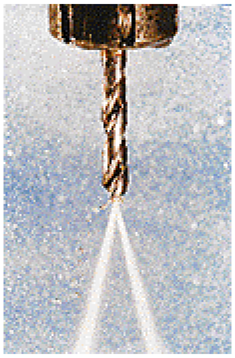
Cutting Fluids (Coolants) and Their Application in Deep-Hole Machining

Viktor P. Astakhov



1. Gutting Fluids (Coolants) – General Information

1.1 Tribology in metal cutting

Tribology plays a pivotal role in materials processing, particularly in metal cutting operations. The tribological conditions in these operations – real area of contact, stress distribution along contact areas, interfacial temperature fields, and highly active and freshly generated (nascent) surfaces – are more severe than in other applications.

Because the economic and technical feasibility of a process or product can be dictated by wear, tribological knowledge can help strengthen the competitiveness of the manufacturing industries and minimize the energy and resources they consume. Consider, for example, machining in the automotive industry, where the cost of the tool itself is insignificant, while the downtime and direct cost to change the tool each time it is worn or fails may be many times greater because such a change, if unscheduled, requires usually to shut down the entire production line. Or consider the cost of an expensive aircraft engine part rejected (at best) or failed (at worst) due to premature fracture of a cutting tool during machining or due to high residual stress generated in machining by the worn tool.

Current demands for tribological advances to support improved productivity coincide with additional challenges to tribology posed by the increased utilization of engineered materials. Some of these materials are useful as tools and dies and can perform optimally due to their improved properties. Others are difficult-to-machine work materials and create tribological problems during machining such as severe tool wear, great residual stresses in the machined surface, metallurgical and structural changes of the machined surface and many others.

Direct effects of tribology in metal cutting, such as wear of the tools and surface quality of finished products, are obvious. Indirect effects, less readily evident, are equally important. It is a know fact, for example, that a product's tribological history during manufacturing may later determine such characteristics as reliability, corrosion and irradiation resistance (important in nuclear power industry), fatigue tolerance, and frictional properties. The tribological problems may inhibit or impede the introduction of new or advanced machining processes such as high speed machining, combined machining, etc.

Figures for the economics of tribology in metal cutting are difficult to obtain due to the diversity and pervasiveness of the field. The replacement of a prematurely worn $2 tool insert or a $80 broken gundrill may hold production of a $1 million machine or assembly line. But how much of the associated cost can be attributed to tribology? Should the costs of replacement, downtime, capital invested in less-than-optimally efficient equipment, missed opportunities, etc. be included? Unfortunately, many researches have concentrated on the energy and direct costs aspects of tribology in metal cutting – energy consumption and energy savings due to tribology, saving on cutting tool consumption and quality improvement that could accrue from advances in tribology.

The ASME Research Committee on Lubrication has studied the role of tribology in energy conservation. It concluded that about 5.5 percent of U.S. energy consumption is used in primary metals and metal-processing industries and that 0.5 percent can be saved through advances in tribology of metal removal and forming processes, achievable through relatively modest research expenditures and effort. The combined potential savings in manufacturing alone of 1.8 percent of the national's energy consumption totaled about $21.5 billion per year [1]. Among the economic activities surveyed, the manufacturing sector was estimated to provide the greatest potential savings per dollar spent on tribology research.

Tribological conditions encountered in machining are severe [2-5]. The contact stress at the tool/chip interface is very high resulting in high shear stresses along the tool/chip contact area. The real area of contact is near the apparent area at the plastic part of the tool-chip contact where the shear stress may be much higher than the yield shear stress of the original work material. The chip surface sliding over the tool face is a virgin and thus chemically active. The mechanical properties of the chip contact layer are different (usually much superior) that those of the work material. The contact temperature may reach more than 1000^{o}C in machining difficult-to-machine materials. As the result, chemical interactions between the tool, the work material, and the environment are crucial in machining. Similarly, abrasion, adhesion, seizure, diffusion or their complex combination may occur between the tool and the chip.

Although there are a great number of research papers and book on the contact conditions on the tool rake face published in the last 50 years, we are very far from a clear understanding of the nature and complicity tribological phenomena in this region. Simple force diagram is still in use for determining "an average friction coefficient" on the tool rake face based on assumptions of equality and colinearity of the resultant force acting on the shear plane and tool face although it is well known that a coefficient of friction is inadequate to characterize the sliding between chip and tool [6]. On the other hand, the friction and normal forces, shear and normal stresses on the tool rake face could be obtained experimentally by conducting orthogonal machining tests and measuring cutting and trust components of the cutting force parallel and normal to the tool rake face. The friction coefficient thus obtained, unfortunately, does not much with common experience [1]. The same can be said about the shear and normal stresses distributions [5].

Similar processes take place at the tool flank face(s) where the tool is in contact with the work material primary due to work material spring back [2]. The nature and importance of this spring back is not fully understood and thus appreciated although the wear of the flank face often defines tool life. When material is cut by the cutting edge, it first deforms elastically and then plastically. When this edge passes over the deformed region, this region springs back due to the reversibility of elastic deformation. The heavier the cut, the greater volume of the work material deforms causing larger spring back. Besides, this work material has been plastically deformed so that its properties are different from those of the original material. As a result, the contact stresses at the flank face(s) are much higher than might be expected from just spring back [7].

