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The mechanisms of bell mouth formation in gundrilling when the drill rotates and the workpiece is stationary. Part I: the first stage of drill entrance

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Abstract

The reliability of the gundrilling process in the automotive industry is greatly affected by tool stability. This stability is defined as a complex issue consisting of the following sub-items: entrance, static, and dynamic stabilities. Entrance stability plays the chief role when the rotational speed and feed rate are high, which is the common case in the automotive industry where engine heads made of aluminum alloys are drilled. Entrance instability is the prime cause for the so-called ‘unpredicted’ drills’ failure, which often appears as a fatigue crack(s) on the drill shank and cannot be explained when only stable drilling is considered. This paper reveals the main design and technological factors affecting entrance stability and provides practical recommendations on the design of gundrills. This subject is covered in two parts. Part one deals with the first stage of drill entrance, which begins when the gundrill touches the face of the workpiece and ends when the gundrill’s cutting edges are fully engaged in cutting. The role of the clearance in the starting bush and the design of the gundrill’s supporting area are analyzed. © 2002 Published by Elsevier Science Ltd.

1. Introduction

The extensive use of gundrilling in manufacturing has given rise in recent years to an increasing volume of research to improve the efficiency of this process. Because of the vast scale on which gundrilling operations are carried out (for example, in the automotive industry), even a slight increase in the general level of deep-hole drill performance would yield important practical and economical benefits to individual firms and the engineering industry as a whole [1].

A gundrill (Fig. 1) consists of a drill body having a shank and a tip [2]. The tip is made up of a hard wear-resistant material such as a metallic carbide. The other end of the shank incorporates an enlarged driver having a flat surface for holding the drill. The design of the driver is machine specific. The shank is of tubular shape having a V-shaped flute on its surface. The flute terminates in an inclined crease formed adjacent to the driver. The tip is larger in diameter than the shank and also has

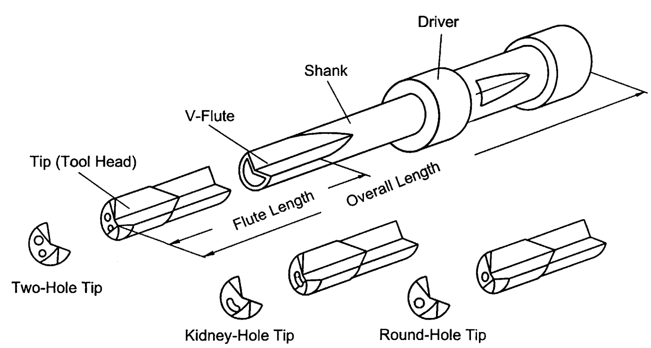

Fig. 1. Typical gundrill.

the V-flute, which is similar in shape to the flute on the shank and extends along the full length of the tip. These two flutes are longitudinally aligned. On the flank surface of the tip, an orifice as an outlet for the coolant is located. Gundrill manufacturers have adopted various shapes for this orifice: one or two circular holes or a single kidney-shaped hole.

The design and geometry of the tip’s terminal end (Fig. 2) largely determines the shape of the chips and the effectiveness of the coolant, the lubrication of the tool, and removal of the chips. The terminal end of the

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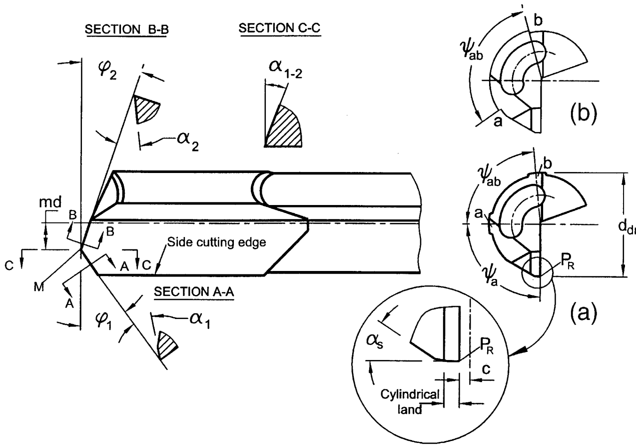

Fig. 2. Gundrill geometry.

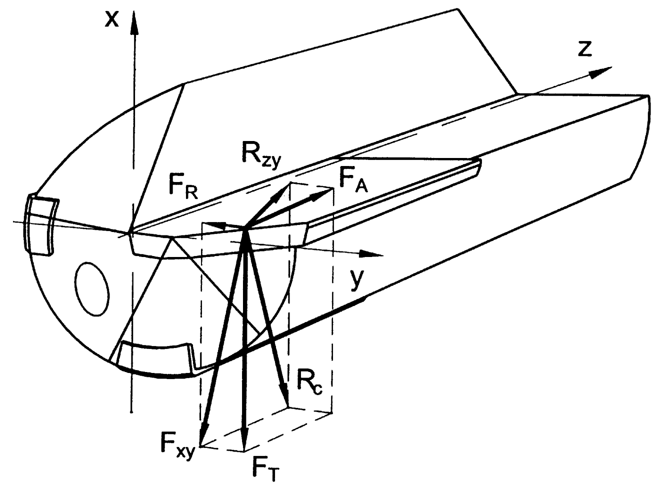

Fig. 3. The system of forces acting in gundrilling.

tip is formed of angles φ_1 and φ_2 of the outer and inner cutting edges, respectively. Normally, the outer angle, φ_1, is 30°. and the inner angle, φ_2, is 20°. A primary relief (with the normal clearance (flank) angle α_1 8–12°) is provided usually on the flank of the outer cutting edge. A secondary flank (approximately 20°) is applied to the outer cutting edge to provide space for the coolant to reach the cutting edge and to avoid the interference of this flank with the bottom of the hole being drilled. To the inner cutting edge a flank, with the normal clearance angle equal to α_2 (normally α_2 is 8–12°), is applied. To prevent interference of the rib formed by the relief surfaces, an auxiliary flank face having the normal clearance (flank) angle α_{1-2} (Section C-C) is also applied.

