Abstract

Gundrilling is known for making first-pass high-finish straight holes of varying depths and diameters. This efficient process is widely used in the automotive industry to drill deep holes in cylinder heads, crankshafts, fuel pump housings, etc. It is also widely used in the mold and die, power and other industries to drill a wide variety of work materials. The process efficiency (the cost per unit length of drilled holes) varies significantly from one application to another, from one engine and/or transmission plant to the next depending on an overwhelming number of variables.

This paper presents a system outlook of gundrilling. It argues that successful implementation of high penetration rate gundrilling is not just a matter of tool design. Rather, optimum drill performance is achieved when the combination of the cutting speed (rpm), feed, tool geometry, carbide grade, and coolant parameters is selected properly depending upon the work material (its hardness, composition and structure), deep-hole machine conditions, and the quality requirements to the drilled holes. Multiple practical examples discussed in the presentation conclusively prove that to get the most out of a gundrilling job, one must consider the complete gundrilling system, which includes everything related to the operation. Such a consideration is known as the system engineering approach according to which the gundrilling system should be distinguished and analyzed for coherency of its components. This paper also discusses some results of implementation of a new line of highly efficient gundrills.

1. Introduction

Gundrilling is known for making first-pass high-finish straight holes of varying depths and diameters. This efficient process is widely used in the automotive industry for producing deep holes in engine blocks, transmission parts, crankshafts, fuel pump housing etc. As such, a wide variety of work materials as aluminum alloys, cast irons, plain and magnesium alloyed steels are drilled [1].

High penetration rate gundrilling has emerged during the last 5 years as the process that allows the penetration rate more than 900 mm/min (approx. 35 imp) for aluminum alloys, more than 250 mm/min (10 ipm) for cast irons and more than 180 mm/min (7 ipm) for alloyed steels. It became possible due to significant improvements in the manufacturing quality of gundrills including the quality of their components, implementation of better gundrilling machines equipped with advanced controllers as well as their proper maintenance, application of better coolants, better training of engineers and operators and many other factors. However, the actual penetration rate and drilling process efficiency (the cost per unit length of drilled holes) vary significantly from one application to another, from one manufacturing plant to the next depending on an overwhelming number of variables. Optimum drill performance in gundrilling
is achieved when the combination of the cutting speed (rpm), feed, tool geometry, carbide grade, and coolant parameters is selected properly depending upon the work material (its hardness, composition and structure), deep-hole machine conditions, and the quality requirements to the drilled holes [2]. To get the most out of a gundrilling job, one must consider the complete gundrilling system, which includes everything related to the operation. Such a consideration is known as the system engineering approach according to which the gundrilling system should be distinguished and analyzed for coherency of its components.

2. Gundrilling system

According to the system engineering theory, it's improper to consider any machining operation's component separately, thereby ignoring system properties. Unfortunately, the "component approach" is a common manufacturing practice in today’s environment, where different manufacturers produce the various components and no one seems to be responsible for the system coherence [3]. As a result of nonintegration of the gundrill components, unpredicted drill failures are common. Potential failures include drill breakage and excessive tool wear. Moreover, it also leads to the deterioration of hole quality including poor surface finish, excessive runout of the drilled holes, drift of the longitudinal axis (position error) of the drilled holes, etc. Such failures often turn gundrilling into a bottleneck operation in the automotive industry.

Reading this, one may ask a logical question – what seems to be the problem? There are a number of gundrill manufactures and even a greater number of gundrilling machine makers. Each manufacturing plant has trained personnel including engineers and operators, maintenance schedules, re-sharpening services etc. However, our recent survey indicates that in the automotive and moldmaking industries:

- The correct gundrill geometry is selected less than 30% of the time.
- The tool is used at the rated cutting regime only 48% of the time.
- Only 57% of the tools are used up to their full tool-life capability.
- The correct tool material is selected less than 30% of the time.
- The correct cutting fluid (coolant) parameters are used 42% of the time.
- The correct parameters of the gundrilling system are used less then 20% of the time.