Although the temperatures at the tool flank(s)/work material contact area are much smaller than those at the tool-chip interface, the properties of the work material in this contact are modified by its strain hardening. Moreover, the sliding speed at the tool flank/work material interface is much greater than that at the tool/chip interface (2-10 folds). Due to this high sliding speed a great amount of heat generated at this interface.

The contact temperatures at the tool flank(s)/work material interface, however, are much smaller that those at the tool-chip interface because the significant amount of the heat energy generated dissipates into the workpiece usually having a significant mass. It may not be the case while machining work materials having low thermal conductivity. As such, much smaller amount of heat energy generated is carried out by the chip and the workpiece so that the tool temperatures become much higher concentrating in the regions to the cutting edge.

There are three principal ways to reduce the severity of the contact processes in metal cutting and thus reduce the tool wear: cooling and lubricating of the machining zone [8-14]; coatings on the cutting tools [15-17]; and modification of the workpiece chemical composition [18-28]. Usually these are used in their combination although the compatibility of a particular combination of the cutting fluid, tool coating and workpiece chemical composition are practically ignored.

It follows from the foregoing consideration that the understanding of the tribology of metal cutting is of great importance. This should provide clear guidelines in the selection of parameters of the metal cutting system maintaining its coherence, high productivity and efficiency. Therefore, this chapter aims to present an entirely new inside into the nature of contact processes at the tool-chip and the tool-workpiece interfaces accounting for their relative motions and the cyclic nature of the cutting process.

