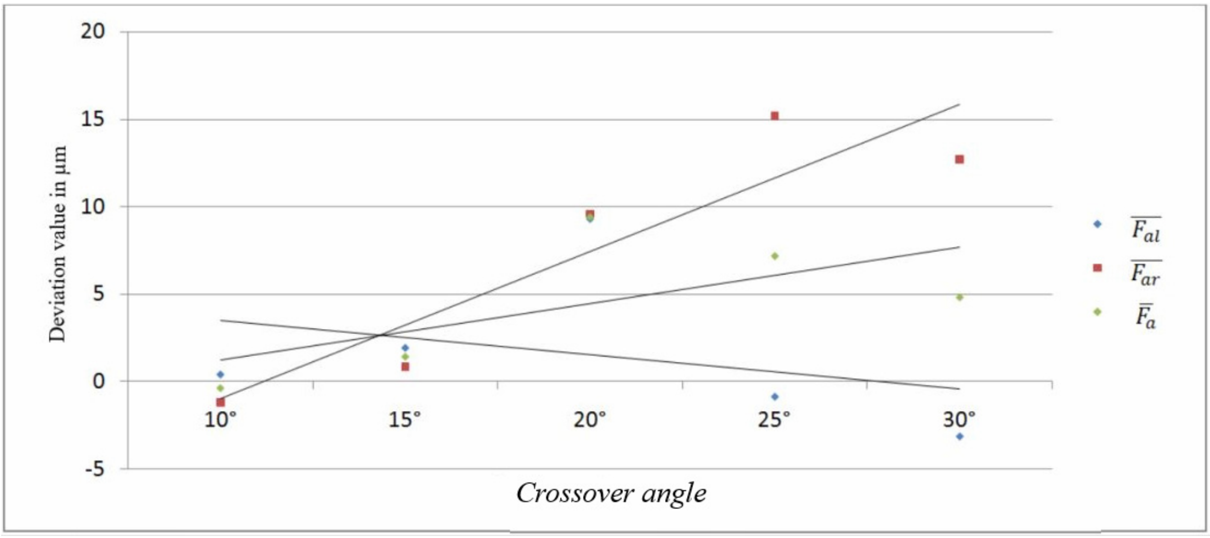

Fig. 3. Influence of the crossover angle on the tooth profile deviation

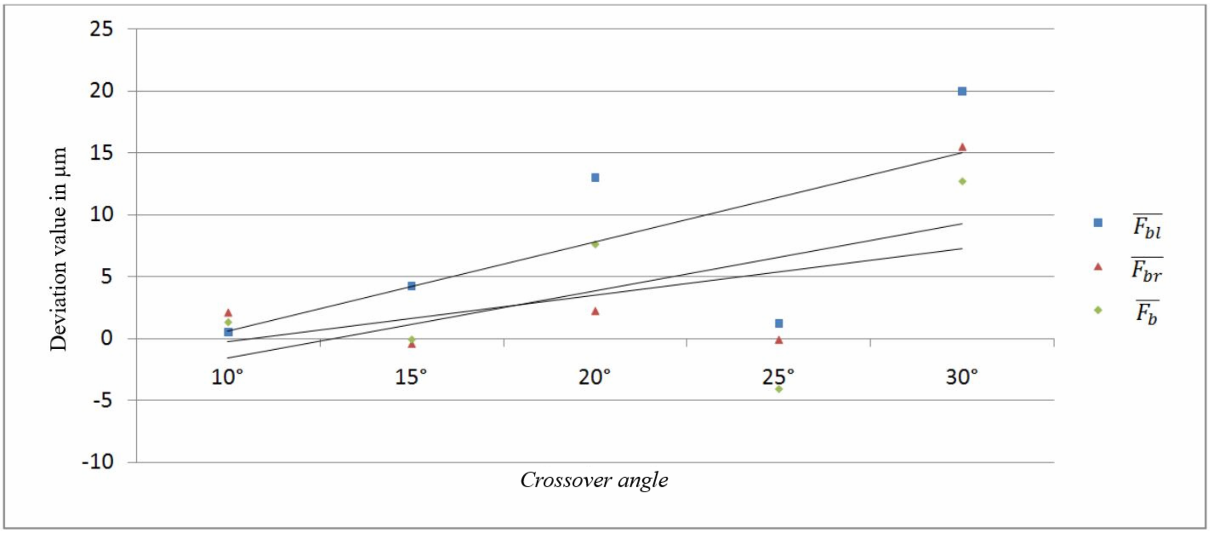

