Gundrilling

an Overview of its Theory and an Analysis of its Performance as compared to Spiraldrilling





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Gundrilling

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Chapter 1

Introduction

This thesis is written as the final part of my study of Mechanical Engineering at the Hogeschool West-Brabant, Faculty Techniek & Natuur. It deals with the theory and practice of deephole drilling in general and more specifically with qundrilling 1 .

1.1 Origin of the subject

The idea to write a thesis on this subject first occured to me while watching a documentary on television, which showed a group of experimental archeologists who were trying to produce a bronze cannon, based upon a description² written in the 16th century. They intended to cast it and afterwards drill it, though they never made it to that last stage: the casting failed, the cannon ended up with a fault.

This documentary fascinated me, because apparently already in the 16th century, engineers were able to produce long, straight bores. A while later I was reading Jules Verne's classic 'From the Earth To The Moon...And...Round The Moon', in which an enormous cannon is constructed to launch a projectile to the moon. In this book (set in about 1870) a lot of attention was paid to the process of casting the cannon, yet Verne discarded the process of boring with just a few lines:

"[after the casting; PD] Immediately the operation of boring was commenced; and by the aid of powerful machines, a few weeks later, the inner surface of the immense tube had been rendered perfectly cylindrical, and the bore of the piece had acquired a thorough polish." (J.Verne, From the Earth to the Moon...and...Round the Moon)

I was puzzled by the lack of a description of the drilling; didn't Verne understand how to do this, so he couldn't write it down? Or did he consider it not interesting enough for his readers ? The latter seemed unlikely to me, given the effort he takes in explaining various scientific and mechanical principles in his books.

When a little bit later I happened to read a description of the process known as gundrilling, my mind was made up: I wanted to know more about this subject, and since I was looking for a subject for a graduation thesis, the natural way would be to choose gundrilling as the subject for my graduation project.

Another goal of this thesis, besides that of increasing my own knowlegde on the subject, is to give this technique a little bit more publicity. During my study the existence of this technique had never been mentioned. Not only that, but relatively little research is available on the subject:

"Among many tools used in automotive industry, gundrills eventually become responsible for a significant loss of production time. In our opinion it happens because not many research and development results and data are available on gundrilling compared to other tool types." (Astakhov, "The mechanisms of bell mouth...[part 1]", p.1)

By doing a thesis on this subject I hope I can increase awareness of the existence and usefulness of this technique and its capabilities a little. The next remark also shows the need for this:

"[...] a practical manufacturing engineer, process planner, or a tool layout designer could ask a logical question: Where can I learn more about the gundrilling system? The answer is unfortunately nowhere. The only book available on gundrilling is a small book published by the American Society of Tool and Manufacturing Engineers in 1967 (Bloch, F. et al., Self-piloting

¹ In Dutch: 'langgat-boren' or 'diepgat-boren'. In German 'Tiefbohren'. Deephole drilling is a broad term, that covers gundrilling (Dutch: 'kanonboren', not entirely correct), STS/BTA and Ejector drilling, as we shall see further on.

 $^{^2}$ This description was only recently discoverd. Back then the techniques of founding a cannon were surrounded by secrecy, for obvious reasons.

drilling, Trepanning, and Deep Hole Machining.[...]). Although this book remains a valuable source on drilling practices (naturally, no others) it describes what might be termed as an 'evolutionary' stage of development. It fails to explain the different reasons why one or another drill designs and components are being used, which one is better and when, what would happen if a particular parameter is altered, etc. [...] A limited number of research papers are written on some particular aspects of tool design [...]." (Astakhov, "Gundrills: very sharp points", p.4)

As I found out myself during the research on this subject, there are indeed some scientific articles which look at little pieces of the process, yet no articles that describe the entire process... As I was writing this thesis, Astakhov was himself writing the first book on this subject. How I wished he had written it a year ago, it would certainly have made the work on this thesis much easier! I believe his book will be welcomed very much by anyone involved in this field, though it doesn't cease to amaze me that it has taken this long for someone to write a book about it, given the effort put into research of other machining techniques, both in universities and companies. Admittedly, deephole drilling is not as widely used as e.g. turning, but even when taking this into account, the literature available on gundrilling is disproportionally little.

1.2 Self-defined research project

Another reason for choosing this way of graduating, as opposed to the more general practice in our school of doing a research project for a company, is the fact that by defining one's own project you are more free to choose the subject and the method of solving the problem. There's less of a link with the actual reality of a business environment. This has both a positive aspect (a good match is possible between the interests of the student and the research subject, something that may be less the case when doing research as requested by a company) and a negative aspect: there's less possibility to see how your solution to a problem is implemented by the company and how good it works. Also, there's no mutual relationship with a company, which is beneficial training preparing for a career. On the other hand though, since we are dealing here (as in my case) with part-time students, who have experience working in a business environment, for me the benefits of doing one's own research outweigh the downside of not having a direct link with a company.

This thesis is written in English, for several reasons. Firstmost, it provides me with an opportunity to practice writing in a foreign language, the practice of which is welcome. Secondly, after writing a thesis for a previous study, I later had difficulties when I wanted to make it available to non-Dutch people that had helped me during the research. The value of my thesis for those English and American persons was very limited. To prevent this from happening again and thus increasing the possible audience (the Dutch gundrill market is small, to use an understatement), I chose to write in English. Thirdly, in the event of a future career abroad, the ability to show the graduation thesis to an employer in a language he understands, would be of great benefit. Lastly, much of the literature on the subject is in English, so many quotes would still be either in English or be translated. For originality's sake I wanted the quotes untranslated. That means that several quotations that are in Dutch will not be translated. In those instances however, the contents of it will be summarized after the quotation, for the benefit of non-Dutch readers.

1.3 Research problem

As has been stated before, the goal of this thesis is to increase my knowledge on gundrilling, both theoretical and applied aspects of it. In order to attain this goal, a research problem has been defined:

what are the capabilities and limitations of gundrilling and how do they compare to those of spiraldrilling in practice.

1.4 Brief overview

This thesis is divided in two parts. The first part has a more theoretical approach in which, via literature study, the different aspects of holes and their creation will be dealt with. The second part is of more practical nature, where I shall show and compare two different methods of drilling holes.

In the theoretical part we will first look at exactly what a hole is. This may seem trivial, yet there are different kinds of holes, all with their specific characteristics. After this introduction to 'the world of holes', a chapter dealing with the applications of deephole drilling will follow. The purpose of this chapter is to give the reader a bit of insight in the uses and users of deep holes. This is followed by a chapter detailing the various deephole drilling techniques. Though this paper mainly deals with gundrilling, for a better understanding of the relative position of gundrilling in the field of deephole drilling it is deemed necessary to at least summarily show the other two common techniques. The final chapter in the theoretical part deals with gundrilling more specifically. Questions that will be addressed are among others, the forces acting on the tool, the importance of coolant and the determining of the optimum machining parameters.

In the second, more practical part, I shall compare two methods for the creation of holes: spiraldrilling and gundrilling. I shall determine the optimum machining parameters for both, after which several holes will be machined in two test objects. These holes will be measured and compared with regards to several of their most important properties, after which we will be more able to compare the benefits and shortcomings of both processes, not only in theory, but also in the (harsh) reality.

1.5 Sources

What's new for me in this project is that at least a part of the information, needed for the theoretical first part of this thesis, is gathered via the internet. During the writing of my last thesis in '98-'99, the internet played a minor role, due to the fact that it was less developed at that time and because I had access to the library of that university, with its wealth of literature on my particular subject. Because of the fact that at the Hogeschool Breda the library is of course much smaller, and because of the specificness of the subject, other sources of information had to be found. One of those is the internet, also because of its easy availability. However, where specific, detailed information is needed, use will be made of more classical sources, like libraries of technical universities.

1.6 Acknowledgements

Even though this is my thesis gundrilling, it couldn't have been made without the help of others. So, first of all I would like to thank Ing. Walraven who coached me when working on this thesis; secondly, Cees van Vught, who made himself available for two days in order to machine the spiraldrilled workpieces and to mr. Wagemakers, who helped with any problems I had when measuring the workpieces. Many thanks also go to Dr. Viktor P. Astakhov, who spent a substantial amount of time explaining some of the theoretical principles of the workings of a gundrill and the functions of its various edges, and whose articles provided an ample source of information. His critical remarks were appreciated. A final word of thanks goes to Ing. Van Hees and mr. Smeenk of Kluin Wijhe, who freed a day in their busy schedule to answer my questions and to gundrill the workpieces.

Chapter 2

The goal: a hole

"What ever you make in life, you have to start with a hole."

The process of deephole drilling is not an end in itself, but merely one method of reaching the goal, in this case a hole with certain characteristics. We have to keep this in mind when making the decision what process to use for the production of that hole. Some processes are better suited for some situations than others. Suffice it to say, deephole drilling is not the goal, it's just a means.

2.1 Definition of a deep hole

In order to be able to define a deep hole we first must take a look at the $length/diameter-ratio^4$. It's a measure of the length of a hole, as compared to its diametert:

L/D-ratio = lenth/diameter-ratio⁵ = length / diameter

Like any ratio, the outcome is a dimensionless figure that's a measure of the relative 6 length of the hole, and is an aid in determining how hard it will be to produce the hole, as we shall see later.

The generally accepted definition of a deep hole in the industry is a hole in which the ratio of length to diameter is larger than ten:

"Diepe gaten worden gekenmerkt door een grote verhouding tussen de diepte en diameter van het gat. De methode van diepgatboren wordt verkozen voor het boren van gaten met een diepte van meer dan $10\ x$ de diameter." (Sandvik-Coromant, p. C4)

This is also stated in an article in Machine shop guide:

"[...] Tanaka advises most users to reserve gundrilling for holes that exceed 10 times diameter because spiraldrilling and other conventional processes are usually more economical for shallow holes. On the other hand, gundrilling makes good economic sense for deep holes and is often the only way to produce one." (Koelsch, Productive deephole drilling)

Kluin Wijhe, a Dutch deephole subcontractor, also considers it the lower limit of the region of deephole drilling.

However, at least one author uses a more stringent definition of deephole drilling:

"In the drilling industry any hole with this ratio greater than about 3:1 is considered a deep hole." (McDonald, Deep hole drilling for the rear endplate..., p.1)

This is backed up by the VDI (Verein Deutscher Ingenieure) who have created several guidelines on deephole drilling:

"Tiefbohrverfahren im Sinne der VDI-Richtlinien 3208-3210 sind spanende Arbeitsverfahren für Bohrungen mit einer Bohrungstiefe ab 1/D = 3 im

³ Ernie Stallman of Badger Barrels (Kolbe, 1995).

 $^{^4}$ See e.g. Kals e.a., p.142 and p.144.

⁵ In the remainder of this thesis, it will be abbreviated to 'l/d-ratio' or just 'ratio'.

⁶ relative with respect to the diameter.

Durchmesserbereich D = 1...2000 mm [...]." (Institut für Spanende Fertigung, "Tiefbohren auf Bearbeitungszentren")

In any case, Sandvik, a major drill manufacturer, recommends the use of standard production processes and spiral drills for holes with L/D-ratios up to 5, which would technically lie in the area of deep holes if one accepts a ratio of 3 as a border.

In this thesis though I shall adhere to the more or less generally accepted definition:

a deep hole is a hole of which the length is larger than or equal to 10 times the diameter.

Some, like Dr. Astakhov, disagree with this definition. He stated in private e-mail exchanges that a hole becomes deep when the process can't cope with it without special measures (like e.g. 'pecking' in spiraldrilling, the breaking of chips and clearing them from the bore). Thus, he links the process (spiraldrilling) to a bore property (L/D-ratio). In my view a hole can be called 'long' if the L/D-ratio is greater than 10, just like the bore can be called 'rough' if Ra is greater than a certain value (linked to the application of the hole), 'straight' if runout is less than a certain value, etc. He is right in his assertion that certain processes have great difficulty in attaining some bore qualities, and therefore, the hole could be called (too) deep for a certain process, but that's a next step, namely the linking of the bore property to the process best suited for machining it. The choice of process depends a lot on the other required qualities of a hole, qualities we shall look at later. Just because according to this (more or less arbitrary) definition something would be called a deep hole doesn't necessarily mean a deep hole process should be used. What may sound even more strange at this moment, gundrilling can be and is used for drilling short holes. Obviously, the process of gundrilling has some other advantages that don't limit its application to the drilling of deep holes.

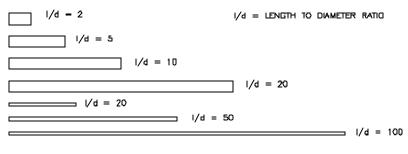
So our definition shouldn't be taken too strictly, the world of holes isn't as black & white as it may initially suggest. In fact it would be better to think of it as a continuum between extremely short holes (e.g. in plate) and extremely long holes. And this grey area between short and deep holes (or rather, which process to use for machining them) is getting even more blurred as process technology advances:

"Zunehmend werden, ins besondere im Überschneidungsbereich zwischen Kurzlochbohren (konventioneller Bohrtechnik) und Tiefbohrtechnik, Bohrwerkzeuge eingesetzt, die Merkmale von Tiefbohrwerkzeugen besitzen oder aber unter tiefbohrähnlichen Bedingungen betrieben werden." (www.tiefbohren.info)



These characteristics and circumstances are e.g. internal coolant channels, high coolant pressures and cutting inserts.

Just to put things into perspective, in the figure below there's an overview of holes with various L/D-ratio's. A L/D-ratio of 100 might sound trivial to someone new to the subject, the figure shows, drawn to scale, what such a hole would look like in reality. Just to wet the reader's appetite, gundrilling is capable of even deeper holes: there exist gundrills of diameter 6 mm, with a length of 7,5 m.



DRAWN TO SCALE

And if one should think that holes with a 1/d-ratio of 100 and higher, as produced by mechanical engineers, are impressive then one should take a look at what people in the oildrilling industry are capable of....

2.2 Sorts of holes

Apart from their length, holes may have other geometric properties that may limit the processes to choose from. We shall not go very deeply into this subject because it's outside the scope of this thesis. They will be mentioned briefly though, because it helps in showing the place that the subset of 'normal, straight' holes has in the more general set of holes.

The typical hole, the one that first comes in to people's minds, is the round one. It's also the one the most easy to produce, or rather there are the most processes to choose from. Then there are the non-round holes: either square, oval, etc. There are only a few processes that can create these kinds of holes, like milling and sink or wire EDM. Threaded holes are another special kind of holes. The usual way to produce them is by means of taps or, if the object allows it, machining them on the lathe or mill; with a special (planetary) tool head it is even possible to use sink EDM. Another distinction that can be made is between through holes and nonthrough holes ('blind holes') and between inclined vs. non-inclined holes, i.e. whether the hole is perpendicular with respect to the surface where it enters (and exits). The machining of non-perpendicular holes may require extra measures to work, but is possible with gundrilling. Holes may cross eachother, or have partial overlap (i.e. two holes that have a distance between their centers less than their diameter). Finally, there are the non-straight holes. These can vary from conical holes, like toolholders with a Morse-taper, to the more 'frivolous' holes, like the helical coolant channels in some spiral drills.

In this thesis we shall focus on normal holes, or rather, normal deep holes: straight, round holes with no other special features.

2.3 Qualities of a bore

There are several possible requirements to bore qualities. These are determined by the designer, who determines what qualities the bore must meet to be able to perform its assigned function.

In this paragraph, we shall take a brief look at these various qualities 8 and how to quantify them.

⁷ It should be noted though, that in oil-drilling the demands at the hole are very different. Roundness, straightness and exact position are usually not an issue, so we're really comparing apples to oranges. But still, it helps to put things into perspective...

 $^{^{8}}$ These are almost the same as recognised by Deckers & Schellekens (p.287), though arrived at independly.

2.3.a Diameter.

This is of course one of the most important aspects of a round hole. Since diameter in itsself doesn't say much about the tolerance of the diameter of the bore, it's usually followed by a measure of tolerance. Either by means of 'direct' tolerance, i.e. 9 (+.1/-.05) or in the ISO format: 9H7.

2.3.b Roundness.

This quality describes how well a section of the bore approaches a perfect circle. According to the NEN-ISO 1101 Norm (p.17),

"De tolerantiezone in het beschouwde vlak is begrensd door twee concentrische cirkels met straalverschil t."

The better the roundness of the bore, the smaller is the difference in radius between the two circles that encompass the hole.

2.3.c Roughness.

This is (one of the many) measures of the surface quality of the hole. It is a measure of how smooth this surface is. There are various indicators for roughness: Ra, Rz and Rmax are just a few of them. In this thesis Ra will be used as indicator, for several reasons. First, it's the most widely used of the aforementioned indicators. This has the advantage that many people have a feeling for the roughness, because they can compare it to roughnesses they have felt or measured in the past. Second, it's the preferred method for watching over the production process, because it's less influenced by extreme deviations:

"Ra geeft géén uitsluitsel over de profielvorm, rilafstand, poriën e.d., terwijl 'uitschieters' nagenoeg geen invloed hebben op het meetresultaat. Ondanks het geringe onderscheidend vermogen is Ra toch vaak een interessante en veel toegepaste ruwheidswaarde, bijv. voor:

- een *globale* indicatie van het oppervlakteprofiel waarbij eventuele 'uitschieters' de functie van het werkstuk niet aantasten, bijvoorbeeld: oplegvlakken [...], afdichtingsvlakken [...], lijmvlakken.[...]
- het 'bewaken' van productieprocessen, bijvoorbeeld van kogellagers (in een bepaald productieproces is de spreiding in Ra gewoonlijk gering)." (Van Gemerden, p.527)

However, in situations where extreme peaks and/or valleys in roughness influence the performance of the object, other measures (like Rz or Rmax) should be used in conjunction with Ra. In this thesis, only Ra will be used.

2.3.d Straightness.

This aspect measures the variation of the bore from a straight line, as drawn through the centres of the bore at both ends.

According to the NEN-ISO 1101 Norm (p.28), where straightness is called 'total radial runout' 9 ,

"De tolerantiezone is begrensd door twee co-axiale cilinders op afstand t van elkaar en waarvan de hartlijnen samenvallen met de referentiehartlijn."

⁹ In Dutch 'totale radiale slagtolerantie'.

The better the straightness of the bore, the smaller the difference in radius (t) of the two cylinders that encompass the cylinder of the hole.

It is sometimes not expressed in mm but in mm per meter bore length: mm/m. This is especially the case in the practice of quadrilling

2.3.e Location.

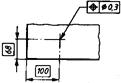
This aspect determines the aspect that the bore is in the place it was intended to be. If a hole is placed in the product but not at the right place, the ability of it to perform its intended function may be impaired.

According to the NEN-ISO 1101 Norm (p.23),

"[plaatstolerantie van een punt; PD] De tolerantiezone is begrensd door een cirkel met middellijn t, waarvan het middelpunt zich op de theoretisch zuivere plaats van het beschouwde punt bevindt."



The smaller this circle (with diameter t) is, the better is the hole placed in its intended location (or reversely, the higher requirement there is on the exact placement of it).

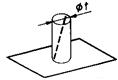


2.3.f Attitude

This quality determines whether the bore (3D) is perpendicular with respect to the surface (2D) in which it is drilled.

The attitude can be measured by drawing a line through the centers of both ends of the bore, and measuring the angle to the surface. Or, according to the NEN-ISO 1101 Norm (p.21),

"[haaksheidtolerantie van een lijn met betrekking tot een referentievlak; PD] Indien de tolerantiewaarde wordt voorafgegaan door het symbool \varnothing wordt de tolerantiezone begrensd door een cilinder met middellijn t en die loodrecht op het referentievlak staat."



2.3.g Hardness

Hardness is another quality of the bore surface (like e.g. roughness). It's generally not taken into account when defining the properties the bore must have, probably because it often doesn't matter much. However since the process of gundrilling may increase bore hardness it's mentioned here as a bore quality. There are several hardness measures that are available to us, of which I shall use the Vickers method.

These qualities will be the ones used further on in the practical part of this thesis to measure the 'overall quality' of the bores produced by the various drilling processes. In this thesis, they'll be used 'in reverse' from normal use: usually, a tolerance is specified in a drawing; after machining, this property can be measured and compared to the specification in the drawing to decide whether the actual hole is within tolerance. In the application part of this thesis, we don't have a drawing with specifications the bores must live up to; I shall machine the holes and then measure their tolerances, which will be the outcomes of the test. No comparison however is made to a drawing with specifications, as is done usually.