1.2 Cutting fluids (Coolants)

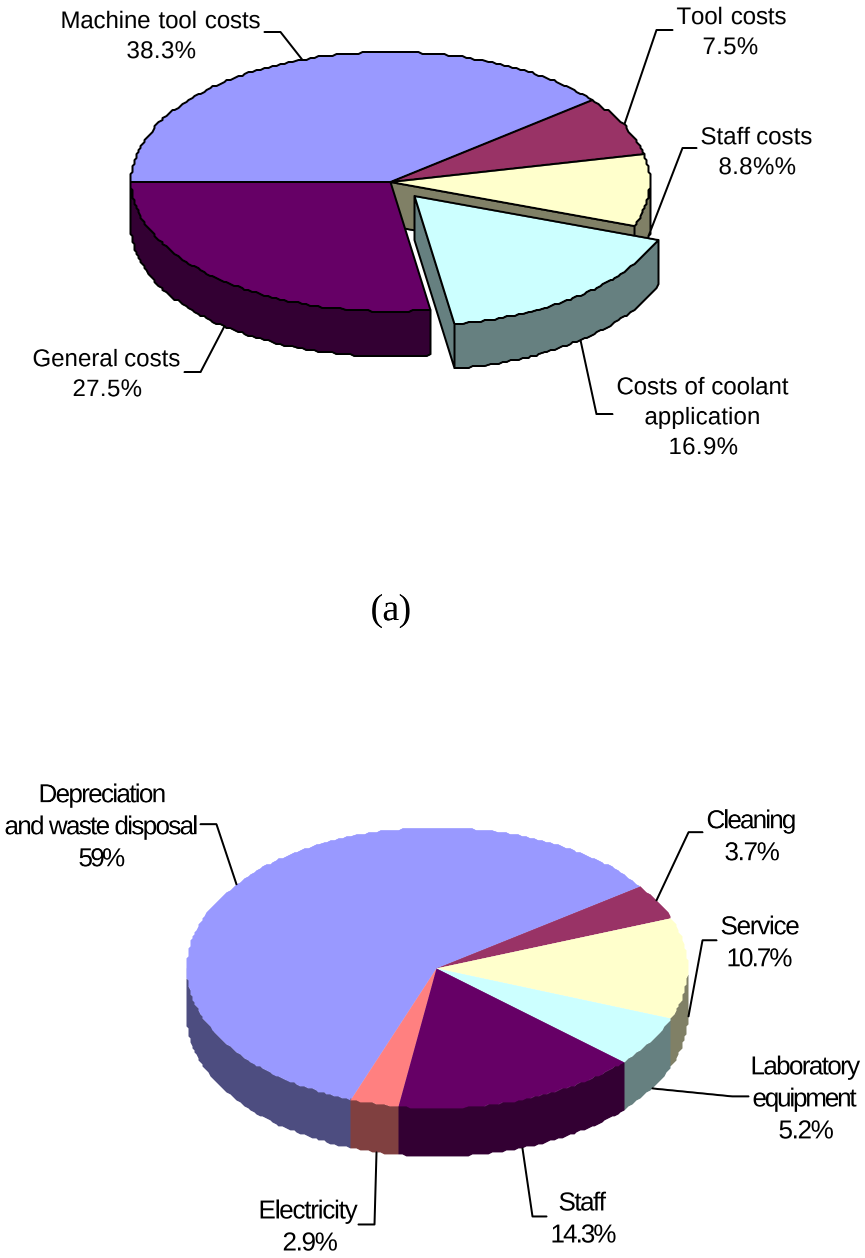
1.2.1 General

Cooling and lubrication are important in reducing the severity of the contact processes at the cutting tool-workpiece interfaces. Historically, more than 100 years ago, water was used mainly as a coolant due to its high thermal capacity and availability [8,9]. Corrosion of parts and machines and poor lubrication were the drawbacks of such a coolant. Oils were also used at this time as these have much higher lubricity, but the lower cooling ability and high costs restricted this use to low cutting speed machining operations. Finally, it was found that oil added to the water (with a suitable emulsifier) gives good lubrication properties with the good cooling and these became known as the soluble oils. Other substances are also added to these to control problems such as foaming, bacteria and fungi. Oils as lubricants for machining were also developed by adding extreme pressure (EP) additives. Today, these two types of cutting fluids (coolants) are known as water emulsifiable oils and straight cutting oils. Additionally, semi-synthetic and synthetic cutting fluids were also developed to improve the performance of many machining operations [10,11].

Although the significance of cutting fluids in machining is widely recognized, cooling lubricants are often regarded as supporting media that are necessary but not important [12]. In many cases the design or selection of the cutting fluid supply system is based on the assumption that the greater amount of lubricant used the better the support for the cutting process. As a result, the contact zone between the workpiece and the tool is often flooded by the cutting fluid without taking into account the requirements of a specific process. Moreover, the selection of the type of the cutting fluid for a particular machining operation is often based upon recommendations of sales representatives of cutting fluid suppliers without clearly understanding the nature of this operation and the clear objectives of cutting fluid application. The brochures and web sites of cutting fluid suppliers are of little help in such selection. The technique of cutting tool application, which includes the cutting fluid pressure, flow rate, nozzles' design and location with respect to the machining zone, filtration, temperature, etc, are often left to the machine tool designers. Moreover, the machine operators are often those who decide the point of tool designers. Moreover, the machine operators are often those who decide the point of application and flow rate of the cutting fluid for each particular cutting operation.

On the other hand, it was pointed out that the cutting fluids also represent a significant part of manufacturing costs. Just two decades ago, cutting fluids accounted for less than 3% of the cost of most machining processes. These fluids were so cheap that few machine shops gave them much thought. Times have changed and today cutting fluids account for up to 15% of a shop production cost [29]. Figure 42 illustrates the cost of production of camshafts in the European automotive industry [12-14]. The conspicuous high share of the costs for cooling lubrication technology reaches 16.9% of the total manufacturing costs. As seen from Fig. 1, the costs of purchase, care and disposal of cutting fluids are more than two folds higher than tool costs although the main attention of researchers, engineers, and managers is focused on the improvement of cutting tools. Moreover, cutting fluids, especially those containing oil, have become a huge liability. Not only does the Environmental Protection Agency regulate the disposal of such mixtures, but many states and localities also have classified them as hazardous wastes.

At present, many efforts are being undertaken to develop advanced machining processes using less or no coolants [7,9,30]. Promising alternatives to conventional flood coolant applications are the minimum quantity lubrication (known as MQL) and dry machining technologies. It was pointed out, however, that the use of MSQ will only be acceptable if the main tasks of the cutting fluid [31] (heat removal – cooling; heat and wear reduction – lubrication; chip removal; corrosion protection) in the cutting process are successfully replaced [7]. As such, the understanding of the metal cutting tribology plays a vital role.



(a)

(b)

Figure 1. Pie-chart representations of: (a) manufacturing cost at the German automotive industry; (b) structure of coolant cost [13,14].

1.2.2 Action of cutting fluids

A still open question in metal cutting regards the action of cutting fluids. When cutting fluids are applied, the existence of high contact pressure between chip and tool, particularly along the plastic part of the tool-chip contact length, should apparently preclude any fluid access to the rake face. In spite of this, to explain the marked influence which cutting fluids have on the cutting process outputs (cutting force and temperature, surface finish and residual stresses in the machined surface, tool wear) the theory considering these fluids as boundary lubricants is still leading [32].

Despite a relatively great number of publications on cutting fluids, only very few of them have been aimed to understand the role of a cutting fluid in the complex mechanics of the cutting process [34-40]. To account for cutting tool penetration to the rake face four basic mechanisms of cutting fluid access to the rake face have been suggested, namely, access through capillarity network between chip and tool, access through voids connected with build-up edge formation, access into the gap created by tool vibration, propagation from the chip blackface through distorted lattice structure. However, no conclusive experimental evidences are available to support these suggestions. It was observed that cutting fluids reduce (sometimes) the tool-chip contact length.