The rake face normally has 0° rake angle and is located below the centerline by a certain distance *c*. Point *M* (location distance *md* from the drill's longitudinal axis) divides this face into two parts, namely, the rake face of the outer and inner cutting edges. The periphery point P_R defines drill's diameter d_{dr}. The side cutting edge is formed as intersection of the rake face and circular land to which the relief (flank) face having the normal flank angle α_s is applied.

The number and location of the supporting pads a and b is optional depending on the particular use for which the drill is intended, but it is desirable to locate one of the pads (pad b) opposite to the circular land to facilitate the measurement of the diameter of the tool and to control the hole size. This is normally the case when a gundrill having two supporting pads is used (design (a) in Fig. 2). Another drill design includes the supporting continuum *ab* (design (b) in Fig. 2). The pads' forces must balance the cutting forces to ensure that the tool itself has guidance and stability.

When a gundrill works, the cutting force is generated due to the resistance of the workpiece material to cutting. This force is a 3-D vector applied at a certain point of the cutting edge as shown in Fig. 3. The cutting force R_c (or the resultant cutting force for multi-edge tools) can be resolved into three components, namely: the power (tangential) component F_T, axial component, F_A, and radial component forces, F_R, respectively. The axial force is balanced by the axial force of the feed mechanism of a deep-hole machine while the tangential and radial forces sum to create force F_{xy} (acts in the *xy*-plane) which (in contrast to other axial tools as twist drills, reamers, milling tools) generally is not balanced, regardless of the number of cutting edges used. To prevent drill bending due to this unbalanced force, some special measures should be taken. The term 'deep-hole drilling' has grown to mean that the unbalanced cutting force generated in the cutting process is balanced by the equal and opposite force due to supporting pads, which bear against the wall of the hole being drilled. As such, the deep-hole drill guides itself initially in the starting bush and then in the hole being drilled so that it can be considered as self-piloted [3–6].

The previously-discussed definition of self-piloting, however, refers to stable drilling conditions and is restricted only to the case where all forces acting on a gundrill are completely balanced. Unfortunately, these ideal conditions can hardly exist in the practice of deep-hole machining where additional forces due to a number of real world imperfections (inaccuracies in real deep-hole machining system including alignments, clearances, drill design and manufacturing inaccuracies, etc.) affect process stability.

Stability is defined as a complex issue consisting of the following sub-items: entrance, static, and dynamic stabilities. Experience shows that depending upon a particular combination of the parameters of a gundrilling system, one or another type of stability plays the chief role. Entrance stability, however, always plays an important role because it is not possible in any practical situation to achieve zero clearance in the starting bush because of a number of different factors. Among them, the clearance in the starting bush which changes with each tool regrind and tool wear is most important.

A special analysis of gundrill failures in drilling aluminum alloy engine heads resulted in the conclusion that the entrance instability is the prime cause for the so-called 'unpredicted' drills' failure in the automotive industry. This failure appears commonly as a fatigue crack(s) on the drill shank and cannot be explained as only stable drilling is considered.

The objective of this paper is to correlate the design parameters of the gundrilling system with entrance instability. The influence of different design features of a gundrill on this stability is discussed and many practical recommendations on the design of gundrills and drilling systems including accessories and machines are provided.

2. Experiments

The instability of a gundrill at the entrance results in the formation of the so-called bell mouth, which is essentially the heavily deformed tapped part of the machined hole. Although such phenomena are observed in everyday practice of gundrilling, it has never been regarded as an essential factor affecting drill performance because the duration of entrance instability is very short (0.3–0.8 s) so it can hardly be noticed in the production cycle, particularly when the existing control systems are used.

To understand the role of drill entrance stability and thus the mechanism of bell mouth formation, a series of experiments were carried out. The experimental setup shown in Fig. 4 is mainly composed of the deep-hole drilling machine, a Kistler six-component dynamometer, charge amplifiers, and Kistler signal analyzer. The system details are as follows.

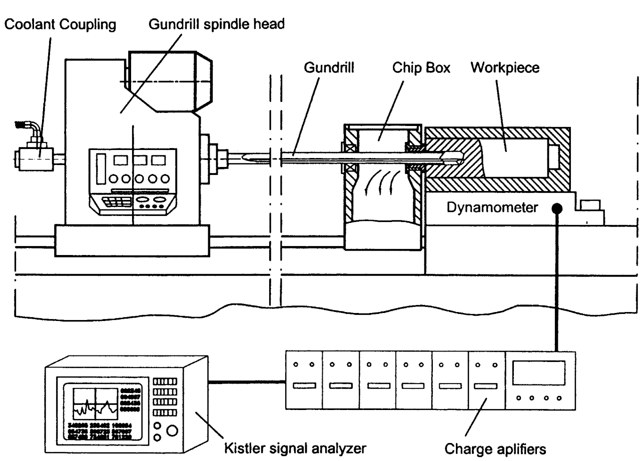

Fig. 4. Schematic of the experimental setup.