Unfortunately, the tool manufacturer is often unfairly blamed as the lone culprit because the gundrill, as the weakest link, fails as a result of improper performance of various components of the gundrilling system. For example, one manufacturer of gundrills for the automotive industry was blamed for gundrill breakage occurring at the tip-shank brazed joint. For over 5 years this manufacturer tried to improve the strength of this joint. When this strength became sufficiently great, breakage of gundrill carbide tip began to occur. An analysis of the root cause of this problem showed that the lack of the coolant flow rate supplied to the drilling zone caused drill breakage. Because the root cause was not properly determined, the increased strength of the discussed brazed joint shifted the breakage to the carbide tip as a new weakest link. Yet another common case is insufficient quality of the coolant in terms of its concentration and purity. When this coolant is used, gundrills’ tool life deteriorates dramatically. Again, gundrill manufacturers are unfairly blamed for poor tool life.
To understand the performance of the gundrilling system and thus the root cause for many gundrilling-related problems, one should always consider the following components of the gundrilling system (Figure 1): gundrill, machine and its control unit, coolant parameters and coolant delivery unit, fixture and accessories, workpiece, operator, and maintenance. One can appreciate the system properties of the gundrilling system if he realizes that the same gundrill used in different gundrilling machines shows a wide range of outcomes from breakage to excellent performance; the same gundrill used on the same machine exhibits different results for different work materials; the same gundrill used on the same machine for drilling the same work material performs differently depending upon a particular brand of coolant used for the operation, the coolant flow rate, filtration and temperature; the performance of the same gundrill used on the same machine for drilling the same work material using the same coolant parameters would depend largely on the extent of the operator’s experience and training. The latter is particularly true if the control system provides relevant information to the operator. As seen, each system component can affect system performance dramatically. The key here is to assure system coherency, i.e. the condition when all system components work as a ‘team’ to achieve the ultimate system’s objective.

Although the complete description of the coherency of the gundrilling systems is a subject for a book, some very important features of the components of such a system will be discussed in this paper. Besides, one should realize that gundrilling is not always a precise science or art that can be defined in exact formulas. The design of gundrilling systems also requires experience to develop skill, methods and know how accumulated over the years. That is why the hands-on approach, combined with the theory of gundrilling, can help solve a variety of design and application problems.

Figure 1. Structure of the gundrilling system.
3. Gundrill

3.1. Basic design

Gundrilling is a method of drilling holes where self-piloting tools with internal coolant supply and external chip removal, known as gundrills, are used. A typical gundrill shown in figure 2 consists of a drill body having a shank 1, a tip 2 and a driver 3 connected together by brazed joints. The tip is made up of a hard wear-resistant material such as sintered carbide. The other end of the shank incorporates enlarged driver 3. The design of the driver is machine specific.

![Figure 2. A typical gundrill.](image)

The shank is of a tubular shape having an elongated passage 4 extending over its entire length and connects to the coolant supply passage 5 in the driver. The shank has a V-shaped flute 6 with a profile angle $\psi_f$ on its surface. The flute terminates in an inclined crease 7 formed adjacent to the driver. The shank outside diameter, $d_{sh}$, should be close to the diameter of the drilled hole in order to prevent the chips from coming into the clearance between the shank and the walls of the hole being drilled – if this happens the gundrill fails in a short time. However, the shank is made of a standard seamless tube and its one outside diameter takes a range of drill (tip) diameters. The practice of gundrilling developed the ranges for the shank outside diameters depending on the drill diameter. The shank wall thickness depends on a particular tube producer. Commonly, it is in the range of 10-13% of the outside diameter of the shank. The shank material and its heat treatment procedure (results in different hardness and structure) vary significantly from one gundrill manufacturer to another.
The tip is brazed at the end of the shank. Flute 8 with profile angle $\psi$, which is similar in shape to flute 6, extends along the full length of the tip. These two flutes are longitudinally aligned. The above description is illustrated in figure 2 as a straight construction, which is preferred, but other constructions such as that of a helical type are also possible. Flute 8 in formed by sidewalls 9 (called the cut-face) and 10 (called the side-face). The depth of this flute is such that the cut-face 9 which extends past the axis 11 of the tip. The terminal end of the tip is formed with approach angles $\phi_1$ and $\phi_2$ of the outer 12 and inner 13 cutting edges, respectively. These cutting edges meet at the drill point $P$. The location of $P$ can be varied for optimum performance depending on the work material and the finished hole specification. The geometry of the terminal end largely determines the shape of the chips and the effectiveness of the coolant, the lubrication of the tool, and removal of the chips. One common point grind calls for the outer approach angle, $\phi_1$, to be 30° and the inner approach angle, $\phi_2$, to be 20°. A primary flank surface 14 (with the normal clearance (flank) angle $\alpha_{n1}$ of 7°–9°) is provided usually on the flank of the outer cutting edge. A secondary flank surface 15 (with the flank angle, $\alpha_{1n-2}$, of 15°–20°) is applied to the outer cutting edge to provide a space for the coolant to reach the cutting edge. To the inner cutting edge, flank surface 16 having the normal clearance (flank) angle $\alpha_{n2}$ (8°–12°), is applied. Additional flank surface 17 (with normal flank angle $\alpha_{n3}$ of 20°–25°) is provided to clear the free drill penetration. The shoulder flank surface 18 (with the shoulder dub-off angle $\alpha_{n4}$) enables the penetration of the cutting edges during machining without interference between point $C$ and the bottom of the hole.

The coolant passage 19 is located on the flank surface of the inner cutting edge. Gundrill manufacturers have adopted various shapes for this passage. It could be one or two circular holes or a single kidney-shaped hole.

The number, location and design of the supporting pads 20,21 are optional depending on the particular use for which the drill is intended. The supporting pads and the side cutting edge 22 are ground with a certain back taper so the drill diameter becomes smaller with each regrind.

