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# Influence of Design and Cutting Conditions on the Accuracy of the Hole Obtained by Drills with Multifaceted Non-Regrind-Able Inserts (MNP)

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**Abstract:** Drills with MNPs have a fundamental design difference from spiral drills, expressed in increased rigidity of the body, a change in geometry and the absence of a wide gauging part. In this article, taking into account the kinematic cutting angles and the real design of the tool, recommendations are given for determining the maximum allowable feed. The shape of the machined hole is proved to a large extent by the ratio of the angular velocities of the precession of the drill axis and its own frequency of rotation.

**Keywords:** Axial tool, deflection, rigidity, gyroscopic moment, twist drills

## 1. Introduction

Currently, the industry is increasingly using new designs of drills with mechanical fastening of multifaceted non-regrind-able inserts, which makes it possible to increase the productivity of machining from 5 to 10 times compared to high-speed drills [1-4]. Compared to conventional twist drills and deep hole drills, they machine a hole that is usually shallow (up to 2 diameters). However, one of their advantages is that they do not require centering and pre-drilling when making holes, even when drilling on beveled planes [5, 6]. Compared to twist drills, MRT (Polygonal Non-regrindable Inserts) drills do not have guides and only the cutting inserts are in contact with the material being machined. The introduction of statistical quality and reliability control methods should be wider than at present and be based on express estimates of the quality parameters of metal-cutting tools using computer technology, the software of which provides the calculation of rational tool designs and their operating conditions using simulation models of technological operations [7, 8]. However, accelerated tests under production conditions are often carried out not to determine reliability indicators, but for a quick comparative analysis of various designs and technologies without setting the task of optimization in terms of technical and economic parameters. Therefore, the development of a selection methodology and justification of the numerical values of the normalized reliability indicators for specific production conditions for the operation of a metal-cutting tool is an important multifactorial problem that requires a large amount of information about the expected operating conditions for its solution [9-12].

## 2. Methods

The software will allow the development of simulation models of technological drilling operations to obtain technical and economic parameters and rational operating conditions for machining tools with a given level of reliability at the design stage of the technological process with a small amount of experimental data. During the actual machining process, the axial cutting tool realizes the movement of the workpiece. The relative additional movements associated with cutting movements are important in defining the error in machining holes. The difference between the

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actual rotation axis of the tool and the rotation axis provided by the machine tool spindle represents the precession, while the deviation of the actual diameter of the hole represents the length subdivision of the feature. The crack can be identified by the effect of feed on the tool axis and the natural vibrations of the tool around its axis. If we take the value of the hole stakeout as a double deviation of the radius vector in the polar coordinate system, then its relationship with the precession value and the natural vibration of the tool will be expressed as follows.

$$\Delta / 2 = \bar{\eta} \cdot (\overline{e_0} + \overline{e_n}) \quad (1)$$

or

$$\Delta / 2 = e_0 \cdot \cos\varphi_0 + e_n \cdot \cos\varphi_n \quad (2)$$

where: $\bar{\eta}$ - unit radius vector directed from the axis of rotation of the spindle to the side face of the cutting tool blade;

$\overline{e_0}$ - drill deviation vector relative to its own rotational axis;

$\overline{e_n}$ - is the precession vector of the drill rotation axis relative to the spindle rotation axis;

$\varphi_0$, $\varphi_n$ are the corresponding angles between $e_0$, $e_n$, and $\bar{\eta}$.

In Figure 1, a diagram of the operating deviation vectors is presented. The unit vector $\bar{\eta}$, directed from the axis of rotation to the side top of the cutting blade, determines the position of the front surface. It can be seen from the diagram that the value of the breakdown is influenced not so much by the absolute values of the deviation vectors as by their projections on the direction parallel to the front surface. In this case, in the case of their orthogonal arrangement relative to n, the breakdown will reach a minimum.

