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STUDY OF NON-STATIONARY CUTTING PROCESSES IN POWER SKIVING

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Abstract. The paper presents the results of the modelling and study of the cutting process in the cut-in phase during the machining of external gears by the power skiving. The studies were carried out on the basis of the previously developed graphical model of the cut layers and the model of the cutting force as a function of the chip cross-sectional area, the shear strength limit of the workpiece material, and the intensity of plastic deformation during cutting. The regularities of the cutting force in the cut-in phase of gear machining are shown for successive tool revolutions in four passes with a gradual increase in the depth of cut. It is shown that the peak values of the cutting force at the contact between the front face of the cutter and the face plane are two times higher than under the conditions of steady stationary cutting in a preformed gap. At the same time, the amplitude of the cutting force and its average value over the cut-in passes are 1.7–3.7 times and 1.2–1.5 times higher, respectively, than the corresponding values of these parameters for steady state cutting. It is these peak jumps in the cutting force that limit the maximum depth of the cut, number of passes, and axial feed. Based on the data obtained, recommendations were developed to modify the traditional gear cutting scheme in power skiving. It is proposed to use short tool strokes with a low cutting depth along the length of the cut-in path and, after forming a gap in this area, to cut at a full depth to the full height of the gear rim. The possibility of a significant reduction of gear machining time using the proposed scheme of technological operation is demonstrated.

Keywords: External gear, power skiving process, cutting force, simulation, cutting, cut-in phase, single-tooth cutting, continuous multi-tooth cutting, force peak, time reduction.

1. INTRODUCTION

In recent years, power skiving, formerly known as gear turning, has become increasingly common in the manufacture of gears. The expansion of this process to external gears and large module gears is due to its significant advantages over traditional gear cutting methods, such as hobbing and gear shaping. The main advantages of power skiving are high cutting speed, short auxiliary changeover times, high productivity, and gear quality. This is made possible by advances in machine design with increased power, rigidity, and vibration resistance, and precise synchronisation of working movements due to CNC system controlled drives. The widespread use of this technology has also been made possible by a large number of scientific studies of the processes and phenomena that accompany cutting and shaping and influence the technical and economic parameters of gear machining. At the same time, despite a considerable number of well-known publications on the subject, there are a number of problems that require an in-depth analysis and solutions in order to improve the technology of this method. One of these problems is the peculiarities of cutting with a pinion cutter at the cut-in stage. This stage of gear formation, which is a non-stationary process with high shock loads, is currently ignored.

Considering the rapid development of the power skiving, the crucial issue is to solve the problems encountered in its practical application. Based on this situation, the task is to investigate the cutting in the cut-in phase of the power skiving method when cutting external gears and to propose recommendations for the selection of its rational operating parameters.

In the well-known studies of the power skiving process, an increased attention has been paid to the study and analysis of force factors, since cutting by this method is accompanied by the occurrence of significant forces. The cutting force and its components affect the accuracy and productivity of machining, tool wear, and the choice of operating modes, in particular, the axial feed, the depth of cutting, and the number of passes. An analysis of current literature on the subject shows that researchers use simplified approaches to describe cutting patterns, chip formation, shaping and the modelling of cutting forces.

Much of the research is based on an experimental analysis of certain indicators and parameters that complement theoretical models and calculations, which limits the scope of the results obtained. A number of studies use a static parameter, the specific cutting force, which does not meet the requirements for an accurate prediction of the cutting force. Some works use a partial parameter, the thickness of the cuts,

(a). Tool with straight teeth. (b). Tool with helical teeth.

Figure 1. “Super Skiving Cutter” [1].

to estimate the cutting force, which does not give a complete picture of the load on the blade.

In particular, in [2], the cutting force is described on the basis of its average values obtained by measurements, and the refinement of this force as a function of chip thickness and the cutter front angle is proposed on the basis of appropriate coefficients. This approach does not provide the necessary flexibility when studying the cutting force, which is a function of many initial data and machining conditions.

In [3], the chip parameters in the power skiving method are derived by considering the position of the front surface of the tool tooth during successive transitions with a change in the depth of the cut, but it is not described how the change in these parameters is taken into account during the continuous rotation of the cutter with the workpiece.

In a number of works, in particular [4–7], the cutting force in the power skiving process is presented as a function of chip thickness only. At the same time, although chip thickness is an important cutting parameter, it only determines the intensity of deformation of the allowance when it is converted into chips. However, an additional and more complete cutting parameter is the chip cross section, which ultimately determines the cutting force. Therefore, this approach to calculating the cutting force is limited and does not provide a complete picture of this parameter.