### 3.2. Design and gundrill manufacturing variables affecting penetration rate

To increase the allowable penetration rate in gundrilling, special attention should be paid to the following design and gundrill manufacturing variables:

1. **The drill length** $L_d$ (Fig. 2). The drill length is one of the most important system parameters. Needless to say that this length should be as short as possible. The proper way to determine this length is to design the so-called tool layout. An example of the tool layout is shown in Fig. 3. The following sequence is recommended in determining the drill length: start with the length of the machined hole then add the approach and overshoot distances, then the length of the bushing including bushing holder, chip box, etc.

At this point an important decision is to be made about the use of whipguide(s) and their number. Figure 4 helps to make such a decision. For example, if the shank length of an 8 mm (0.315")
drill rotating at 3000 rpm is 400mm (15.75”) then a whip guide is needed because the maximum distance between supports for these conditions is 350mm (13.78”).

Figure 3. A typical tool layout to determine the drill length.

Figure 4. Maximum distance between supports.

It is worthwhile to point out that gundrills can be also classified according to drill length ($L_w$, in figure 2)-to-diameter ($D$ in figure 1) ratio. When this ratio is less than 10, gundrills are called short; when it is between 11 and 50, gundrills are called normal; when it is between 51-100 are called long; and when this ratio exceeds 100, gundrills are called extra long. The properties of the gundrill system must be adjusted depending on the category a particular gundrill falls in to.
For short gundrills, the alignments ‘tip-shank’ and ‘drill holder-starting bushing’ are a key factor. This is because the shank of short gundrills is rigid so a significant additional force directly proportional to the misalignment acts on the gundrill. This force, which may well exceed the cutting force, causes multiple problems in drilling such as chipping of the cutting edge, poor surface finish, inadequate diametral accuracy, and low tool life.

Therefore, the discussed alignment should not exceed 2 microns. When this alignment cannot be adjusted to this accuracy (for example, when the gundrill is to be used on a versatile CNC machining center or on a gundrilling machine which does not have suitable alignment adjustments), the length of the gundrill must be deliberately increased to allow the gundrill to be truly self-piloting and thus to reduce the consequences of shank high rigidity.

Gundrills of normal length require that the alignment ‘drill holder-starting bushing’ is adjusted to be no worse then 4-6 microns. This is particularly important when drill rotates because the addition force due to misalignment caused shank failure due to accumulated fatigue. As such, a fatigue crack develops in the shank as shown in figure 5a. The worse case scenario occurs when the additional forces due to misalignment act in the direction of the side cutting edge (Position 22 in figure 2). This normally leads to the fracture of this edge (as shown in figure 5b) because its geometry is not designed to cut the work material in the transverse direction.

Figure 5. Gundrill failures due to excessive misalignment: (a) shank fatigue crack; (b) fracture of the side cutting edge.

Long and especially extremely long gundrills suffer low torsion strength. The alignment ‘drill holder-starting bushing’ becomes not that important and should be not worse than 15-20 microns. For a given drilling torque, the angle of twist of the shank is proportional to its length and thus the maximum twist angle is at the shank-driver connection. When this angle exceeds its critical value, the shank fails. When it happens, the failed gundrill looks like a twist drill having a helical V- flute.

2. **Shank.** The shank must be designed and made properly. Although there are a number of issues that affect shank performance, the excessive corner radii and shank material related considerations are of prime concern in high penetration rate gundrilling.
Figure 6a shows corner radii as it appears on a shank cross-section. Such excessive corner radii trapped chips removed along the V-flute because the shank rotates very fast in high penetration rate gundrilling. As a result, chips penetrate in the space between the wall of the hole being drilled and the shank side surface damaging the shank (as shown in figure 6b) and the walls of the drilled hole causing increased drilling torque that limits penetration rate.

![Shank edge radii](image)

Figure 6. Shank corner radii: (a) as it appears on a shank cross-section; (b) shank damaged by the chip penetrated between the shank and the wall of the hole being drilled due to excessive corner radii.

Gundrill shanks must be made of a high yield strength material and properly heat treated. Unfortunately, these issues are not always followed by gundrill manufacturers. First, high yield strength materials present problems (such as excessive warping, wrinkling cracking) when the V-flute is formed (crimped) using old tube crimping technology. So tubular products made of 4130 and 34Cr6Mo steels having moderate strength are common in the gundrilling industry. Second, very few gundrill manufacturers understand the proper heat treatment procedure for shanks and thus a fact that it must include a thermo-mechanical rather than pure thermal relief of the stresses formed on producing the V-flute. The best structure of the shank for short gundrills is a tempered martensitic structure while for normal and long gundrills the upper bainitic structure is the best choice. This is the only structure that possesses a very unique combination of high hardness, large toughness and great wear resistance suitable for gundrill shanks. Unfortunately, no one shank produced today has this structure.