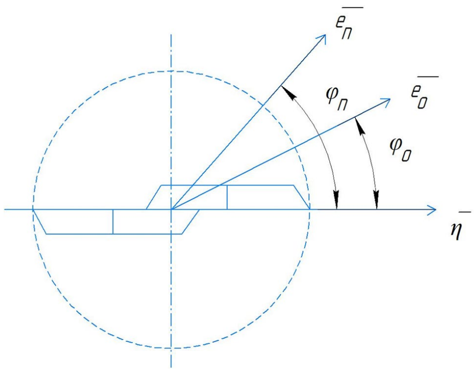


**Fig. 1 - Scheme of deviation vectors during drilling**

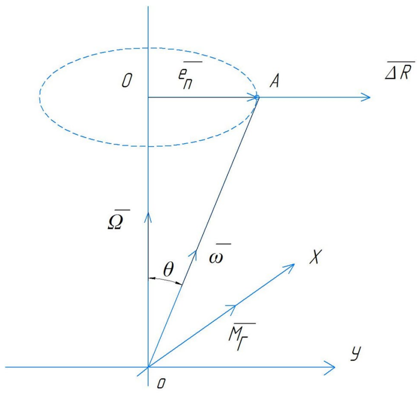


**Fig. 2 - Scheme of angular velocities during drilling operation**

The main cause of precession is the imbalance of cutting forces in the radial direction. Neglecting random perturbations, the main factors leading to the appearance of an unbalanced force include the error of the angles in the plan, the asymmetry of the location of the cutting edges, the sharpening error, etc [13]. The amount of precession is determined by the value of the unbalanced radial load and the rigidity of the axial tool. At low angular velocities, the precession takes the following view,

$$e_n = \frac{\Delta R}{j} \quad (3)$$

Where, ΔR- is the unbalanced radial component;
j - is the rigidity of the tool.
At high angular velocities, a significant influence is exerted by the gyroscopic moment, the value of which is as follows,

$$M_g = J_0 \omega_0 \cdot \frac{\partial \theta}{\partial \tau} = J_0 \cdot \omega_0 \cdot \Omega \quad (4)$$

Where $J_0$ – is the inertial moment of the drill;
$\omega_0$ - angular velocity of the tool;
Ω - the angular velocity of precession.
In this case, the gyroscopic moment is defined as the vector product of the angular velocities of rotation of the body and precession, and the inertial moment plays the role of a constant coefficient determined by the weight and geometric shape of the tool body. The direction of the gyroscopic moment is perpendicular to the plane of the location of the vectors and $\overline{\Omega}$, i.e., with the arrangement according to (Fig. 2), the gyroscopic moment is directed along the *x*-axis (in the diagram $M_g$). Representing in the first approximation the elastic line of deformation of the body of the drill in the form of a straight-line OA, the precession value can be determined as follows,

$$e_n = OA \cdot \sin\theta \quad (5)$$

$$\Omega = -\frac{1}{J_0 \cdot \omega_0} \cdot \overline{OA} \cdot \overline{\Delta R} \quad (6)$$

Dependence equation (6) shows that with an increase in the moment of inertia of the drill body and the rotational speed of the tool, the angular velocity of the precession decreases.

## 3. Results and discussions

Studies have shown that the rigidity [11, 13] of the drilling tool with MNP exceeds the helical one by almost four times (measurements were carried out on drills who's the diameter of Ø22 mm with a working part length of 60 mm, when loaded with a radial force of 85 kg) vector product.

$$\left|\overline{OA} \cdot \overline{\Delta R}\right| = 2 \cdot OA \cdot \Delta R \cdot \sin\theta \quad (7)$$

Taking into account (5), expression (6) takes the following form,

$$\left|\overline{\Omega}\right| = \frac{2}{J_0 \cdot \omega_0} \cdot e_n \cdot \Delta R \quad (8)$$

