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Application of variable teeth pitch face mill as chatter suppression method for non-rigid technological system

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Abstract. The article describes the results of experimental studies on the effects of variation type for variable teeth pitches on low-rigidity workpiece chatter suppression efficiency in a feed direction and in a direction of the normal to the machined surface. Mill operation performance was identified by comparing the amplitudes of dominant chatter harmonics using constant and variable teeth pitches. The following variable pitch formation variants were studied: alternative, linear rising, and linear rising falling. The angle difference of adjacent teeth pitches ranged from 0 to 10°, from 5 to 8° and from 5 to 10° with interval of 1°. The experiments showed that for all variants, machining dynamics performance resulted from the difference of adjacent pitches corresponding to a half the chatter wavelength along the cutting surface. The alternative nature of a variable teeth pitch is most efficient as it almost completely suppresses the chatters. Theoretical explanations of the results are presented

1. Introduction

Chatter excitation during cutting is a highly undesirable process as it reduces machining performance, accuracy and quality of part surfaces, tool and machine lives. It is true for face milling operations widely used in modern machine building, including machining of non-rigid workpieces. So, development of chatter suppression methods without reducing machining performance is a crucial task.

For multitoothed tools, including face mills, one of the ways out is to create a variable teeth pitch. In Russia, multivariable teeth pitch face mills have been applied since the mid of the last century [1]. At present, a leading Swedish tool company Sandvik Coromant offers a range of multivariable teeth pitch end and face mills [2]. However, these mills ensure chatter suppression only for narrow areas of the cutting speed. It checks down their industrial application and necessitates improvement of their design based on studies of the operation dynamics.

The idea of improving the dynamic stability of milling by using a multivariable teeth pitch mill was substantiated by J. Slavicek in 1965 [3]. Later, the studies were carried out by H. Opitz [4] and P. Vanherck [5]. J. Slavicek and H. Opitz studied conditions of chatter suppression varying two neighbor teeth pitches, and P. Vanherck increased the number of pitches. All the studies used a so-called alternate teeth pitch variation interchanging larger and smaller pitches. The differences in pitches corresponded to a half wavelength on the cutting surface. J. Tlusty [6] studied the dynamic stability of the end mill with a linear teeth pitch variation – a gradual growth with equal increments. E. Budak [7] showed that when a pitch difference is a half wavelength, the linear variation is more efficient than the alternate one. The third option of the unstable teeth pitch was suggested by Y. Altintas [8]: uneven tool pitches correspond to a certain number of waves with a fractional remainder equal to a quarter of wave, and even pitches – to their integer.

Over the last years, researchers have paid attention to ensuring the dynamic stability of end mills by varying pitches and helix angles [9…15].

They simulated the dynamics of milling processes whose accuracy is determined by the degree of idealization of relevant factors. Cutting experiments give more reliable results, which necessitates experimental studies of multivariable teeth pitch mills.

Recommendations on differences in pitches for neighbor tool teeth were suggested by S.S. Kedrov [16]. For the target cutting speed, the difference should be a half chatter wavelength. Further, the recommendations were developed by V.G. Shalamov [17], according to whom the difference of pitches can be a half, one and a half, two and a half and so on the wave length, but the first difference is the most efficient.

Along the cutting surface between neighbor teeth, a number of chatter waves influence the chatter excitation due to regeneration effects [18]. It can be presented by means of a dynamic stability diagram developed by H.E. Merritt [19]. According to the diagram, the highest chatter excitation occurs when the number of oscillations has a fractional remainder which is 0.75 wavelength. Chatter elimination occurs when the remainder is 0.25 wavelength. In this context, cutting dynamics control involves search for an optimal cutting speed rate and a tool teeth pitch.

The review shows that chatter suppression by applying a variable teeth pitch was studied for end mills, while for face mills the issue has not been paid sufficient attention. To this end, the purpose of the present research is to determine effects of teeth pitch variations on chatter suppression efficiency for a non-rigid technological system having a low rigid rate in the feed direction in one case, and in the normal to the machined surface direction in the other case.

2. Equipment and research methods

The experiments of machining non-rigid workpieces with a multivariable teeth pitch mill were carried out using a horizontal milling machine 6M82. A special face mill with a random teeth pitch and two devices for reducing stiffness along the feed direction and normal direction to the surface machined were developed.