Chapter 3

Applications of deephole drilling

Gundrilling was developed about 150 years ago simultaneously by Russian and French gunsmiths. It was developed to provide a solution for manufacturing barrels that could withstand the high pressures of the new propellant nitrocellulose. This problem created a drive to come up with a material (steel) and a manufacturing process that could produce barrels of the quality that was required. Before gundrilling was invented, barrels were made by forging iron strips round a mandrel.

Despite its origin in the ordinance industry, only a small fraction of all gundrilling operations is nowadays used for that purpose. Only custom barrel makers, that use the process to produce very small volumes of high quality, accurate barrels for matches and precision shooting, still use it extensively; the major companies in the ordinance industry use different processes to produce their barrels, like hammering on a mandrel.

So, then, if gundrilling is hardly used any more for its original purpose, what then is it used for?

3.1 Modern applications of deephole drilling

The main applications nowadays are in a wide variety of industries, like automotive, die and mold manufacturing and the production of turbines (Astakhov "Why gundrills?", p.1). Basically anywhere where there's a need for deep holes with demand of a certain quality deephole drilling can and is used. In a brochure of Kluin Wijhe, the following list is given (Kluin Wijhe, 'langgatboren precisie onderdelen'):

- automotive industry
- petro-chemical industry
- electromechanical industry
- hydraulical & mechanical industry
- plastics industry
- aeronautics and space industry
- machine construction
- offshore and onshore
- shipbuilding
- food industry.

This list is in good agreement with the applications that Sandvik lists in its catalog:

"matrijzenbouw: gaten voor koelvloeistof; automobiel/truckindustrie: assen, zuigerpennen, motorblok (diesel), hydraulische cylinders, rupsbandschakels; procesindustrie: oliegaten; lucht-en ruimtevaartindustrie: landingsgestellen; scheepsbouwwerf: gaten voor koelolie in motorblokken; algemene constructiewerkplaatsen [...]." (Sandvik, p. C13)

"Defensie: kanonlopen." (Sandvik, p. C19)

Die and mold makers use deephole drilling to create the coolant-channels in dies and molds. Obviously the process of deephole drilling is capable of producing holes much in excess of what is needed for this application but that's not really a problem. Then again, the location of coolant holes is often more important than one might think: in the aluminium extrusion industry for example, a constant distance from the coolant hole to the cooling surface is very important, as to have a constant temperature gradient as the freshly extruded product is transported. Differences in surface temperature can lead to non-even cooling of the extruded aluminium product, leading to deformation or a non-even surface finish, a cosmetic defect.

In the automotive industry deephole drilling is used very extensively, for example to drill axles, piston pens, engine blocks and hydraulic cylinders. It's also used in the drilling of brake pads, an example of a short hole application.

Aircraft and spacecraft manufacturers use it to machine holes in landing gears. In the picture on the right, made at Kluin Wijhe, a landing gear of Airbus Industries is shown. It's made of titanium and is in its non-finished state: first it's machined to roughly the correct dimensions, then drilled (STS/BTA), whereafter it will be machined to the correct dimensions, with the drilled holes used as reference.

As can be seen, in a great variety of industries is the process of deephole drilling used. Anyone who has a need for a deep hole may find a use for one of the three processes of deephole drilling.



However, the processes are not only used for the machining of deep holes; the technique can have its advantages when drilling short holes, if high requirements must be met by the hole. An example is the earlier mentioned example of the drilling of brakepads in the automotive industry.

The fact that deephole drilling is used in a large variety of industries may also have to do with the fact that its application is not limited to easy to machine materials: gundrilling makes it possible to produce close tolerance holes in cast iron, carbon and alloy steel (including austenitic stainless steel), tool steel, high temperature alloys, titanium, beryllium, copper, brass, and aluminum, as well as graphite, wood and plastic; it can even be used to produce a bagpipe or clarinet:

"[...] or the instrument maker in Boston who uses his gundrill to generate the hole in a stick of ebony wood that will one day become a clarinet." (Gundrilling solutions)

Its productivity (and its capability to reduce what otherwise might take 3 processes, i.e. spiraldrilling, 3-flute drilling and reaming) makes it also very suited for machining workpieces with many holes: there was one demanding application I've read about, the drilling of the backplate of a drift chamber 10. This plate needed to be drilled with 30.000 holes, .95 mm diameter and 25 mm deep 11. Imagine having to perform 3 processes on each of these 30.000 holes. The savings that gundrilling produced in this application are significant.

As can be seen, the application of deephole processes has undergone a major shift, from primarily being ordinance oriented to use over a wide variety of industries ¹². But still deephole drilling is strongly associated with the manufacturing of arms, by those who know little about the process. The process is much more common that that, though; in fact, probably everyone has a piece of equipment that had the operation of deephole drilling performed on it (excluding people who own cannons or Airbuses): a car is the first thing that comes to mind, with deephole drilling being used in a large variety of parts, from the coolant channels in the engine-block and the hole in the crank shaft to the short holes in the brake-pads.

 $^{^{10}}$ an instrument used in nuclear research, a particle detector that measures the particle's position and shows its trace on a computer screen (Giancoli, p.1120).

¹¹ A cycle for each hole took about 20 seconds (machining and repositioning of drill). 30.000 holes of 20 seconds each... Compare this with having to perform thee times as many operations using conventional techniques.

¹² The gundrill would be a better symbol for the peace movement than the old one of the 'rifle broken in two': gundrilling may well be the process that has seen the strongest shift 'from arms to plowshears' than any other technique around.

Chapter 4

Overview of deephole drilling

Drilling is one of the most common methods of metal removal. It is estimated that almost 75 percent of all metal cutting material removed comes from drilling alone (www.equipment-news.com, 'the holey quest'). What the share of deephole drilling processes is in this is unknown, but it is a very much smaller fraction of it.

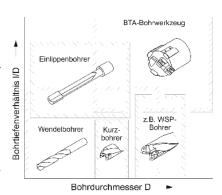
Less than 70 years ago, if someone was talking about deephole drilling it automatically meant he was talking about gundrilling, simply because there didn't exist any other processes at the time. Nowadays though, the mechanical engineer is in the fortunate position of having more processes to choose from when faced with the problem of deephole drilling. There are three commonly used techniques that are available:

- 1. gundrilling
- 2. STS/BTA system
- 3. Ejector system

Note that this classification does not reflect the tool design and specifics of deephole drilling but is based upon the method of coolant supply (rather, how the energy of the coolant is used) and chip removal.

The picture on the right gives an overview of the various methods for machining a bore, as a function of the $\rm L/D$ ratio and diameter. In reality most holes that need to be drilled lie in the bottom left corner of the graph, which explains the extensive use of spiraldrills. However for those applications with a larger $\rm L/D$ -ratio than usual, deephole drilling is the way to go.

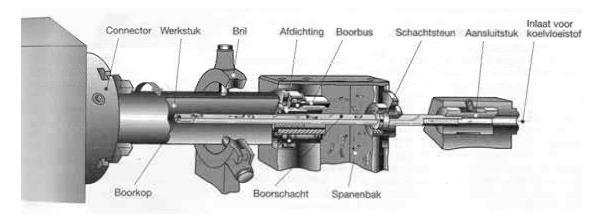
In this chapter, we shall take a closer look at the three deephole drilling processes, their characteristics, similarities and differences.



4.1 The Gundrill system

Of the three processes this one is the oldest, over 150 years old in generally the same form.

It is used for the drilling of holes with a diameter of about 0,95 to 35 mm with bore tolerances of IT9; roughnesses of $P_{\!_{\rm R}}$ in the range 0,1 to 3,2 um can be achieved with it (Sandvik-Coromant, p.C9). Maximum L/D-ratio's of 250 are possible (VDI-3208), though the technique is known to produce even deeper holes.

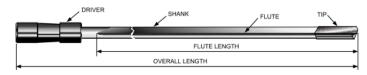


The gundrill system consists of several parts. Central is the gundrill tool itsself. Coolant is pumped through a hole in the inside of the drill to the drill tip where it exists and transports the chips via the outside of the drill (a V-groove in the shank) to the chip box, where chips and fluid are separated. The chip box also contains support for the shank of the gundrill to prevent excessive bending and a start bushing ('boorbus') that guides the drill during its entry stage. Also present is a seal which prevents leak of fluid to the outside (note that this fluid is under high pressure, up to 200 bar, depending on diameter). In this picture is shown a steady rest ('bril') to provide support to the workpiece. In the situation above it's the workpiece that rotates, the gundrill itsself is stationary; other methods exist, as we shall see later. The tool is held in a tool holder ('aansluitstuk') on the machine. This tool holder has a coolant channel inside and guides the fluid into the driver of the gundrill.

Perhaps the most characteristic aspect of gundrilling is the drill itsself, which looks very different from a regular spiral drill. One might even wonder how it is possible to drill very straight holes with a drill that is so very asymmetrical...

The gundrill consists of several parts:

- 1. tip (made of carbide, either entirely or partly)
- 2. shank (steel of high yield strength)
- 3. driver



It is not like the usual metal cutting tool, in the sense that it performs two different tasks at the same time:

- 1. cutting (at end of the tip)
- 2. burnishing (at support pads of the tip)

It is because of the burnishing that occurs that the hole has such good surface roughness, which can even be better than may be accomplished with reaming and honing.

The driver is brazed to the shank and acts in the transferring of torque from machine to drill. The design of the driver is machine specific. It has some sort of coupling system integrated in it, so coolant can be pumped from the machine to the tip of the head. The driver is the place where the coolant enters the drill.

The shank has a slightly smaller diameter than the tip, in order to provide clearance from the bore. It is made of a tempered sectional tube with a V-groove in it (included angle $110^{\circ}-120^{\circ}$) to allow the coolant with chips a way out. The shank is very important in that it determines how the drill will behave in the sense of torsional stiffnes, vibration and fluid flow (Titek, p.2). A gundrill shank must be constructed from high yield-strength material, followed by heat treatment to a tempered martensite structure (Astakhov, A primer on gundrilling). Usually 4130 steel (25CrMo4; Werkstoffnr. 1.7218) is used. Notice that the V-groove reduces torsional stiffness, something on which the other 2 systems (STS/BTA and Ejector) perform better with their round boring bars.

The tip of the drill is $brazed^{13}$ to the shank and usually consists of solid carbide (only in diameters greater than about 20 mm are carbide inserts used, because of the cost of carbide). The bearing pads are a decisive factor in the surface quality and dimensional accuracy of the hole (Titek, p.2).

The end of the tip ('point') is the part that does the actual cutting along with the side cutting edge. The design and geometry of it largely determine the shape of the chips and the effectiveness of the coolant, the lubrication of the tool and removal of chips (Astakhov, "The mechanism of Bell mouth [...] part.1", p.1135). It is immediately obvious that the drill is not symmetrical like a spiral drill. It is this asymmetrical shape, together with guiding pads on the tip, that give the drill its self-piloting characteristics, as we shall see in another chapter.

The gundrill can relatively easy be re-sharpened by the user, up to 60 times, according to literature. According to Astakhov, one should be happy to be able to sharpen 7-8 times, while mr. Smeenk of Kluin Wijhe stated that, if one doesn't let the wear get too bad, 15 to 20 times should be possible. However, since the tip is slightly conical (it has a back taper, i.e. further back the diameter decreases), the diameter slightly changes after a regrind operation:

"Beachtet werden muß, dass die ELB-Werkzeuge eine Konizität aufweisen (je nach Typ ca. 1:2000 - 1:400). Die Bohrer werden also bei 10 mm Nachschlifflänge im Durchmesser um ca. 0,005 - 0, 0125 mm kleiner." (www.tiefbohren.info)

This not only has consequences for the diameter of the bore but also for the size of the starting bushing or pilot hole that should be used for starting the hole, because the clearance between the tip of drill and the bushing gets larger after each re-grind operation.

A nice thing about the gundrill is that it is capable of producing holes that are burr-free, so no subsequent operation is necessary to remove the burr. This also leads to less risk of machine operators cutting themselves accidentally and thus bleeding to death.

Gundrilling can be used for drilling in a wide variety of materials, from plastics like Teflon and composites like fibreglass, to special high-strength die and mould materials like P20 and Inconel. Cast iron, aluminum, brass, molybdenum, steel, heat-treated stainless, polycarbonates, plastics, and many other materials too tough to spiral drill normally are easily gundrilled. Materials with a hardness of up to 46 HRC can be drilled.

16

¹³ this is the most common, 'classical' gundrill, like the Botek type-113 and type-110. There nowadays do exist gundrills with detachable tips or carbide inserts for the cutting or guiding part. These are more common in gundrills of larger diameter (>18 mm; www.tiefbohren.info).

Below are the various advantages and disadvantages of the gundrilling system according to Astakhov ("Why gundrills?", p. 5):

Advantages of gundrilling over STS(BTA) and Ejector systems

- good surface finish and close tolerance of the machined holes.
- can be used for holes with small diameter (about 1 $\ensuremath{\mathsf{mm.}}\xspace)$
- same nose geometry can be used for a wide variety of materials. If needed, geometry can be changed quickly by re-grinding.
- simple tool design results in relative low tool costs
- long life: gundrill can be re-sharpened 8-15 times

Regrinding can be performed by shop-floor operator.

- long tool life because of coolant supply to the flank-workpiece interface.
- much less sensitive to misalignment of start bushing. Often a starting hole will be sufficient.
- simple change to another drill of different diameter.
- relatively (with respect to STS & Ejector) low coolant flow rate required.
- gundrilling machines and their accessories are much less expensive compared to those for STS and Ejector drills.

Of course, gundrilling also has disadvantages when compared to the other systems of deephole drilling:

- relatively low productivity due to slow feeds.
- difficulties in re-sharpening of long gundrills of small diameters.
- requires higher coolant pressure.
- smaller allowable length-to-diameter ratio 15.
- not economical for diameters more than 2" (50 mm)

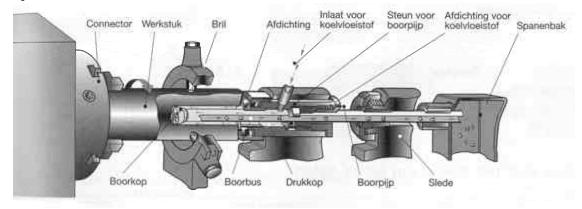
The technique of gundrilling, though basically unchanged for over 150 years, is still being improved upon (the other 2 techniques, STS/BTA and Ejector, are relatively young in comparison to gundrilling). The biggest modification of the process has been the introduction of carbides (in 1927, in Germany by the Heller company) with their longer tool life, better wear characteristics and higher productivity due to higher cutting speeds. At the moment experiments are being done to end the necessity of coolant fluid by using compressed air or a mixture of compressed air and fluid. In the field of the machines, new methods are being developed to reduce the sensitivity of the process to vibrations, like installment of dampers and using PLC's to control the process in such a way that when vibrations do occur, machining parameters are adjusted to stop the occurrence of it. But despite these innovations, the basics of the process have remained unchanged.

 $^{^{14}}$ according to another source 40-60 times (Metalworking Equipment News).

 $^{^{15}}$ Sandvik recommends a maximum L/D-ratio of 80 on p. C9, while on p. C98 up to 100.

4.2 The STS/BTA system

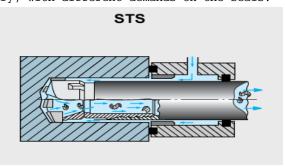
STS is the abbreviation of 'Single Tube System', while BTA stands for 'Boring and Trepanning Association'. Both names are used to describe the same process. Historically the process was first known as BTA, so called because of the German association BTA that started to market the process in the rest of the world after 1945. Nowadays it's also known under the more descriptive name of 'Single Tube System'.



The main difference between the various deephole drilling systems is fluid-flow and chip removal. In this picture we can see that the global setup of the STS/BTA system looks a bit like the gundrill system. Fluid enters the drill through the inlet ('inlaat') in the pressurehead, from where it is transported via the outside of the drill (with the wall of the bore acting as a pipe) to the cutting area. There it flows over the cutting edges, picks up the chips (while in the process cooling the area) after which the swarf is transported via the inside of the tube to the chip box. This is a difference with gundrilling where the chips were transported via the outside of the drill, the flute. Another difference is that 2 seals are needed; one between the drill and fluid coupler and a seal between the workpiece and fluid coupler (this last seal has to withstand high pressure and high rotational speeds).

Note that this is just one possible setup; other setups are possible in which the tool rotates and the workpiece is stationary, with different demands on the seals.

In the picture on the right is a closer detail of the STS-tool itsself. It can be seen clearly that fluid flows via the outside of the drill to the bottom of the bore, over the cutting edges and outside via the inner tube. Often carbide cutting inserts are used in this type of tool.



A major disadvantage of the system is that it can't be used for small diameters: the minimum that's achievable with Sandvik's tools (a major manufacturer) is 15,6 mm (Sandvik, p. C55). When small diameters are needed (down to 1 mm) gundrilling is the only option. The STS system can be used for drilling holes of over 200 mm in diameter (Sandvik, p. C6). Achievable roughness is Ra = < 2,0 um (Sandvik, p.C8) which is much worse than can be obtained by gundrilling (Ra up to 0.1 um).

The STS (and Ejector) system is newer, more modern than gundrilling. It isn't necessarily better, despite claims of the manufacturer:

"Eerste keuze voor hoge productiviteit. [...] De productiviteit van STS-boren is tot 5 maal hoger dan die van kanonboren." (Sandvik, p.C5)

and a bit further:

"4 tot 6 maal sneller dan kanonboren; [...] lage investeringskosten bij productie kleine series; standaard programma." (Sandvik, p.C55)

Serious questions can be asked as to their claim of 'low investment' 16 . Then again, the catalog is meant to help in the sale of their products, so like any commercial it should be interpreted with a grain of salt.

However, as Astakhov explains, the claimed benefits of STS drilling are not always arrived at fairly and may have great influence in the field of deephole drilling. The claims of some tool manufacturers even seem to discard gundrilling as non-productive and old fashioned:

"Improper gundrill designs and applications were probably the prime foundations for a legend that the so-called STS (Single-Tube System) drills have overhauling advantage over gundrills showing up to five-fold higher productivity. This legend is actively promoted by Sandvik Coromant Co who claims that STS deep-hole drills double throughput compared to gundrills [references removed; PD] or that a STS drill is 4-5 times faster than a gundrill [references removed; PD]. Such comparisons are often unfair due to the diference in quality of the tools to be compared. A conventional gundrill having a number of design and manufacturing flaws and made of relatively low quality of carbide of not even suitable grade is compared with the STS drill optimized for a given operation and equipped with the cutting edges made of superior carbide selected for the application." (Astakhov, "Why gundrills?", p.2)

and a bit further:

"When a gundrill is properly designed, its tool life is always higher than that of an STS drill of the same diameter $[\dots]$ " (Astakhov, "Why gundrills?", p.4)

I had noticed this bias of Sandvik to Ejector and STS drilling, as opposed to gundrilling, also in their catalog before I read the articles of Astakhov. This makes me wonder, maybe a bit cynical 17, but for a tool manufacturer the sale of a STS or Ejector drill is more attractive than that of a gundrill. The tool is more complicated, thus more expensive, probably with larger profit margins. A gundrill on the other hand is quite a simple tool in comparison, which can be reground many times by the user. In the catalog of Sandvik only a few pages are dedicated to the gundrill system, while 90+ pages are filled with STS and Ejector drills and their accessories.

Anyhow, this pushing of the STS system doesn't mean there's nothing good to it, as one might be tempted to think after reading some of this (I think correctly made) criticism; below is a summary of the advantages and disadvantages of the STS (BTA) system, according to Astakhov ("Why gundrills?", p.6):

Advantages of the STS (BTA) system:

- high productivity 18.
- the highest possible L/D-ratio.
- special tool heads that may combine a number of different operations (reaming, skiving and roller burnishing, trepanning, pull boring, chamber boring)

 $^{^{16}}$ Or perhaps they should explain what they compare it to; certainly not gundrilling...

¹⁷ Because one might argue that for a long-term mutually beneficial relationship, the tool supplier should help to solve problems together with their customer; not push their products with the highest margin.

with the highest margin.

18 I have trouble understanding this, given Astakhov's earlier criticism. My guess is that he means productivity is higher than with gundrilling but not 4-6 times as high as claimed by Sandvik.

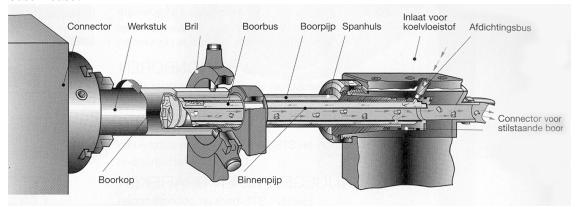
- theoretically, no restrictions on the upper diameter of the hole being drilled.
- different carbide grades can be used for different parts of the cutting edge.