In [2–4], the cutting force is considered on the basis of the specific cutting force and a number of coefficients are used to refine the calculated cutting force. However, it is known that the specific cutting force is a function of the chip thickness ratio, the value of which is not constant and varies according to the cutting conditions, namely the thickness of the cut. Since in power skiving, the thickness of the cut varies with the angle of rotation of the tool tooth, the calculation of the cutting force based on the specific force is only an approximation and an estimate.

A similar approach to modelling the parameters of the cuts is presented in [8]. From the analysis of the graphs of the cross-sectional area and thickness of the cuts in this paper, obtained on the basis of the above approach, it follows that the maximum parameters of the cuts and the cutting work fall on the centroid position of the tooth on the centre line, but this is not true, as can be seen from the footage of high-frequency filming of the chip formation process in power skiving [9].

A similar solution to the problem of modelling the power skiving method by combining calculations of cutting parameters and cutting forces with experimental results is proposed by the authors of [5], where the components of the cutting force in gear turning are calculated on the basis of experimental coefficients linked to the cutting parameters. Again, a major drawback of such methods is that the research results are strictly linked to the conditions under which the experimental studies were carried out.

Common to most of the articles discussed above is that errors are made in the approach to describing the kinematics when modelling sheared layers and calculating their parameters. Most authors identify or accept the kinematics of hobbing as close to power skiving. This is the case in [2–5, 8, 10–12].

In both cases, the axes of intersection of the tool and the workpiece when machining spur gears are 20°–25°, but the angle between the perpendicular to the tooth face and the cutting speed vector is 20°–25° for the hob and 65°–70° for the pinion skiving cutter. As a result, the contact angle of the tool tooth with the workpiece, within which the tool rotates and cuts, is within 20°...25° (i.e. less than 30°) for the hob and −30°...+30° for the skiving cutter and it can be within 90° when cutting internal gears. Obviously, the results of modelling chips and other parameters of the rover skiving process will not correspond to the real values in this case.

2. Materials and methods

The solution to a similar problem to that presented in this article is given in [1], where the design of the “Super Skiving Cutters” was developed (Figure 1). Let’s analyse how the design of the two tools affects their ability to work.

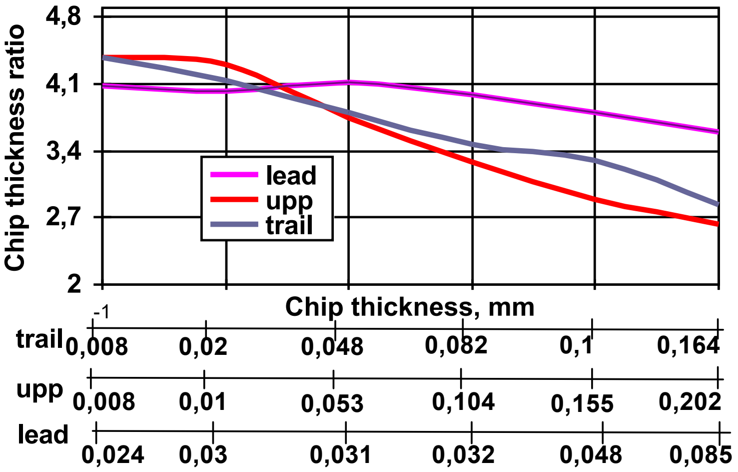


FIGURE 2. Dependence of the chip thickness ratio on the thickness of the cut on the tool blades.

The first cutter (Figure 1a) increases in tooth height along its length, corresponding to a gradual increase in the depth of the cut, but the circumferential pitch remains unchanged. This means that the same gaps are machined at all stages of the cut-in, but with a low depth of cut and wide width of the cut at the initial cutting time. In other words, the cut is accompanied by shock loads throughout the cut-in stage and it is not possible to eliminate the unevenness of the cut completely.

The tool in Figure 1b also has the same number of teeth from the base to the top, but the circumferential pitch, i.e. the modulus, is different at different levels of the cutter. This means that the number of teeth that the tool starts to cut is not the same as the number of teeth that need to be formed and that will be formed at the end of the cut-in stage.

To develop and justify a cutting scheme that would allow us to improve the power skiving process, we will use the approach described in [13] and [14]. The study of cutting forces in power skiving is based on the original method developed for hobbing [13]. The methodology for analysing the cutting force and its components is described in [14].