To understand the action of cutting fluids, the above-discussed system-based model should be considered as shown in Fig. 2. At the beginning of a chip formation cycle (Phase 1) the action of the cutting fluid is as follows: (1) contamination of the rake face at A providing lubricating between the chip and the rake face, (2) contamination of the two chip elements sliding over each other, (3) cooling the zone of plastic deformation at C and thus limiting the flow shear stress in this zone, (4) lubrication and cooling of the flank-workpiece interface at D. At the middle of the cycle (Phase 2): (1) contamination of the rake face at A providing lubricating between the chip and the rake face, (2) cooling of the free surface of the partially format chip at B, (3) cooling the zones of plastic deformation at C and E that increases the flow shear stress of the work material in these zones [41]. As such, the stress at fracture of the work material is achieved with less plastic deformation that promotes the formation of cracks [5, 42], along the surface of the maximum combines stress (4) lubrication and cooling of the flank-workpiece interface at D. At the end of a chip formation cycle (Phase 3): (1) contamination of the rake face at A providing lubricating between the chip and the rake face, (2) cooling of the free surface of the partially format chip at B reducing its plastic deformation and thus the chip compression ratio [2,5, 43], (3) cooling the zones of plastic deformation at C and E promoting propagation of cracks. When the cutting fluid penetrates into the crack formed in the chip free surface it suppresses the above-discussed healing of these cracks. Our multiple analyses of the chip structures obtained in cutting with and without cutting fluid prove this fact [44]. (4) lubrication and cooling of the flank-workpiece interface at D. Multiple experimental results are available to prove adequacy of the proposed model [5, 41,42,44-49].

When the cutting fluid is applied by simple flooding of the machining zone, the weakest actions of the cutting fluid is observed at A and D. The application of a high-pressure cutting fluid jet significantly increases tool life and lowers the cutting forces [50,51].

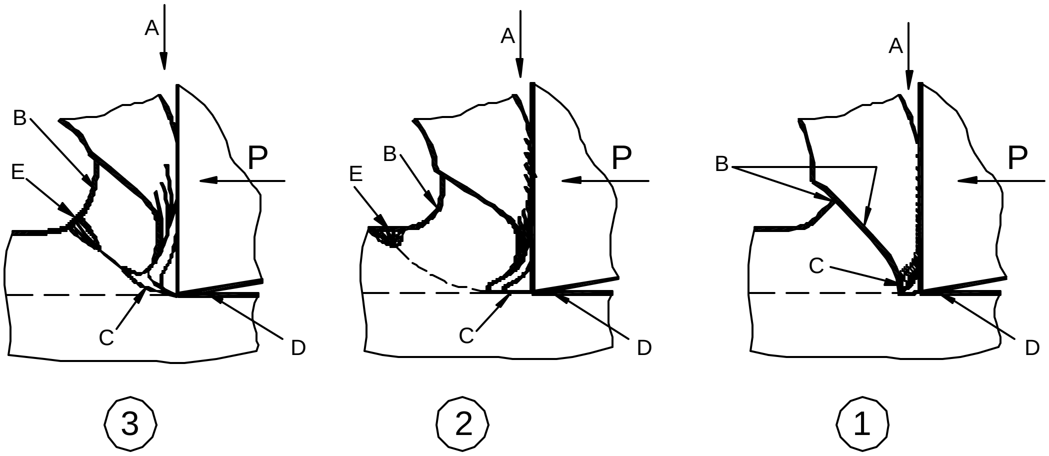


Figure 43: Cutting fluid action at different stages of a chip formation cycle.

The relative influence of the cutting fluid actions at A-D significantly depend on the frequency of chip formation and thus on the cutting speed [5]. The higher the cutting speed, the lower viscosity of the cutting fluid should be in order to penetrate into the above discussed cracks formed on the chip free surface. This explains why soluble oils of low viscosity are more efficient at high cutting speeds compare to straight oils.

1.2.3 Types of cutting fluids

There are the five major types of the cutting fluids available today:

1. Straight Cutting Oils. These are oil-based materials, which generally contain what are called extreme pressure or anti-weld additives. These additives react under pressure and heat to give the oil better lubricating characteristics. These straight cutting oils are most often used undiluted. Occasionally they are diluted with mineral oil, kerosene or mineral seal oil to either reduce the viscosity or the cost. They will not mix with water and will not form an emulsion with water. The advantages of straight cutting oils are good lubricity, effective anti-seizure qualities, good rust and corrosion protection, and stability. Disadvantages are: poor cooling, mist and smoke formation at high cutting speeds, high initial and disposal cost. Straight oils perform best in heavy duty machining operations and very critical grinding operations where lubricity is very important. These are generally slow speed operations where the cut is extremely heavy. Some examples would include broaching, threading, gear hobbing, gear cutting, tapping, deep hole drilling and gear grinding. Straight oils do not work well in high speed cutting operations because they do not dissipate heat effectively. Because they are not diluted with water and the carryout rate on parts is high, these oils are costly to use and, therefore, only used when other types of cutting fluid are not applicable.