2.1. Workpiece material

Heat treated aluminum alloy 316 supplied by Ford Motor Co. was used. The composition, element limits, porosity, and heat treatment practice were selected to be the same as used for engine heads. The actual chemical composition has been analyzed using LECO™SA-2000 Discharge-Optical Emission Spectrometer. Special metallurgical parameters such as the element counts, microstructure, grain size, inclusions count, etc. were inspected using quantitative metallography.

2.2. Cutting tool

The geometry parameters of the tool were controlled according to American National Standard B94.50-1975. Tolerances for all angles were ±0.5°. The roughness R_a of the tool face and flank did not exceed 0.25 μm and was measured according to American National Standard ANSI B46.1-1978. Each cutting edge was examined at magnification of 15× for visual defects for chips or cracks.

2.3. Dynamometer

A six-component Dynamometer 9257B (Kistler) for measuring the three orthogonal components (including their frequency composition) of the cutting force was used. This is because the drill rotates, so force fluctuations along six directions were analyzed in order to measure three orthogonal components of the cutting force and their spectral characteristics. The static and dynamic calibration of the dynamometer, the measuring setup, data acquisition, and analysis were accomplished using methodology presented earlier [7–9].

The experiments were carried out using a wide variety of cutting regimes, gundrills of different design and geometry, and different parameters of the gundrilling system (the starting bush tolerance, the distance between the faces of the starting bush and the workpiece, the pressure of the cutting fluid) to avoid any bias in the experimental result associated with a particular set of parameters.

Fig. 5 shows a typical example of variation of components of the cutting force and coolant pressure during a drilling cycle. As seen in the figure, the axial force does not change significantly at the entrance, while the tangential and radial forces do. It was found that the radial and power force fluctuations are 10–20-fold larger compared to the rest of the cycle.The duration of entrance instability is approximately 0.28 s so it can hardly be noticed while drilling. A similar trend was observed in all experiments conducted. Based on these experimental results, the following can be concluded.

1. The clearance between the drill and the starting bush

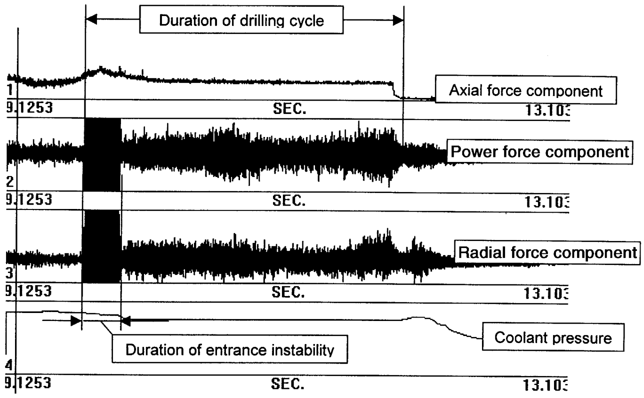

Fig. 5. Variation of components of the cutting force and coolant pressure during a drilling cycle. The cutting regime: drill rotational speed 8000 rpm; feed rate 1118 mm/min; pressure of the cutting fluid 7 MPa; the approach angles: the outer cutting edge 45°, the inner cutting edge 30°; the normal flank (relief) angles: the outer cutting edge 12°, the inner cutting edge 20°; the radial clearance in the starting bush 10 μm; the distance between the face of the starting bush and that of the workpiece 0.3 mm. The same scale for cutting forces is used. Time duration is shown from the beginning of recording.

is the most critical factor in entrance stability. When this clearance is zero (in the experiments it was achieved by the selective combination of a gundrill and a starting bush) the instability was at its minimum depending on the gundrill design.
2. Among tool parameters, the design and location of the supporting pads (supporting continuum) are critical.
3. Experimental comparison of gundrills with the supporting continuum and two supporting pads shows that the force fluctuations are 30–50% smaller for the latter under the same working conditions.
4. A need is felt for a comprehensive theoretical analysis to understand the inter-influence of different parameters of the gundrilling system at the entrance.

3. Two distinctive stages of the entrance

Unfortunately, little is known today about the mechanisms and mechanics of bell mouth formation and thus the major factors affecting this phenomenon are still unclear. At best, the existence of the bell mouth is recognized and the process of its formation is called bell mouthing [1,3]. Although some studies analyzed variation of the cutting force at the entrance [4], the real source of these forces was not revealed. To the knowledge of the author, no single attempt has been made to understand the influence of the design, kinematic and/or dynamic parameters of the gundrilling system on bell mounting. The present study aims to correlate gundrill entrance stability with bell mouth formation.

The entrance of a gundrill into the workpiece should be considered as consisting of two distinctive stages. The first stage is the entrance of the gundrill's cutting part. At this stage, the cutting force and its components change (in terms of their magnitude and direction) steadily with the corresponding increase of the length of the cutting edges engaged in cutting. It is important to note that at this first stage, the supporting (burnishing) elements of the gundrill remain in the starting bush. The second stage, which completes the entrance, is the entrance of the supporting (burnishing) gundrill's elements into the workpiece. For the first time, these two stages are considered separately.

4. First stage

4.1. Initial location

Fig. 6 shows the initial relative location of a gundrill and the starting bush. For clarity, the initial location of the gundrill is considered to be coaxial with the starting bush, i.e. the origin of the gundrill's original coordinate system O_1 is assumed to be coincident with the center O of the starting bush having diameter d_{sb}. Although, in practice this is rarely the case, it will be shown later that the initial location of the gundrill does not affect the drill's behavior at the entrance unless severe additional forces due to the misalignment of the gundrill and the starting bush are high enough to affect the proper entrance and working conditions of the gundrill.