On the basis of these approaches, we consider the peculiarities of the formation of the cutting force during the cut-in phase in multi-pass cut-in by the power skiving method of a gear with different cutting depths. Initial data: involute spur gear; module 2.5 mm; number of teeth: 33 gears, 24 cutters; gear ratio in the tool-gear mesh 1.38; axial feed 0.75 mm rev^{-1}; cutting speed 190 m min^{-1}; number of passes four; depth of cut per pass: 0.5 m, 1 m, 1.5 m and 2 m; outer diameter of the cutter 66 mm; gear height 22 mm; cutter tooth angle and axis crossing angle 25°; cutter insert material – hard titanium-tantalum alloy; coefficient of friction on the face at a given cutting speed is 0.63.

The engagement zone of the tool with the gear workpiece is divided into 13 successive angular positions, marked -6, -5,...0, +1, +2,...+6, with the zero position coinciding with the centre line.

3. RESULTS AND DISCUSSION

According to the methodology of modelling and calculation of cutting force in gear turning [3], the main component of the cutting force P_o, which coincides with the direction of the axial feed and the vector of plastic deformation during cutting and cutting speed determined; this cutting force is represented by the following dependence: titanium-tantalum alloy; coefficient of friction on the front surface for a given cutting speed is 0.63:

$$P_o = [\tau] \cdot S \cdot \xi, \quad H, \tag{1}$$

where

S is the cross-sectional area of the chip [mm^2],

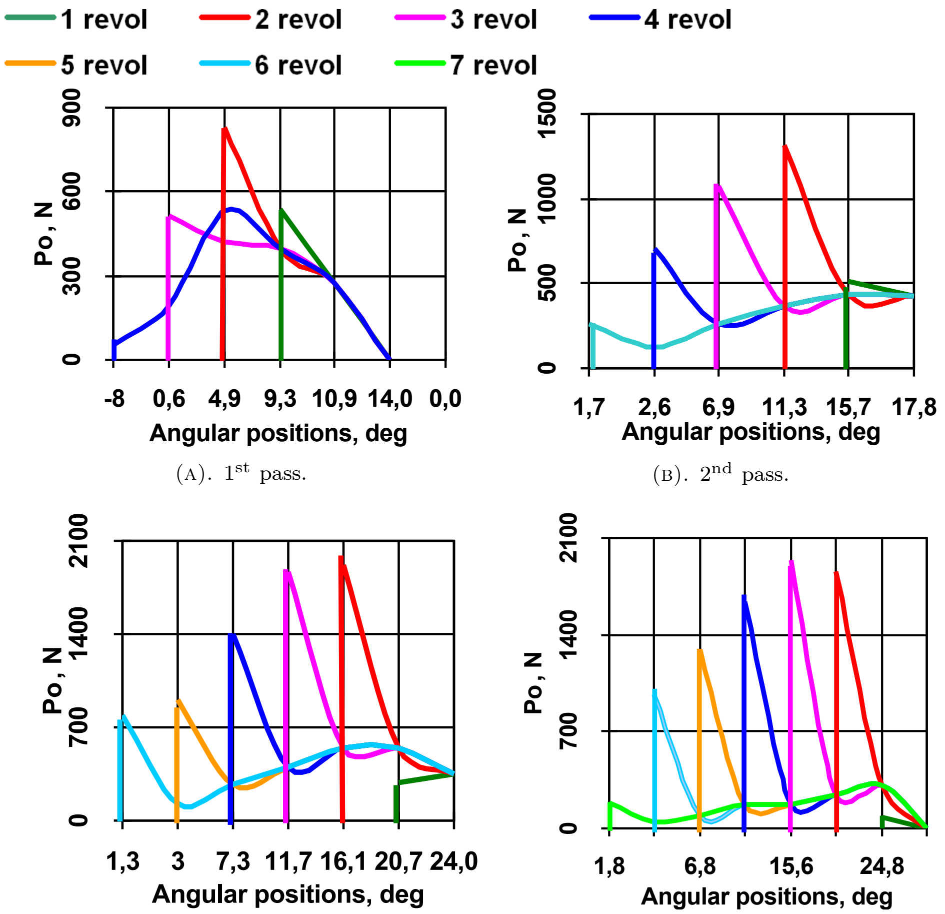
$[\tau]$ is the shear strength limit of the workpiece material [MPa],

ξ is the chip thickness ratio or chip compression ratio.