2. Water Emulsifiable Oils. More commonly referred to as soluble oils. This, however, is a misnomer because they are not really soluble in water but rather form an emulsion when added to water. These emulsifiable oils are oil based concentrates, which contain emulsifiers that allow them to mix with water and form a milky white emulsion. Emulsifiable oils also contain additives similar to those found in straight cutting oils to improve their lubricating properties. They contain rust and corrosion inhibitors and a biocide to help control rancidity problems. Advantages of water emulsifiable oils are:

good cooling, low viscosity and thus adequate wetting abilities, non-flammable and non-toxic, easy to clean from small chips and wear particles using standard filters, relatively low initial and disposal cost. Disadvantages are: low lubricity, rancidity, misting, low stability (components have different degradation levels), in mass production require everyday expensive maintenance in order to keep the required composition. Water emulsifiable oils are the most popular cutting fluids in use today. Because they combine the lubricating qualities of oil with the cooling properties of water they can be used in a wide range of both machining and grinding operations.

3. Synthetic Fluids. Sometimes referred to as chemical fluids, these synthetic cutting fluids are water based concentrates, which form a clear or translucent solution when added to water. These fluids contain synthetic water-soluble lubricants, which give them the necessary lubricating properties. In addition, these synthetic fluids contain rust and corrosion inhibitors, biocides, surfactants and defoamers. Synthetic cutting fluids do not contain any oil. Advantages of synthetic cutting fluids are: resistance to rancidity, low viscosity and thus good cooling and wetting, good rust protection, little misting problems, non-toxic, completely non-flammable and non-smoking, good filtration with standard filters, biodegradable. Disadvantages are: insufficient lubricity for heavy duty applications, reaction with non-metal parts, residue is often a problem. As disposal problems become an ever increasing problem with the advent of the Resource Conservation and Recovery Act, synthetic fluids, because they present less of a disposal problem than emulsifiable oils, become more popular because synthetics are easier to treat than emulsifiable oils before they can be disposed. Synthetics are most definitely the products of the future. A very large percentage of the development work on cutting fluids is devoted to improving the synthetic fluid technology. However, there are still some problems and still some machining and grinding operations that for one reason or another cannot be done using a synthetic fluid. The major problem is that lubrication has always been the big problem for synthetic coolants. Another problem caused by synthetics is the sticky and gummy residue that is sometimes left when water evaporates from the solution mix. Metal safety on non-ferrous metals is a problem with some synthetics because of their relatively high pH (8.5 to 10.0) and the lack of oil to act as an inhibitor.

4. Semi-Synthetic Fluids. These are synthetic fluids, which have up to 25% of oil added to the concentrate. When diluted with water, they form a very fine emulsion that looks very much like a solution, but in fact, is an emulsion. The oil is added to improve lubricity. When synthetic fluids were in their early stages lubricity was a big problem, so the semi-synthetics were introduced. However, with the technology in synthetic lubricants improving, lubricity is not the problem it once was for synthetic fluids and, therefore, the semi-synthetic is becoming less popular.

5. Liquid nitrogen. Liquid nitrogen(having temperature -196^{o}C) is used as a cutting fluid for cutting difficult-to-machine materials where chip formation and chip breaking present a significant problem [52,53]. Liquid nitrogen is used to cool workpiece (for example, internally supplied under pressure in case of tubular-shaped workpieces), to cool the tool (which has the internal channels through which liquid nitrogen is supplied under pressure), or by flooding general cutting area.

Although the required properties of the cutting fluid should be formulated for each particular machining operations, some of the qualities required in a good cutting fluid could be listed as: (a) good lubricating qualities to reduce friction and heat generation, (b) good cooling action to dissipate the heat effectively that is generated during machining, (c) effective anti-adhesion qualities to prevent metal seizure between the chip and the rake face, (d) good wetting characteristics which allow the fluid to penetrate better into the contact areas as well as in the cracks, (e) should not cause rust and corrosion of the machine components, (f) relatively low viscosity fluids to allow metal chips and dirt to settle out, (g) resistance to rancidity and to formation of a sticky or gummy residue on parts or machines, (h) stable solution or emulsion, (provide safety work environment (non-misting, not-toxic, non-flammable (smoking), (i) should be economical in use, filter and dispose.

If there were one product that met all the particular requirements to the cutting fluid, the selection of a cutting fluid would be easy. But there just is not such a product. Moreover, many of the above-listed properties often cannot be guaranteed without actual testing of a particular cutting tool in a production environment. Such a testing, however, is expensive and time consuming. Therefore, a method to compare different cutting fluids for a particular machining operation should be beneficial. Although a number of attempts to develop such a method (for example, [38,54-56], no method has been developed for qualifying and comparing the performance of one cutting fluid to another [57].

2 Cutting Fluids (Coolants) in Deep-Hole Machining

2.1. Introduction

The cutting fluid plays an important role in chip formation and its removal, tool life, and hole specifications. Water based coolants and their aqueous mixture produced from them such as oil-in-water emulsions or solutions are inferior to the water emulsifiable lubricants, especially in their lubricating effects [58-60]. In deep-hole machining, there is a greater demand on the cooling and lubricating properties of the coolants than that in most common machining operations. Water emulsifiable oils can only be used in exceptional cases as in machining of easy machining materials under light cutting conditions.