An experimental mill with a diameter of 125 mm (Figure 1) has body 1. The cylindrical peripheral part of the body has two T-slots. Joints 3 are put into the T-slots. The joints connect eight cutters 2

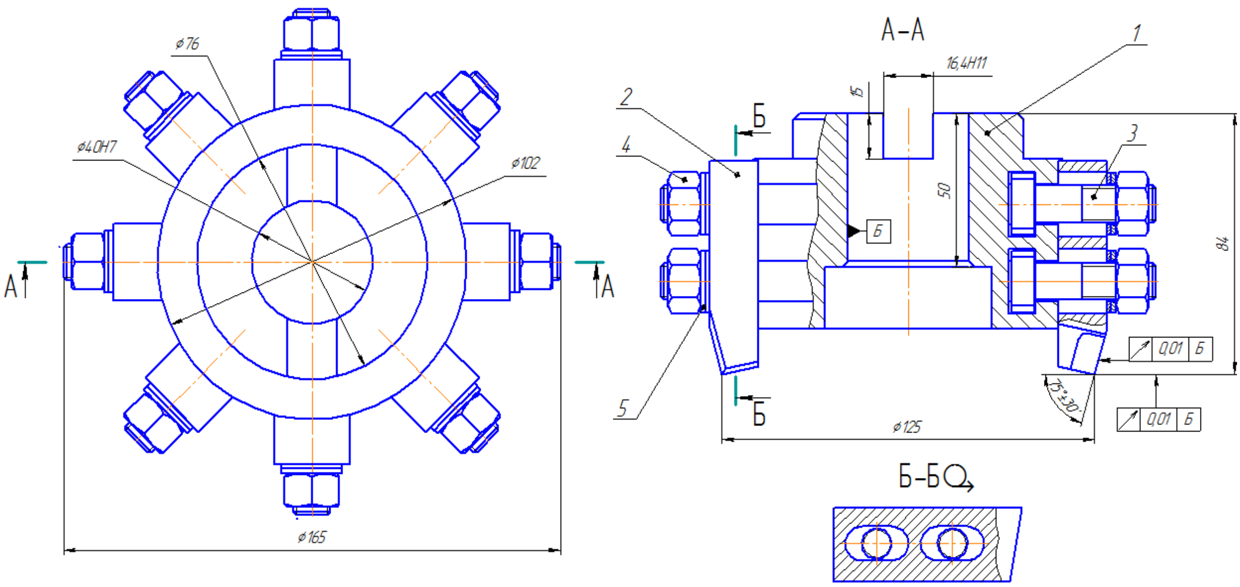

Figure 1. Face mill with an adjustable teeth

with nuts 4 and washers 5. Mill teeth with cutting plates made from cemented-carbide T5K10 are grinded with accuracy of 1° according to the recommendations in [19] and have the following geometrical parameters: the primary angle in the plane φ=75º; the side rake angle γ=-5°; the side relief angle α=16°; the rake angle of the side-cutting edge λ=15°. Adjustment of the angle teeth pitch with an error of about 0.25° was performed on an optical indexing attachment ODG-2 using a height gauge. The adjusted teeth runout value did not exceed 0.03 mm along the radial direction and 0.05 mm along the axis direction at their admissible values of 0.05…0.1 mm [20].

A device ensuring compliance of the workpiece along the feed direction is an inverted U-shaped holder bearing a workpiece made from steel 45 (HB = 207) 150x90x10 mm in size (Figure 2). Device stiffness adjustment along the feed direction was performed by varying the extension of the holder out of the vises. In the second device, the elastic plate which the workpiece was fixed on can shift under the influence of the cutting force along the mill axis direction (Figure 3). To adjust the stiffness of the elastic plate, the distances between two symmetrical background supports were varied. The stiffness of both devices was adjusted to the equal frequency of workpiece oscillations of 151 Hz.

During cutting, workpiece oscillations along the direction of reduced stiffness were recorded using a contactless eddy current sensor AP2000A. Signals were sent through an analog digit converter ZETLab 210 to a PC. Workpiece oscillation vibrograms were displayed on-screen. To determine a frequency oscillation spectrum, numerical data of each vibrogram were subjected to Fourier analysis using MatLab.