Disadvantages of the STS (BTA) system:

- significant down time to change to another diameter.
- high sensitivity to the machine alignment and the clearance in the start bushing.
- complicated re-sharpening procedure, can only be done with specialised tools. Thus, often no sharpening is done, which increases tooling costs. The adjusting of the carbide inserts is complicated.
- high sensitivity to the shape of the chip produced. A drill ground for one material may not be suitable for another material, even though they may have similar chemical and mechanical properties.
- ${\mathord{\text{--}}}$ requires special drilling machines, high qualification of operators, engineering support and complicated maintenance procedure.
- requires highest coolant flow rate, with associated big coolant tanks, powerful pumps, big filters, cost of coolant disposal, etc.

4.3 The Ejector system

The Ejector system looks a bit like the STS system, but differs in the way the fluid is supplied: the boring bar and the drill consist of two coaxial tubes. The drilling fluid to the drill head is supplied through the annular clearance between the boring bar and the inner tube; chips and fluid are removed through the inner tube, like in the STS system. The torque of the drill is mainly taken up by the outer tube.



The system is sometimes also described as the Dual Tube System (DTS), for obvious reasons.

The advantage of it is that it can more easily be retrofitted to machines than the STS/BTA system. This is because no seal is needed between workpiece and drill: the outer tube of the Ejector system negates the need for it, which makes this system more easy to retrofit (Sandvik, p.C8). The STS system can only be used on special deep hole drilling machines, whereas the Ejector system can be used on deep hole drilling machines, NC machines, lathes, most conventional machines and machining centers (Sandvik, p.C8).

The name 'Ejector' is derived from the special way the coolant flows: when the fluid gets near the drill head (where the actual machining takes place), part of it is routed towards the cutting area; the rest goes via 'ejector nozzles' that re-route the fluid towards the outgoing stream. This creates a partial vacuum in the inner tube that facilitates chip removal. So, on the one hand there's overpressure in the outer tube and cutting area that pushes the chips away with the fluid that has made a 'full' loop, while in the inner tube there's a low-pressure area that pulls the fluid with chips out. The ejector nozzles can either be located in the drill head or near the connector of the drill.

As in the other 2 systems, in the picture above is just one possible situation; other setups are possible in which the tool rotates and the workpiece is stationary.

If we compare the Ejector system to the STS system, we see that at first sight they mainly seem to differ in the place the fluid enters the drill/boring bar; upon closer look, however, the real difference lies in the way the energy of the drilling fluid is used to remove chips. An advantage of the Ejector system is that the guide bushing can be much simpler, because there's no need for a seal. The major benefit though is that it can be retrofitted to almost any machine. But chip removal is worse than when using the STS/BTA system: with that system the high pressure fluid gets to the drill head, though locally there can be great variations in resistance, fluid velocity and thus pressure, which can (locally) be much lower than the pressure at the connector of the drill. In the Ejector system there is a lower pressure area in the inner tube (due to the venturi effect of the ejector nozzles) that helps to remove chips, but this underpressure is limited; the

 $^{^{19}}$ the ratio is somewhere between 40:60 and 60:40 (Astakhov, "On the design of ejectors $\left[\dots\right]$ ")

overpressure in STS/BTA is theoretically unlimited. The overpressure in the Ejector system is theoretically unlimited too, but since this system is mainly used to retrofit on other machines, which often don't have the capability to generate the high pressures needed in deephole drilling, coolant pressures in the Ejector system are usually lower than in the STS/BTA system.

Like the STS system it's not usable for small bores; the minimum diameter that can be made with Sandvik's tools is 18,4 mm (Sandvik, p.C8). Achievable roughness is Ra = < 2,0 um, equal to that of STS/BTA, but worse than can be obtained with the qundrill system.

Chip formation is even more important than in other deephole drill systems due to the limited diameter of the inner tube and the fact that the ejector nozzles can become blocked by chips, thereby hindering chip removal and possibly causing breakage of the tool. The generally lower pressures in the Ejector system doesn't make matters better.

The criticism that Astakhov has on the pushing of the STS system by the tool manufacturers is also valid for the Ejector system. Basically, these systems look alike, as far as appearance of the tool is concerned. The only (and main) difference is the way the process uses the energy of the coolant and how the chips are removed. Because there are basically two pipes in series (though mechanical they're mounted coaxially) the pressure loss of the fluid is greater than in the STS/BTA system, which limits the maximum length of holes that can be drilled. If long lengths are needed the STS/BTA system may be the better choice.

Below is a summary of the advantages and disadvantages of the Ejector system, as compared to gundrilling and the STS (BTA) system, according to Astakhov ("Why gundrills?", p.7):

- can be used on a wide range of versatile machines.
- high productivity.
- requires relatively low pressure of the cutting fluid.
- different carbide grades can be used for different parts of the cutting edge.
- simple change of a worn drill head. A number of different drill heads can be used with the same boring bar.

Disadvantages of the Ejector system:

- cannot be used for holes smaller than 20 mm.
- high sensitivity to the machine alignment and the clearance in the start bushing.
- very high sensitivity to the shape of the chip produced. They cannot handle any chip pileups due to specific design of their hydraulic circuit. This is a major disadvantage of the ejector system.

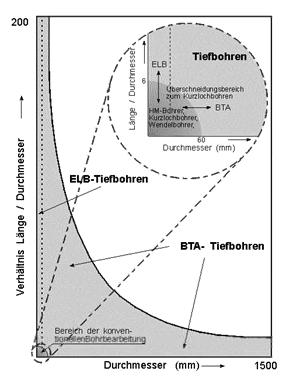
4.4 Final remarks on the 3 systems

In the graph on the right is a summary of 200 the preferred application area of these 3 systems.

Note that this graph looks mainly at BTA-drilling; Ejector drilling is not included but shares so much similarities with BTA, as will be understood after reading the previous explanation of it, that in this graph we may equate BTA to Ejector. ('ELB' in 'ELB-Tiefbohren' stands for 'Einlippenvollbohren', the German term for qundrilling).

There is a caveat to this graph though:

"Das gesamte Feld der durch Bohren herstellbaren Innenkonturen wird Tiefbohrtechnik durch die beherrscht. Lediglich im Bereich kleinerer Bohrtiefen (bis ca. Länge/Durchmesser und Durchmesser bis ca. 60 mm) werden andere Bohrverfahren und Bohrwerkzeuge eingesetzt. Da diese Abmessungen im allgem. Maschinenbau vorherrschen, wird die Dominanz und Vielseitigkeit der Tiefbohrverfahren oft nicht wahrgenommen." (www.tiefbohren.info)



Note also that in this graph the area of gundrilling ('ELB-Tiefbohren') is pretty small, which might suggest that the application of gundrilling is very limited. Cause of this is the large final value of the X-axis (1500 mm diameter): the majority of deephole applications in the real world deal with bores of small diameters, for which gundrilling is the best solution... This should be borne in mind, otherwise the graph can be deceiving. The major advantage of this graph is that it shows a (more or less) complete set of drilling problems (diameter vs. L/D-ratio) and the applicable process. It also shows that spiraldrilling is just a subset (though a very often used one) of the general set of drilling solutions. Spiraldrilling is so often used that some people may forget that there's a large range of holes that can only be made by deephole drilling techniques. Besides, the techniques of deephole drilling are trickling down to the realm of short holes:

"Tiefbohrwerkzeuge beherrschen das gesamte Feld der durch Bohren herstellbaren Innenkonturen. Insbesondere im Bereich der tiefen Bohrungen und der Bohrungen mit großen Durchmessern werden fast ausschließlich Tiefbohrtechniken eingesetzt.

Wegen seiner hohen Produktivität und erreichbaren Bohrungsgüte wird das Tiefbohren heute zunehmend für Fertigungsaufgaben eingesetzt, bei denen das Verhältnis zwischen Bohrungstiefe und Bohrungsdurchmesser kleiner als 10 ist. Auch im Bereich geringerer Werkzeugdurchmesser, in dem naturgemäß die meisten Einsatzfälle für das Bohren liegen, zeigen zahlreiche Bearbeitungsbeispiele die Präsenz der Tiefbohrtechnik. Schwerzerspanbare Materialien lassen sich mit Tiefbohrverfahren im Regelfall vergleichsweise gut bearbeiten." (www.tiefbohren.info)

The same is observed by Astakhov:

"Originally the self-piloting tools (SPTs) served as deep-hole tools, but the method has now been adopted to even short workpieces to gain benefits of hole-axis straightness and short machining time. In mass production, a very close tolerance can be held and a reasonably high surface finish maintained." (Astakhov, "an analytical evaluation...", p.1189)

What these writers don't mention here is that deephole drilling can eliminate the need for several other processes; if the choice is between spiraldrilling, followed by drilling with 3 fluted drill and finally reaming - vs. deephole drilling, the latter process may well be the most economical one, even for not-so-deep holes. A German website sums up the benefits of deephole processes in the drilling of short holes thus:

"Vorteile beim Einsatz der Tiefbohrverfahren sind:

- * sehr hohe Zerspanleistung
- * ideale Bedingungen bezüglich Kühlung und Schmierung
- * kurze Hauptzeiten
- * hohe Bohrungsqualität hinsichtlich Durchmessertoleranz, Oberflächen-güte und geometrischer Formgenauigkeit
- * hohe Fluchtgenauigkeit, geringer Bohrungsverlauf
- * Ersatz mehrerer Arbeitsvorgänge z.B. Vorbohren, Aufsenken und Reiben durch einen Arbeitsvorgang
- [...]
- * Bearbeitung schwer zerspanbarer Werkstoffe
- [...]
- * geringe Gratbildung beim Ausbohren und beim Überbohren Querbohrungen" (www.tiefbohren.info)

These advantages can make deephole drilling an attractive machining process even for short holes. And to add to its versability, it can be used not only for drilling but also for boring, i.e. increasing the diameter of an existing hole (just as STS/BTA and Ejector system can).

Chapter 5

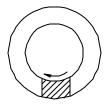
Theory of gundrilling

In this chapter we shall take a closer look at gundrilling. Various aspects of the process will be considered along with the impact on hole quality.

5.1 Gundrilling: combination of cutting and burnishing

Unlike most other hole-producing processes, which usually depend only on the cutting action of the tool, gundrilling also executes a different process at the same time: burnishing (Astakhov, "Why gundrills?", p.2). While the tip of the drill is cutting new material, the supporting pads perform the burnishing action. It's thanks to the burnishing that the drilled hole can have superior smoothness, up to $R_a = 0.1$ um, and have such a tight tolerance on diameter (IT9, according to one source even IT6).

If such roughnesses or diameter-tolerances are needed with other machining processes, an extra process step would have to be performed with a burnishing tool or reamer. Because of that burnishing action of the gundrill (basically a cold-forming process), we should see an increase in hardness of the hole surface. I've found only one (qualitative) reference with respect to cold deformation, a picture that shows a cross-section of a gundrilled hole and the change in material structure. However, no (change in) hardness values were given.



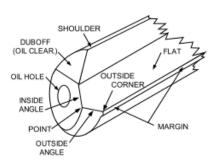


In this picture can clearly be seen that deformation of the crystals has occurred; it would be interesting to know how big an influence this would have on the hardness. Therefore, in the application part of this thesis I shall make measurements of the increase in hardness of a gundrilled hole.

5.2 Description of the gundrill-tip

In the previous chapter we have taken a look at the various components of the gundrill: the driver, shank and tip. In this paragraph, we shall take a closer look at the tip itsself and its various angles.





TIP NOMENCLATURE

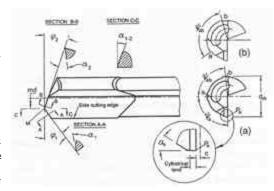
In the picture above are the names of the various parts of the tip of a gundrill; the point is the part that is the first to touch the material of the workpiece. The support pads (guiding pads) or support area (not shown in this picture) provide the guidance to keep the drill going straight. The oil hole is where the fluid leaves the gundrill; often there are 2 holes (a smaller one and a larger one near the point) or a kidney-shaped hole, to provide better lubrication and flow:

"The oil passage opening can be in the form of one or two round holes or a kidney. The kidney provides a larger clearance, but reduces the strength of the tool. Consequently, the kidney is only used for smaller diameter drills." (www.tbt-usa.com)

However, another highly respected source regards the above comment as 'nonsense' and 'technical illiteracy', unsubstantiated by either theory or experience. Hard to find out which really is the case, without setting up some experiments to find out for myself.

In the drawing below are shown more clearly the various angles of a gundrill 20 :

"The terminal end of the 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 innter 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. Α 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 $\alpha_{1\text{-}2}$ (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. [...] 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 a_s is applied." (Astakhov, "The mechanisms of Bell mouth formation... part. 1", p.1136)

This is the 'standard' grind. Like with spiraldrilling, different angles can be ground on a gundrill to better suit different materials:

"There is a large number of "standard" grinds available for different workpiece materials. In praxis many deviations from these "standard" grinds are made in order to optimize the drill process." (www.tbt-usa.com, a major American gundrill manufacturing firm)

This brings us to some criticism of Astakhov: some gundrill manufacturers include all kinds of fancy grinds, without theoretical support. One of these variations includes supporting pads in such a way that it is impossible to measure the diameter (with standard tools) or even worse, that can cause instability (no discrete pads but a guiding surface). These actually degrade performance of the $drill^{21}$.

 $^{^{20}}$ this is a simplified picture; for a more complete view, see Appendix I.

^{21 &}quot;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." (Astakhov, "The mechanisms of Bell mouth [...] part.1", p.1143).

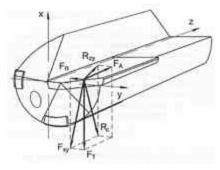
Also explained in http://gundrilling.tripod.com ('inherent instability')

Now we have a better idea of the various components and angles of the tip, in the next paragraph we shall have a closer look at the various forces acting on the qundrill.

5.3 Self-piloting gundrills

Gundrills are self-piloting, which means that they guide themselves to achieve a straight hole. The reason they have self-piloting properties is because of their asymmetrical profile which generates a force that pushes the guide pads of the drill against the wall of the hole being drilled. We shall now take a closer look at these forces and guiding pads.

"When a gundrill works, the cutting force generated is 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. [...] The cutting force $R_{\rm c}$ (or the resultant cutting force for multi-edge tools) can be resolved into three components, namely: the power (tangential) component $F_{\rm t}$, the axial component $F_{\rm a}$, and radial, $F_{\rm r}$ forces, respectively. The axial force is balanced (equal in magnitude and opposite directed) 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 spiral drills, reamers, milling tools) generally is not balanced, regardless of the number of the 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 bushing and then in the hole being drilled so that it can be considered as self-piloted." (Astakhov, "What is the meaning of 'self-piloting'?", p.1-3)

However, not everything that looks like a gundrill is actually self-piloting. As Astakhov continues to explain:

"For example, the term 'two-flute gundrills', which is currently wide used in the automotive and tool industries to describe a deep-hole drill with two identical cutting elements symmetrically located with respect to the drill longitudinal axis. Because there is m (at least, theoretically) unbalanced

radial force, it is simply wrong to regard such a tool as a gundrill. It is not self-piloted although it is a drill with internal coolant supply and external chip removal along straight V-flutes. Unfortunately, such drills are treated as SPTs 22 and thus often misused. In our opinion this became possible because the so-called 'deep-hole drilling experts' from the leading gundrill



producer in this country [USA; PD] have no idea about the working principles of SPT." (Astakhov, "What is the meaning of 'self-piloting'?", p.5)

-

²² SPT = Self Piloted Tool

In the picture on the right are shown several configurations of the guiding pads. The first configuration is used the most and is the standard configuration for machining steel; it also has the advantage of being micable. The other 3 configurations are sometimes used for other materials (the middle 2 are used for aluminium, the bottom one for brass).

The middle 2 drills in this picture don't have guiding pads but a 'guiding continuum',

"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 other words, a gundrill with the supporting continuum is inherently unstable." (Astakhov, "Bell mouth formation... part.1)

Others (esp. manufacturers) recommend for example the 2nd type of guide pad for drilling aluminium, without offering an explanation as to why it would work better, according to them. Now, if I were a tool producer I'd prefer to sell different drills for different materials... A major benefit of the gundrill is that one drill can be used for many different types of materials.

The 2 guiding pads can be located in various places. As Astakhov has remarked, one of the pads should preferentially be opposite of the margin so the diameter of the drill can easily be measured. The place of the other guiding pad can be varied, however.

"The exact position and form of these pads have a great influence on the drilling result. A wrong form can cause the tool to get "jammed" in the bore, overheat the tool, ream the bore or increase the bore run-out." (www.tbt-usa.com)

After reading the above it should be obvious that the design of the guiding pads of a gundrill is not trivial and can greatly influence the performance and tool life of it and have significant effect on bore quality.

5.4 The starting bushing (or guide hole)

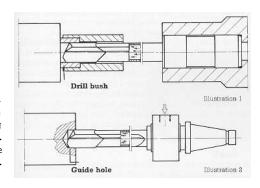
Gundrills are self-piloting. However, they're not self-centering: to guide the drill while starting a hole, it's necessary to use a starting bushing. It's the starting bushing that has a major influence on the quality of the hole.

The straightness from the hole derives from the fact that the tip of the drill guides itsself (by means of the guiding pads) with respect to the freshly drilled part of the hole. However, when starting a new hole no such reference is available from the workpiece itsself. Therefore another means of guiding the drill during the initial stage has to be devised.

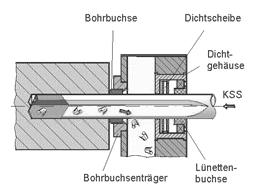
In general, there are two ways:

- 1. pilot hole
- 2. starting bushing

The method chosen doesn't have a fundamental influence on the quality of the hole, since they both perform the same function: guiding the gundrill during the initial entry-stage. It will usually depend on other factors, like ease of setup and tool-change (gundrill vs. pilot drill), which method is chosen.



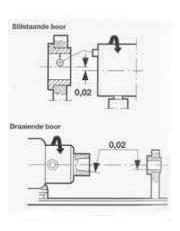
In the drawing on the right is in closer detail how the bushing is mounted in the chip



Whatever method is chosen, pilot hole or starting bushing, it's vitally important for bore-quality that it is exactly in the center

of the axis of rotation. If it isn't, hole straightness is compromised and early failure of the gundrill might occur: the gundrill will bend back and forth in the frequency of rotation, while amplitude of the deflection will increase as the drill gets deeper. At a certain moment, a fatigue crack will develop.

This may result not only in the loss of the tool, but may also cause the scrapping of the workpiece and should therefore be avoided. On the plus side, it's easy to prevent this from happening: make sure the starting bushing or pilot hole is properly centered. It's also important that the gundrill is properly aligned to the machine axis of rotation. If the gundrill itsself is out of alignment then straightness will also be reduced; the hole will have the form of a 'banana'.



The starting bushing is usually made of either hardened steel or carbide. Bushings made of carbide last, on average, 10 times longer than those of hardened steel (Sandvik-Coromant, p.C127). Sometimes rotating bushings are used to limit wear of the bushing. Sandvik also gives info regarding diameter of the starting bushing:

"Om een lange standtijd en gaten van goede kwaliteit te garanderen, wordt de boorbus tot dezelfde nominale diameter als de boorkop geslepen, maar aan de pluskant van de tolerantie." (Sandvik-Coromant, p.C124)

This is consistent with another source that states that the starting bushing should never be smaller than the diameter of the drill; bigger is less of a problem, but too large should also be avoided to prevent instability of the drill. Over time, this clearance can increase due to wear of the starting bushing and wear of the gundrill (especially the guiding pads), so periodical checking may be necessary. If the diameter of the bushing is more than 0,02 mm greater than that of the gundrill it should be discarded²³. Care should be taken when selecting bushings that they are suited for gundrilling; ordinary drill bushings, meant for spiraldrilling, haven't got the tight tolerances (ISO-H6; Sandvik p.C96) that are necessary for gundrilling and should therefore be avoided.