The value of the chip thickness ratio as a function of the thickness of the cuts for each material of the workpiece and tool has been determined using the Deform 2D system [15]. The graphs of this parameter on the cutter blades for the conditions corresponding to this article when cutting to the full height of the profile are shown in Figure 2.

The product $[\tau] \cdot \xi$ in Equation (1) characterises the specific cutting force, which is a variable value and has different values even for individual blades when cutting with one tooth. This confirms the above hypothesis that using the specific force to calculate the cutting force on the basis of its specific average value leads to significant errors.

The cut-in phase is a special step in the process of forming a tooth surface. At the moment of first contact, the tool tooth makes contact with the face of the workpiece. After cutting within a certain contact angle, the first contours of the gap are formed as the tool rotates and moves in the axial feed. Cutting in this recess continues after this tooth is rotated



(a). 1st pass.

(b). 2nd pass.

(c). 3rd pass.

(d). 4th pass.

Figure 3. P_o force when cutting in a gap with successive tool revolutions in different passes.

to an angle of 360° and the tool is moved in the axial feed by $f \cdot i$, where i is the tool-work meshing ratio and f is the axial feed rate. The number of tool revolutions before the final gap is formed and the start of stationary cutting in this gap for certain initial conditions (modulus and number of teeth of the gear and tool), depends on the depth of the cut and the angle of intersection of the axes.

The transition from the cut-in stage to the stationary cutting stage is accompanied by a decrease in shock loads, but the cutting force fluctuates due to the unevenness of the cross-sectional parameters of the cuts – variable area and thickness, as well as a variable value of the chip thickness ratio. During steady-state cutting, the tooth operates within the formed transition surface and the patterns of chip parameters and cutting force changes are repeated cyclically with each cut.

It has been found that for the initial data of this article, the above-mentioned cut-in stages are characterised by the following: the number of cut-in revolutions on the passes is 1–4; 2–5; 3–6; 4–7, respectively; the angles of contact between the tool and the workpiece in the gear face 1–14°; 2–21.7°; 3–25.4°; 4–26.8°, respectively; the coefficient of end overlap in passes is: 1–0.78; 2–1.45; 3–1.7; 4–1.91, respectively.

The patterns of change in P_o force when cut-in into a gap at successive tool revolutions in the passes are shown in Figure 3.

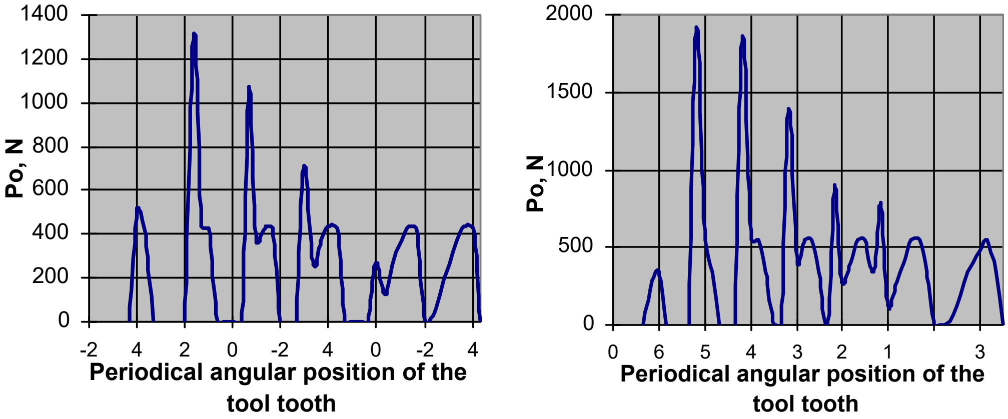
The Figure 4 shows graphs of the change in the P_o force acting in one gap over the cutting time during the second and third passes.

The graphs in Figures 4–6 show the single tooth cutting forces when modelling the process of machining with one tool tooth in one gap. Figures 5a, and 6a show graphs of the total P_o force as a multi-tooth cutting force at the second revolution during the second (Figure 5a) and third (Figure 5b) passes. These graphs represent the actual gear cutting conditions according to the face overlap coefficients.

As can be seen from the graph (Figures 5 and 6), the cutting force is highest at these steps of the cut-in.

For comparison, Figures 5b and 6b show the forces on the same passes under steady state cutting, after the gap machining has been completed.