Fig. 4. Tooth direction deviation depending on the crossover angle

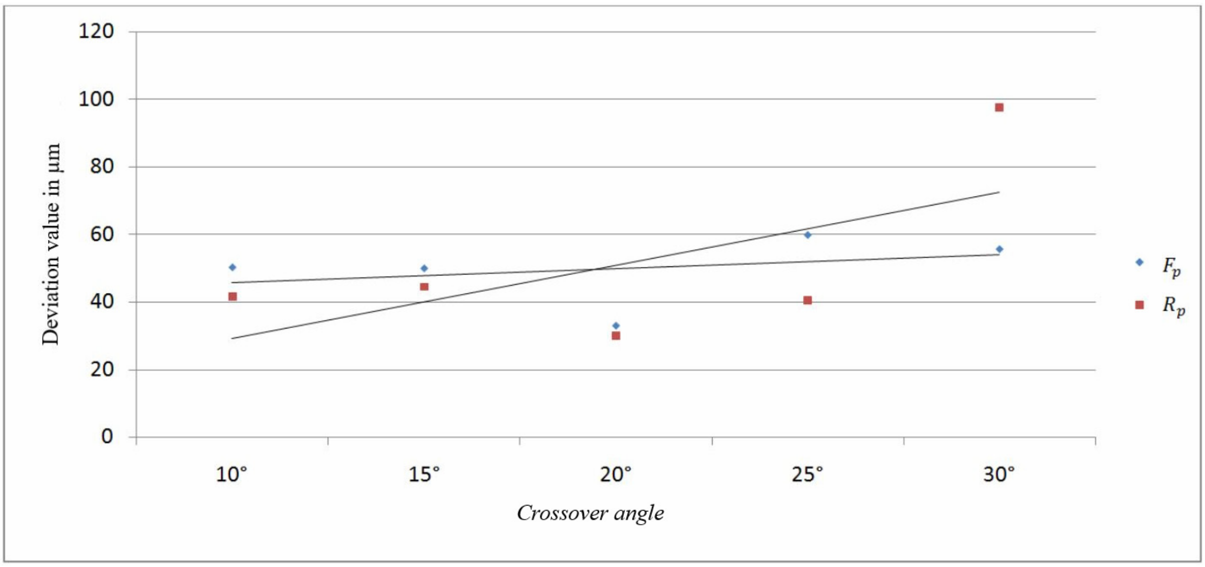

Fig. 5. Tooth pitch deviation - cumulative pitch error and largest pitch difference