In some cases a starting bushing may not be possible because of the geometry of the workpiece; and when gundrilling is done on CNC machines starting bushings are not the best choice, it's usually easier to drill a pilot hole, especially when the machine is suited for quick or automatic tool-change. And just like the starting bushing must be of high quality, a pilot hole must fulfill the same high demands on diameter tolerance:

"Hinsichtlich der Durchmessertoleranz werden an Pilotbohrungen hohe Anforderungen gestellt, um ein gute Anbohrführung des ELB und somit die

 $^{^{23}}$ This is in fact a function of the diameter of the drill; .02 mm would be the value for a 30 mm gundrill, but would be unacceptable for a 2 mm one

Voraussetzungen für einen geringen Mittenverlauf zu gewährleisten." (Institut für spanende Fertigung, "Tiefbohren auf Bearbeitungszentren".)

Another source states basically the same:

"Während auf Tiefbohrmaschinen zur Führung der Werkzeuge beim Anbohren eine Bohrbuchse verwendet wird, arbeitet man auf CNC-Bearbeitungsmaschinen mit sogenannten Pilotbohrungen die als Anbohrführung direkt in das Werkstück eingebracht werden. Die Bohrtiefe der Pilotbohrung ist abhängig vom Bohrdurchmesser. Als Richtwert gilt ca. 1,5 x Bohrerdurchmesser mit einer Bohrungstoleranz F7. Die Qualität der Anbohrführung beeinflusst wesentlich die Standzeit des Werkzeugs und den Bohrungsmittenverlauf." (Werkzeug Technik nr. 79, p. 50)

As far as depth of the pilot hole is concerned it's possible to more accurately determine the depth needed than with the rule of thumb of 1.5 * D:

"The depth of the pilot hole must be sufficient to bury the outside corner of the gundrill without the tip touching the bottom of the hole." (website of 'Gundrilling solutions')

When the pilot hole is drilled (or a bushing is present), actual drilling can be started. One final comment on the subject of bushings and pilot holes: the rotation of the drill may only start when the gundrill is guided by either the bushing or the pilot hole. Never should a gundrill be allowed to rotate freely:

"Never run the spindle [...] before the drill tip is engaged in the pilot hole! Remember that a gundrill is asymmetrical 24 - revving it up with no support will tend to make it do a 90 degree turn (for the worse)." (website of 'Gundrilling solutions')

This is of course not an issue when the drill is stationary, as is the case in the rotating-workpiece system.

5.5 Whipguide: support of the drill

When gundrilling, the starting bushing is one support for the gundrill. The drill holder is the second supporting point. However, since the gundrill is a relatively long, slender tool with little resistance to bending, when drilling deeper holes it's necessary to add extra support to the drill (it may also be necessary to

further support the workpiece, but this doesn't differ from e.g. lathe operations). The support is in the form of whipguides, as can be seen in the picture on the right. There are guidelines to determine how many whipguides are to be used, as we shall see in the chapter on the determining of machining parameters; the general rule though is that holes up to a L/D-ratio of 32 can be machined without whipguide; this is a general rule, the situation may call for more support,



depending on the particular drill design, work material and cutting regime.

If it isn't possible to add extra support in the form of a whipguide, feed and speed of the process must be proportionally lowered to reduce the risk of shank whip and buckling.

The importance of whipguides can be seen in the picture above, where the drills are supported in 2 places; it doesn't take an expert to see that without support the drill would sag even under its own weight, let alone what would happen when a feeding force was present...

 $^{^{24}}$ contributing factors are the high rotational speeds (10.000+ RPM) used in gundrilling, coupled with the long, flexible shank of the gundrill.

Not only has the gundrill low bending stiffness, its torsional stiffness is also small. There's not much that can be done about this. The low torsional stiffness can lead to vibrations (chatter) when machining, which show themselves in the bottom of the hole (if it's a blind hole):

"Chatter in deep hole drilling is a form of self excited²⁵, mainly torsional vibration of the tool-boring bar assembly. Its effect on the workpiece is usually restricted to radial chatter marks at the bottom of the bore hole [...]. In extreme cases, chatter vibration may also lead to marks on the cylindrical surface of the bore hole wall." (Weinert, "Analysis and Prediction [...]", p.1)

So unless chatter is extreme and the hole isn't a blind one, there's hardly a problem for the workpiece. Yet it is a problem for the gundrill, where vibrations lead to increased wear (of the cutting tip and guiding pads) and possible breakage of the drill. One possible solution to reduce torsional vibration is the use of a damper between the driver of the gundrill and the machine.

At my visit to Kluin Wijhe, it was stated that a little bit of chatter ('controlled chatter') would actually improve machining, because of the better chip breaking that occurred. However, there are other and better ways to control chip breaking than having to rely on chatter.

5.6 Lubrication & cooling

Like most other metal-cutting processes, gundrilling needs cutting fluids. The difference with e.g. milling and turning is that the coolant is an absolute necessity for the process to work, not just a means of improving the process (regarding processtime, toolwear or quality of the work). Without sufficient fluids gundrilling can't work!

In general it is recognised that coolants perform three functions 26 : (Deckers & Schellekens, p.152)

- heat removal (cooling)
- 2. reduction of friction (lubrication)
- 3. removal of chips

As important as fluid is for drilling, as hard is it to get it where it is needed. With milling and turning, it's relatively easy to make sure some coolant gets in the actual cutting area. With drilling this is harder, because the cutting process is shielded from view and reach by the surrounding product.

The solution in gundrilling is the use of a hollow coolant channel in the drill 27 . Usually this hole is round, though there exist 'improved' holes with a kidney-like shape or 2 holes instead of one.

The amount of coolant needed (flow rate) is a function of only one variable, according to Sandvik-Coromant (p. C122): diameter. In order to clear the actual cutting part of the drill, copious amounts of fluid are needed. The larger the hole, the greater the flow rate. The fluid-pressure though can be smaller with large holes, but should be higher with small holes. L/D-ratio of the hole does not influence flow rate; however, it does influence the pressure that's needed to ensure the correct flow rate. A graph shown in chapter 5.10.c presents specific values for the coolant flow rate and pressure.

Apart from choosing the right flow rate and pressure for the job, the right fluid should be chosen. There are several types of coolants, with different

 $^{^{\}rm 25}$ according to Astakhov, it's not self-excited but forced vibration

 $^{^{26}}$ De Chiffre acknowledges a 4th function, corrosion protection (De Chiffre, "Function of cutting fluids in machining").

²⁷ this method is not only used in gundrills, but sometimes in spiral drills too. The advantage is obvious, coolant gets to where it is needed. The disadvantage though is a weaker drill and a more expensive manufacturing process of the drill. Also, the drill is weaker due to the internal coolant channels.

characteristics and applications. Astakhov recognizes the following types ("cutting fluids and their application in deephole machining", p. 7-8):

- Straight cutting oils
- Water emulsifiable oils
- Synthetic fluids
- Semi-synthetic fluids
- Liquid nitrogen

According to Astakhov, water emulsifiable oils should only be used "in exceptional cases as in machining of easy machining materials under light cutting conditions." (Astakhov, p.9). He recommends the use of straight cutting oils, which despite their higher costs and consumption rate, provide the best results. Especially recommended is the use of the right additives to provide lubrication at high temperatures (400-800 $^{\circ}$ C). These high pressure (HP) or extreme pressure (EP) additives (active components are chlorine or sulphur 28 29) form a thin, solid layer at these temperatures and it is this layer which actually provides the lubrication.

Apart from choosing the correct type of coolant, it's also necessary to keep it at a low temperature ($20-40^{\circ}$ C) and clean:

"Kühlschmierstoffe können ihre Aufgabe nur dann erfüllen, wenn sie optimal gereinigt der Wirkstelle zugeführt werden. Hierfür stehen eine Vielzahl, von Kühlschmierstoffreinigungs-Verfahren zur Verfügung. Selten werden heute bei Tiefbohranlagen noch magnetische Abscheider und Filter verwendet. Eingesetzt werden aktuell eher Papierfilter, Saugbandfilter und vorzugsweise filterhilfsmittelfreie Siebfilter oder Zentrifugen." (www.tiefbohren.info)

During my visit to Kluin Wijhe, it was stated that for some jobs, they maintained coolant temperature at $18\,\mathrm{^{\circ}C}$, within one degree. They stated that if this wasn't done hole straightness would suffer. This statement is hard to justify by theory, and no other references to it have been found. However, I have little reason to doubt their statement, considering the effort they have to make to keep the temperature within that narrow bandwith. The only way that temperature could have an influence is because of its effect on viscosity. To learn more about this phenomenon, a test might be devised where the viscosity of the coolant is varied, as opposed to the temperature, to check whether this assumption is correct or whether other phenomena come into play.

The coolant shouldn't contain particles greater than 15-25 um; when gundrilling very small holes no particles greater than 10 um should be present. This is more important in gundrilling than in for example milling, because the coolant also functions as lubrication for the guiding pads; too many (large) particles in the fluid may lead to a rough bore surface and early wear of the guiding pads, with consequences to diameter tolerance, stability of the process and roughness of the bore.

Because of the high flow rate of coolant used (for example, a hole of 20 mm needs 60 1/min flow rate; that's a liter per second!) and the need to keep it cool, relatively large volumes of coolant and large containers are needed, as compared to other machining operations. This increases the investments in gundrilling.

In response to stricter environmental standards and the increasing cost of the (disposing of) coolants, research is in progress 30 of deephole drilling without the supply of liquid coolant. Only compressed air is used or a combination of compressed air and a small amount of mineral oil. There are promising results for some materials (e.g. cast iron with only compressed air) and other materials with combination of air and mineral oil. There may be a need for a different geometry of the drill tip to what is normally used but that might be a small price to pay for the cost savings that can be achieved.

²⁸ Sulfur has anti-weld properties, chlorine is a lubricant (source: Star cutter) Due to stricter environmental regulations, some of these additives are already forbidden and others may be in the future. This has especially severe repercussions for deephole

drillers, where these additives are needed very hard. To the best of my knowledge, no real solution to this problem, that will become more severe in the future, has yet been found.

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5.7 Rotating tool, rotating workpiece and counterrotation

Drilling operations are based on a relative movement of workpiece and tool. In general, we can recognise three different situations:

- a. rotating tool
- b. rotating workpiece
- c. counter rotation of tool and workpiece



These different methods have their own pros and cons, as will be shown belo, and have different effects on hole straightness. If this bore quality is an issue, thought must be given to which system can and should be used. Of course if straightness is not an issue (but the other bore qualities that can be attained with gundrilling are) then this is a moot point.

5.7.a Rotating tool

The rotating tool system is the most widely used, not only in gundrilling but also in spiraldrilling. Its major advantage is its simplicity, with only the tool that rotates; the workpiece can be clamped down solidly when machining. With this system, care should be taken to never let the gundrill rotate freely, i.e. without the guidance of a bushing or pilot hole; because of the unbalance of a gundrill, this may result in a dangerous situation.

In case of a rotating gundrill, the machine must have a connector to clamp the driver while preventing (excessive) leakage of coolant. This requires the installment of sealings which must be able to withstand both high pressures (up to 200 bar) and high rotational frequencies (up to and above 10.000 RPM), not a simple thing to accomplish.

Coupled with the fact that it leads to the worst hole-straightness, it's one of the least attractive systems, but is still used a lot. In fact, when the workpiece is not rotational symmetric this system is the only option to gundrill it.

5.7.b Rotating workpiece

The method of 'rotating workpiece' is used in gundrilling, but can also be seen in drilling operations on the lathe, with the drill in the tailstock. The situation of 'rotating workpiece' is the one that's also used when turning is done with a lathe: the workpiece rotates while the tool is stationary. What matters is that they have a relative velocity with respect to eachother.

The advantages are that it leads to better straightness than when the rotating drill method is used, plus it's easier to seal the high-pressure fluid because the sealing doesn't have to rotate (this is not an issue in gundrilling, but more important in STS/BTA and Ejector drilling). It can not be used when the workpiece is not rotational symmetric.

5.7.c Counter rotation

This system gives the best possible straightness of the hole. It's basically a combination of the previous 2 systems:

De zo gespannen werkstukken laat men dan vaak ook nog tegen de draairichting van de boor in draaien, met æn vast en niet te hoog toerental. In de praktijk is gebleken, dat hiermee het verloop van de boring ten opzichte van een vaste opspanning ongeveer gehalveerd wordt. Dit verschijnsel wordt verklaard, doordat de eventueel optredende afwijkingen in centerlijnen, ten gevolge van opspanfouten gemiddeld worden alsook door het opheffen van het doorhangeffect van de boor.' (Kluin, 1977)

So according to mr. Kluin, by using counterrotation of the workpiece at a relatively low RPM, hole deviation can be reduced in half, since the errors of non-aligned centerlines are averaged out and the effect of the sagging of the drill is negated.

The advantage is that high straightness can be achieved, but at a cost: the machinery is more complicated than in the previous systems: both the drill and the workpiece must rotate. This results in larger, heavier and more expensive machinery. The system of counterrotation can only be used on workpieces that are rotationally symmetric.

By the way, what has been said above about the achievable straightness of these 3 systems also goes for spiraldrilling: rotating drill systems perform the worst with regard to hole straightness (though they are used the most), while counterrotation performs the best (and is used very little).

Unfortunately, I've found little quantified data on how straightness is influenced by these 3 methods. This is important information when determining whether the available process is capable enough for the task at hand. The only information on straightness was found in the catalog of a tool manufacturer:

"Met een roterende boor wordt een relatief goede rechtheid verkregen bij korte gaten, maar die is bij diepe gaten aanzienlijk minder, vanwege doorbuiging van de boorpijp. Voor een roterende boor kan ruwweg een afwijking van 0,3-1,0 mm/m geboorde lengte worden aangenomen." (Sandvik, p.C7)

Even though this may look good at first glance, remember that this is the attainable straightness using the worst 31 of the three systems.

When the drill rotates higher straightness can be attained:

"Bij een niet-roterende boor wordt de afwijking van de rechtheid van het gat meestal uitgedrukt in vereenvoudigde termen, zoals 0,1-0,3 mm/m geboorde lengte." (Sandvik, p.C7)

In the chapter on the achievable hole qualities (chapter 5.9.d) is a bit more data of achievable bore straightness, but only for the systems of rotating drill and counterrotation; I haven't been able to find data on straightness with the system of rotating workpiece (with the exception of data by Astakhov; see next paragraph). This would be interesting information when deciding whether it's worth the trouble to invest in a machine with counterrotation capabilities or to use the more standard rotating drill or rotating workpiece systems.

5.7.d Or not quite...?

The above description is based on several sources; in fact, all the sources I had available were in good agreement, until in a private mail exchange dr. Astakhov mentioned it was wrong. In an article in 'Fabricating & Metalworking magazine', he gives the following description:

'[...] three characteristics are usually most important -- deviation (drift) of the hole axis, surface finish and diametric accuracy. [...] [with the rotating gundrill system, PD] The best diametral accuracy and surface finish, along with worse axis deviation of the machined hole, are common in this method. [...] [rotating workpiece, PD] Use this method when the workpiece

³¹ with respect to straightness.

shape allows for accurate clamping and high speed rotation. [...] Minimum hole-axis deviation and worse diametric accuracy are common features. [...] [counterrotation, PD] Use when gundrilling small diameters where one rotation speed cannot achieve the necessary cutting speed. Though long and expensive special machines with two spindle heads are required, this method must be used when the hole-axis position and diametral accuracy are equally important.' (Astakhov, a primer on gundrilling)

In a graph in the article, he shows that hole straightness ('deviation of the hole axis') is worst for the rotating drill system (which agrees with the other sources), but also that the system of rotating workpiece gives better straightness than the system of counterrotation. This is in sharp contrast to the other articles I had available. His statement seems to be backed up by measurements, which are the basis for the two graphs in his article. According to Astakhov, counterrotation should be used when the speed of the spindle is too low to achieve sufficient cutting speed; mr. Kluin's comment that the workpiece should rotate at low RPM (thereby hardly increasing cutting speed) is in contradiction with this statement.

Therefore, what first seemed very clear to me ('worst straightness when using rotating drill, best when using counterrotation') has now become very blurred. I can not say which one is right; the simplest thing to do would be to set up an experiment and try for myself.

5.8 Machinery used for gundrilling

In general machines for gundrilling can be separated in 2 broad groups: specially designed gundrilling machines and retrofitted machines.

5.8.a Gundrilling machines

Like most metalworking machinery, gundrill machines come in all sizes and shapes. However, there are some common characteristics they share.

In the image below is an example of a gundrilling machine of the potating-tool system (Mollart Omnisprint 3). It's just one of the many brands and types available, but might be considered an 'average' example, not the smallest or biggest one available. It's of the single-spindle type. Like with industrial spiraldrilling machines there also exist multi-spindle variants. The main advantage is being able to drill several holes at the some time, thus higher productivity can be attained.

Machines that work on the basis of the rotating-workpiece system are physically larger than the one pictured here: their workpieces are rotationally symmetrical and (usually) long, while the drill is another lengthy component.

One of the most important aspects in gundrilling is the coolant, which is supplied under high pressure (up to 200 bar) and with a high flow rate. This has implications for the coolant supply system of a gundrill machine, that must have high pressure pumps that can generate and hoses and couplings that can withstand these pressures. This also puts high strain on the



rotating unit, where the fluid enters the drill. Depending of the system used (rotating tool, workpiece or counterrotation) this unit must not only be able to withstand this pressure and deliver a high flow rate, but also be able to rotate at high speeds.

Because the coolant can only function adequately when it remains cool (ideally between 20° and 40° C, to prevent chemical decomposition), clean (no particles greater than 15 um present, or 10 um when drilling small holes) and free of fungi

and bacteria, the coolant reservoir must be large enough (rule of thumb: the coolant tank should have its volume no less than 10 minutes flow rate. For example, if the maximum flow rate is $50\ 1/min$, then the minimum volume of the coolant tank is $500\ 1$.) It may be necessary to install a refrigeration system to cool the fluid down sufficiently if natural or forced convection is not enough.

In the image is not shown the extra support provided to the gundrill by a (moving) whipguide, to prevent excessive shank whip. These whipguides are clearly shown in a photo in chapter 8.4. These whipguides are something that isn't usually found on 'normal' machines like mills and lathes. The moving whipguide is controlled independently by the CNC unit.

Another characteristic of gundrill machines is the high RPM their spindle can provide. These high RPMs are especially needed when drilling small diameters, in order to achieve sufficient cutting speed. This RPM is usually infinitely adjustable by the operator to provide a maximum of control, e.g. when vibrations occur.

One of the important specifications of a gundrill is its maximum length of holes that can be machined (diameter is more or less determined by maximum RPM and coolant pressure. For example, the stroke of the machine that was used in drilling the samples at Kluin Wijhe (a TBT made M02 1000 KT-NC) is 1600 mm.

The minimum diameter of holes that can be made is a function of the maximum coolant pressure (the higher the pressure available, the smaller the hole that can be drilled), maximum spindle speed and type of power transmission: the transmission (which transfers power from the motor to the spindle) should introduce as little vibration as possible, which is why gears are not recommended; it's better to use belt-type transmissions. Maximum diameter of holes that can be machined is a function of available power and coolant flow rate: when machining holes of large diameter large flow rates are needed. However, the usual limiting factor in gundrilling is not flow rate but pressure; when drilling small holes, high pressures are needed to provide sufficient flow rate. Often gundrilling machines can't provide these high pressures (without resorting to after-market solutions), thus limiting the minimum size of holes that can be drilled.

In order to help suppres vibrations of the machine-tool-workpiece combination it's important that the machining setup has great static and dynamic stability. Whipguides and steady rests installed on the machine may help to solve the problem with vibrations.

Apart from stand-alone gundrill machines there also exist CNC machining centers with gundrilling capability; it may make it possible to integrate several process steps in one machine and in one setup, thus enhancing accuracy and increasing productivity:

"Die Tiefbohrzentren der Reihe BW beruhen auf dem Konzept, dass auf einer solche Maschine klassische Fräsbearbeitung, Zirkularfräsen, Zentrieren, Bohren (einfach oder stufenweise) und Aufbohren verbunden werden. Da die Nullpunktfestlegung bei allen Bohr-operationen unumgänglich ist, kann diese Tiefbohrzenter auch mit den erforderlichen Messvorrichtungen ausgerüstet werden. Der wesentliche Vorteil liegt in der Verkettung der Bearbeitungen mit einer einzigen Werkstückerfassung und ohne überflüssige Transferzeiten. Daraus ergibt sich eine erhebliche Zeiteinsparung welche in der Reduzierung der Rustungszeiten ihren Ausdruck findet. Sie ist beträgt [sic; PD] 2-3mal kürzer im Vergleich zu den früheren Fertigungsweisen." (Werkzeug Technik nr. 68, p. 40)

5.8.b Retrofitted machines

Even though deephole drilling is a specialty technique, that doesn't mean specialty machines have to be used. In fact any conventional or CNC machine that has a means of supplying high-pressure coolant (or can be adapted to it) can be used for deephole drilling.