Deep hole drilling coolants must therefore be made in such a way that they will form a coherent lubricating films under the high contact pressure and temperatures at the cutting edge of the tool, the chamfer, and the guide (supporting) pads. Metallic contact in these regions should be reduced to its possible minimum to avoid seizing. Liquid lubricants, especially mineral oils without additives, cannot fulfill these duties with the desired results under present-day requirements [58]. Under mentioned high contact pressures and temperatures, any solid lubricant film can separate the contact surfaces reducing friction and wear. These pressure-resistant films are produced by additives, which are blended into the oils. The basic task of these additives is to react chemically with the materials involved, and to form intermediate layers of high compressive and low shear strengths which act as solid or plastic lubricating films. These reactions should only take place at certain temperatures of the contact surfaces. At room temperature, the additives must not react with the tool, the surface of the hole being drilled, the components of the machine and its slide ways.

When water emulsifiable oils are used, especially when high stresses and temperatures exist between the contact surfaces, steam bubbles can form on the working surfaces of the cutting tool. Collapsing of steam bubbles produces a quenching effect by the incoming coolant. This shock-like cooling process can lead to the formation of cracks and thus leads to premature failure of the cutting edges [58].

The properly selected, mixed and maintained additives constitute the coolant suitability for a given deep- hole drilling operation. There are a number of such additives available in the market.

The polar additives were found very useful [58]. Such additives consist of the molecules containing polar groups. Polar oil molecules are said to be attracted by the metal surfaces so that an orientated and adhesive oil film is produced. This film has a greater load capacity and also a greater resistance to tearing than a film of untreated coolant. Also, polar additives form metal soaps, which act as high-viscosity plastic lubricant films. These metal soaps, however, have a relatively low melting point of around $120\ ^oC$ that makes them less attractive in deep-hole machining of steels. When light metals, such as aluminum, are machined, these soaps may be very useful. As such, these additives affect mainly sliding friction processes in the mixed and boundary friction regions (supporting pads, drill shank, auxiliary flanks).

Additives, which are primary intended to prevent seizing, or to reduce it, at high pressures and temperatures, are known as extreme pressure additives (EPA) [58-60]. Sulphur, chlorine, and phosphorus are used as EPA in most of deep hole machining coolants. Under high local pressures and temperatures, thermal decomposition of EPA takes place. Corresponding reaction products are formed with the metal sliding on one another as, for example, metallic sulphides, chlorides, and phosphades, which act as solid lubricant films. These must still be resistant at the contact temperatures preventing at the working point, i.e. they must not yet have reached their melting point, which is about 400^oC for ferric chloride films and about 800^oC for iron sulphide films. As seen, chlorine additives are suitable for deep-hole machining of light ferrous materials while sulphur additives are used for machining of high-alloy steels and heat-treated cast irons. Special attention should be paid to the use of such additives in machining of non-ferrous materials because these additives already discolor these materials at room temperature. Therefore, when drilling non-ferrous metals using a coolant with EPA, the parts should be subsequently washed if a bright hole is required.

A carefully selected combination of polar and EP additives may be very useful protecting the tool regions at different temperatures and contact pressures. Account must be taken of the fact that the individual additives also influence each other in their effectiveness, and that the working performance of a blended coolant depends, to a decisive extent, on the optimum addition of suitable additives, both in nature and quantity. In these processes, both compatible and incompatible effects are possible.

Figure 3 shows the effect of the coolant on the deep-hole machining process economy [58]. As seen, the use of a high-performance coolant results in the reduction of the total drilling cost. The results show that the drilling costs can be reduced quite considerably through the high-compounding and thus better coolant, as a result of the higher cutting speeds and feed-rates (which are possible with high performance coolants) and longer tool life. In application examples [58], the savings of the total costs with the high-quality coolant amount to 53% in solid drilling, 57% in trepanning, and 65% in

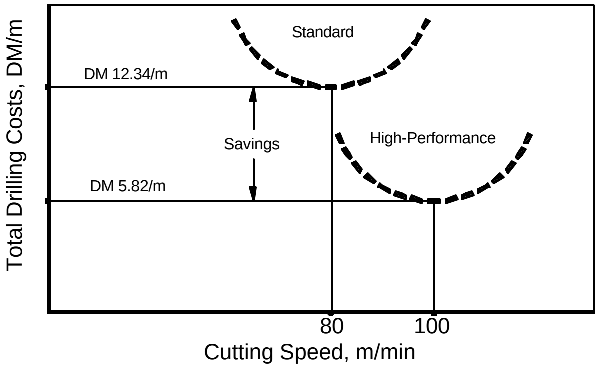


Figure 3. Effect of the coolant on the deep-hole machining process economy.

counter-boring. The calculations were made on the assumption that the higher quality coolant is 50% more expensive than standard.

Figure 4 shows the influence of different EP additives on tool life. The straight lines in a log-log coordinate system average the results of many tests with carbon and low-carbon alloy steels [59]. As seen, at relatively low cutting speeds, the coolant with a chlorine additive gives higher tool life while at higher cutting speeds the coolant blended with a sulphur additive is superior. This confirms that chlorine additives give longer life in the lower temperature range and sulphur additives are efficient at higher contact temperatures.