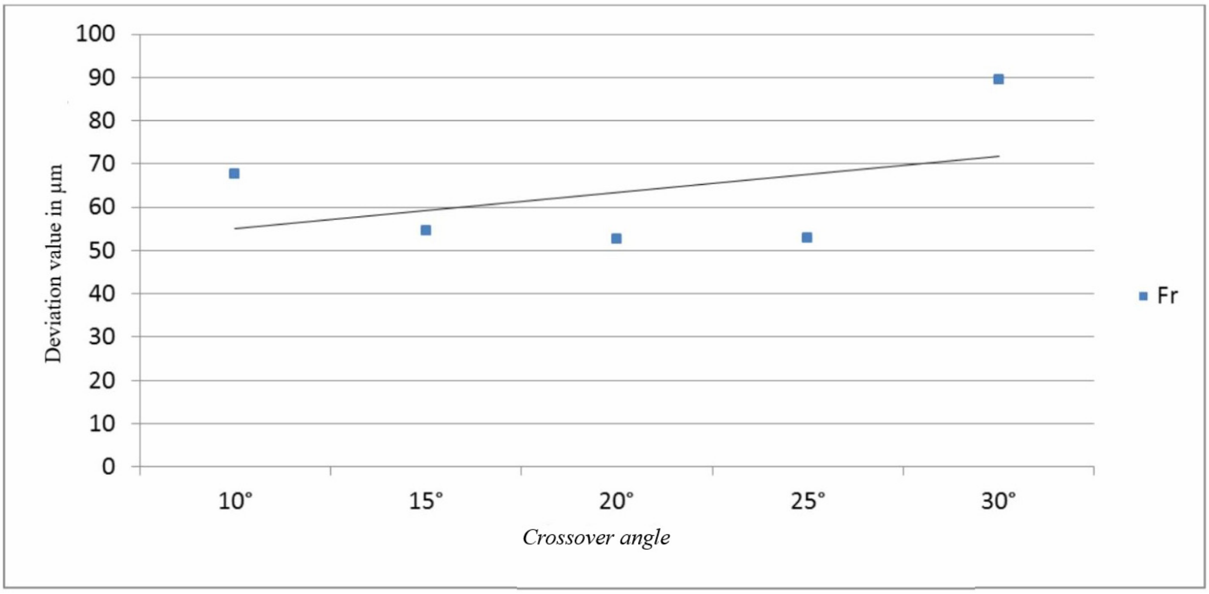

Fig. 6. Radial runout error

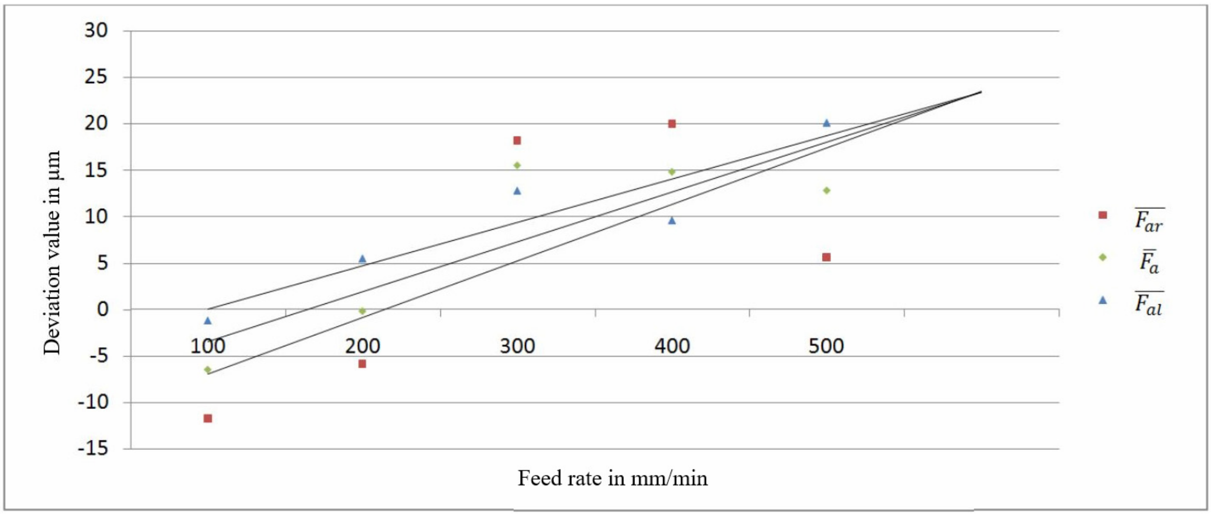

Fig. 7. Effect of feed rate on tooth profile deviation

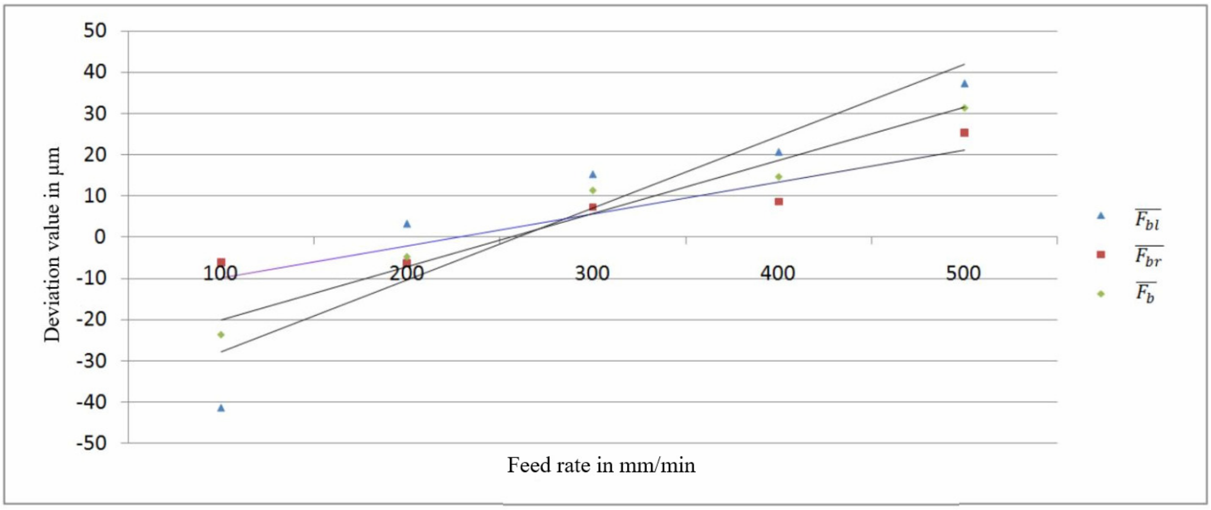