When retrofitting machines, the same points go as for specially-designed gundrill machines. There are some adaptations that must be made to the machine in order to be able to gundrill. One of those is the coolant system, which usually isn't capable of generating the high pressures needed. High pressure seals³² have to be installed in the spindle since these usually aren't able to withstand the high pressures. Finally some means of mounting and feeding the gundrill has to be present. When converting a lathe this could mean replacing the tailstock or cross-support with a connector for the qundrill and providing a means to feed the drill.

Another advantage of retrofitting an existing machine to gundrilling capability is that the machine is usually already present, thus eliminating the need for new investments. If for some reason it's decided that deephole drilling capability is needed but that the gundrill system is not ideal, then use can be made of the Ejector system, which is much more suited for retrofitting than the STS/BTA system.

5.8.c Gundrilling machines & lack of quality33

Above were explained some of the demands that must be met by a gundrill machine for it to be of use in gundrilling. However, in practice even specially designed gundrill machines do not always possess these very basic qualities, as is observed by Astakhov, who has done research on the subject of gundrilling in the automotive industry in the USA:

"Failing to find these answers, the user has no choice but to accept the 'default characteristics' suggested by the machine producer hoping that 'they are specialists and thus they must know.' In reality, they do not. To the best of my knowledge, no one qundrilling machine producer in this country has a gundrill test machine dedicated to conducting studies on gundrilling. As a result, the designs of gundrilling machines, particularly for the automotive industry, suffer severe flaws. Often, it is very difficult to check and/or to change the starting bushing, it is next to impossible to check and adjust misalignment, the coolant distribution systems on multi-spindle machines 'starve' some qundrills while the other are over flooded. The control systems of such machines measure irrelevant process parameters. For example, the coolant pressure is measured instead of the coolant flow rate; the amperage of the drive motor is measured to check the drill load instead of the actual force on the drill. No wonder such control systems cannot 'predict' drill failures. [...] First, why don't gundrill machine producers equip their machines with coolant supply systems capable of delivering high-pressure coolant, which is mandatory for gundrills of small diameters? Second, because the drill rotates in most qundrilling applications, a rotating connector, which is also known as the pressure joint, is a part of the machine to supply the coolant into rotating spindles. With these connectors, however, the maximum allowable pressure of the coolant is up to 7 MPa (1000 Psi) [70 bar; PD] and, besides this is way too low for gundrills of small diameters; it makes it impossible to use a high-pressure coolant pump." (Astakhov, "Gundrilling: very sharp points", p. 5)

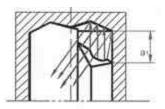
"Most of the coolant supply systems have the wrong type of pumps, called variable-displacement pumps [...]. A variable volume pump is designed to maintain 'set' pressure. Unfortunately, if an obstrucion is encountered by the coolant flow, the 'set' pressure (the pressure seen on the gauge by the operator) will be maintained 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." (http://gundrilling.tripod.com)

Not only the gundrill machine manufacturers do seemingly strange things; gundrill tool manufacturers sometimes implement the wrong solution to a problem:

 $^{^{\}rm 32}$ not the animal kind, known for its nice fur.

³³ quality being defined as 'fitness for purpose'.

"Having noticed a problem with chip removal when the coolant flow rate is insufficient due to relatively low inlet preessure, gundrill manufacturers, instead of understanding the structure of the coolant pressure loss in gundrilling, arrived at a 'simple' solution, which became known as the stepped-slash design [...]. According to this design, the coolant hole in the gundrill tip located on the stepped-slash flank surface, which is far





behind the cutting edges and the bottom of the hole being drilled. Because the coolant has a huge opening, the apparent flow rate increases significantly for the same inlet coolant pressure. However, a number of other problems, which gundrill manufacturers refuse to admit, arise. First, most of this increased flow rate is directed by the bottom of the hole being drilled and not to the cutting edges [...]. Second, because the coolant has an easy way to escape, it does not flow to the relief surfaces where its presence is mostly needed." (Astakhov, "Gundrills: very sharp points", p.5)

But no all the blame can be put on the manufacturers of gundrill tools and machines, as might be suggested by the above. Plenty of problems are not equipment related but caused by a lack of knowledge and/or understanding of the gundrilling process, but are falsely attributed to equipment:

"Such failures turned gundrilling into the bottleneck operations in the automotive industry. Unfortunately, the tool manufacturer is the only one blamed, although it is unfair in my opinion. [...] If a manufacturing engineer (having limited knowledge in gundrilling) in order to save money for his company uses relatively cheap Acme spiral drill starting bushings instead of expensive precision gundrill starting bushings, it results in poor performance. Why should the gundrill producer be responsible for this technical illiteracy? Why should the gundrill producer be responsible for poor drill performance if the end user does not supply sufficient coolant flow rate to the gundrill(s); if he uses unsuitable coolant brand, if he uses 'standard' gundrills for making inclined holes; if the distance between the face of the starting bushing and that of the workpiece is excessive; if the alignment 'starting bushing - spindle' is more than 5 micrometers (0.0002") off, etc?" (Astakhov, "Gundrills: very sharp points", p. 2)

On the other hand, if I were a user of the gundrilling process and experienced problems that I didn't know the cause of, I'd expect my supplier of tools and/or machines to be able to help me in finding out about the true nature of the problem. If they can't because the suppliers themselves lack the specialistic knowledge on gundrilling (and if anyone should have this knowledge it's the suppliers; for the users, gundrilling may be just one of the many processes they use, though this doesn't excuse them for not understanding their own processes), it might be time for those last to start looking for another supplier that can. If one doesn't exist yet, it's just a matter of time and when that time comes, the other gundrill and machine manufacturers may be in for a big surprise.

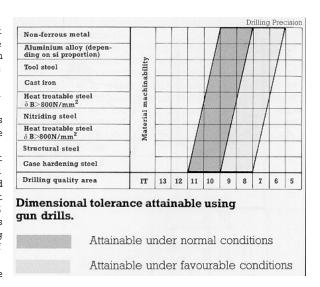
5.9 Achievable bore qualities

Before deciding whether gundrilling is the correct process to machine a bore as specified by a construction drawing, it's important to be able to predict if gundrilling can achieve the quality level necessary. We shall look at the seven bore qualities, as explained earlier:

- diameter
- roundness
- roughness
- straightness
- location
- attitude
- hardness

5.9.a diameter

We see in the graph on the right that the diameter tolerances vary with the used, depending material machinability. Worst perform the case hardening steels (low carbon steels?), best the non-ferrous metals (e.g. brass and bronze). Within a material group there's a range of tolerances (of 4 IT classes) that can be achieved, depending on the amount of care taken with the process. What should be considered here are coolant type, flow rate, cutting speed and rate. Note that the best tolerance that can be achieved is IT6 when machining aluminium. This is better than can be attained by reaming (IT6-7). Even with the worst group of materials, the case hardening steels, diameter tolerances of IT8 can be achieved under favourable conditions.



If we compare this with the diameter tolerance that's achievable when spiraldrilling (IT11-12), we see that gundrilling performs equal to much better on this account. A reamed bore has a tolerance of IT6-7, but three subsequent operations are necessary to arrive at it; with gundrilling only one operation is needed.

This tight diameter tolerance can be achieved thanks to the burnishing action that occurs at the drill tip; this not only lowers surface roughness but also produces a hole with a tightly defined diameter.

5.9.b roundness

No data with respect to roundness have been found. This leads me to conclude for the moment that non-roundness is not an issue in gundrilling, i.e. roundness is good enough for all practical purposes. This is probably due again thanks to the burnishing action that not only creates a bore with tight diameter tolerance but also of good roundness. However, in the application part of this thesis I shall make measurements of the roundness of a gundrilled hole in order to establish how well the gundrilling process performs on this account.

5.9.c roughness

In the graph on the right the attainable surface quality levels are shown for 3 performance indicators: Rt, Ra and Rz. In this thesis we use Ra, which can vary from 3,2 um to 0,1 um; this last value can only be attained under favourable conditions.

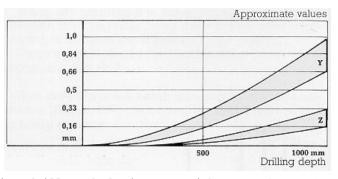
If we compare these roughnesses to what's achievable with spiraldrilling (Ra = 10-16 um), 3-flute drilling (Ra = 2.5-4 um) and reaming (Ra = 0.16-0.25 um), we see that gundrilling performs much better on this account. And this in only one operation. The reason for this good surface quality

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N
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lies in the burnishing effect the gundrill has on the surface of the bore.

5.9.d straightness

In this graph are 2 curves; 'Y' shows straightness when the drill rotates, 'Z' when the workpiece is rotating. Note that no data for counterrotation are given! It's immediately obvious that the method of rotating workpiece gives much better results, as we've already seen earlier. It is possible to achieve a deviation of 0,16 mm over a length of 1 m with a rotating workpiece! The

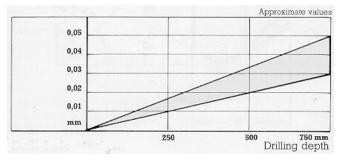


worst case, when using the rotating drill method, is a straightness of 1 mm/m, which is still pretty good (when compared to other methods of drilling).

No data with respect to the straightness of spiraldrilling has been found. In the application part of this thesis I shall make measurements of this, in order to be able to compare it to gundrilling.

5.9.e attitude

Attitude was defined as the amount of of perpendicularity of a straight line through both ends of the hole with respect to the reference surface (the surface it was drilled in). Note that a bore can have zero attitude (i.e. perfectly perpendicular to the surface) yet be as crooked as a banana, i.e. have very low straightness.



The range of attitudes that can be achieved is from 0,04-0,07 mm/m as can be seen in the graph.

5.9.f location

No data with respect to the ability of gundrilling to accurately place the hole where it's needed was found. On second thoughts this is not so strange, since it fully depends on the accuracy with which the pilot hole is drilled or the starting bushing is placed. It's therefore not really a measure of performance of the process itsself. An accurate machine operated by an experienced operator will perform good on this performance indicator independent of the question whether the hole is drilled by gundrilling or spiraldrilling. However, it's still a demand that must be fulfilled by the bore even though it has little to do with process capability.

The same also goes for spiraldrilling of course; with the right machine and an accurately drilled centerhole, accurate locating of the hole should be possible. However, when no pilot drill is used location can vary; not only because of slight unevenness of the surface of the workpiece, but the location of the tip of the spiral drilleven varies before the drill actually touches the surface (Wijeyewickrema e.a., 1995).

5.9.g hardness

No data with respect to the (increase in) hardness of a gundrilled hole were found. This could either mean that this is not an issue (i.e., hardly ever must a bore meet a demand with respect to hardness) or is so low as to be neglectable. In the application part, measurements will be made of the gundrilled bore in order to establish which of these 2 possibilities is the case. Also no data with respect to changes in hardness of a spiraldrilled bore were found, but since this kind of drilling doesn't produce any cold deformation, it's unlikely hardness will change.

5.10 Determining the machining parameters

There are 6 important machining parameters that must be considered when qundrilling:

- cutting speed
- feed rate (feed speed)
- coolant flow rate
- coolant pressure
- max. unsupported length
- power requirement

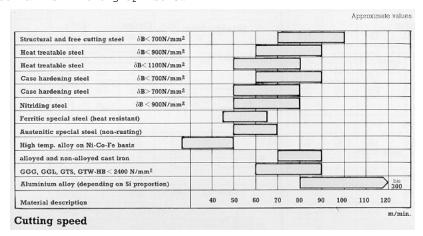
In this paragraph I shall describe a method for determining these parameters. Just to put things into perspective, it's possible to machine with very different parameters than we shall determine. However, in 'normal' applications, where cost-effective production plays an important role, the machining parameters below should be considered as the starting values 34 for further optimalisation of the process.

To help in the explanation of these parameters, I'll make use of an example: A hole of 12.5 mm dia with a depth of 300 mm (1/d-ratio = 24), drilled in free-cutting steel.

A thing that anyone who has tried to determine machining parameters must have noticed is that different sources usually give (sometimes not so slightly) different values³⁵. This doesn't necessarily mean that one is wrong and the other is right. These tables and graphs were made for specific circumstances (of which it's not always stated exactly what the circumstances were). These sources usually state that the outcomes are meant to be used as a starting value only, to be optimised by the engineer by observing the process, workpiece and toolwear. Based on these observations the various machining parameters can be changed to get better performance.

5.10.a Cutting speed

As is usually the case with metalcutting processes, cutting speed (Vc) is selected depending on the properties of the work material. An overview of cutting speeds for various material is in the graph below:



We see that for each material there's a range of cutting speeds that are acceptable. Speeds should not be chosen lower, because of problems with e.g.

³⁴ One would arrive at different values, depending on the goal: highest efficiency of production, vs. highest bore-quality and tool-life.

production, vs. highest bore-quality and tool-life. 35 like the saying 'A man with a watch knows the time; a man with two watches never knows the time'.

material buildup on the cutting edge (BUE, built-up edge). Higher speeds shouldn't be used because of the higher temperatures that will be developed at the cutting edge, which may cause problems. The best speed is probably in the middle of the range; when later on it's necessary to vary the speed (based on observations of the cutting process), there'll be ample range left both above and below the initially used speed to correct or improve the process.

However, when setting up a machine it's not the cutting speed that's needed but the spindle RPM. In order to determine this, we can use the common equation:

 $V_{c} = \pi * n * D / 1000$

Which can be re-arranged to

 $n = 1000 * V_c / (\pi * D)$

Where D is the diameter of the drill (in mm) and Vc is the cutting speed (m/min); n is in RPM (min^{-1}) .

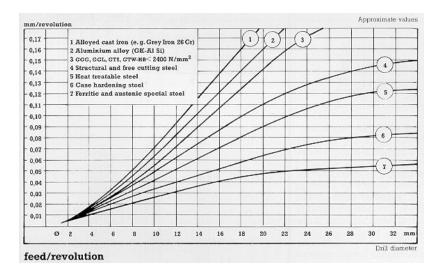
It should be noted that in gundrilling, the spindle RPM is much higher than when spiraldrilling. A reason for this is that the tip of the gundrill is made of carbide, while most spiraldrills are made of HSS, with or without TiN-coating.

In the example, we would arrive at a V_c = 70-100 m/min (for structural and free cutting steels); this gives an n = 1780...2550 min⁻¹.

5.10.b Feed rate

Like the cutting speed, the feed (per revolution) varies depending on the properties of the work material (e.g. chemical composition, metallurgical structure, hardness). In the table below are feed/revolution values (in mm/rev.) for several materials. The easiest machinable materials (cast iron, alu-alloys) have the highest possible feed rate, while the case hardening and special steels need to be machined with much lower feed rates.

Note that the values for feed rate are given in mm/revolution. Even though these feed rates are quite low in gundrilling, this is compensated by the generally high RPM's, which results in high feed speeds (speed = feed/rev * RPM). Also no time is lost in 'pecking', as must be done with spiraldrilling, to break and clear the chips.



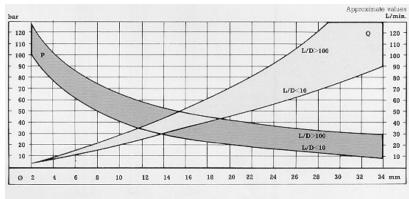
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As is shown in the graph, feed rate is a function of workpiece material and drill diameter.

In the case of our example, we deal with curve nr. 4 (structural and free cutting steel); the diameter was 12,5 mm so feed/revolution is about 0,06 mm/rev. This gives a feed speed of 0,06 mm/rev * (1780...2550) min⁻¹ = 107...153 mm/min.

5.10.c Coolant Pressure and flow rate

To determine the amount and pressure of the coolant we use the graph below. In this graph 'Q' is the flow rate in liter per minute and 'P' is the fluid pressure in bar. It's immediately obvious that this graph doesn't display lines but areas: depending on the L/D-ratio we should choose a value in the correct region. In the case of higher L/D-ratio's we should use higher pressure (at an equal flowrate) to ensure that the chips overcome the extra friction of the longer bore. Also note that the pressure needed rises rapidly as the diameter gets smaller.

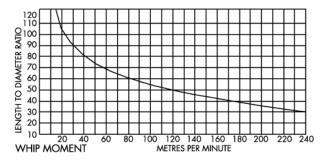


Cooling Lubricant Pressure/Cooling Lubricant Quantity

If we want to gundrill a hole with a diameter of 12.5 mm the graph shows we should use a pressure in the range of 35-58 bar; with a L/D-ratio of 50 (the middle region in these graphs) we should choose about 46 bar. The flowrate should be between 25-35 l/min; in the case of L/D = 50 an initial flow of 30 l/min should be used. Note that these pressures and flows are in excess of what's normally used in machining (turning, milling). In other machining operations the chips will be more or less automatically removed from the machining area, if only by gravity. In gundrilling this is not the case, the only way the chips can clear the (closed off) machining area is by means of the fluid.

5.10.d Unsupported length

To produce a bore that's straight it is important that the machining setup is as rigid as possible. Special attention is given to the drill because of its length and inherent low rigidity. To prevent bending of the drill extra support is given when the length of the drill is high. The amount of support depends on the L/D-ratio and the cutting speed (V_c) . In the graph to the right we see that for a cutting speed of 100 m/s the maximum allowable L/D-ratio is 55; we could



also use this graph reversely to determine the maximum cutting speed that can be used (as limited by drill whip; the workpiece material is another limiting factor for cutting speed).

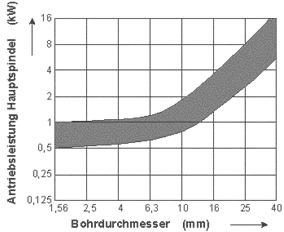
In our example we drill a hole with a L/D-ratio of 24 and a V_c = 70...10 m/min. We can see in the graph that this should pose no problem, no extra support will be needed. In fact, with a speed of 100 m/min our L/D-ratio could be as high as 55, more than double our actual L/D-ratio.

Again, these data are not absolute; when higher demands are set on hole straightness, it might be wise to use more support. I haven't been able to find what straightness is used as the reference for producing the graph above. Therefore I will assume that machining according to these data will produce a hole of average straightness, as is shown in the graph of straightness in the paragraph 'achievable bore qualities' in ch. 5.9.d.

5.10.e Power requirement

The last thing that must be checked is whether the machine has the power necessary to perform the operation. The graph to the right shows the curve that gives the net-power (power available at the spindle) as a function of the diameter.

In the case of our example of $12,5\,\mathrm{mm}$ the required net-power is between 1 kW and $2,5\,\mathrm{kW}$. This means our machine must be able to deliver this amount of power to its spindle. In case the system of counterrotation is used then both motors (for workpiece and drill rotation) must be able to deliver this amount of power.



Note the large band of values that the power requirement has. In our specific case, the ratio is 2.5:1 ! This is generally a problem with these kinds of graphs, as also stated by Kalpakjian:

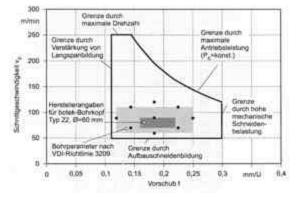
"Because of the many factors involved, the reliable prediction of cutting forces and power is still largely based on experimental data [...]. The wide range of values shown can be attributed to differences in strength within each material group and various other factors, such as friction, use of cutting fluids, and processing variables. The sharpness of the tool tip also influences forces and power. Because it rubs against the machined surface and makes the deformation zone ahead of the tool larger, the duller the tool, the higher are the forces and power required." (Kalpakjian, p.610)

5.10.f Final remark

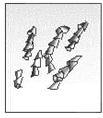
In this paragraph we've taken a look at the various machining parameters by themselves. If we take a step back and look at the process we can establish a bounded region, within which the machining should take place. This region is limited by various factors, as is shown in the graph to the right.

This is of course a general picture, the exact boundaries vary depending on the actual machine, tool, workpiece material, quality demands, etc. on a case-by-case basis.