A comparison of the 'Neat Oil' coolant with water emulsifiable oils in deep-hole drilling was made by Nicholson [60]. His study consisted of three full tool life drilling tests, a drill life being considered the point at which it becomes necessary to re-grind the tool. The test conditions were identical in all the cases except the composition of the coolants. The tests were conducted with neat oil, a heavy duty EP soluble oil at 10:1 dilution ratio and the same EP oil at 5:1 dilution ratio. The tests were conducted on EN8 steel. The following parameters were investigated: drill wear, hole accuracy, and hole surface finish.

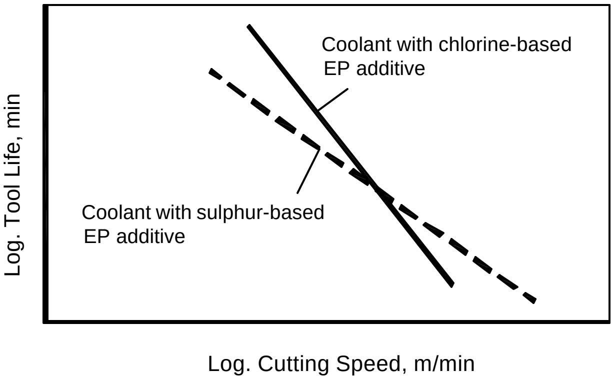


Figure 4. Influence different EP additives on tool life.

Figure 5 shows some results. As seen, the coolant concentration has sound effect on the tool wear and thus on tool life. Therefore, it is very important to keep this concentration in certain defined limits. The obtained results allowed to conclude that the neat oil is more suitable for deep-hole machining because its use results in: reduced wear at different regions of the cutting edge and supporting pads; better surface finish of the machined holes; higher accuracy of drilling; lower production costs; tool life is up to five times greater with neat oil than with water emulsifiable oils; even though the neat oil is more expensive, its cost is offset by the other gains such as increased tool life and the total production costs.

2.2 Requirements To The Coolant And Circulation System

The foregoing consideration suggest a number of requirements to the cutting fluid have been formulated as follows:

1. Good cooling ability. There are significant friction forces at the bearing areas of a gundrill, which result in heat generation. Heat also forms as the result of the plastic

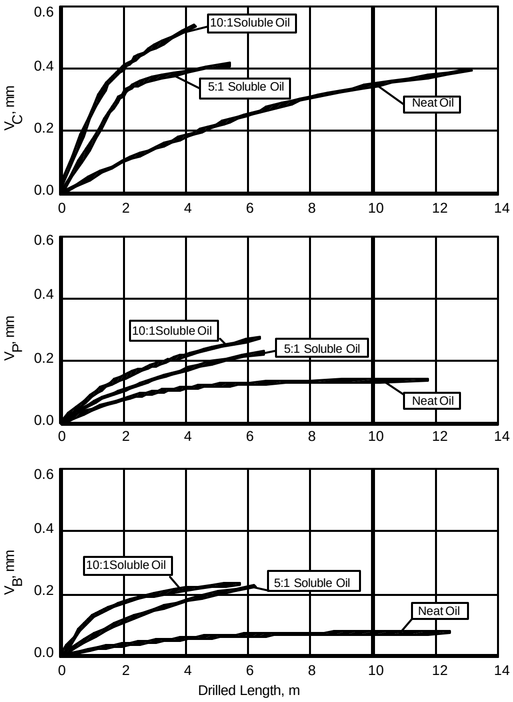


Figure 5. Influence of the coolant on three basic parameters of tool wear.

deformation of the workpiece material due to its cutting by the cutting edges and burnishing by the supporting areas (pads). It is known that approximately *(2 – 4)* 10^3 *Kcal.per hour* is generated in gundrilling of *5-20 mm dia*. The coolant must carry a greater portion of this heat away from the machining zone. It is then only necessary to ensure that the heat, taken up by the coolant during the drilling process, can be dissipated, either by adequate size of the coolant tank or through its refrigeration. The inlet temperature of the deep hole coolant should be *30 - 40*^oC. Lower coolant temperatures make a higher pressure necessary with the required flow velocity, or this velocity becomes too low. At temperatures above *40*^oC, the effectiveness of the coolant decreases significantly.

2. Good lubricity. To prevent dry rubbing and, as the result, seizure, at the cutting and burnishing contact areas, the cutting fluid should have some means to resist high contact pressures. Usually, it is achieved by adding sulpherized fats and/or chlorine.

3. Low viscosity. This is to assure its penetration in the relatively small passages at the restricted areas between the gundrill flanks and the bottom of the hole being drilled; and between the gundrill side surface and the wall of the hole being drilled. It also assures relatively low pressure losses in the hydraulic conduit of a gundrill making it possible to use standard coupling to introduce the cutting fluid into the rotating spindles. As the result, the kinetic viscosity of the coolants used in deep-hole drilling should not exceed *20 - 30 cSt/20*^oC. Only in exceptional cases can coolants up to about *45 cSt/20*^oC be used.