Taking into account (8), we finally obtain the following equation,

$$\left|\overline{\Omega}\right| = \frac{2}{J_0 \cdot \omega_0} \cdot e_n \cdot \Delta R = \frac{2 \cdot \Delta R^2}{J_0 \cdot \omega_0 \cdot j} \quad (9)$$

From (9), it can be seen that with an increase in the rigidity of the drilling tool body [15], the angular velocity of precession decreases. Analytical determination of the angular velocity of the drilling tool precession presents certain difficulties associated with the complex profile of the section of the tool body, which makes it difficult to accurately calculate $J_0$. Therefore, using the known relations from [16], we determine the ratio of the angular velocities of the recessions of a twist drill and a drill with MNP.

$$\frac{\Omega_{SPIR}}{\Omega_{SPIR}} \approx 3.216 \qquad (10)$$

A twist drill has a higher precession angular velocity and, as a result, a larger deviation, and given that the drill with MNP is operated at higher rotational speeds, the ratio of precession angular velocities according to (10) should increase even more.

An important factor determining the accuracy of the machined hole and, in particular, the form error, is the ratio of the angular velocity of the precession and the rotational speed of the tool itself. The machined hole is formed as a trajectory of movement of the peripheral cutting edge, which moves along the arc of a circle $\overline{R_u}$ relative to the axis of rotation of the tool. In this case, the drill axis itself moves along the hodograph of the radius precession vector $\overline{e_n}$ representing a closed curve. Consider the case when the precession radius vector describes a circle with radius $e_n$ with an angular velocity Ω, and the tool itself rotates with an angular velocity ω since there are cases when ω>Ω, ω<Ω, and ω=Ω. At the initial moment of time, the radius vector of the precession coincides with the vector n, i.e., it is directed along the end cutting edge (Fig. 3). After some time, the drill axis will shift from the initial position $E_1$ to $E_2$ determined by the rotation angle Ω·t, and the cutting edge itself will rotate relative to the initial position by the angle ω·t and take position $A_2$, while the machined surface will be described by a curve $A_1A_2$. The opposite cutting edge will move from point $A'_1$ to $A'_2$ and the machined surface will be described by the arc $A'_1A'_2$. Point radius $A_2$.

$$R_0 = (e_n^2 + R_n^2 + 2 \cdot e_n \cdot R_u \cdot \cos(\Omega - \omega)t)^{\frac{1}{2}} \qquad (11)$$

and points $A'_2$

$$R_0^* = (e_n^2 + R_u^2 + 2 \cdot e_n \cdot R_u \cdot \cos(\Omega - \omega)t)^{\frac{1}{2}} \qquad (12)$$

Given that,

$$e_n^2 \langle\langle R_u^2 \quad \text{or} \quad e_n^2 \langle\langle R_0^2$$

Expressions (11), (12) and (13) can be represented in as follows,

$$R_0 \approx (e_n^2 + R_n^2 - 2 \cdot e_n \cdot R_u \cdot \cos(\Omega - \omega)t)^{\frac{1}{2}}$$

$$R_0^* \approx (e_n^2 + R_u^2 + 2 \cdot e_n \cdot R_u \cdot \cos(\Omega - \omega)t)^{\frac{1}{2}} \qquad (13)$$

In this case, the radii of the points $A_2$ and $A'_2$ do not lie on the same diametral chord. Therefore, the length of the diametrical chord, for example $K_1K'_1$ will be different from twice the tool radius. The final size of the machined hole is formed by the largest radius $R_0$ or $R^*_0$, the numerical value of which will be determined by the value ω·t, and the position of this radius ω·t and Ω·t. At ω·t "Ω·t, the machined hole is formed as an envelope of circles with a radius $R''_u$, the center of which moves along an arc with a radius $e_n$. The shape of the hole will be strictly cylindrical with the radius.