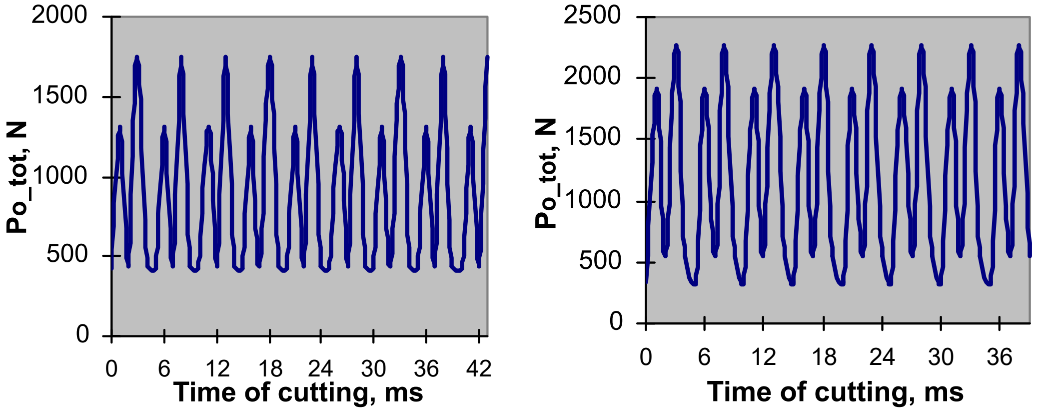
The results of the study indicate the following features of the cutting process at the cut-in stage. In the first few revolutions of the cutter during the cut-in stages, the tool tooth is subjected to intense impacts at the moment of contact with the plane of the gear face and the cutting force increases abruptly. In all passes, the force peak occurs at the



(a). 2nd pass.

(b). 3rd pass.

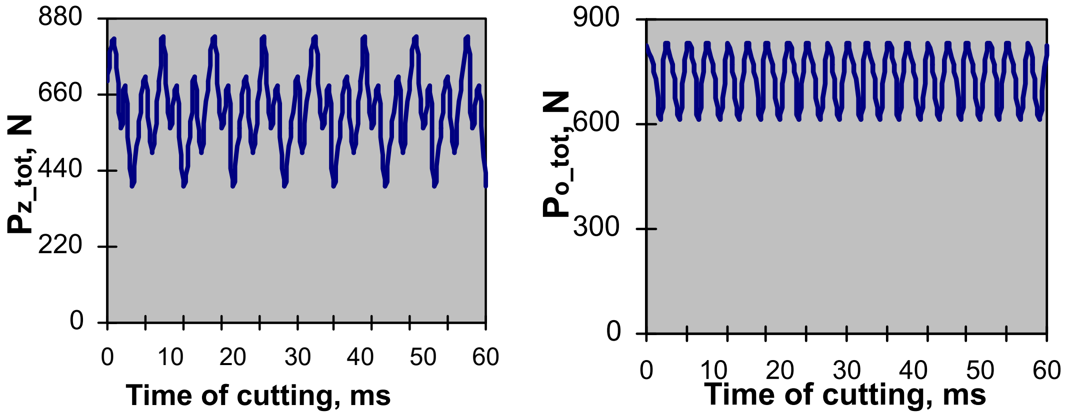
Figure 4. Graphs of the change in P_o force acting in a single gap during the second and third cut-in passes.



(a). 2nd pass.

(b). 3rd pass.

Figure 5. Graphs of the evolution of the force P_o during cutting: force at the cut-in stage during the second revolution.



(a). 2nd pass.

(b). 3rd pass.

Figure 6. Graphs of the evolution of the force P_o at the steady cutting stage during the third revolution.

second revolution of the cut-in and is 828 N in the first pass, 1 313 N in the second pass, 1 862 N in the third pass, and 1 935 N in the fourth pass. It is these conditions of impact cutting and significant dynamic loads on the elastic system of the machine tool, which are peak in nature, that limit the depth of cut, the minimum number of passes, and the axial feed rate in power skiving.

The force of total (multi-tooth) continuous cutting has a harmonic character with a large amplitude fluctuation and a significant average (quasi-static) value. Thus, the maximum range (double amplitude) of the axial force P_x (P_o) is 874 N for the second pass and 1 922 N for the third pass. Accordingly, the average values of this force on these passes are 1 087 N and 1 305 N, respectively.