Fig. 6(a) illustrates the initial position of a gundrill having the supporting continuum *ab*. Hereafter, the initial position of a gundrill in the starting bush is achieved when the drill point *M* touches the face of the work-

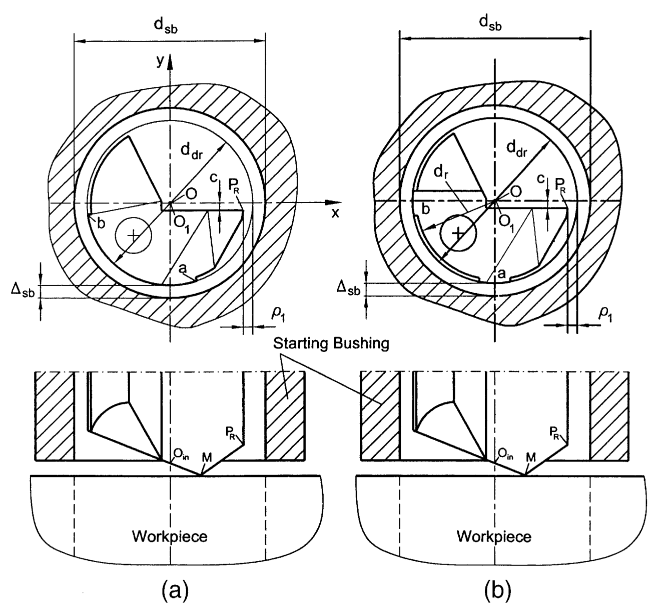

Fig. 6. Initial position of the gundrill in the starting bushing.(a) Gundrill having supporting continuum *ab*.(b) Gundrill having two supporting pads a and b.

piece. In this figure, d_{dr} is the drill's nominal diameter, c is the distance between the x-axis and the rake face, Δ_{sb} is the clearance between the drill and the starting bush, and ρ_1 is the shift of the drill's peripheral point P_R from the drill's nominal diameter. This shift sometimes occurs in tip grinding when the grinding sequence is not properly adjusted accounting for the interrupted surface, i.e. the circular land ground on the side cutting edge has a smaller circular width compared to that on the supporting pads. As such, when the same pressure from the grinding wheel is applied to the supporting pads and to the circular land, the volume of the carbide material removed from the circular land would be greater. This can be avoided, however, if the contact areas on the supporting pads and circular land are kept the same during tip grinding. Therefore, by applying the proper grinding technology, the shift ρ_1 could be made close to zero. In our further consideration, we assume more general case when $\rho_1 \neq 0$.

Fig. 6(b) illustrates the initial position of a gundrill having two supporting pads, a and b. The relief surface having diameter d_r is ground between these pads as shown. All other notations are the same as in Fig. 6(a). The initial position of this drill is exactly the same as that shown in Fig. 6(a).

4.2. Cutting forces

When the feed motion is applied, the cutting edges of the gundrill start to penetrate into the workpiece. As discussed earlier, the resistance of the work material causes the cutting force R_c applied to a certain point of the cutting edge. F_T and F_R acting in the xy-plane up to the force resultant F_{xy}. The line of action of F_{xy} should intersect the supporting continuum ab (Fig. 2(b)) at certain point d for the drill to be stable. In other words, if point d does not belong to continuum ab, the resultant force F_{xy} tilts the drill about point a to the left so that the side cutting edge (periphery point P_R) is forced into the workpiece, which may break the drill. The important point for the current consideration is that the picture shown in Fig. 3 is valid only when the cutting edges are fully engaged in cutting which would not be the case until the outer and inner cutting edges completely enter into the workpiece.

To understand the variation of the discussed tangential and radial forces at the entrance, it should be clearly realized how the force diagram shown in Fig. 3 is constructed. The unit tangential force acting along the cutting edge having unit length dx_i is calculated as [6]

$$F_{Ti}-C_{pi}a_i^{x_p}dx_i \tag{1}$$

where C_p is the constant which depends upon the work and tool materials, cutting fluid, and process parameters; x_p is the exponent determined by the influence of the uncut chip thickness on the cutting force; a_i is the uncut chip thickness over dx_i.

The overall tangential force is calculated as the sum of the unit tangential forces as

$$F_T = \int_R a_i^{x_p} x_i dx_i \tag{2}$$

The distance m_1, which defines the point of application of F_T with respect to the x-axis, is calculated as [6]

$$m_1 = \frac{\int_R a_i^{x_p} x_i dx_i}{\int_R a_i^{x_p} dx_i} \tag{3}$$

Although the same methodology is applied to calculate the radial force P_R, such calculation should be carried out for each part i of the cutting edge having different approach angle

This consideration is valid only when both the outer and the inner cutting edges are fully engaged in cutting. Obviously, this is not the case at the first stage of the entrance, which begins when the lengths of the inner and outer cutting edges are equal to zero, i.e. when $b_{ot} = b_{in} = 0$ and then proceeds with ever-changing b's until the outer and inner cutting edges are fully engaged with the workpiece. Because the forces acting on the cutting edges are directly proportional to the corresponding length, these forces are of ever-changing nature during the first stage of drill entrance.

4.3. Variation of the tangential and radial cutting forces during the first stage

To understand the correlation between drill design and its entrance stability, consider the force dynamics at this entrance at its first stage. This stage begins when the drill point M touches the face of the workpiece and ends when the periphery point P_R enters the workpiece provided that this point is located behind the point O_{in} in the axial direction (Fig. 7). If this is the case, the first stage of the gundrill's entrance should further be divided into two phases. The first phase takes place from the initial position when point M touches the workpiece's face (Fig. 7) till point O_{in} comes in contact with the workpiece (i.e. when the inner cutting edge completely enters). The second stage starts from this moment and takes place until point P_R engages with the workpiece.