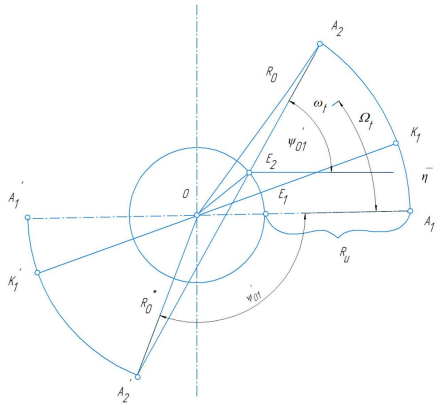

**Fig. 3 - To determine the shape error of the machined hole**

$$R_0 = e_n + R_u \tag{14}$$

When Ω=ω, the relative position of the vector η and the vector $e_n$, remains unchanged, while the hole will also have a strictly cylindrical shape with a radius,

$$\overline{R_0} = \overline{e_n} + \overline{R_u} \tag{15}$$

For any other arbitrary ratio of ω and Ω, the representation of the machined surface as an envelope of the sequential position of circular arcs with radius $R_u$" becomes invalid and can only be described by the equations system (14). The trajectory of the movement of the cutting blades of the drilling tool in cross-section will always represent an unfinished contour with a maximum shape error. The trajectories of the cutting edge for various ratios of ω and Ω are shown in (Fig. 4 and Fig. 5). Considering that the angular precession rate when working with MNP drills is lower than that of twist drills, and the tool rotation frequency is usually higher, one should expect a higher hole accuracy when working with such a tool. When working with an axial tool with asymmetric cutting edges, a negative breakdown of the hole is sometimes observed, i.e. the diameter of the hole in some sections is less than the diameter of the tool, which is not observed when using twist drills. The considered mechanism for the formation of the error in the shape of the machined hole when operating a tool with a symmetrical two-tooth arrangement of cutting blades shows the possibility of a negative breakdown at ω=Ω and an "incomplete" contour.

Due to the axial movement of the tool, the cutting edge makes a helical movement. Consequently, the point of the cutting edge, located at the initial time in $A_1$ (Fig. 3), after one complete revolution of the tool will not return to its previous position but will shift along the axis by the amount of feed rate. In addition, given the presence of the angular velocity of the precession, this point will also have a shift in the radial direction. With a constant ratio of the angular velocities of the precession and the rotational speed of the tool, after each revolution of the tool, the displacement will increase proportionally.

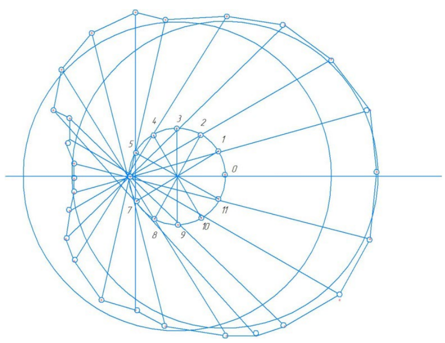


**Fig. 4 - Typical trajectory of movement of the periphery of the cutting-edge drill ω>Ω**

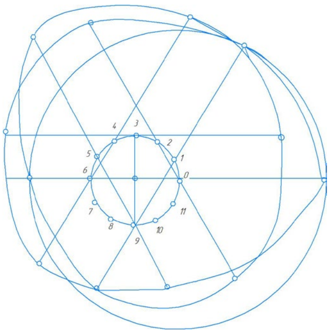

**Fig. 5 - Typical trajectory of movement of the periphery of the cutting edge of the drill ω<Ω**

If at the initial moment the breakdown value is determined according to equation (2), it takes a following form,

$$\frac{\Delta}{2} = e_0 \cdot \cos\varphi_0 + e_n \cdot \cos\varphi_n = e_0 + e_n \qquad (15)$$

Then after one revolution, it becomes equal to following expression,

$$\frac{\Delta}{2} = e_0 \cdot \cos(2\pi o + e_n \cdot \frac{\cos 2\pi o}{\omega}) \qquad (16)$$