Ordinary symmetrical workpiece milling without cutting coolant was performed under the following cutting conditions: n=400 rev/min, S_{min}=500 mm/min, t=2 mm, B=90 mm. The spindle rotation frequency (measured with an eddy current sensor installed opposite the mill teeth) was n = 419.58 rev/min, and the cutting speed rate was v = 164.77 m/min = 2.746 m/sec.

Four series of experiments with different nature of tool teeth pitches were conducted. Each experiment was repeated three times, and the sequence of experiments was randomized. In the first and second series of experiments, an alternate variation of teeth pitches was applied. To create an alternate variable pitch, the mill even teeth were shifted in one direction to their uniform position by 0°- 10° with a discrete interval of 1°, and the angle position of uneven teeth remained unchanged. In the first series of experiments, a workpiece which is non-rigid along the feed direction and in the second series – a workpiece which is non-rigid in the normal to the machined surface were used. As far as the experiments of both series gave similar results, experiments of the next series were conducted using a device generating a workpiece elasticity along the feed direction. In the third series, a linear increase in a teeth pitch with a difference of 5, 6, 7 and 8° was applied. The author did not manage to create a difference of teeth pitches of more than 8° due to limited structural parameters of

Figure 2. An experimental unit with a fixture for creating a low-rigidity workpiece in a feed direction

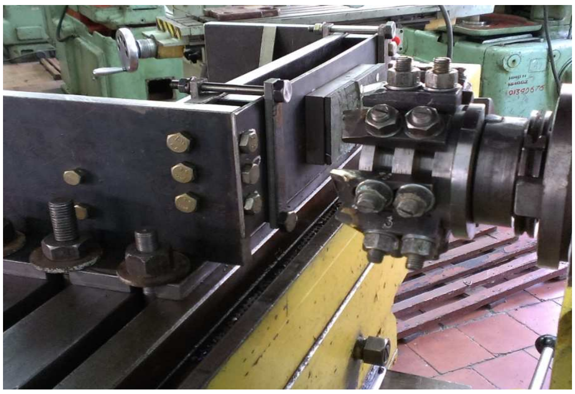

Figure 3. An experimental unit with a fixture for creating a low-rigidity workpiece in a normal direction

the experimental mill. The experiments of the fourth series were conducted using a tool with two kinds of teeth – with a linearly increasing pitch and a linearly decreasing pitch with a difference of 5, 6, 7, 8, 9 and 10°. In total, 32 experiments were conducted.

3. Results and discussion

The results of the first and second series of experiments are presented in Figures 4 and 5. When the mill teeth are positioned in a uniform way during cutting, intensive vibrations of the workpiece occur if it is fixed in both devices. The vibrations were accompanied by specific noise and wave formation along the cutting surface (Figure 6a). By their physical nature, these vibrations are chatter which is proven by the nature of their frequency spectrum (Figure 7a) with explicit dominant harmonics on frequencies of 159 and 165 Hz in the first and second series of experiments which are close to the frequency of workpiece oscillations without cutting – 151 Hz.

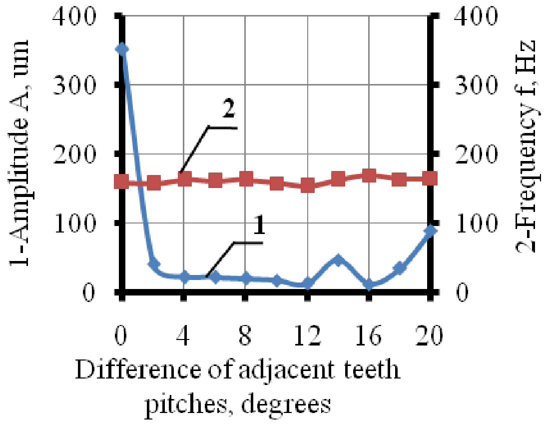

Figure 4. Effect of the alternative angle difference of adjacent teeth pitches on chatter amplitude A (1) and frequency f (2) for a low-rigidity workpiece in a feed direction