Now consider what happens during the first phase. The force distributions at the end of the first phase are shown in Fig. 7. The current tangential forces F_{T-c} as well as radial forces F_{R-ot-c} and F_{R-in-c} increase steadily during this phase. Because point M is the first point of contact, the initial location distance (m_1) of F_{T-c} is

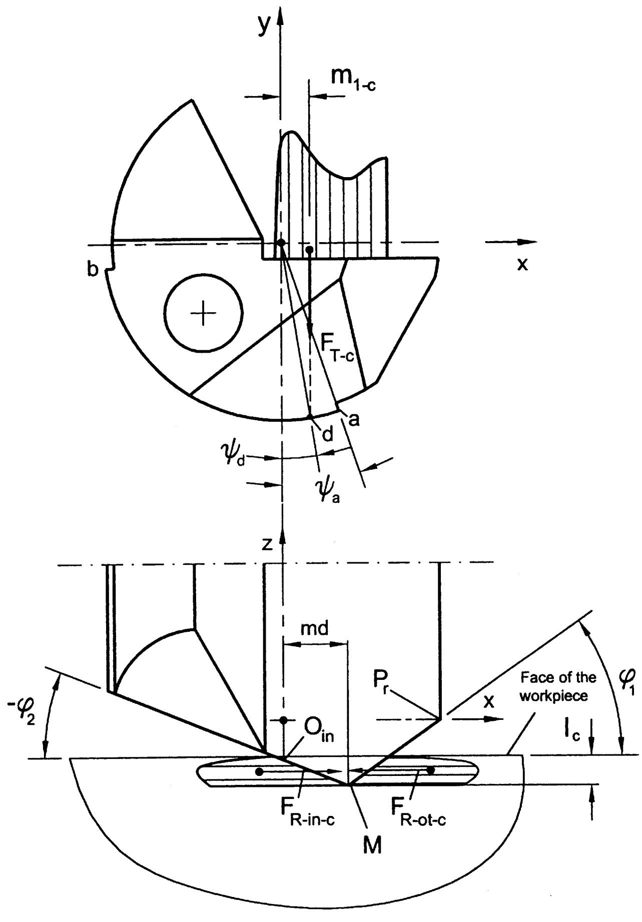

Fig. 7. Force distribution at the end of the first phase.

equal to *md*. Provided that constants C_p and C_R are used to calculate tangential and radial forces, respectively as well as the uncut chip thicknesses on the outer, a_{ot} and inner, a_{in} do not change with drill penetration, the only parameters that affect the discussed increases in the tangential and radial forces are the cutting lengths b_{ot-c} and b_{in-c}.

Consider the manner in which the tangential forces on the inner and the outer cutting edges change with drill penetration over a certain distance l_c. Referring to Fig. 7 and accounting for Eqs. (1)–(3), one can obtain

$$\frac{F_{T-ot}}{F_{T-in}} = \frac{C_p b_{ot-c} a_{ot-c}{}^{x_p}}{C_p b_{in-c} a_{in-c}{}^{x_p}} = \frac{l_c (f\cos\varphi_1)^{x_p} \sin\varphi_2}{\sin\varphi_1 l_c (f\cos\varphi_2)^{x_p}} \quad (4)$$

$$= \frac{\cos^{x_p}\varphi_1 \sin\varphi_2}{\sin\varphi_1 \cos^{x_p}\varphi_2}$$

where $a_{ot(in)}-f\cos\varphi_{1(2)}$, $b_{ot(in)-c} = l_c/\sin\varphi_{1(2)}$, and f is the feed per revolution.

It is seen that F_{T-ot}/F_{T-in} = Const during the first phase. Using the same approach for the radial forces, we may write

$$\frac{F_{R-ot}}{F_{R-in}} = \frac{C_R b_{ot-c} a_{ot-c}{}^{x_k} \tan\varphi_1}{C_R b_{in-c} a_{in-c}{}^{x_k} \tan\varphi_2} \quad (5)$$

$$= \frac{l_c (f\cos\varphi_1)^{x_k} \sin\varphi_2 \tan\varphi_1}{\sin\varphi_1 l_c (f\cos\varphi_2)^{x_k} \tan\varphi_2} = \frac{\cos^{x_k}\varphi_1 \sin\varphi_2 \tan\varphi_1}{\sin\varphi_1 \cos^{x_k}\varphi_2 \tan\varphi_2}$$

It is seen that F_{R-ot}/F_{R-in} = Const during the first phase. Therefore, the tangential and radial forces do not change their directions and point of application during the first phase. This is a very important conclusion showing that gundrill's stability does not change during the first phase and thus it can be analyzed at any time instant during the first phase. Ratio (4) defines the location of application of the resultant tangential force m_{1-c} during the first phase. If this ratio $F_{T-ot}/F_{T-in} = 1$ then $m_{1-c} = md$, if $F_{T-ot}/F_{T-in} < 1$ or $F_{T-ot}/F_{T-in} > 1$ then $m_{1-c} = F_{T-ot}/F_{T-in}\, md$. Ratio (5) defines the direction of the radial force at the first phase. There are three distinctive cases possible. They are as follows:

1. If $F_{R-ot}/F_{R-in} = 1$, then the resultant radial force is zero. The drill stability in this case would depend on the position of point *d* with respect to point *a* (Fig. 7). If m_{1-c} is so that point *d* is within the continuum *ab*, i.e. $\psi_d \le \psi_a$ then the drill is located properly. If m_{1-c} is so that point *d* lays outside the continuum *ab*, then the drill is unstable due to the additional tilting moment $M_{T-c} = F_{T-c} l_{T-c}$. The sense of the arm l_{T-c} is clearly seen in Fig. 8(a). This tilting moment presses the side cutting edge against the starting bush that results in wear of both the side cutting edge and the starting bush. Therefore, the location of point *d*, defined by angle ψ_a, is critical at the entrance.
2. If $F_{R-ot}/F_{R-in} > 1$, then the resultant radial force is as shown in Fig. 3. As seen in this figure, the line of action of the resultant force in the *xy*-plane is always within the continuum *ab*, i.e. $d \subset (a,b)$. This is a preferable case in terms of entrance stability. According to Eq. (5), the approach angles of the inner and outer cutting edges (φ_2 and φ_1, respectively) should be selected to achieve this condition.
3. If $F_{R-ot}/F_{R-in} < 1$, then the resultant radial force is as shown in Fig. 8(b). As is seen in this figure, point *d* is located outside the continuum *ab*. Therefore, the

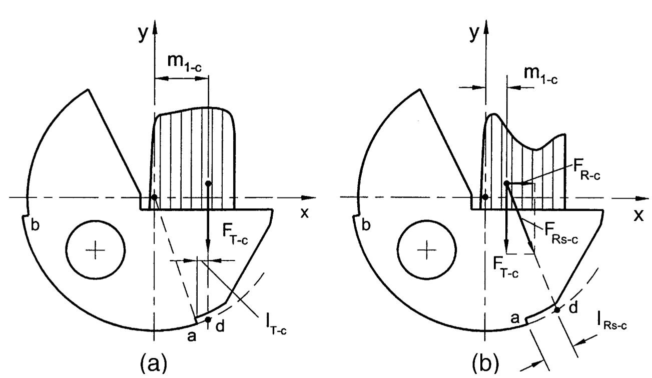

Fig. 8. The location of point *d* defines drill's stability at the entrance.

additional tilting moment $M_{Rs-c} = F_{Rc} l_{Rs-c}$. The sense of the arm l_{Rs-c} is clearly seen in Fig. 8(b). This tilting moment is much higher than that in case 1. It presses the side cutting edge against the starting bush that results in wear of both the side cutting edge and the starting bush. This case is the worst scenario at the drill entrance and should be avoided by proper selection of the approach angles according to Eq. (5).

5. The position of the gundrill in the starting bush after the first stage

Fig. 6 shows the initial position of the gundrills having supporting continuum *ab* and two supporting pads a and b gundrill in the starting bush. It was discussed that if the drill is designed properly, the direction of the resultant force is within the continuum *ab* or within the angle between supporting pads a and b. Now let us consider what position drill assumes in the starting bush at the end of the first stage of the drill entrance.

5.1. Gundrill having the supporting continuum

We start our consideration with the drill shown in Fig. 6(a), i.e. with that having the supporting continuum *ab*. When the cutting edges are fully engaged with the workpiece, the drill's tip moves in the direction of the resultant force F_{xy} because the clearance Δ_{sb} between the drill tip and the starting bush (Fig. 6) allows this motion. Since the tip is a rigid body, all tip points move in this direction. As a result, the tip comes in contact with the starting bush at certain point $d_1 \subset (a,b)$ which is shown in Fig. 9.

As seen, the gundrill has only two locating points in the *xy*-plane, namely, point d_1 and the periphery point P_R. It is well known from the principles of locating that proper location of a cylindrical body is achieved when three locating points are involved. In the case considered , where only two points are available, any change in cutting forces (variation of hardness of work material, cross hole, cavity, etc.) results in the variation of angle

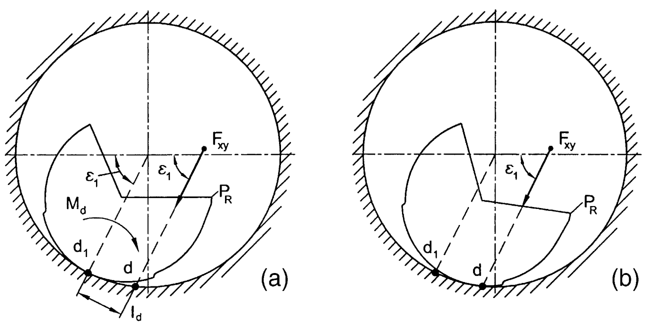

Fig. 9. The additional tilting moment M_d as an inherent feature of any gundrill having the supporting continuum.

ε_1 and thus the location of point d_1 with the continuum *ab*. This, in turn, leads to a corresponding change in the position of the periphery point P_R with respect to the axis of rotation that changes cutting forces. This change again affects angle ε_1 and so on. Because the cutting forces are of ever-changing nature (due to the accumulated misalignment and runout, variable bending rigidity of the shank within a drill's revolution and with drill penetration into the hole being drilled, shank weight, and many other factors), this angle also changes permanently causing vibrations, poor integrity of the machined surface, deviations of the axis of the machined hole, and poor tool life.

Moreover, as soon as the supporting continuum touches the starting bush at point d_1, the resultant force F_{xy} creates the tilting moment $M_d = F_{xy} l_d$, where the sense of l_d is illustrated by Fig. 9(a). This moment forces the drill to rotate about point d_1 until the drill takes the position shown in Fig. 9(b), i.e. when the supporting continuum *ab* contacts with the starting bush at point *d*. It may happen, however, if the periphery point P_R has no resistance from the work material to move. In reality, it does not happen because the circular land is ground on the side cutting edge to prevent the drill to 'dive' into the workpiece. In other words, a gundrill with the supporting continuum is inherently unstable.