4. High clearness. To achieve reasonable tool life, the maximum size of the particles found in the cutting fluid, supplied into the machining zone, the deep-hole coolant should be reasonably clean. In production drilling, impurities down to about *50 mm* must be filtered out. Up to these particle sizes, the harmful effects of impurities on friction and tool wear generally remain within tolerable limits. However, when tool life is of prime concern, the maximum size of particles found in the coolant, should not exceed *35* micrometers when the quality of the produced hole is not an issue. Further improvement of the cutting tool filtration up to *15-20* micrometers yields a practically best combination of the hole specifications, tool life, and costs associated with filter maintenances.

We have to point out here that oil films supporting a gundrill is about *4* micrometers thick (*0.00015*”) so that theoretically any particle in the cutting fluid should be smaller than *4* microns to protect the contact surfaces. It is proven by our experience that further improvement in the filtration yields further increase in the tool life and hole quality and when the filtration reaches *1-2* micrometers, the tool life can be increased up to *10* times although it is not economical from the point of filtration. The great practical difficulties with filtration occur when drilling cast irons, aluminum, austenitic steel high alloys, and some other non-magnetic materials.

5. Good transportability. Because a gundrill produces a hole of any reasonable depth in one pass, the chip formed in the cutting area should be continuously removed as fast as it is produced. The supplied cutting fluid flow rate should be sufficient to carry out the formed chip at sufficient rate.

To deliver the coolant to the machine, a suitable circulation system should be used (designed, employed). The necessary pump power for the circulation system is calculated from the required coolant velocity, the flow cross-sections and the coolant flow-rate needed (these three will be discussed later). The size of the coolant tank should then be selected so that its capacity is at least ten times the maximum pump output per minute. Another way to look at this issue is that the volume of the coolant tank should be selected so that the charge of coolant will be circulated about 6 times an hour. With this circulation rate, one can still generally manage without coolant refrigeration allowing sufficient time for the coolant self-cleaning in the 'clean' tank (or section) due to gravitation. The latter is particularly important in machining of non-ferrous materials when magnetic filters cannot be employed.

All coolant containers should be so designed that they are easily accessible and can be cleared without difficulty. Any water, which has found its way in, should settle on the bottom of the container (tank) and one should be able to drain it out easily.

In the design of the coolant-carrying parts of the circulation system, care is to be taken to reduce foam formation. Although, this is particularly important when oil-based coolants are used, it also may happen with water-soluble coolants containing high concentration of EP additives. The coolant return lines should only emerge into the tank tangentially and never from a greater height, so that no air bubbles are contained in the coolant. The coolant tanks should have the largest possible liquid surface areas, so that the distance through which the bubbles rise in short and entrapped air bubbles cab separate quickly. The pumps must be so arranged and sealed off that no air can be entrained. An adequate baffle system is required to increase the maximum residence time of the returning coolant.

The collapse of surface foam can be accelerated by the addition of foam damping agents. However, care must be taken, since, through the addition of surface-foam-preventing agents, the capability of the coolant to release air is impaired. Foam dumping agents must therefore be dispensed carefully and should only be added gradually. A few *ppm* (g/m^3) are generally sufficient and should not be exceeded, otherwise the coolant becomes more and more permeated with entrapped air and the whole gundrill installation can become incapable of operating [61].

The time period to change the coolant (coolant life) mainly depends on how efficiently the impurities, which the coolant accumulated in its use, are removed and on the measures taken to restore coolant composition.

The action of the additives in the deep-hole coolant results in a certain consumption of these additives during the drilling process. The amount taken out is, however, so slight that with regular topping up with the fresh coolant, the effectiveness of the charge of coolant in the deep-drilling system is maintained. When refilling with recovered coolant from swarf centrifuges, care must be taken that this does not contain lower-blended coolant from other machine tools; otherwise, through the consequent dilution in additive content, the performance of the deep-drilling coolant can fail critically. When there is no facilities to centrifuge the swarf form deep-hole drilling machines separately, the recovered coolant should not be used for topping up deep-drilling systems. Rather, it can be used in machine tools with less severe requirements. As such, only fresh coolant is used for topping up.

There is no danger of excessive aging of the deep-hole coolant, if the coolant temperature of 40^o is not significantly exceeded. Significant aging of coolant occurs only above $50 - 60^oC$, and experience shows that the rate of aging approximately doubles for every 10^oC rise in temperature.

THE MAIN OBJECTIVE OF THIS CHAPTER IS TO PROVIDE RELEVANT ANSWERS TO THE FOLLOWING QUESTIONS:

1. What is the flow rate needed for optimum performance of a given deep-hole machining system?
2. What is the coolant pressure to achieve this flow rate?
3. How is the coolant energy distributed in the deep-hole machining system?
4. What are the design methods (as applied to the all relevant components of the deep-hole machining system) to optimize coolant parameters?
5. How to calculate parameters of ejectors for Ejector and other deep-hole tools?
6. Is it possible to achieve MQL in gundrilling? What exactly has to be done?

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