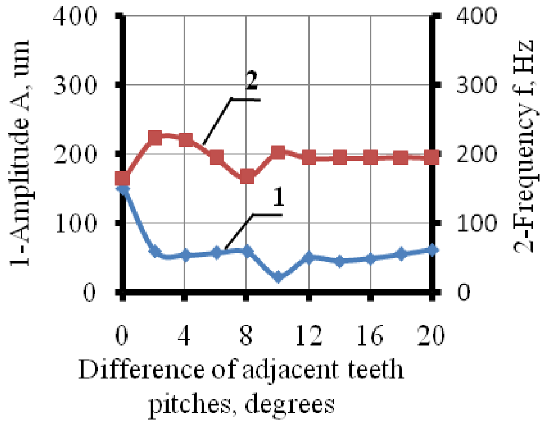

Figure 5. Effect of the alternative angle difference of adjacent teeth pitches on chatter amplitude A (1) and frequency f (2) for a low-rigidity workpiece in a direction of the normal to the machined surface

The difference of neighbor teeth pitches caused a sharp decrease in oscillation intensity. The best results were obtained at an angle difference of teeth pitches within the range of 8 and 12°: amplitudes of dominant oscillation harmonics fell from 352 to 12 um, i.e. 29 times in the first series of experiments (Figure 7b). In the second series, they fell from 150 to 23 um, i.e. 6.5. times. Chatter suppression caused a decrease in the depth of their marks on the cutting surface and improvement of machined surface quality (Figure 6b). The frequency of chatter with an increasing difference of teeth pitches was also slightly changed (see Figures 4 and 5). In the third (Figure 8) and fourth (Figure 9) series of experiments, the amplitudes of chatter were reduced to 33 um and 27 um, i.e. 10 and 13 times. Thus, the experiment showed that during face milling, alternate variations of a tool teeth pitch can eliminate chatter most effectively.

The results obtained can be interpreted in the context of the theory of regeneration chatter [18]. They develop due to the self-organization by adjusting the phase of current oscillations to the phase of vibration marks along the cutting direction. When the phase difference is +90°, this adjustment occurs during one…two oscillations after interaction of the tooth and the vibration mark on the cutting surface formed by the previous tooth. In these experiments with a non-rigid workpiece along the feed direction and uniform teeth arrangement, the oscillation frequency is 159 Hz. At a cutting speed rate of v=2.746 m/sec, the chatter wave length is l=v/f=17.271 mm. At a constant pitch rate, the distance between the teeth is L=πD/z=3.14x125/8=49.087 mm. The number of waves between the teeth along the cutting surface is n=L/l=2.84. The theory of regeneration chatter says that when the fractional

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a b

Figure 6. Machined surface and workpiece cutting surface when machining with a constant teeth-pitched mill (a) and a variable alternative teeth-pitched mill at a difference of 8° (b)

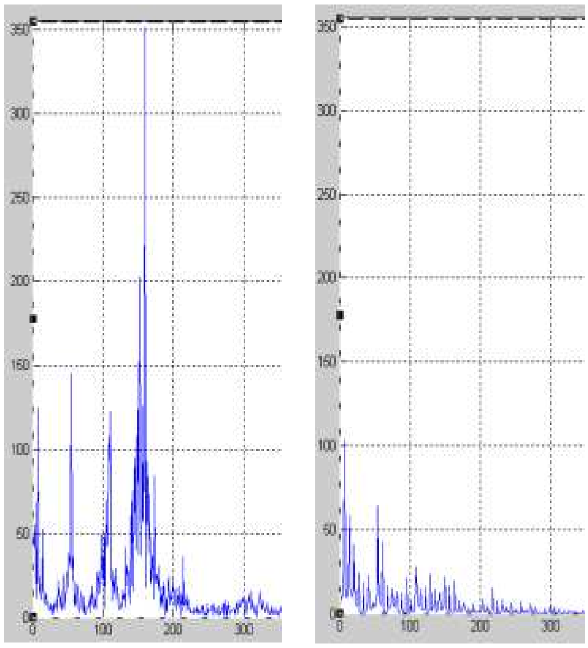

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Figure 7. Chatter spectrogram for a non-rigidity workpiece in a feed direction when machining with a constant teeth-pitched mill (a) and a variable alternative teeth-pitched mill at a difference of 8° (b)

remainder of the number of oscillation waves is 0.75, which corresponds to the initial phase shift of 270° (+90°), the chatter increase. When the fractional remainder is 0.25 corresponding to the initial phase shift of -90°, the chatter are damped. When the fractional remainder is 0 (1) or 0.5, the initial phase shifts are 0° and 180°. These two values of the initial phase shift are indifferent to chatter excitation and damping.