Then the value of the radial displacement is determined as follows,

$$\Delta_{rad} = -e_n \cdot [1 - \cos(\frac{2\pi\pi}{\omega})] \qquad (17)$$

and the value of the tangential displacement will be equal to following,

$$\Delta_{tan} = e_n \cdot \sin(\frac{2\pi\pi}{\omega}) \qquad (18)$$

Thus, one of the reasons for the appearance of a negative breakdown is, in our opinion, the result of the combined influence of the precession of the rotation axis and the deviation of the tool itself relative to its own axis. So, according to expression (2), the conditions for the appearance of a negative breakdown can be determined as follows,

$$e_0 \cdot \cos\varphi_0 + e_n \cdot \cos\varphi_n \langle 0 \qquad (19)$$

Given that $\varphi_0 = \omega \cdot t, \varphi_n = \Omega \cdot t$, then we will have following,

$$e_0 \cdot \cos(\omega \cdot t) \langle -e_n \cdot \cos(\Omega \cdot t)$$

$$\cos(\Omega \cdot t) \rangle -\frac{e_0}{e_n} \cdot \cos(\omega \cdot t)$$

or finally

$$(\Omega \cdot t) \rangle \arccos[-\frac{e_0}{e_n} \cdot \cos(\omega \cdot t)] \qquad (20)$$

Therefore, the appearance of a negative breakdown is determined by the ratio of the angular velocity of the precession and the rotational speed of the drill. For $e_0=e_n$ condition (17) takes the following form,

$$\Omega \rangle \omega \qquad (21)$$

Analysis of the accuracy of the machined hole in terms of the precession of the drill axis and its own deviation of the drill axis relative to the axis of rotation is a methodological difficulty associated with the difficulty of experimentally determining the law of change of $e_0$ and $e_n$. Therefore, further analysis was carried out according to the following characteristics: the amount of drift of the drill axis as the distance between the axis of rotation of the spindle and the center of the true profile of the hole, and the size of the hole breakdown as the difference between the diametrical chord and the size of the tool. The amount of drift of the drill axis represents the total deviation of the tool axis relative to the axis of rotation of the spindle and is generally calculated by formula (1). It reflects the overall positional deviation. The breakdown value is defined as the algebraic sum is as following,

$$\Delta R = \Delta R_1 + \Delta R_2 \tag{22}$$

Where, $\Delta R_1$, and $\Delta R_2$ are the radial deviations of the hole profile in the section of the diametric chord. The cutting modes of drills with MNP differ significantly from the modes for all types of drills with jumper and guide elements. The design of drills with MNP allows machining at significantly higher cutting speeds, which, depending on the materials being worked out, lie in the range of V=1.3... 1.5 m/s, S-0.1...0.25 mm/rev. Steel 12X18H10T and steel 45 were chosen for the experiment. When machining holes, one of the important steps is the plunging process. Twist drills have a better geometry in terms of centering; however, MSP drills have advantages in terms of penetration. Indeed, a twist drill with a lead angle of 2φ=120° is characterized by the fact that initially the cutting-edge sections with zero cutting speed and a small, and sometimes negative kinematic clearance angle are determined and it falls on the jumper of the twist drill. (Fig. 6 and Fig. 7) presents data from experimental studies characterizing the effect of rotational speed on the drift of the drill axis when machining holes in workpieces from 12XI8H10T and steel 45 with a twist drill and a drill with MNP with a diameter of 24.5 mm. Analysis of the research results shows that a twist drill having 2φ=120° acquires the property of centering, processing materials of normal machinability. So, when drilling steel 45, the maximum withdrawal value for a twist drill was 0.095 mm, and for a drill with MNP - 0.08 mm, which is practically within the range of experimental data. When drilling 12X18H10T, the withdrawal value was 0.18 mm, and for a drill with MNP - 0.075 … 0.08 mm, i.e. in this case, the centering effect due to the rigidity of the tool is more significant than due to the geometry of the cutting part. Indeed, stainless steel 12X18H10T is characterized by almost 3 times worse machinability (machinability factor $k_0 = 0.3$) compared to steel 45. Therefore, the amount of drill retraction with MNP remained practically unchanged, while for a twist drill it increased by two times.