When the shank is brazed to the tip and to the driver (brazed joints 1 and 2 in figure 2), the excessive heat from this brazing often ruins the results of the heat treatment at the brazed joints. Often this heat causes high residual thermal stresses hidden in the tip. When an increased drilling torque occurs due to, for example chip blockage or tool wear, the tip fails as shown in figure 7. Therefore, the use of low temperature, high-strength brazing filler materials (known as BFM) combined with infrared in-process temperature control followed by a 100% torque test are mandatory for gundrill brazing operations.

The result of our experimental study show that when the shank is made of high yield strength material, properly heat treated to achieve small grain size binate structure, and are properly
connected to the driver (using a low-temperature brazing filler metal), the increase in the gundrill penetration rate can be as high as twice compare to gundrills commonly used today.

Figure 7. Failure of the drill tip due to the residual stresses formed on brazing.

3. Carbide grade. Hundreds of different carbide grades are used in metal cutting depending on the work material, coolant, cutting operations, required quality of the machined part and so on. Surprisingly, only a very few carbide grades are used to make gundrill tips.

There was a time not long ago when only two grades of carbide were used to produce gundrills for the automotive industry, namely C2 and C3. It is still believed that C2 is a ‘forgiving’ carbide and thus can be used on any drilling machine with much less than perfect working conditions. A ‘small’ price to pay includes relatively short tool life and poor surface finish. The other is C3 proving to be much harder and thus more wear-resistant. Unfortunately, it is also more brittle and therefore cannot be used in gundrilling systems having excessive misalignment and runout. Recent advancements in the development of carbide materials and their technology resulted in the appearance of new micro- and sub-micro grain carbides. The use of such carbides for gundrill tips significantly enhances the tip strength and its wear resistance. Another problem, however, has emerged: How to select the proper grade for the given application from the great variety of available grades? Experience shows that the improper selection of even sub-micro-grain good quality carbide leads to premature tool failure. In other words, the margin for errors in carbide selecting becomes significantly smaller with the discussed variety of different carbide grades. Figure 8 presents an example of drill tip chipping due to improper carbide grade selection for crankshaft gundrilling.

Figure 8. Tip chipping due to improper carbide grade selection for crankshaft gundrilling.
It seems that there should not be any problem for a tool/process designer in the selection of the suitable carbide grade if the corresponding correlations between the properties of carbide (carbide grades) and drilling conditions (including work material, its metallurgical state, machine conditions, coolant, etc.) are known. Unfortunately, this is not the case in practice. The properties of carbide grades presented in the carbide manufacturers’ data (brochures, catalogs, etc) have little to do with gundrill working conditions though these tool materials were developed for gundrilling applications. For example, hardness that usually listed as the prime parameter is given at room temperature and no dependence of this parameter upon the temperature in the region of cutting temperatures (which reaches 600-800°C) is ever provided. The Transverse Rupture Strength (know as TRS) is another example of non-relevant parameters accounting for the method of its determination (ASTM B528-99 Standard). The most important parameters as fracture toughness, homogeneity, purity and wear resistance (both adhesion and abrasion) are not normally available.

Unfortunately, there is no relevant information or reliable data on the behavior of multiple coatings used for gundrills. Because gundrills are re-sharpened by removing a certain layer of the tool material from their flank surfaces (positions 14-16 and 21 in figure 2), the use of coatings is only justified if prime tool wear takes place on the cut-face (position 9 in figure 2) as the crater wear and/or on the supporting pads (positions 20 and 21 in figure 2).

### 3.3. Tip design and point grind.

Among many issues in the selection of proper tip design and its point grind, the following are of prime importance in high penetration rate gundrilling: the shape, dimensions, and location of the coolant passage (position 18 in figure 2), two/three supporting pads vs. non-micable supporting continuum (figure 2), and tip point grind which often results in the choice between to the facet and cam grinds.

The shape, dimensions, and location of the coolant passage (position 18 in figure 2) in the gundrilling tip differ from one carbide manufacturer to another. In terms of shape, gundrill manufacturers have adopted various shapes for this passage: one or two circular holes or a single kidney-shaped hole as shown in figures 1,8 and 7 respectively. Interesting to mention that the shape, dimensions and location of this passage are determined by carbide manufactures having very limited knowledge in gundrilling. Moreover, there is an opinion among gundrilling practitioners that the kidney-shape hole makes the tip weaker causing its breakage.