The machining parameters that were



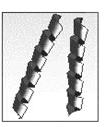
determined in this chapter should only be used as starting values. They may have to be adjusted depending on how well the actual machining goes. If for example chatter or vibration (spiraling) occurs or if chip formation is unsatisfactory, then the machining parameters will have to be adjusted. It's important that the chips are small enough to be removed from the tip of the drill by the fluid. If chip jamming occurs the drill may break. In less extreme cases it can damage the surface finish of the hole. So, chip formation is an important aspect of gundrilling that should be kept under control. In the picture below are various type of chips that can be formed by deephole drilling.











unacceptable

good

good

unacceptable

unacceptable

Fortunately the high pressure of the fluid is a strong aid in the removal of even less-than-optimal chips:

"Die Bohrbearbeitung erfordert generell günstige Spanformen, es kommt sonst schnell zu sog. "Spanverstopfungen", die das Werkzeug in der Bohrung einklemmen können und damit zu Schäden am Werkzeug und am Werkstück führen. Beim Tiefbohren sind die Bedingungen unter denen der Zerspanprozess abläuft besonders günstig. Es gibt eine Zwangsführung des KSS³⁶-Stromes und damit verbunden ist die Zwangsabführung der Späne." (www.tiefbohren.info)

Chips should not be too big in order not to become jammed in the flute, nor should they be too small (e.g. scrapings): in that case they can get stuck in the small space between shank and bore (notice that the shank is of slightly smaller diameter than the tip), causing damage to the surface of the bore or even leading to breakage of the gundrill.

Finally, it should be borne in mind that the machining parameters as were determined above are for your average industrial machining contractor that seeks to maximize productivity; if this is not the objective (e.g. when a machine shop needs to incidentally drill a deep hole with machinery that is 'less than ideal') the process can be used with very different machining parameters:

"These are the other, seldom heard of uses- the guy in a Montana 'Mom & Pop' machine shop who straps a gundrill to his shop lathe and pokes deep holes (very slowly) with 100 psi [7 bar; PD] of coolant pressure." (Gundrilling solutions)

Like many things in life, there's no absolute truth in gundrilling...

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 $^{^{36}}$ Kühlschmierstoff.

5.11 Typical deephole deficiencies

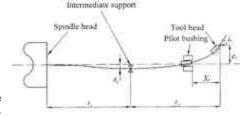
As in any drilling operation, several things can go wrong when gundrilling which may impair the quality of the machined hole. For example diameter can be incorrect, roughness too big, straightness is lacking, hole is in the 'wrong' location or has incorrect attitude. This doesn't differ from an ordinary, non-deep hole as may be made with for example a spiral drill.

However, in gundrilling there are several other things that can go wrong and impair bore quality:

5.11.a lack of straightness

This is of course a serious failure for a process that's mostly used to produce long, straight holes. The most common cause is the starting bushing or gundrill that isn't in line with the rotational axis. This causes deflection of the gundrill when entering. The amount of deflection may change during drilling, as can be seen in the picture below, which shows the effect of a gundrill and intermediate support misalignment.

The corrective course of action is simple: properly center the bushing and the gundrill with respect to the axis of rotation. However, this is not always as simple as it may sound; with some deephole machines it's difficult to determine whether tool and workpiece are on the axis of rotation, as was explained in ch. 5.8.c, but this shouldn't stop one from correcting the



misalignment error. If not corrected, bore straightness will suffer and the drill may break, possibly ruining the workpiece in the process.

5.11.b bell mouth

When the gundrill enters the workpiece instability can occur which causes the hole at that place to have a 'bell mouth' shape. When the drill enters the material a bit more the instability may stop and the rest of the hole will be drilled properly.

There's a correlation between early gundrill failure (fatigue crack) and bell mouth formation; both can have a common cause in too much clearance between gundrill and starting bushing. If bell mouth formation is observed and isn't necessarily a problem for the workpiece, measures still have to be taken to prevent early failure of the gundrill.



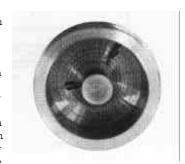
5.11.c chatter

Chatter in deephole drilling is a form of self excited, mainly torsional vibration of the tool-boring bar assembly (Weinert, "Experimental investigation [...]"). The result of it is usally only visible at the bottom of blind holes as radial chatter marks:

"Torsionsschwingungen (Drehschwingungen) von Schaft/Bohrrohr und Werkzeugkopf bedingen eine gleichfrequente Längsschwingung. Hierbei dominieren die Eigenfrequenzen der Bohrstange. Es entsteht am Bohrungsgrund die entsprechende Welligkeit (strenggenommen Zonen geringerer bzw. größerer Bohrtiefe). An der Bohrungsoberfläche (Bohrungswand) selbst ist meist nur ein geringer Einfluss vorhanden (Zonen unterschiedlicher Reflektion)." (www.tiefbohren.info)

Only in extreme cases may the effects of chatter be seen on the walls of the hole. However, this doesn't mean that chatter is an innocent phenomon:

"Durch die Torsionsschwingung werden Schwingungen der Schnitt- und Vorschubgeschwindigkeit erzeugt, die die Schneide stark beanspruchen und zu einer Verkürzung der Standzeit der Schneiden und damit indirekt auch der der Führungsleisten führen. Ein Werkzeug, das in einer der Torsionseigenfrequenzen schwingt, erzeugt zudem für das Umfeld (z.B. für den Bediener) sehr laute und unangenehme Schallwellen." (www.tiefbohren.info)



In the picture on the right, the area marked '1' is made by a stable process while the guide pads are still in the starting bushing; '2' shows an area where chatter occurs; '3' shows an area with spiraling.

My initial idea was that any vibration would be unwanted. However, mr. Smeenk of Kluin Wijhe stated during my visit that 'a little bit of vibration gives a better performing process, because the chips are smaller due to better chip breaking [because of the torsional vibration; PD]'. One



should wonder, though, whether vibration is the real solution to the problem (i.e., chips not breaking properly), or that there are other issues involved (like an incorrect drill geometry).

5.11.d spiraling

Spiraling is another form of dynamic instability which leads to a multi-lobe shaped deviation of the cross section of the hole from absolute roundness. It can be compared to the occurrence of tri-angular and quint-angular holes when spiraldrilling plate, with the difference that this non-round section progresses in a spiral through the hole. In general multi-lobe shaped holes result from a circular movement of the center of the rotating tool around the ideal center of the hole where the number of points of contact of the rotating tool with the workpiece determines the number of lobes of the cross section (Weinert, "Experimental investigation..."). The phenomenon is related to the various bending modes of the drill. A solution to stop spiraling can be to make sure there's enough support of the drill to prevent excessive bending.

Spiraling can occur in several phases of the process: when the gundrill enters, reproducibly at the same drilling depth, or seemingly at random.

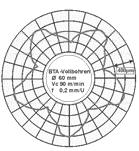
In the picture on the right is another example of spiraling. If we compare that picture with the picture above (area 3), it's immediately obvious that in the top picture there are much more grooves. This can be explained by the difference in



bending frequency of the drills (these two workpieces were machined under different conditions, with different machinery and tools).

In the picture on the right we see how the cross-section of a hole with spiraling would look like; in this particular case (STS/BTA drilled) the height of the peaks over the valleys is $0.4~\mathrm{mm}$ with 5 lobes.

This fault in the machined bore is very easy to spot (unlike e.g. straightness). However, it can also be heard and felt

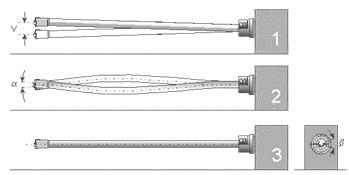


during the actual machining, which may help in correcting the process:

"Geübte Maschinenbediener können den Drallvorgang hören bzw. durch Berühren des aus der Bohrung ragenden Teils des Bohrrohres/Schaftes ertasten. Der Tiefbohrvorgang wird durch "Drallbohren" stark beeinträchtigt, das Bohrergebnis ist mangelhaft und der Werkzeugverschleiß steigt stark an." (www.tiefbohren.info)

When looking at the above problems, notice that many of them are caused by instability: bell mouth, chatter and spiraling. These are caused either by bending-mode or torsional-mode vibration. There are several things that can be done:

reducing clearance between bushing and gundrill (reduces amplitude of vibration), correct amount and location of guiding pads on the gundrill (supporting continuum is not recommended) and enough whipguides to prevent the gundrill from bending. Fortunately the occurrence of instability is generally easy to diagnose by the sound it produces. Only instability that occurs when entering the workpiece can be so short (about 0,3 s) that it may go unnoticed.



There are other problems that may impair the quality of a gundrilled hole. It's outside the scope of this thesis to describe them all, so in Appendix C is a short table that lists the various problems and their possible causes.

Part 2: Application

In the previous part we have taken a look at some of the theory behind drilling, deephole drilling and gundrilling. The 3 kinds of deephole drilling techniques have been explained, with an emphasis on gundrilling. In the chapter on gundrilling, the various forces acting on the drill have been shown, as well as several aspects of gundrilling, like coolants, the importance of the starting bushing, the variants of gundrilling (rotating tool, rotating workpiece and counter rotation). Finally, we have taken a closer look at the calculations that are made to establish the process parameters of gundrilling.

In this part we shall apply what we've learned to a more practical use: a direct comparison will be made between two processes, spiraldrilling and gundrilling, and their resulting bores. Measurements will be made to determine how well the holes perform on their most important qualities.

The main goal of this part is to check if the theoretical predictions regarding bore qualities are consistent with reality and in how far the gundrill overcomes the problems of the spiral drillwhen drilling deep holes.

Chapter 6

Comparison of gundrilling to spiraldrilling

In this chapter I shall explain how the comparison between gundrilling and spiraldrilling will be made. First of all it's important to note that this comparison may not be entirely fair: we are comparing a highly specialised process (gundrilling) to a common, more or less allround process (spiraldrilling). As we've seen gundrilling is especially good for drilling deep holes with high tolerances on diameter, excellent roughness, straightness and roundness. Spiraldrilling, on the other hand, performs much worse on all these aspects. So, then, why compare apples to oranges?

One reason is to have a benchmark: by using the performance of spiraldrilling as a reference, we can determine how much better (or worse) gundrilling performs and whether the benefits outweigh the costs. We could compare, for example, gundrilling to STS/BTA or Ejector deephole drilling. However, the result would have less meaning: we then would know which process performs better (in those specific circumstances), yet the link with the more down-to-earth technique of spiraldrilling is non-existent. So, by using the process of spiraldrilling, we establish a reference that's widely known.

The second reason is of more practical nature: I do have access to the machinery for spiraldrilling; the highly specialised equipment of STS/BTA or Ejector drilling is far less accessable.

However, to make the comparison a bit more fair (and at the same time gather a lot more information) not only shall I use standard spiraldrilling (the reference), but also compare gundrilling to the more generally used process of producing high quality holes: by following it up with a multi-fluted drill operation and reaming.

I shall compare the bores based on their seven qualities:

- diameter
- roundness
- straightness
- roughness
- location
- orientation/attitude
- hardness

These bore qualities are measured on different workpieces: two that are gundrilled (aluminium and steel) and two that are spiraldrilled (aluminium and steel). This makes it possible to draw conclusions with respect to both materials.

Correct location of the hole is measured using a manually operated 3D coordinate measuring machine, of the type 'Mitutoyo MXF 203'; the data-processor is of the type 'Mitutoyo Micropak 120'. Both the location of the ingoing and outgoing part of the hole will be measured, along with the position halfway in the hole.

Attitude is not measured by itsself, but can be determined based on the locations of the ingoing and outgoing center of the bore. With this information it's possible to calculate the perpendicularity with respect to the reference surface.



Diameter and roundness are also measured with the 3D measuring machine. Both diameters were measured, i.e. where the drill entered the material (ingoing diameter) and where it exited (outgoing diameter). Also, both the ingoing and outgoing roundness are measured, to determine if there's any variation between the two.

Roughness measurements are made using a Mitutoyo roughness tester of the type 'Mitutoyo Surftest 301, pictured in the photo on the right. More because of luck than foresight, it proved unnecessary to open up the bores to perform the roughness measurement: the diameter of the holes was just big enough to let the measurement-tip of the roughness tester in. This proved to be of great practical advantage, since it negated the need to saw the workpieces in many smaller pieces in order to have acces to the inside surfaces of the bores.



The determination of increase in hardness is done by measuring the hardness before and after drilling, using the Vickers method. The Vickers method is used, since the other two available hardness measurement machines can't measure hardness of small curved surfaces due to the physical size of the measuring head. In the gundrilled holes it may be possible to see an increase in hardness due to the cold deformation that took place. Hardness of the spiraldrilled holes isn't measured, since an increase in hardness is not expected here.



Chapter 7

Spiraldrilling the samples

In this chapter, I shall explain how the samples have been designed, machined and measured, and the results of those measurements.

7.1 The samples

To determine the qualities of holes drilled with the spiraldrilling process, we'll have to perform the spiraldrilling operation and measure the results. The undrilled sample is basically a square cube of 100*100*100 mm, as can be seen in the drawing in Appendix D. The reference surfaces are milled as accurately as possible, to ensure that they are square to each other. The errors were measured after milling and proved to be negligable, always less than 5 um. This is important, since we only want to measure the errors of the holes, not errors in the reference surfaces.

In total 15 holes are made per sample; 5 of these are only drilled in a single step to 10 mm; 5 others are spiraldrilled, then drilled to 9,8 mm with a multi-fluted drill; the final 5 holes are spiraldrilled, multi-fluted drilled and finally reamed to a size of 10 mm. These operations are based on the standard practices of drilling holes of various qualities; see e.g. Deckers & Schellekens, p.300. These operations are performed on both the aluminium and steel sample.

Using each process 5 holes are drilled to exclude some variance. However, this is not nearly enough to be able to draw conclusions that are statistically significant. This would require the drilling of at least 30 holes, possibly more, depending on variation in the process. However, other researchers on this subject (Deng e.a., 2001) have used single measurements to draw their conclusions, so at least my results should be more reliable.

The holes have a final diameter of 10 mm (actually 9,8 mm in the case of the 3-flute drilled hole; for all practical purposes it may be equated to $10~\text{mm}^{37}$). I haven't chosen a smaller diameter since this might hinder measurement of roughness due to curvature of the surface. Accidentally, this diameter proved large enough to measure roughness without needing to destroy the sample. Also, when measuring with the 3D measuring machine, some clearance between the measuring tip and hole should be present. A bigger hole diameter than 10 mm with a L/D-ratio of 10 would give the need for a bigger block of steel or aluminium, with corresponding increase in material cost.

The depth of the holes is 100 mm, so the L/D-ratio is 10, the start of the region of deep holes; this is more than the spiraldrilling process should be capable of (max. recommended L/D-ratio of about 4-6) so I expect to see some errors of the hole, especially with regard to straightness. This is of course what we are looking for.

Two of such workpieces are made, one in free cutting aluminium (AlMgSi1) and one in free cutting steel (9SMn28K). No further information with respect to material characteristics could be given by the supplier of the material. As it is, they had enough trouble finding out what the material was exactly. So, in order to have a little more information on the condition of the material, hardness was measured and found to be 207 HV10 for the steel sample and 117 HV10 for the aluminium sample (average of 3 measurements).

I've chosen to machine two such workpieces after discussion with an experienced metalworker, according to whom machining in aluminium would lead to much greater deviations in straightness than when machining steel. Plus, surface roughness in aluminium would be much worse, according to him. Since the extra effort needed to machine two workpieces, as compared to one, would be little (considering that machining time is only a fraction of the total time of preparation 38) I've decided to machine two different materials. This would effectively double the data

 $^{^{37}}$ by choosing a diameter of 9,8 mm for the 3-fluted drill, it was possible to get by with only one drill, instead of two (9,8 mm and 10 mm). The high cost of such drills (over 30 Euro) was the main reason for this decision.

 $^{^{\}rm 38}$ Known as 'decreasing costs to scale'.

available and makes it possible to draw more general conclusions. However, this experiment remains a comparison of two processes, not an experiment to compare the 'drillability' of various materials, so no more materials than this are tested.

7.2 Machining setup

The machine used for the drilling and reaming operations is a Bridgeport Cambridge 460, a CNC milling machine with automatic tool change. A photo of it is on the right. This made it possible to both mill the raw aluminium and steel block to the correct outside dimensions, and then spiraldrill, 3-flute drill and ream it in one setup. The specimen was first drawn in Autocad, after which it was imported in Esprit to simulate machining and generate the ISO-code program for the CNC milling machine.



The values of the machining parameters $(V_c,\ f)$ that are used in drilling the holes are shown in Appendix F. They were calculated by the method as described by Deckers & Schellekens on p. 282 & 300. Since these parameters are based on machining with a coolant, coolant is used.

The actually used cutting speeds (Vc) that were used were those as given in App. F; the feed-rates however had to be drastically reduced, to about 30%-40% of the calculated values. The two times that we tried to increase them to the calculated values resulted both times in the destruction of the tool...

Drilling is done in steps ('pecking'), in order to facilitate breaking of chips.

Spiraldrilling is done with a new drill of 10 mm diameter with TiN-coating; 3-flute drilling with a new drill of 9,8 mm; and reaming with a (not new) HSS-reamer of 10H7.

First all holes (1-15) are spiraldrilled to 9,5 mm; then holes 6-15 are drilled with the 3-fluted drill to 9,8 mm; finally holes 11-15 are reamed to 10H7 (by machine)³⁹.

The aluminium specimen is machined first to reduce the effect toolwear might have when drilling the second (steel) sample.

7.3 Practical machining

In the pictures below are the two samples, after they are milled and drilled. On the left is the steel sample, on the right the aluminium sample. Note that the cut in the middle of both samples was made afterwards, in order to be able to measure hole-location halfway the length of the bore.





 $^{^{39}}$ The actual drilling sequence was not 1-15, but 5-4-3-2-1-6-7-8-9-10-15-14-13-12-11. This isn't very important, but explains that when the 3-fluted drill broke at the last hole of the aluminium sample, it was at hole nr. 11.

Drilling itsself wasn't without problems. First of all, the size of the workpiece was at the very limit of the machine's capability. There was hardly enough room to drill it, the long drill being a major factor. This called for some tricks (different toolholder, manouvering of the tool before and after toolchange) in order to be able to drill it.

Secondly, chip removal was problematic, with the chip winding itsself around the shank of the drill and scraping over the surface of the workpiece, as can be seen in the photo on the right. This meant that the process had to be stopped several times during a drill-cycle, in order to remove chips from the drill. The presence of this large clot of chip prevented the flow of coolant to the drill.

Thirdly, the machining data, as determined based on the data by Schellekens & Deckers, shown in Appendix

F, was not correct for the drilling of these holes. Even though correction tables for holes with high L/D-ratio's are included in it, the value for feed rate was much too high. The calculated values were used in the ISO-program for the CNC-machine, but the manual override button was used to reduce feed-rate, to 30-40% of the calculated values. We tried to increase the speed two (separate) times, both times resulting in the destruction of the tool. On the left is the 3-flute drill after breaking, on the right is the spiral drill, after overheating and breaking. Drill sharpness couldn't have been an issue here, since both drills were new and never used before. Application of coolant may have been a major contributing factor, since it's nearly impossible to apply the coolant to where it's needed (the cutting area of the drill) in spiraldrilling.





Finally, the machine itsself seemed to be unhappy with the task it was provided with, and decided to 'take a break', needing some care by a repair-mechanic. This meant that part of the drilling had to be done on another day, however, the machining setup wasn't disturbed in that period, so exactly the same machining conditions were present.

7.4 Measurement results

After the machining of the holes, measurements of the hole qualities were made. First diameter, roundness and location were measured, after which attitude was determined. After these were made, the sample was sawed in two pieces to measure the location of the bore halfway, so the straightness could be determined (the assumption is made that variation of straightness is greatest halfway through the hole).

For the complete results of the measurements I advise the reader to take a look at Appendices G and H, for the aluminium and steel samples respectively, where the complete results, both raw data and calculated results, are shown. In this part of the thesis I shall only deal with some parts of the measurement results, i.e. those that are in some way interesting.

As can be seen, not all holes could be measured, since two (different) drills broke off.

Locational accuracy

If we take a look at graph G.1 in Appendix G, which shows the locational accuracy of the spiraldrilled aluminium sample, it's hard to notice any relationship between the process used (2-fluted, 3-fluted and reaming) on the locational accuracy of the hole. This is not surprising, since locational accuracy is mainly determined by the first step, spiraldrilling; once an initial hole is drilled, it's very difficult, if not impossible, to shift its position. Graph H.1 in App. H shows the same results for the spiraldrilled steel sample.

On average, for both the aluminium and steel sample, error in position is about .1- .12 mm.

Attitude

Graph G.2 in App. G shows the attitude of the holes in the aluminium sample; no improvement in attitude can be seen for bores 6-10 and/or 11-15 compared to 1-5. The same goes for the steel sample in graph H.2 in App. H. This suggests that if attitude of a hole is important, no improvement can be had when, after drilling of the initial hole, 3-flute drilling and/or reaming are performed. Also, for both samples the average error in attitude is about .15 mm, suggesting that material has no or little influence on this hole quality.