Fig. 10(a) shows the location of the drill's rake and periphery point P_R at the initial drill location. The necessity and significance of c_0 and μ_0 have been discussed in [2]. Fig. 10(b) shows the location of the drill periphery point P_R, drill center O_1, and the drill rake face after the first stage of the drill entrance. It can be seen that

$$R_{dr1-W} = \sqrt{\Delta_{sb}^2 + R_{dr0}^2 - 2\Delta_{sb} R_{dr0} \cos\left(\frac{\pi}{2} - \varepsilon_1 + \mu_o\right)} \quad (6)$$

$$c_1 = c_0 + \Delta_{sb} \cos \varepsilon_1 \quad (7)$$

$$\mu_1 = \arcsin \frac{\Delta_{sb} \cos \varepsilon_1}{R_{dr1-W}} \quad (8)$$

where

$$\Delta_{sb} = \frac{d_{sb} - d_{dr}}{2} \quad (9)$$

Here, d_{sb} and d_{dr} are the actual diameters of the starting bush and gundrill, respectively.

5.2. Gundrill having two supporting pads

The initial location of a gundrill having two supporting pads in the starting bush is shown in Fig. 11(a). As before, the axis of the drill and that of the starting bush are shown coincident. As discussed previously, such an

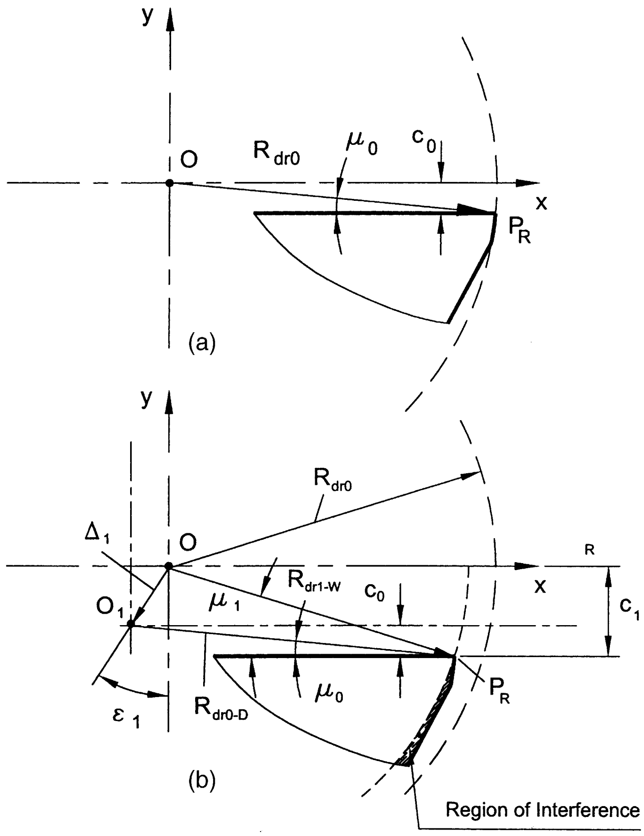

Fig. 10. The displacement of the drill periphery point P_R after the first stage of drill entrance.

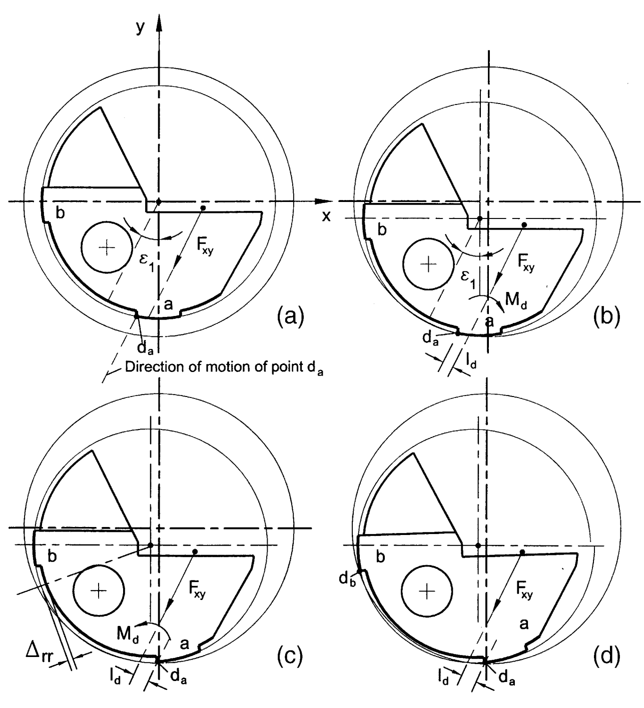

Fig. 11. Position of a drill having two supporting pads in the starting bushing after the first stage of drill entrance.

idealization does not affect the final position of the drill in the starting bush after the first stage of the drill entrance unless additional forces due to misalignment of the drill and the starting bush are greater than the cutting forces.

The complete entrance of the cutting edges results in the force F_{xy} which, as has been discussed, is the resultant force in the *xy*-plane. This force causes the drill's tip to move in the direction defined by the angle ε_1 which the resultant force makes with the *y*-axis. Because the tip is a rigid body, all its points move simultaneously. As the result, the corner d_a of the supporting pad a first comes in contact with the starting bush as shown in Fig. 11(b).