In any consideration of the discussed parameters of the coolant passage one has to realize that these parameters are of hydraulic nature [4]. Deliver the sufficient coolant flow rate with minimal pressure losses should be considered as the objective of all coolant channels and passages in a gundrill. These pressure losses determine the inlet coolant pressure for a given flow rate or, vice versa, determine the flow rate through the gundrill under a fixed inlet coolant pressure (as often used in practice). The total pressure loss is the sum of (a) the frictional losses in the tubular shank, (b) pressure losses due to flow sudden contraction from the shank passage into the coolant passage in the tip, (c) the frictional losses in the coolant passage in the tip, and (d) pressure losses due to coolant flow interaction with the bottom of the hole being drilled. Experiments have shown [4-6] that for short and normal length gundrills, losses (b)-(d) are an
order greater than (a) while for long and extra long gundrills these losses are of the same order. The minimum pressure losses occur when the tips having a kidney-shaped coolant passage are used. As such, the kidney-shape hole does not make the tip weaker. In other words, it does not cause tip breakage as shown by FEM analysis and by direct testing. Rather, tip fracture is often caused by improper brazing and coolant insufficient flow rate. Therefore, the kidney-shape coolant passage in the tip should be unconditionally adopted for high penetration rate gundrills because these tools require a high coolant flow rate which normally cannot be achieved with one and two-hole coolant passages under the inlet pressure allowed by the many existing gundrilling machines used in the automotive industry.

The design and location of the supporting pads (supporting continuum) greatly affect entrance stability, deviations of the holes axis and diametral accuracy. The results of multiple studies on the matter [7-9] have conclusively proven that gundrills with the supporting continuum, which are now common in the automotive industry, are always inferior to that with the supporting pads. The use of the supporting continuum does not have any advantages in gundrill performance. Although it only simplifies drill’s periphery grinding in drill production, the supporting continuum results in unstable drill locating in the starting bushing and in the hole being drilled. Gundrills with two and three (when cross-hole gundrilling is the case) 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 pads and sufficient radial relief are used.

Tip point grind plays a crucial role in high penetration rate gundrilling. In the automotive industry, there are three principally different grinds of the gundrill flank surfaces known as the facet (plane-shaped flank surfaces), partial cam and cam (helical flank surface(s)) grinds. These are shown in figure 9.

Figure 9. Gundrill point grinds used in the automotive industry: (a) facet, (b) partial cam, (c) full cam.

The facet grind is used primary by automakers outside the U.S. while car manufacturers in the U.S. still prefer the cam grind. In the cam grind, the flank surface of the outer cutting edge is a helical surface having the lead defined by that of the cam of the grinding fixture. Different gundrill manufacturers use different standards on the lead and generating diameter of such a surface depending upon drill diameter. Modern designs use great lead and generating diameters
so that the flank surface of the outer cutting edge does not affect the shape of the flank surface of the inner cutting edge and that of the shoulder dub-off surface (position 18 in figure 2) as seen in figure 9b. It is believed that, compared to the facet grind, such a grind makes the outer cutting edge stronger. In older designs (for example US Patent No. 2,325,535) which are still in wide use for gundrilling of crankshaft and powertrain parts, a relatively small lead and generating diameter of the helix surface is used so that this surface cuts through the outer flank and shoulder dub-off as shown in figure 9c.

In conventional gundrilling, there is no significant difference in tool life of gundrills with the discussed point grinds. The facet grind provides better cooling and lubrication conditions of the outer cutting edge while the cam grinds assure better heat conduction into the tip from this edge. In high penetration rate gundrilling, however, the facet grind shows significantly better performance when the location of the facets that form the flank surfaces are properly assigned by the drill design and its point grind.

3.4. New patented gundrill designs

Having analyses working conditions of the gundrilling system, Ford Motor Co developed and patented a new methodology (VPA methodology) for designing gundrills. The following constitutes the background of the VPA methodology: the first law of metal cutting [10]; a new physical concept of efficiency of the metal cutting system [11]; a new physical concept of tool wear [12] and resource [13]; new cutting tool testing methods [6, 14, 15].

Any particular VPA design assures minimal tool wear rate and the maximum tool resource in the areas of the cutting edges where tool wear limits tool life. This is accomplished by properly distributing the coolant that flows around the drill tip. As such, the desirable temperature distribution is achieved in combination with gundrill static and dynamic stability.

Figure 10 shows some results of the comparison of the best conventional gundrills used in the automotive industry (light bars) with the VPA gundrills (dark bars).

4. Machine

The most common method of gundrilling in the automotive industry is one where the gundrill rotates and the workpiece is stationary. This method imposes special requirements on the accuracy of gundrilling machines and their components. The alignment of the gundrill components should be next to perfect when drilling holes having diameters less then 10mm (0.4”) in light materials such as aluminum alloys, i.e. when the rotational speed (6,000-15,000 rpm) and the feed rate (600-1000 mm/min (24-40 in/min)) are high. The clearance in the starting bushing, drill holder-starting bushing and whipguide alignments, and the accuracy of the feed motion are key factors in using this method.

Although awareness of the importance of machine alignment grows in the automotive industry, there are at least three important issues that remain. First, there is no simple way to check the discussed alignment. in many gundrilling machines built in production lines. Normally, it takes many hours to clean up the space for such a testing. Second, the discussed gundrilling machines
do not have any means to correct alignment when needed. Commonly, shims are used to adjust this alignment that reduces the machines dynamic stability. Third, the alignment is normally checked between the starting bushing holder and the spindle of the machine. Although it is an important parameter, it is not sufficient. It should be clearly understood that the alignment in the system ‘actual gundrill holder- actual starting bushing’ should be examined although it is not that easy accounting for the current method and accessories used for misalignment checking.