Straightness

Graph G.3 in App. G shows the straightness of the various holes in the aluminium sample. It's immediately obvious that for holes 11-15 straightness is better (on average, about .01 mm) than for the other holes. Straightness of the holes that were only spiraldrilled or 3-flute drilled is worse than that of the reamed holes. No obvious difference can be seen between holes 1-5 and holes 6-10.

The situation for the steel sample, as shown in graph H.3 in App. H, is slightly different. Here, the improvement of 3-fluted drilling can be seen for holes 6-10, but for holes 11-15, which also had a reaming operation performed, straightness seems to have suffered (ignoring hole 14, which couldn't be measured). An explanation for this I haven't. One would expect that with each successive operation, straightness of the hole would be improved. On the other hand, there are relatively few measurements available; more reliable statements can only be made when more data points are available (i.e., more holes drilled and measured).

Diameter

In graph G.4 are the results of the aluminium spiraldrilled sample concerning diameter. In this and following graphs, the differences between holes 1-5, 6-10 and 11-15 are more obvious, but one should remember that holes 6-10 have a different diameter (9.8 mm) for practical reasons, as discussed earlier. In graph G.4 are the diameters of each hole, measured both at the top, bottom and in the middle. The first thing that can be noticed, esp. in graph G.6, is that the variation in diameter over the length of the hole is smallest in the holes that were only spiraldrilled. In the 3-fluted and reamed holes, this variation over the length was greater! This strikes me as a strange result. I initially thought that, in the case of the reamed holes, this might have something to do with the fact that the reamer hadn't entered the hole deep enough, but this can't have been the case. Nor could it be because of the 'conicity' of the reamer, since it's not a hand reamer but a machine reamer, with very short conical guide part. So, the real cause remains unclear.

But if we look at the steel sample, at graph H.6 in App. H, the results make more sense: variation in diameter is least for the reamed holes (note that hole 14 hasn't been reamed), and most for the spiraldrilled holes. Not only is the variation in diameter the smallest for the reamed holes, but also is the (average) diameter closest to the target of 10H7. Nothing very new here, it was expected that for accurate diameter, reaming should give the best results.

However, for the aluminium sample, this last doesn't seem to hold true. In fact, reaming caused greater variation in diameter (graph G.4; G.6). Plus, the target

diameter of 10 (with tolerance H7) was not achieved by any of the reamed holes! When visually inspecting the holes that were reamed in aluminium, roughness of the bore surface is striking.

So, as far as accurate diameter is concerned, reaming seems to perform as expected on the steel sample, but seriously fails in the aluminium sample.

Roundness

As can be seen in graph G.7, App. G, there's no relationship between the operations performed and the achieved roundness of the holes in the aluminium sample. Nor does roundness range (graph G.9), i.e. range between the highest and lowest roundness per hole, depend on the operations performed. This strikes me as strange, since I'd expect that the reamed holes would have a better roundness than the holes that were only spiraldrilled.

The situation is different for the holes in the steel sample, as can be seen in graph H.8, where roundness range is a function of the operations: the reamed holes, nr. 11-15, show a much lower variation in roundness over their length than the other holes. However, little improvement in range can be seen of the 3-flute drilled holes over the ones that were only spiralldrilled. As graph H.9 shows, the average roundness of the holes gets better as more operations are performed. This trend is not present for the aluminium sample (graph G.8).

If we compare graph G.7 to H.7, we see that there's little difference in achieved roundness for the aluminium and steel sample; they perform about the same on this bore quality.

Roughness

If we look at graph G.10 in App. G, it's immediately obvious that roughness of the aluminium sample is best for the spiraldrilled holes (with exception of the top of hole nr.2), worst for the 3-flute drilled holes (6-10) and 'in between' for the reamed holes. The bad surface finish of the reamed holes has already been mentioned in a previous paragraph on 'diameter'.

For the steel sample, the results are as would be expected: worst Ra for the spiraldrilled ones, best for the reamed ones, with 3-flute drilling producing intermediate results. This is just as predicted by literature (Deckers & Schellekens). There is an exception (hole nr.12, bottom), but on average, a roughness smaller than Ra=1.5 um is attainable in steel.

On the other hand, if low roughness is desired in an aluminium workpiece, the results suggest that it would be better NOT to ream, but instead to only spiral drill(or, as we shall see later, to gundrill).

Hardness

Increase in hardness has only been measured for the gundrilled holes, not for the spiraldrilled ones, since no increase in hardness is expected. Apart from this, surface quality of the spiraldrilled sample was too low to perform accurate hardness measurements using the Vickers-method.

In the table below, the results of the measurements and the analysis are summarized, with 0 meaning neutral or average, + being good or better than average and - being less good.

		loc.accuracy	attitude	straightness	diameter	roundness	roughness	hardness
Alu	spiraldrilled	0	0	0	+	0	-	N/A
	spiral & 3-flute	0	0	0		0		N/A
	spiral, 3-fl & reamed	0	0	+	-	0	-	N/A
Steel	spiraldrilled	0	0	-	-	-	-	N/A
	spiral & 3-flute	0	0	0	0	0	0	N/A
	spiral, 3-fl & reamed	0	0	-	+	+	+	N/A

It seems that locational accuracy and attitude of the hole are not a function of the various operations, but may depend more on the machining setup (e.g. are reference surfaces of the workpiece aligned with machine references and axes, whether the pilot holes are on the correct locations, or whether a drill bushing is used, as in gundrilling). Regarding the four other qualities, we get results as expected for the steel sample (with the exception of straightness when reaming, which, as has been stated, I can't explain). However, the situation is very different for the aluminium workpiece, where there does seem to be a negative relationship with operations to bore qualities: when 3-flute drilling and reaming, hole quality suffers (diameter, roughness), stays the same (roundness) or improves (straightness)... Clearly, the results for the aluminium workpiece are very mixed.

These results of aluminium are in sharp contrast to the generally found recommendation in textbooks that, if a high quality hole is desired, holes should be reamed. In my experiments, the reamed holes perform worse (on several bore qualities) than the holes that were only spiraldrilled. The textbook recommendation does hold true for the steel sample.

Chapter 8

Gundrilling the samples

In order to compare gundrilled holes to the spiraldrilled ones, one has first to be able to gundrill the holes. Gundrilling isn't the kind of operation that could be performed in the shop at school. In fact, to the best of my knowledge, there's only one company in The Netherlands that performs gundrilling operations as a subcontractor. Only one other company performs gundrilling, but primarily for their own use. I know of several companies that perform the STS/BTA process in The Netherlands, but all of these companies do it first of all also for own use, not primarily as subcontractor.

Therefore I was very pleased that mr. Van Hees, manager of Kluin Wijhe, invited me for a company visit and offered to gundrill the samples. On march 18th 2004, I visited the company.

8.1 Kluin Wijhe40

Kluin Wijhe, part of the AEX-notated Aalberts group, is a medium size company located in Wijhe, Overijssel. The company has a total of about 75 employees, divided over 2 business units, 'deephole drilling' and 'bimetallic cylinders'. The bimetal unit produces bimetallic cylinders for the use in plastic die casting and extrusion machines. These cylinders consist of a steel outer part, with a carbide coating on the inside, that provides a wear resistant layer. This layer is produced by means of a centrifugal casting process.

The other business unit, 'deephole drilling', is the one that I visited. This unit has the use of currently 11 deephole drilling machines, all of the same make (TBT) except the newest one, a Degen UTB1600 S-H/CNC 41 . Kluin can perform both gundrilling and STS/BTA-drilling. They act as jobber on these processes. As mr. Van Hees, the company manager, said: 'almost every hole is a prototype', since runs are usually very short. This separates their business from e.g. an automobile manufacturer, which has long runs of identical products, which need to be drilled with maximum efficiency. In fact, DAF trucks, which does its own gundrilling of engine blocks, outsources the gundrilling of special test engine blocks to Kluin Wijhe. The hole sizes they can drill, as stated in their brochure, range from 2 mm to 250 mm, with a L/D-ratio of 100-200. However, in practice they perform more challenging operations; the latest drill they ordered had a diameter of 6 mm and a length of $7.5~\mathrm{m}$. This gives a L/D-ratio of 1250... As they said themselves, this won't be a run-of-the-mill hole, but nevertheless they expect to be able to drill it. Other feats include the routinely drilling of 6 mm holes with a length of 3.5m, followed by another hole, now drilled from the other side, where the two holes should meet in the middle with a maximum discontinuity of about 1.5 mm.

The materials they drill in vary, from construction steel to AISI303 to Titanium. Anyone familiar with machining processes knows the difficulties with which machining these materials are associated.

The products that are drilled vary from parts for car manufacturers (engine parts for DAF Trucks), aircraft manufacturers (landing gears for Airbus Industries), parts for the off-shore industry, machine constructors, etc.

All in all, the visit was very impressive; it's one thing to read about a hole with L/D=500 and a diameter of 6 mm, but to actually see such a hole with one's own eyes is simply amazing, words can hardly describe the experience.

Finally, I would like to thank mr. Van Hees and mr. Smeenk for the cooperation in the gundrilling of the samples. This wasn't an easy thing, since the shop was fully planned and in operation, so in order to drill the samples for this thesis, mr. Smeenk had to actually stop the processing of one product in order to be able to drill the samples. Thanks!

 $^{^{40}}$ For an article on Kluin Wijhe, see also Metaalbewerking, nr 11-12, dec. 2003.

 $^{^{41}}$ The Degen 1600 is a CNC machine with 5 axes and two spindles, capable of drilling workpieces up to 10 tons. (source: Metaalbewerking, dec. 2003)

8.2 The Samples

The same samples that were spiraldrilled were also used for the gundrilling tests. Two holes with a length of 100 mm and a diameter of 8 mm were drilled in each of them. For the positions of the holes, see Appendix E. The reason the holes were drilled with a diameter of 8 mm was out of practical motives: since the shop was operating at full capacity, it was only with some difficulty they managed to squeeze the drilling of these samples in. Since a drill of 8 mm was present in that machine, and the changing of it to a drill of 10 mm was too time-consuming, the holes were drilled with that drill. This had the added benefit of slightly increasing the L/D-ratio to 12.5 (As mr. Smeenk stated, they don't usually drill shallow holes with L/D-ratio of 10. According to them, spiraldrilling could be used up to ratio's of 10..15). The downside might be that the comparison of the gundrilled and spiraldrilled holes might be complicated, but this hasn't been an issue, as we shall see later.

8.3 Machining setup

Drilling was performed on a machine made by TBT, of the type M02 1000 KT-NC. This particular machine can drill holes of $4..40~\rm mm$ in diameter. The stroke of the machine is 1600 mm.

A picture of the machine and its operator, mr. Smeenk, is on the right. On the table of this machine is another workpiece, that had just been drilled. This product is substantially longer than my sample workpieces...



The holes were drilled under the following machining conditions:

n=2500 RPM (Vc=57 m/s)
f= 0,03 mm/rev. (75 mm/min)
oil flow rate = 12 l/min
oil pressure = 55 bar

The cooling fluid used was oil (no further specifications of it known to me) with EP additives.

The drill used was a Botek one, of the type 110 with a diameter 8,00 mm.

The same machining parameters were used for both the aluminium and steel samples. The machining parameters were calculated with the help of a slide-rule, made by Botek. The parameters are not in good agreement with those determined according to the data in ch. 5.10: Vc and f are a bit on the low side.

8.4 Practical machining

As can be seen in the pictures on the next page, the gundrill is a bit long for this kind of holes: with this particular drill, it would have been possible to drill a length of over 1 m. Note in these pictures the use of whipguides for the qundrill; without it, the drill would sag under its own weight.

The gundrilling went much smoother than the spiraldrilling: no problems occurred while machining, with the exception of a 'fountain' (Dutch: 'spuiter') of oil, when the drill exited the other end of the workpiece. Countermeasures had been taken (putting a solid block of aluminium behind the workpiece), but at pressures of 50+bar, the small space between the workpiece and the aluminium block provided plenty of room for the oil to find its way out. As a result, we were greeted by a shower of oil.

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 $^{^{\}rm 42}$ One man's deep holes are another man's small holes...







In the left picture the 3 whipguides for the gundrill can be clearly seen; in the middle picture, we see the drill exiting the guide bushing, which is mounted in the chip box. In the picture on the right, drilling is in process.

8.5 Measurement results

After the drilling of the holes measurements of the bore qualities were made. First diameter, roundness and location were measured, after which attitude was determined. After these were made, the sample was sawed in two pieces to measure the location of the bore halfway, so the straightness could be determined (the assumption is made that variation of straightness is greatest halfway through the hole).

The complete measurements of the gundrilled holes are below:

bore	Х	Y	Х	Y	X	Y	top	mid	bottom	top	mid	bottom	remark
1	24,378	34,560	24,388	34,464	24,475	34,248	7,994	7,978	7,988	0,025	0,052	0,050	
2	24,347	64,508			24,448	64,220	7,993		7,987	0,046		0,057	middle not measured
	2 1,0 11	0 1,000			21,110	01,220	7,000		1,001	0,010		0,007	madio not mododro

Steel	gundrilled		all values measured with Mitutoyo roughness tester (Mitutoyo Surftest 301)								
		top of s	ample; [Ra	a in um]		bottom of sample; [Ra in um]					
bore	m.1	m.2	m.3	m.4	max.	m.1	m.2	m.3	max	remark	
1	0,51	0,54	0,32	0,21	0,54					bottom not measured	
2										not measured	

The aluminium specimen:

Alu gundrilled all values measured with Mitutoyo 3D measuring machine (Mitutoyo MXF 203 & Micropak 120)

	top)	m	id	bot	tom		diameter		roundness			
bore	Х	Υ	Χ	Υ	Х	Υ	top	mid	bottom	top	mid	bottom	remark
1	26,745	32,485	27,239	32,550	28,185	32,657	7,973	7,965	7,977	0,056	0,073	0,060	
2	27.096	62,492			28.635	62.640	7,990		7.985	0.015		0.047	middle not measured

Aluminiun	1	gundrilled		all values measured with Mitutoyo roughness tester (Mitutoyo Surftest 301)							
	top of sample; [Ra in um]						om of sam				
bore	m.1	m.2	m.3	m.4	max.	m.1	m.2	m.3	max	remark	
1 2	0,08	0,08	0,09		0,09					bottom not measured not measured	

Not everything has been measured. First of all, only two holes were gundrilled per specimen, because of the restricted amount of time that was available at Kluin Wijhe. Secondly, only one gundrilled hole has been completely measured (i.e., sawn in half and measured in the middle). This was done to have at least one complete gundrilled hole left to show. Thirdly, roughness wasn't measured in the bottom of the samples, since this would require an extra cut of the specimen and because no great difference in roughness could be seen after visual inspection.

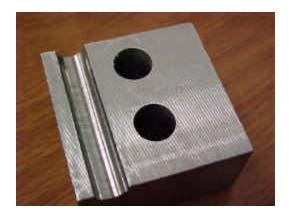
Finally, the two workpieces that were gundrilled were not fixed properly on the machine. More specifically, the reference surfaces of the workpiece weren't aligned with the machine axes. What this means is that locational accuracy and attitude of the qundrilled holes can't be measured.





One the left: the gundrilled aluminium sample, on the right the steel one. The two gundrilled holes are in the side of the specimen (see also App. E).





Roughness

The first thing that became clear after looking at the samples even before making any measurements, was the good surface quality of the gundrilled hole. In the aluminium one, it's actually a mirror finish of Ra=0,08. Such a roughness is normally only achieved with processes like honing, lapping or polishing (Schellekens & Deckers, p.157). With gundrilling, this kind of surface finish is achievable in one single step! The steel sample, which doesn't have the mirror finish of the aluminium one, still has an Ra=0,40 (on average); the worst measured was Ra=0,52. According to the Botek sliderule for type-110 drills, expected Ra should be 0,25 um; however, it isn't stated for wich material this is valid. As can be seen, the aluminium sample performs very much better, but the steel one has almost double the expected roughness.

The roughness is spoilt by the presence of concentrical grooves. These grooves were present in both the gundrilled holes in the steel sample, none were present in the aluminium sample.

I tried to link this surface finish defect to the errors described in ch. 5.11 on typical deephole deficiencies. It comes closest to the case of 'spiraling', even though the distance between consecutive spirals is very much shorter than is shown in the picture. If spiraling was the case, it would have been a case of dynamic instability. On the other hand, it looked very similar to the surface finish caused by a built-up edge in turning. Therefore, I asked dr. Astakhov for his opinion. He

concluded it was caused by a built-up edge and would be easy to prevent. The low Vc could explain why a built-up edge was present when machining the steel sample.

Diameter

If we look at the diameter of the holes, we see that the diameter of the entry holes in steel are 7,993 mm and 7,994 mm; the exit holes 7,988 mm and 7,987 mm. There are not enough measurements made (i.e. holes drilled) to get statistical significant results, but the small range of values is immediately obvious. The range is 0,001 mm (1 um), both at entry and exit of aluminium. If we compare the variation in diameter over the length of the holes we see that in both cases the diameter gets smaller, by about 6-7 um. If we use the worst value (7,987 mm) as basis, the tolerance class would be IT-7.

In the aluminium specimen, the variation is a little larger: entry holes are 7,973 mm and 7,990 mm; exit holes are 7,977 mm and 7,985 mm. At the entry holes, there's a range of values of 17 um; at exit, the range is 8 um. If we use the worst value (7,973 mm) as basis, the tolerance class would be IT-9.

Roundness

Worst roundness of the holes is 52 um and 57 um in steel, and 73 and 47 um in aluminium, as can be seen in the tables above.

Location and attitude

As was explained before, location and attitude haven't been measured since the workpiece wasn't properly aligned.

Since we had two holes, we might try to circumvent this problem by using one hole as reference, to which the errors of the other hole would be compared. However, this method can't determine any systematic error that may be present. If, for example, both holes have a tendency to shift to the right by the same amount, this method would result in the answer that attitude error would be zero, while compared to an external reference, both holes may have a serious error. The same is valid for the locational error.

Straightness

Straightness has only been measured for one hole, in order to preserve the other gundrilled hole. Straightness of the hole in aluminium is 230 um, of the one in steel 71 um. As can be seen, straightness of the aluminium sample is very bad; in fact so bad, that I wonder whether this isn't caused by an error in measurement or by the fact that the workpiece wasn't properly aligned. Either this, or something has very seriously gone wrong when drilling the holes. The straightness, when calculated for a length of 1 m, would be 2,3 mm/m which is about 4 times as bad as what should be possible according to the graph in ch. 5.9.d (0,75 mm/m for the rotating drill system, which was used in this case). In the case of the steel sample, straightness would be 0,7 mm/m, which is as expected. So, the steel sample behaves just as expected, while the aluminium sample shows quite a large deviation.

Hardness

Finally, hardness of the gundrilled holes was measured using the Vickers method. Initial hardness of the aluminium sample (as measured on a milled surface) was 117 HV10 (average of 3 measurements); after gundrilling, the hardness of the bore surface was 139 HV10, an increase of 19% in hardness. The steel sample, however, showed no increase in hardness: initial hardness was 207 HV10, after gundrilling hardness was 204 HV10 (3 measurements each). Initially, I was surprised that the

Gundrilling

steel sample showed no increase in hardness. However, after discussion with dr. Astakhov it was clear that this was quite to be expected, by looking at the strain-hardening curve of free machining steel, which is almost flat, as opposed to that of aluminium, which is more steep: the more strain the material has undergone, the harder it gets.

Something that was also remarkable were the very small burns that were present at the entry and exit of the gundrilled holes. They were much smaller than those produced by spiraldrilling. What this means is that apart from the fewer process steps in gundrilling, there might also be the possibility to do away with one secondary operation, deburring.

Chapter 9

Comparison of the results of both processes

In the previous 2 chapters we have looked at the two different processes that were used to create the samples, spiraldrilling and gundrilling. In this chapter the results of both processes will be compared with eachother.

Locational accuracy

In chapter 7, we had determined that the average locational accuracy was .1-.12 mm for the spiraldrilling process, no matter whether holes were only spiraldrilled, 3-flute drilled or reamed. Because of an error in the fixing of the workpiece in the gundrill machine, no such measurements could be made for that process. This is a shame, since gundrilling is known (amongst other things) to perform good on this account. But this has more to do with the use of guide bushings in gundrilling than with the process itsself.