The amount of retraction of the drill with an increase in the frequency of rotation in the processing of steel 45 tends to decrease monotonically, which is more pronounced for twist drills. The processing of steel 12X18H10T with twist drills is characterized by a non-monotonic change in the amount of withdrawal, reaching a maximum in the range of 160–200 rpm. A drill with an MNP when processing 12X18H10T behaves identically to the processing of steel 45.

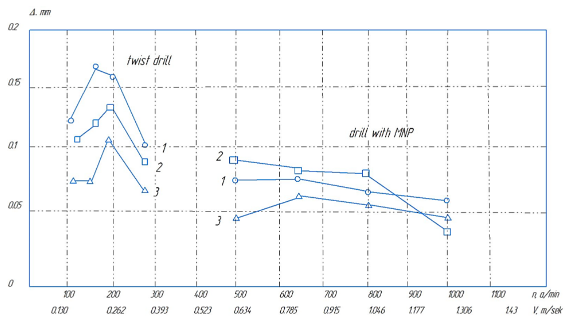


**Fig. 6 - Influence of cutting speed on the drift of the drill axis when drilling in a solid workpiece from 12X18H10T. 1 - beginning of the hole, 2 – middle of the hole, 3 – end of the hole**

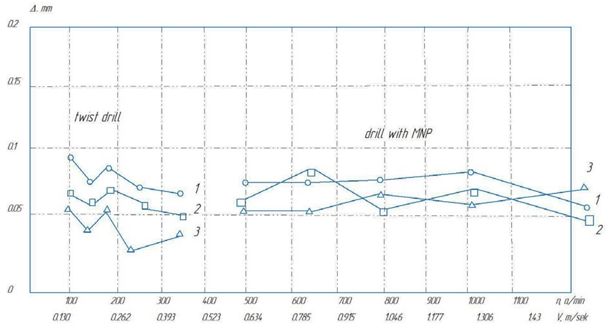


**Fig. 7 - Influence of cutting speed on the drift of the drill axis when drilling in a solid workpiece of steel 45. 1-beginning of the hole, 2-middle of the hole, 3-end of the hole**

The drift of the drill axis takes on different values along the length of the drilled hole. For twist drills, there is a phenomenon of “copying” the infeed error on the accuracy of the hole in the middle and at the exit. On (Fig. 6 and Fig. 7), it manifests itself in the fact that the nature of the drift curve of the drill axis in the middle and at the exit repeats the curve of the axis withdrawal at the entrance, only at a somewhat low level. This is explained by the fact that the initially drilled part of the hole acts as a guide bushing for the drill during its further operation. This is possible if there is a sufficiently long gauge part, which is typical for a twist drill.

## 4. Conclusions

Representation of the mechanics of the formation of the error in the shape of the machined hole from the standpoint of vector analysis made it possible to clarify the role of the precession of the drill axis in the machining accuracy and show that a drill with a MNP, which has a more rigid body and operates at a higher rotational speed compared to a twist drill, forms holes of a higher accuracy. The error in the shape of the machined hole is largely determined by the ratio of the angular velocities of the precession of the drill axis and its own frequency of rotation. Based on the theoretical analysis of the hole shaping process during drilling, the conditions are determined under which the appearance of a "negative breakdown" is possible. It is theoretically substantiated and experimentally confirmed that this condition is more often achieved when working with a non-rigid tool at low cutting speeds, typical for twist drills. One of the significant distinguishing features of a drill with MNP compared to a spiral one is the absence of a jumper, which first of all manifests itself when the tool plunges into the workpiece and exits it. It has been established that the less favorable insertion conditions of a drill with MNP compared to a twist drill are compensated, in terms of accuracy, by its more rigid body and higher rotational speed. The process of exit of the drill with MNP is characterized by smaller dynamic perturbations.

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