Yet another important issue in the consideration of alignment is the whipguide (figure 3). Unfortunately, there is not much data on the influence of this alignment on the drill performance. Extremely important and unknown to end users fact follows from the comparison of data presented in figures 11a and 11b: the whipguide alignment affects the deviation of the hole axis much more than that of the starting bushing. Unfortunately, there is no simple way to check and to correct the alignment of the whipguide(s) on many machines used in the automotive industry.

The clearance between the gundrill tip and the starting bushing is another important but often ignored system parameter. Ideally, this clearance should be next to zero. However, it is not possible in any practical situation due to a number of different factors (drill free rotation and penetration, tip back taper, wear of the tool and starting bushing etc.). The excessive clearance in the starting bushing is the prime cause for entrance instability in gundrilling when the rotational speed and feed rate are high. This instability causes the formation of a bell-shaped part at the hole entrance known as the bell mouth as seen in figure 12a. A special analysis of gundrill failures showed that excessive clearance in the starting bushing is the prime cause for the so-called “unpredicted” drills’ failures. One of the most common failures is that of the side cutting edge as shown in figure 12b. Therefore, when one uses high penetration rate gundrilling, only specialized gundrilling bushing should be used and gundrills should not be re-sharpened beyond approximately 1/3 of the original tip length. Unfortunately, the later is not yet a common practice as can be clearly seen in figure 6b.
Figure 11. Deviation of the hole axis (position error) for different gundrilling methods: (a) influence of the misalignment of the starting bushing, (b) influence of the misalignment of the whip guide. Gundrill 10 mm (0.394”) dia, n=1600rpm, f=0.04mm/rev (0.0016in/rev).

Figure 12. Common consequences of entrance instability: (a) bell mouth, (b) failure of the side cutting edge.

The wear of starting bushings and bushing holders should be inspected periodically and the starting bushing should be changed when the clearance in the starting bushing exceeds that assigned by ISO fit H9/h9. Unfortunately, this is not yet a common practice in the automotive industry. This is due to a common design of gundrilling machines with “inaccessible” starting bushings. It other words, if one wants to check and/or change the starting bushing a lot of time has to be spend doing so. Naturally, there is no time available in production environment to check these items regularly. As a result, many starting bushings and bushing holders are overworked way beyond the acceptable level as shown in figure 13ab.

5. Coolant system

High-pressure coolant delivery is necessary to cool the workpiece and the tool, to provide lubrication between tool and workpiece as well as to carry away chips from the cutting area along the flute to the chip box. Cooling action dissipates both the external heat of friction and the internal heat of plastic deformation due to cutting and burnishing. Lubrication between the workpiece and the drill contact areas reduces contact stresses and amount of the thermal energy generated on these areas so it reduces adhesion and/or diffusion wear of the gundrills. To
effectively carry chips away, the coolant should possess a sufficient combination of viscosity and velocity. Improper selection of this combination causes chip plugs in the flute that lead to an increase in torque and probable drill breakage.

Figure 13. Overworked (a) starting bushing and (b) shirting bushing holder.

There are three basic types of coolants used in gundrilling in the automotive industry:

Oil-based coolants known as ‘Straight Oils’ are generally used for gundrilling of alloyed steels on stand-alone machines having own coolant supply system. Compared to water soluble, oil-based coolants significantly reduce tool wear, yield better surface finishes, and generally improve the accuracy of drilling. However, it happens only when such coolants contain EP (extreme pressure) additives of sulphur (2.5-3.5 %) for high alloy steels and heat treated cast irons, and chlorine (3.5-5 %) for light ferrous materials, and 10-14% of fat. Low coolant viscosity aids in good heat dissipation and good load carrying capacity. It also reduces the risk of pump starving when cold starting, improves the efficiency of filters, and reduces the amount of oil carried off with the chips. The kinematic viscosity should generally not exceed 20-30 cSt/20°C. In exceptional cases, 45 cSt/20°C can be used.

Water-based coolants known as ‘Water Soluble Oils’ are used for machining aluminum alloys on in-line gundrilling machines where the coolant is supplied from a central coolant pump station. These coolants generally more economical and can be used for non-ferrous metals and high machinability steels under light cutting conditions. EP additives contained in water soluble oils prevent work material adhesion to the tip. These coolants also contain film strength enhancers (animal and vegetable fats) to reduce friction and wear. Dilution 8 to 1 is normally used while dilution greater than 10 to 1 significantly reduces film strength and creates vapor pockets at high tool load areas in the gundrilling zone that reduces tool life dramatically.

Synthetics are water-based fluids that are easier on the environment but harder on the gundrill. It is used, however, in gundrilling cast irons with great success.