As soon as it happens, the additional tilting moment, $M_d = F_{xy}l_d$, (where the sense of l_d is illustrated by Fig. 11(b)) comes to the picture. If the location of the supporting pad is as shown in Fig. 11(b), this moment causes the drill's periphery point P_R and thus the side cutting edge to dive into the workpiece. Such a drill behaves exactly as that discussed previously with all listed disadvantages. However, if the location of the supporting pad a is as shown in Fig. 11(c), the additional tilting moment M_d rotates the tip counterclockwise so that the corner d_b of the supporting pad b comes into contact with the starting bush. Such a gundrill has three locating points, namely, d_a, d_b, and P_R in the *xy*-plane so that this drill is located properly. The variation of the cutting forces during drilling does not change the location of such a drill providing that the line of action of the resultant force F_{xy} remains within the angle between corners d_a and d_b.

In order to assure proper location of the gundrill as shown in Fig. 11(d) and thus to avoid the interference of the relief surface of the tip with the starting bush, the sufficient radial relief Δ_{rr} (Fig. 11(c)) should be applied. A simple analysis shows that to prevent this interference, the radial relief Δ_{rr} applied on the drill should be

$$\Delta_{rr} > \sqrt{R_{sb}^2 - 0.5R_{sp}^2\left[1-\cos\left(\psi_{ab}-\arcsin\frac{R_{sp}}{b_a}-\arcsin\frac{R_{sp}}{b_b}\right)\right]} - R_{sp}\cos\frac{1}{2}\left(\psi_{ab}-\arcsin\frac{R_{sp}}{b_a}-\arcsin\frac{R_{sp}}{b_b}\right)-\Delta_{sb} \qquad (10)$$

Analysis of Eq. (10) shows that the radial relief applied on a gundrill depends on the clearance in the starting bush and on the location and width of the supporting pads. It is important that the maximum allowed radial wear of the starting bush and minimum drill diameter (because drill diameter changes with each regrind due to the back taper applied on the drill tip) are considered in these equations. Moreover, some gundrill users utilize standard ACME twist drill starting bushes on their machines that gives excessive clearance in the starting bush even for a new bush.

Fig. 10(a) shows the location of the drill's rake and periphery point P_R at the initial drill location. The meaning and significance of c_0 and μ_0 have been discussed in Ref. [2]. Fig. 10(b) shows the location of the drill periphery point P_R, drill center O_1, and the drill rake face after the first stage of the drill entrance. As seen previously, for a gundrill with two supporting pads

$$R_{dr1-W} = \sqrt{\Delta_{int}^2 + R_{dr0}^2 - 2\Delta_{int}R_{dr0}\cos\left(\frac{\pi}{2} - \varepsilon_1 + \mu_0\right)} \quad (11)$$

$$c_1 = c_0 + \Delta_{int}\cos\varepsilon_1 \quad (12)$$

$$\mu_1 = \arcsin\frac{\Delta_{int}\cos\varepsilon_1}{R_{dr1-W}}, \quad (13)$$

where

$$\Delta_{int} = \sqrt{R_{sb}^2 - 0.5R_{sp}^2\left[1 - \cos\left(\psi_{ab} - \arcsin\frac{R_{sp}}{b_a} - \arcsin\frac{R_{sp}}{b_b}\right)\right]} - R_{sp}\cos\frac{1}{2}\left(\psi_{ab} - \arcsin\frac{R_{sp}}{b_a} - \arcsin\frac{R_{sp}}{b_b}\right) - \Delta_{sb} \quad (14)$$

6. Conclusions

The first stage of gundrill entrance into the workpiece was investigated. The conclusions can be summarized as follows.

The entrance of a gundrill into the workpiece is considered as consisting of two distinctive stages. The first stage is the entrance of the gundrill's cutting part. At this stage, the cutting force and its components change (in terms of their magnitude and direction) steadily with the corresponding increase of the length of the cutting edges engaged in cutting. It is important to note that at this first stage, the supporting (burnishing) elements of the gundrill remain in the starting bushing. It was shown that the tangential and radial forces do not change their directions and point of application during the first phase. This is a very important conclusion showing that gundrill's stability does not change during the first phase and thus it can be analyzed at any time during the first phase.

The second stage, which completes the entrance, is the entrance of the supporting (burnishing) gundrill's elements into the workpiece. For the first time, these two stages are considered separately.

Entrance instability in gundrilling appears as excessive fluctuations of the tangential and radial forces during drill entrance. This is the prime cause for the so-called unpredicted drills' failure, which appears commonly as a fatigue crack(s) on the drill shank. The prime cause for this instability is the excessive clearance in the starting bush combined with the improper design of the gundrill's supporting area.

The excessive clearance between the starting bush and the gundrill's tip is often the case in practice. The reasons for this clearance are as follows.

- To assure the drill's free penetration into the hole being drilled, the so-called back taper of the drill's outside diameter is applied. Therefore, this diameter decreases with each re-sharpening.
- Re-sharpening practice does not follow the recommendation on the minimum tip length beyond which the gundrill tip should not be re-re-sharpened.
- The internal diameter of the starting bush increases with its wear. The design of many deep-hole machines, particularly those used in the automotive industry, does not allow free access to the stating bushing to check its diameter or to change it. As a result, the replacement of starting bushings takes place only occasionally.

The design and location of the supporting pads (supporting continuum) greatly affect entrance stability. Gundrills with the supporting continuum, which are now common in the automotive industry, have inherent instability and should not be used at all. It does not have any advantage in drill performance. It only simplifies drill's periphery grinding which cannot be justified by poor drill locating in the starting bushing and in the hole being drilled.

In our opinion, gundrills with two supporting pads should become common in the automotive industry. Their use results in the reduction of force fluctuations by 30–50% when proper angle between the supporting pad and sufficient radial relief are the case.

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