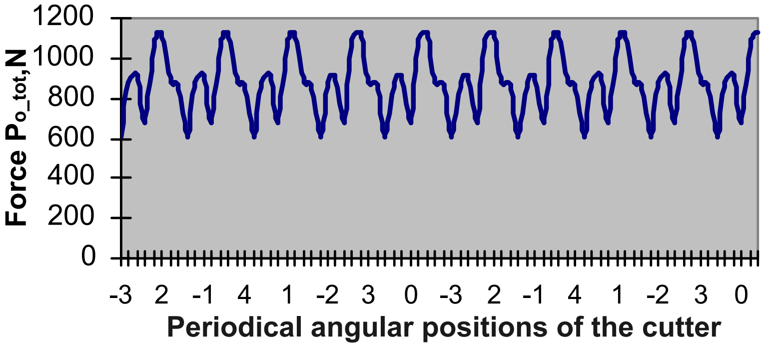


Figure 7. Continuous stationary total cutting force when cutting a gear to the full height of profile.

Figure 7 shows a graph of the total force for continuous cutting to full depth in one pass for the initial data used in this article. As can be seen, the maximum single-pass cutting force at the stationary cutting stage (1 132 N) is 1.53 and 2 times less than the peak values of this force at the cut-in stages on the second revolution of the second and third passes, respectively. If we compare the maximum harmonic forces for the cut-in stage with the harmonic forces in the process of steady (conditionally stationary) cutting in the formed gap after the cut-in stage, we can see that the average value of this force (882 N) decreases by 1.23–1.5 times and its range (527 N) by 1.7–3.65 times.

Based on the results obtained, the following is a way to improve the efficiency of the power skiving process. For the majority of gears produced in series, the cutting path is much smaller than the height of the rim. In our case, this path is 7.5 mm with a gear height of 22 mm. In order to significantly reduce the shock loads on the tool and machine, it is necessary to significantly increase the number of passes, i.e. to reduce the depth of the cut on each pass, but only at the stage of cut-in, i.e. at a length of 7.5 mm. Once the gap is complete, it is often possible to continue cutting the remaining gear height to the full depth in one pass. If necessary, two or three passes can be used if the force is too high. Efficiency can be increased by machining a batch of several workpieces.

Using this example, you can calculate the reduction in the machining time for a gear cutting operation according to the above recommendations. Let's assume that the number of passes in the cut is 10 and that the depth of the cut increases by 0.1 m on each pass, i.e. 0.25 mm. At a cutting speed of 190 m min^{-1}, the tool speed is 1 074 rpm, the time for one pass at the cut-in is 0.8 s and the time for ten cut-in passes is 8 s. The total cutting path of a set of five gears will be 110 mm and the time for cutting five gears to the full depth of the profile after the cut-in phase will be 0.15 min, i.e. 8.5 s. The total time for cutting five gears will be 16.5 seconds.

If five gears are cut using the traditional scheme of 10 consecutive cuts at a depth of 0.1 m, the time required is 85 s. The reduction in machining time for five gears is 68 seconds, i.e. 1.13 minutes. If the set of parts to be put into production is 200 gears, the total reduction time of the operation according to the proposed methode will be 45 minutes.

4. Conclusion

(1.) The cut-in phase of the gear cutting process differs significantly from the sustained phase of power skiving. During the first few revolutions of the cutter during the cut-in phase, the tool tooth is subjected to intense impacts at the moment of contact with the face of the gear and the cutting force increases abruptly. For all passes, the force peaks during the second tool revolution and the peak force is many times greater than the steady state cutting force. This type of load on the machine and tool has a negative effect on their condition, reduces their life, and worsens the quality of machining.

(2.) Due to the shock loads at the cut-in stage, cutting conditions are limited to reduce their negative impact on the process efficiency: cutting depth, minimum number of passes, and axial feed.

(3.) The considered variant of the cutter design, which is intended to ensure that overloading is avoided at the cut-in stage, will not have a significant effect on the reduction of dynamic loads, and the other cutter design variant changes the transmission ratio in the machine tool-gear meshing during cutting and is unworkable.

(4.) In order to reduce the effect of instability at the cut-in stage, it is proposed to modify the gear cutting operation. Instead of several passes along the full length of the gear with a gradual increase in the depth of cut, it is proposed to make several short passes along the length of the cut-in and, after forming a short gaps and reaching a steady state, to make one pass along the full height of the gear. This solution can result in significant time and cost savings.

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