When the teeth are arranged in a uniform way, the fractional remainder of 0.84 is close to 0.75,

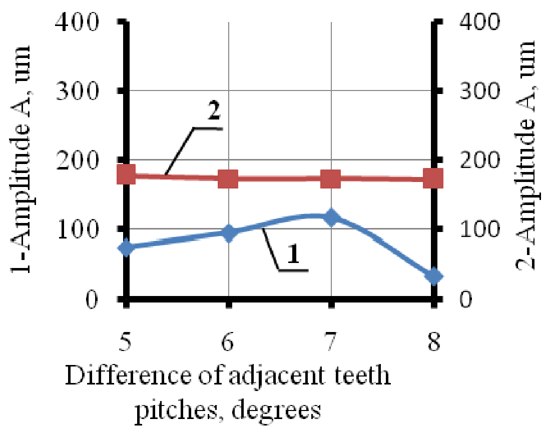

Figure 8. Effect of the linear rising angle difference of adjacent teeth pitches on chatter amplitude A (1) and frequency f (2) for a low-rigidity workpiece in a feed direction

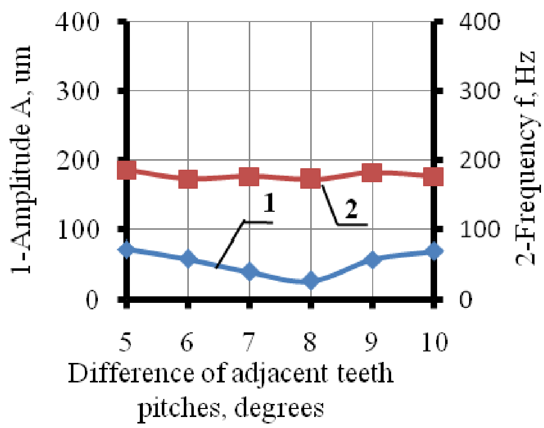

Figure 9. Effect of the linear rising-falling angle difference of adjacent teeth pitches on chatter amplitude A (1) and frequency f (2) for a low-rigidity workpiece in a feed direction

which causes chatter, i.e. the system should not adjust to oscillations of the mark and chatter increase up to 352 um. As can be seen from Figure 4, when the teeth pitch difference is alternate, the absolute damping of oscillations and decrease in their amplitude 29 times occur. It can be explained as follows. When the teeth pitch difference is a half wavelength which is about 8°, the oscillations of adjacent teeth occur in an opposite phase which is impossible due to their position on the common body. Besides, initial phase shifts have values which are close to 0 and 0.5. In fact, the distance between teeth 1 and 2 is 49.087+4.318=53.405 mm, and the distance between teeth 2 and 3 is 49.087-4,318=44.769 mm. The number of oscillation waves between teeth 1 and 2 is n=53.405/17.271=3.09. The number of waves between teeth 2 and 3 is n=44.769/17.271=2.59.

When the angle difference of neighbor pitches is 16°, which corresponds to the length of one oscillation wave, chatter have to increase. However, as can be seen from Figure 4, chatter are damped away. It is due to the initial phase shift value. The distance between teeth 1 and 2 is 49.087+4.318×2=57.723 mm, the distance between teeth 2 and 3 is 49.087-4.310×2=40.451 mm. The number of chatter waves between teeth 1 and 2 is n=57.723/17.271=3.34, and between teeth 2 and 3 – n=40.451/17.271=2.34.

The fractional remainder 0.34 is close to 0.25 (initial phase shift is +90°) which causes chatter damping. Besides, the non-synchronism of transient processes of the adjacent teeth contributes to chatter damping. With other teeth pitch differences, chatter damping can be caused by the collective effect of the above-described factors. To use multivariable teeth pitch mills, chatter waves can be measured along the cutting surface, and the angle teeth pitch difference should be a half wavelength.

4. Conclusions

Multivariable teeth pitch mills can be used to damp regenerative chatter during the face milling of non-rigid workpieces. These tools are efficient due to alternate teeth pitch variations. Besides, as compared to linear variations, they do not increase a disbalance of the rotation tool and do not strengthen forced oscillations of the technological system which has a positive effect on the accuracy of part machining. For industrial application of these tools, special mills with an adjustable teeth position should be developed. The development described in [21] is the first experience in this direction.

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