Fig. 8. Tooth direction deviation

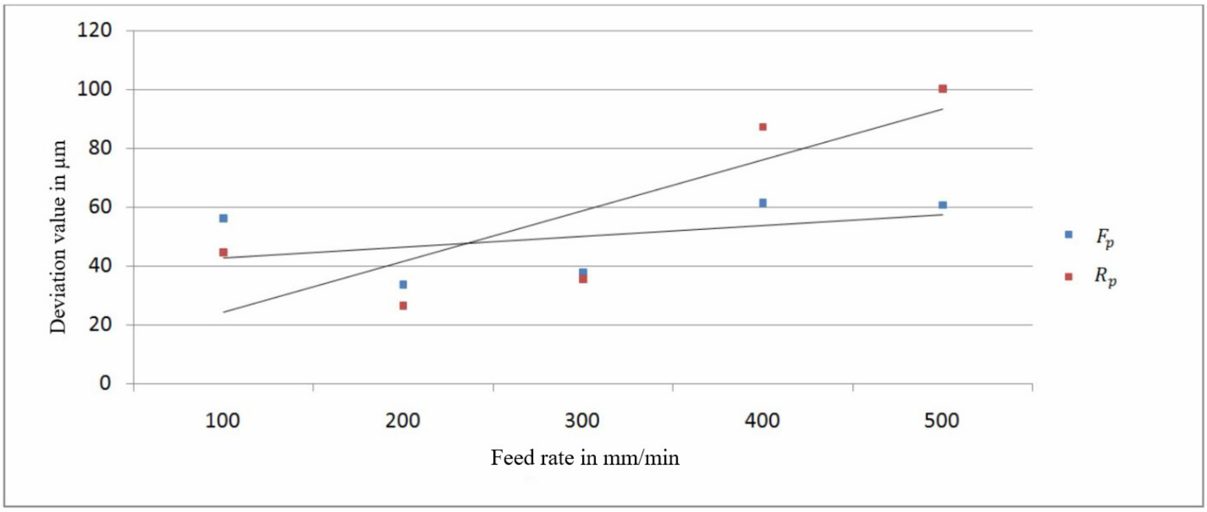

Fig. 9. Tooth pitch deviation - cumulative pitch error and largest pitch difference between two non-adjacent teeth