Coolant filtration is essential to system performance. Because the coolant collects and circulates considerable quantities of both coarse and fine chips, it must be carefully purified in the interests of both tool life and hole quality. Poor filtration leads to increased coolant temperatures and rapid failure of the coolant pump. It also causes premature failure of solenoid valves, leaking servo valves, and bearing failure in the rotating coupling. Cartridge filters of size in the range of
5-10 microns for high precision holes should be used. Filtration of particles of 15-20 microns for precision holes and in the range of 20-30 microns for normal holes should be guaranteed. Drilling cast iron requires rough filters, magnetic drums, or rolled media, followed by a bag type or woven media polishing filter.

The coolant temperature defines to a large extent its cooling, lubricating, and transportation abilities. This is particularly important with oil-based coolants. About 40-50°C (100 to 120°F) is generally recommended as the maximum temperature of the coolant. It can often be maintained by circulation through a heat exchanger or even by installing a fan to blow across the surface of the coolant reservoir. When precise holes are to be drilled, refrigeration systems may be necessary.

Coolant pump(s) plays a more important role than one thought. Unfortunately, most of the gundrilling coolant supply systems have the inferior type of pumps, called variable-displacement pumps. A variable volume pump is designed to maintain 'set' pressure. If an obstruction is encountered by the coolant flow, the 'set' pressure (the pressure seen on the gauge by the operator) will be maintained but the flow rate supplied to the tool will actually decrease because coolant will be diverted through the pump's internal relief valve. As a result, the obstruction (in the case of a chip jam in the flute of the tool) can, in fact, be worsened and quickly lead to drill failure. Experienced practitioners in industry change these pumps with fixed-displacement pumps.

Coolant flow rate and pressure are two important system parameters falling in the category of frequently asked questions on gundrilling because of the discrepancies in the data provided by different gundrill and gundrilling machine suppliers. It causes an ever-going endless discussion on the coolant pressure and flow rate – which one is more important and thus should be controlled in gundrilling? The answer to this question is unconditional and straightforward: the coolant flow rate. The coolant pressure must only be considered as means to assure the required flow rate. Unfortunately, this issue is not well understood by gundrill and gundrilling machine manufactures and end users.

Figure 14a shows the reaction of the chip lying on the side of the V-flute to the coolant velocity. When this velocity is small (zone 1), the chip does not have any reaction as shown by the flow profile, which is shown next to the gundrill cross-section. If the coolant velocity increases then isolated chip fragments start to move in the direction of the coolant flow (zone 2). Still, other chip fragments are not moving and thus a chip plug may form at any time to obstruct chip removal. At certain coolant velocity (transition between zones 3 and 4), called the critical velocity, all chip fragments start to move along the V-flute without forming a stationary deposit in the V-flute. Although the flow profile is not uniform (and thus the flow is in the so-called heterogeneous mode), i.e. more chip concentrated in the region close to the V-flute wall, it is already acceptable in gundrilling. The coolant velocity that corresponds to the beginning of the heterogeneous mode of chip transportation in the V-flute is called the critical velocity, \( v_{cr} \). This can be calculated as

\[
v_{cr} = 8.4 \left[ C_v \left( \frac{\rho_h}{\rho_c} - 1 \right) g D_{hv} V_s \right]^{1/3}
\]
where $C_v$ is the weight concentration of the chips in the coolant expressed as fraction of unity; for reliable gundrilling $C_v = 0.004 - 0.005$; $g$ is the free-fall acceleration; $\rho_c$ is the density (or volumic mass according to International Standard ISO 31) of coolant, $\rho_{ch}$ is density of chip; $D_{hv}$ is the hydraulic diameter of the V-flute, mm; $V_s$ is the setting velocity of the chip calculated as

$$V_s = \frac{(\rho_{ch} - \rho_c)d_p^2}{18\mu}$$  \hspace{1cm} (2)

Here, $\mu$ is coolant dynamic viscosity, $d_p$ is the equivalent diameter of a chip particle.

![Figure 14](image)

**Figure 14.** Influence of the coolant velocity (flow rate): (a) diagram showing the influence of the coolant velocity (flow rate) in the chip-removal passage (the V-flute) of a gundrill on chip transportation mode and (b) a typical failure of a gundrill due to insufficient coolant flow rate (velocity) in the V-flute.

Because the coolant velocity in the V-flute is determined as the coolant flow rate over the V-flute cross-sectional area ($A_{vf}$), the flow rate which assures the critical velocity calculates as

$$Q_{cr} = V_{cr}A_{vf}$$  \hspace{1cm} (3)

and called the critical flow rate.

When the coolant flow rate in the V-flute is insufficient to transport the formed chips, a chip plug(s) forms in this flute causing an excessive drilling torque and thus drill failure as shown in figure 14b. To prevent this from happening, the coolant should be delivered at the sufficient flow rate, which is 20-30% higher than the critical flow rate to assure reliable chip removal.