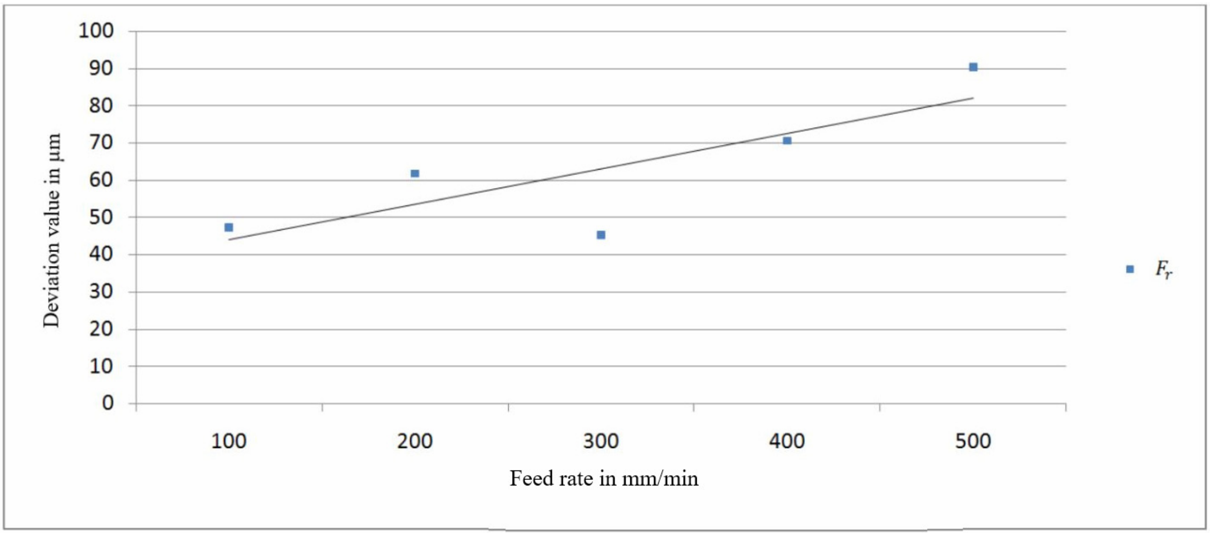

Fig. 10. Radial runout error

In the tooth direction deviation (Fig. 8), an increase in F_b is observed as the feed rate increases. At a feed rate of 100 mm/min, the deviation is 20 µm with a negative sign, and as the feed rate increases to 500 mm/min, the F_b reaches 37 µm. This variation corresponds to an accuracy of 7 - 12.

The pitch deviation relationships are shown in Fig. 9. The cumulative pitch error F_P depends minimally on the feed rate, with its value varying within 15 µm, which corresponds to an accuracy of 7. The largest pitch difference R_P increases up to 70 µm as the feed rate increases.

The radial runout error F_R depending on the feed rate (Fig. 10) varies linearly, and it increases by 45 µm over the entire range. The resulting values from 49 µm to 90 µm correspond to an accuracy degree of 12.

3. CONCLUSION

The feasibility of the skiving process on a turning and milling machining center has been demonstrated by analyzing the influence of the crossover angle and feed rate on the accuracy parameters of the machined tooth profiles (tooth profile deviation, tooth direction deviation, accumulated pitch error, largest pitch difference and radial runout error).

The obtained results prove that the skiving method is characterized by sufficient accuracy for preliminary and, in certain cases, final machining of tooth profiles.

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