The coolant inlet pressure should be as high as needed to deliver the sufficient flow rate. For a given tool layout, this pressure may vary within a wide range (up to 2 times) depending on the design of a particular gundrilling system including the gundrill design. The critical parameters defining this pressure for a given gundrill diameter are: the viscosity of the coolant, the length of the gundrill, the cross-sectional area of the coolant passage in the shank (deferent gundrill manufactures use tubes of different wall thicknesses to produce their shanks), the shape and cross-sectional area of the coolant passage in the drill tip, and point grind.
Unfortunately, there are a number of limitations on the inlet pressure in practice. Among many, the following two are most common. First, many in-line machines in the automotive industry are supplied with the coolant from a central coolant system. Thus, the inlet pressure is the same for all gundrill lengths and diameters used in this line. As such, some gundrills are overflowed with coolant while others are starving with insufficient flow rate. Second, the limit on the coolant pressure for many stand-alone machines is imposed by the rotary union which introduces the coolant to the rotating spindle.

Having noticed problems with chip removal when the coolant flow rate is insufficient due to relatively low inlet pressure, gundrill manufacturers were forced to introduce the so-called stepped-slash gundrill point grind shown in figure 15a. According to this point grind, the coolant hole in the gundrill tip located on the stepped-slash part, which is far behind the cutting edges and the bottom of the hole being drilled. Because the coolant has a huge opening to pass through, the flow rate increases significantly for the same inlet coolant pressure and thus the problem with chip transportation should be resolved. However, a number of other problems come into existence. First, most of this increased flow rate is deflected by the bottom of the hole being drilled into the V-flute as shown in Fig. 15b. The deflected coolant flow is far from the cutting edge and does not help chip formation. The chip formed at the cutting edges has a hard time joining this flow and a ‘dead’ (or stagnation) zone is formed. When penetration rate is high and thus a lot of chips are formed, this stagnation zone may be the cause for the formation of a chip plug in the region adjacent to the cutting edge. This often results in drill failure shown in figure 15c. Second, because the coolant has an easy way to escape, it does not possess sufficient pressure to flow into small clearances formed between the gundrill flanks and the bottom of the hole being drilled. As a result, there is not much coolant at the flank surfaces where the presence of the coolant is vital for tool life.

![Figure 15. Common way of increasing the coolant flow rate: (a) stepped-slash point grind; (b) coolant deflection from the bottom of the hole being drilled and the formation of a stagnation zone, and (c) tool failure due to a chip plug formed in the region adjacent to the cutting edge.](image)

The only solution to assure the proper coolant flow rate is to apply sufficient inlet pressure. It may present a problem for long gundrills of small diameter (less than 4mm or 0.157”) because many of the existing coolant delivery systems are capable of generating maximum 1,500 psi (10MPa) coolant pressure that may not be sufficient to assure the sufficient flow rate. One of possible solutions is to install the coolant booster developed by Interface Devices, Inc. (Milford,
which is capable to supply the coolant at high pressure (up to 3,000 psi or 20 MPa). It can be installed on existing coolant-delivery systems as shown in figure 16 at a fraction of the cost of a new high-pressure coolant system.

Figure 16. Installation scheme of a coolant pressure booster (Interface Devices Inc., Milford, Conn).

Adequate process control parameters

The process control unit is a part of the gundrilling system and thus the proper selection of its inputs and outputs enhances system coherency. The selection of such inputs and outputs should be balanced: on one hand their number should be kept to a minimum to reduce the cost of the gundrilling system (initial cost and maintenance); on the other hand the control unit should control and adequately represent all possible normal and abnormal situations that might happen within the gundrilling system. Unfortunately, many existing control units do not utilize the relevant process parameters.

The variation of the amperage of the driving motor is used to measure the load on the gundrill. One should realize that the gundrill and the drive motor are installed on the opposite ends of the spindle unit. As a result, the part of the signal due to gundrilling itself often becomes insignificant compared to the inputs of other members of the driving train (the spindle, bearings, pulleys, driving motor’s rotor, etc.). It is clear that the situation gets worse when the diameter of the gundrill becomes smaller.

The inlet coolant pressure is controlled instead of the coolant flow rate. If any obstruction is encountered by the coolant flow, for example the brazing filler metal partially covers the coolant passage at the brazed joint ‘tip-shank’, and inlet pressure is kept the same by the control system, the actual flow rate decreases that leads to the reduction in tool life, poor chip removal and even breakage of the gundrill. The same situation happens when a chip plug forms in the V-flute.

The advanced gundrilling control system aimed for high penetration rate gundrilling should be able to control the following process parameters: the axial force and its acceleration, the drilling torque, the coolant inlet pressure and flow rate and the chip flow rate. To handle these parameters properly, an expert system should be a part of the control system. Existing control
systems can be retrofitted at low cost to control: drilling torque, inlet coolant pressure and flow rate. The corresponding transducers to control these parameters are commercially available and tested in applications to gundrilling systems.

References