Despite this, some conclusions can be drawn. The results of the spiraldrilling process were obtained using a CNC machine. I had expected better results than this, especially when taking into account the use of a pilot drill. I find it strange that locational accuracy in the spiraldrilling process isn't very good, despite the use of an accurately controllable CNC machine and the use of pilot holes to initiate the drilling process. I had expected better results, 5-10 times better than what we ended up with.

I'd like to conclude this bore quality with the remark that locational accuracy is a function of first of all the accuracy of the machine and secondly of the method used to initiate the hole: by means of a pilot hole, guide bushing or nothing (only in the case of spiraldrilling). The influence of the process itsself, i.e. gundrilling vs. spiraldrilling, probably only has very limited influence on this bore quality. If a guide bushing would be used with spiraldrilling, the locational accuracy would probably be just as good as that of gundrilling.

Attitude

With respect to the bore quality 'attitude' we have seen that attitude, in the spiraldrilling process, was unrelated to the process steps used; no difference could be seen between the holes that were only spiraldrilled, 3-flute drilled or reamed, nor was there any great difference between the aluminium and steel sample.

In gundrilling, because of the error in fixing the workpiece, no such measurements could be made. Since we had two holes, we might try to circumvent this by using one hole as reference, to which the attitude error of the other hole would be compared. However, this method can't determine the systematic error, and therefore no further comparison between the two can be made; however, if we compare the attitude error of spiraldrilling with the expected attitude error of gundrilling, as shown in the graph in ch. 5.9.e, we would expect an attitude error of about 60 um. If we compare this with the errors in table G.3, we see that spiraldrilling produces much larger errors, ranging from 100-400 um for the aluminium sample and 60-190 um for the steel sample.

Straightness

Straightness of the gundrilled samples varied, as we've seen: the steel sample behaved exactly as expected, with a straightness of 71 um (0.71 mm/m), while the aluminium sample performed much worse, with a straightness of 230 um (2.3 mm/m). If we compare these values to the spiraldrilled samples, than we see that for the aluminium sample straightness varies from 6 um to 57 um (table G.3), which is much better than the 230 um of gundrilling! For the steel spiraldrilled sample,

straightness varies from $4\ \mathrm{um}$ to $57\ \mathrm{um}$ (table H.3), again better than the $71\ \mathrm{um}$ of the gundrilled sample!

These results are very remarkable, considering the fact that one of the strong points of gundrilling should be the excellent straightness. But we must take into account that only one gundrilled hole has been measured per sample. Even then though, one would expect at least better straightness than that of the spiraldrilled holes.

The misalignment of the workpiece on the gundrill machine couldn't have had an influence on the straightness of the gundrilled hole, if we look at the definition of straightness as used in this thesis.

It gives rise to the conclusion that, as far as straightness goes, spiraldrilling produces at least as good results up to an L/D=10 as gundrilling does; we must take into account however, that the L/D-ratio of the gundrilled holes is 12,5, because of the smaller diameter.

It has been suggested earlier that the gundrill, as installed into the machine, was too long (it was about 1 m long) for the holes it had to drill in the specimen (100 mm). However, if the whipguides and starting bushing were accurately aligned, this shouldn't have presented a big problem. Also, it can't have been the case that the whipguide or the starting bushing hadn't been properly aligned, since the gundrilled hole in the steel sample had the straightness that was expected. So there is some other, unknown reason why the straightness of the aluminium sample is so bad.

I can only conclude that spiraldrilling, in this particular setup, has performed better than deephole drilling with respect to the hole quality 'straightness'. An unexpected result, to say the least, especially when taking into account that spiraldrilling isn't advised for holes with an L/D greater than about 5. This is good news for the many users of spiralldrilling, and is in agreement with the statement that Kluin Wijhe doesn't usually drill such short (L/D=10) deepholes; apparently, those holes are produced by conventional means (i.e. spiraldrilling), and the results of these tests show that, as far as straightness is concerned, this is absolutely no problem. It would be interesting to find out how much further spiraldrilling could be pushed before straightness would begin to suffer.

Diameter

The gundrilled holes in aluminium had a diameter that fell into class IT-9; the ones in steel in class IT-7. When comparing this to the holes in aluminium, we find that gundrilling performed much better than spiraldrilling, 3-flute drilling and/or reaming in aluminium. In the case of reaming, the error in diameter is at least 3 times less for gundrilling than for reaming (error of average spiraldrilled & reamed diameter in alu, compared to gundrilling).

In the steel sample, the average diameters of both gundrilling and the reamed holes are about the same. But, the range in values (diameter of top of the hole, as compared to the bottom) is much less for gundrilling than for reaming (5-6 um, as compared to 9-53 um). So, in the case of the steel sample, gundrilling outperforms reaming too.

As was to be expected, gundrilling outperforms reaming (and spiraldrilling & 3-flute drilling) with respect to tolerance on diameter. Is a hole with tight tolerance on diameter required, gundrilling would be recommended. Especially when we take into account that gundrilling is one operation, as compared to the 3-operations that are needed for reaming.

Roundness

In the gundrilled steel sample the worst roundnesses were 52 and 57 um in the steel sample. The aluminium sample had worst roundnesses of 73 and 47 um. Comparing it

with the roundness of the spiraldrilled aluminium sample, we see that it performs slightly better, with spiraldrilling resulting in a roundness of about 40-50 um (see graph G.7). For the steel sample, we see in graph H.7 that roundness does depend on the operation; the reamed holes have the best roundness, at about 40 um. The other holes have a foundness of about 40-50 um, comparable with that of gundrilling. We see that spiraldrilling performs slightly better on this hole quality than gundrilling does, both in the aluminium and steel sample, but the difference isn't very large. If roundness of the hole is an issue, spiraldrilling has a slight head start. The only exception are the entry holes of the steel sample that were only spiraldrilled; here, roundness is worse, at about 70 um, than would be achieved with qundrilling (see graph. H.7).

I find this result, i.e. that spiraldrilling performs better on this quality, a bit surprising. I expected that the burnishing of the gundrill would improve roundness, as it does with roughness. Obviously, this doesn't seem to be the case. It should be noted that the difference between gundrilling and spiraldrilling isn't very large and that only two holes were gundrilled per sample. Nevertheless, the results indicate that spiraldrilling provides better roundness.

Roughness

As seen in chapter 8, roughness of the gundrilled samples varied a bit: aluminium being the best performer, with a Ra=0.08 um, while the steel sample had a Ra=0.40 (on average), worst Ra being 0.52 um. The Botek sliderule shows that expected Ra is 0.25 um.

The results of the spiraldrilled sample were mixed: for the aluminium sample, roughness was best for the spiraldrilled holes, worst for the 3-flute drilled holes, and in-between for the reamed ones. The steel sample performed exactly as expected, with the spiraldrilled hole having the worst roughness and the reamed ones the best, with an average Ra=1.5 um.

Generally, gundrilling is known for the excellent surface finish it can produce. In my samples this is obvious only for the aluminium sample, but even for the steel sample, roughness could be much better than it now is. The problem was probably a built up edge (BUE) on the drill, which has a simple remedy (increasing Vc, using other type of carbide, polishing the rake face, right additives in the coolant). While visiting Kluin Wijhe I was showed some holes drilled in AISI-303 steel, which, like most austenitic steels, isn't easy to machine. The surface finish of those holes was excellent.

In order to produce such a surface finish with an 'ordinary' process, one would have to drill, 3-flute drill, ream AND hone! It's immediately obvious that when surface finish of a hole is important, gundrilling quickly becomes the best method, also for holes that aren't deep.

Hardness

No measurements of the increase in hardness when spiraldrilling have been made. Because of the general roughness of the surface, this wouldn't have been very easy to do, using the Vickers method; the other machines that were available for hardness measurement (of Rockwell and Brinell hardness) couldn't measure in the confined space of a hole of 10 mm diameter. Secondly, no significant increase in hardness is to be expected in the case of spiraldrilling. However, it would have been nice to be able to confirm this assumption by measurement.

In the case of gundrilling, significant increase in hardness could be measured. Especially in the case of the aluminium sample, where hardness increased by 19%, from 117 HV10 to 139 HV10 (average of 3 measurements). The steel sample showed no increase in hardness. This may be explained by the difference in the strain-hardening curve, which is almost flat for steel, while the one of aluminium is more steep. **true?****.

So, depending on the question whether an increase in hardness of the bore is wanted, e.g. to reduce wear, it may be beneficial to drill the hole by gundrilling.

Summary

In the table below is a summary of the results.

		loc.accuracy	attitude	straightness	diameter	roundness	roughness	hardness
Alu	spiraldrilled	0	0	0	+	0	-	N/A
	spiral & 3-flute	0	0	0		0		N/A
	spiral, 3-fl & reamed	0	0	+	-	0	-	N/A
Steel	spiraldrilled	0	0	-	-	-	-	N/A
	spiral & 3-flute	0	0	0	0	0	0	N/A
	spiral, 3-fl & reamed	0	0	-	+	+	+	N/A
Alu	gundrilled	N/A	N/A		++	-	++	+
Steel	gundriled	N/A	N/A	0	++	-	-	0

Chapter 10

Conclusion

The research goal of this thesis is 'what are the capabilities and limitations of gundrilling and how do they compare to those of spiraldrilling in practice'. The capabilities and limits of gundrilling and, as a reference spiraldrilling, have been determined with respect to the seven bore qualities (diameter, roundness, roughness, attitude, straightness, locational accuracy), both theoretically and practically.

In the theoretical part, indications have been given for achievable roughness, straightness, etc., which have been later verified and compared in the application part of this thesis.

The results of that last part have been surprising: despite evidence from literature of the capabilities of gundrilling and despite the undertone in the available literature that gundrilling is a superior process over spiraldrilling, the results of the drilling tests have been very mixed: straightness, often one of the most important parameters of a deep hole, was better in the spiraldrilled holes than it was in the gundrilled holes. In the aluminium sample, this difference was very remarkable, but a clear difference was also present in the steel sample. With respect to roughness of the bore, the aluminium gundrilled hole was the very best one that was produced in the entire test. Reaming didn't even come close (in fact, the reamed aluminium hole scored worse on roughness than the holes that were only spiraldrilled). The steel gundrilled sample however performed worse than the reamed holes. The cause for this was the presence of a built-up edge that was present during the gundrilling of the steel sample. By taking some simple measures, this problem could be solved and roughness of the steel sample should be able to be about 0,25 um, the expected value.

With respect to the other hole qualities and the measurement results of them, no surprising outcomes were found, with one possible exception: the straightness of the reamed holes in the steel sample was actually worse than that of the 3-flute drilled holes. An explanation for this strange result I haven't been able to find.

One final result, and one that I haven't been able to find in literature, is the quantitative determination of the increase in hardness of a gundrilled bore. So far I've only been able to find broad statements that claim coldforming is present during gundrilling. In these tests, I've been able to quantify the increase in hardness of a gundrilled hole: 19% increase in Vickers hardness for the aluminium sample, and no increase in the steel sample. These results can be theoretically explained by the difference in their respective strain-hardening curves. When considering these results, it has to be remembered that only two holes were gundrilled per sample, and only one hole per sample has been completely measured (i.e. including straightness, roughness and hardness). Nevertheless, one would expect that every gundrilled hole would perform better than a spiraldrilled one.

Another conclusion would be that spiraldrilling actually performed quite well in the measurements. This shifts the border for choosing between gundrilling and spiraldrilling more towards gundrilling, i.e. the area of application of spiraldrilling is greater than I at first considered it to be, after reading the literature. But it should be borne in mind that the actual drilling of the spiraldrilled holes wasn't easy: on two occasions did a drill break, chip formation was very unsatisfactory despite pecking cycles, with a long spiraling chip forming around the drill, hindering coolant flow and scratching the surface of the workpiece. But while drilling itsself wasn't easy, the resulting holes didn't perform as bad as I initially expected. An overview of the various hole qualities as produced by gundrilling and spiraldrilling is in the table below.

		loc.accuracy	attitude	straightness	diameter	roundness	roughness	hardness
Alu	spiraldrilled	0	0	0	+	0	-	N/A
	spiral & 3-flute	0	0	0		0		N/A
	spiral, 3-fl & reamed	0	0	+	-	0	-	N/A
Steel	spiraldrilled	0	0	-	-	-	-	N/A
	spiral & 3-flute	0	0	0	0	0	0	N/A
	spiral, 3-fl & reamed	0	0	-	+	+	+	N/A
Alu	gundrilled	N/A	N/A		++	-	++	+
Steel	gundriled	N/A	N/A	0	++	-	-	0

Finally, the drilling tests, especially the spiraldrilling tests, have shown that obtaining nice holes in aluminium isn't as simple as is often suggested in the textbooks. Many anomalies were present in the spiraldrilled aluminium sample, where e.g. roughness of a spiraldrilled hole was a little better than that of a reamed hole, and much better than that of a 3-flute drilled hole. Also, the holes that were only spiraldrilled performed better on diameter tolerance than both the reamed and the 3-flute drilled holes. These results are remarkable and put the generally given advice, that when a hole of high quality is needed it should be reamed, in an entire new light.

So, all in all the results of the practical drilling tests were a mixed bag, that help to put some statements on the capabilities and limits of gundrilling in perspective. The fact that the gundrilled holes didn't score as good as might be expected may to a certain extent be explained by the fact that, due to time constraints, less time and effort was put into the gundrilling than in the spiraldrilling, 3-flute drilling and reaming. This was the cause that two bore qualities, locational accuracy and attitude of the gundrilled holes couldn't be measured, since the workpiece wasn't fixed on the gundrill machine accurately enough.

Taking all the above into account, it would have been better to have more gundrilled holes per sample, preferably with different L/D-ratios, up to ratios that are really into the region of deephole drilling as opposed to the borderline case of L/D=10-12. The same goes for the spiraldrilling tests: it may be informative to have data available on the performance of spiraldrilling with respect to different L/D-ratios, like 3, 5, 10 and above. Because as we've seen, the resulting holes (excluding the failed ones, due to broken drills) performed better on some qualities than the gundrilling holes, it would be interesting to see where the qundrilled holes start to win it from the spiraldrilled holes, for each aspect of quality. The fact that the measured results from the aluminium and steel samples differ quite a lot suggest that a further extension of this research might be the comparison of other materials as well. We could think of for example brass, stainless steel, grey casting iron, titanium, etc., but also of plastics. As was stated before, the goal of this thesis was to compare two drilling processes and not to do a comparative study of the drillability of various workpiece materials, but the results from the tests suggest that it may be interesting to perform these tests on other materials as well.

10.1 Further research

The good news is that there's plenty of opportunity left for future research. As was mentioned in the beginning of this thesis, research on the subject of gundrilling is not plentiful, to use an understatement. Yet this technique offers some very interesting possibilities, not exclusively for the drilling of deep holes. Future research might include the development of a model to decide when to use which technique of deephole drilling, or even broader, drilling. Several variables for such a model (the bore qualities) have been mentioned in this thesis, but other aspects (like the economics of the process, material characteristics and limitations in the way of equipment present) would have to be included in it. Also it would be interesting to compare the various systems (rotating tool vs. workpiece vs. counterrotation) with each other. As has been stated earlier, the various sources in literature come to different conclusions with respect to performance of these three methods. Or the influence of the various angles of the gundrill on the machining process could be further researched, and the possible link with certain material properties of the workpiece. Or the influence of the place of the guiding pads; or the shape and place of the fluid hole in the tip and its effect on drill strength. Or the influence of carbide type and coatings on hole properties and tool life. According to dr. Astakhov, on some of those subjects there are plenty of myths and few facts. The research that is available is often fragmented and on adhoc basis, while a systems approach is needed. Clearly enough room for future research on the subject is present.

10.2 Goals

My graduating on the subject of gundrilling and the writing of this thesis had multiple goals. First of all, I wanted to learn more about the subject of

gundrilling. Secondly, I wanted to let more people know about the existence and usefulness of the technique. Thirdly, since research on the subject isn't plentiful, maybe this thesis could help in some small way.

As to the first goal, I can say I've learned a lot on the subject in a relatively short time. My initial knowledge on it was practically zero, much of my current knowledge is in this thesis. Despite the fact that there is little literature available on the subject, by gathering information from various sources (mostly articles, both scientific and popular, but also advertisements) one can learn quite a lot. However, there are also many things that can't be learned from these sources, and the current inexistence of good 'standard' literature on the subject is a definite problem, that will hopefully won't last too long.

The second goal, the dissemination of knowledge of this technique, I can say I've made a small contribution to this too. Several people in my direct surrounding now know that this technique exists; others now know quite a bit of detail on the subject. If teachers in school were unaware of the (details of the) technique, I can now say that my work on the subject has resulted in their knowing more about it. Finally, personal friends (whose initial reaction sometimes was 'what, you can graduate on drilling? What's there about it that we don't know yet') and family that I've bored with my talking on the subject, now know at least something about it.

The third goal being the advancement of science, I can't say that this thesis has in some way provided great new thoughts on the subject. The only thing that I haven't been able to find in literature (which doesn't mean it doesn't exist) is the increase in hardness of the bore. Only found were general statements that burnishing occured while gundrilling, without bothering to explain how much of it was present. The determination of the increase in hardness provided data that was entirely new (to me), plus the fact that spiraldrilling performed much better than I had initially expected, in some cases even better than gundrilling. For the rest, this thesis is an entry, a first step into this matter and should be considered as such.

10.3 In der Beschränkung zeigt sich der Meister...?

The 'budget' for this project was 40 pages (excluding appendices), the maximum allowable size of a thesis at this school. However, like so many projects, this one also has a budget overrun. From the beginning the goal was to limit the number of pages to at least somewhere near 40.

Several painful decisions had to be made in the process: no space was available to give an overview of other hole producing processes; a chapter about the history of deephole drilling had to be rejected; a more detailled description of STS/BTA and Ejector deephole drilling had to be drastically reduced; a chapter about the economic aspects of gundrilling never saw the light because of space restrictions. As is clear, some tough choices had to be made in the process, to at least limit budget overrun while remaining focused on the research problem. But,

"La perfection est atteinte non quand il ne reste rien à ajouter, mais quand il ne reste rien à enlever." $^{\rm 43}$

10.4 Finally

For me this project has been one of the most interesting parts of the course of Mechanical Engineering. It took a lot of time and effort on my part, but results have been worthwhile, in that I have learned much about gundrilling in a relatively short time. Part of the reason for this is my personal interest in the subject; it would have been much more difficult to develop an enthusiasm for a subject that would have been 'dropped on my plate' by a company with a problem. I would definetely recommend this way of graduating as opposed to the usual way of allocating graduating projects, at least for those students who have a clear view on what they want to learn more about.

_

⁴³ Antoine de Saint-Exupéry.

Appendix A

References

- Astakhov, V.P., **A primer on Gundrilling**, Fabricating & Metalworking Magazine. Taken from: http://www.ndx.com/article archives.asp?action=details&magarticle id=327
- Astakhov, V.P., Gundrilling Know-How, understanding the entire gundrilling system helps resolve tooling problems, Cutting Tool Engineering, december 2001, vol.53, nr.12.
- Astakhov, V.P., 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, International Journal of Machine Tools & Manufacture, no. 42, p.1135-1144, Elsevier Science Ltd., London, 2002.
- Astakhov, V.P., The Mechanisms of Bell Mouth Formation in Gundrilling when the Drill rotates and the Workpiece is Stationary. Part II: The Second Stage of Drill Entrance, International Journal of Machine Tools & Manufacture, no. 42, p.1145-1152, Elsevier Science Ltd., London, 2002
- Astakhov, V.P., Osman, M.O.M., **An Analytical Evaluation of the Cutting Forces in Self- piloting Drilling using the Model of Shear Zone with Parallel Boundaries. Part 1: Theory,**International Journal of Machine Tools & Manufacture, vol. 36, no. 12, p.1187-1200, Elsevier Science Ltd., London, 1996.
- Astakhov, V.P., Osman, M.O.M., An Analytical Evaluation of the Cutting Forces in Selfpiloting Drilling using the Model of Shear Zone with Parallel Boundaries. Part 2: Application, International Journal of Machine Tools & Manufacture, vol. 36, no. 12, p.1335-1345, Elsevier Science Ltd., London, 1996.
- Astakhov, V.P., Subramanya, P.S., Osman, M.O.M., **An Investigation of the Cutting Fluid Flow in Self-piloting Drills**, International Journal of Machine Tools & Manufacture, vol. 35, no. 4, p.547-563, Elsevier Science Ltd., London, 1995.
- Astakhov, V.P., Subramanya, P.S., Osman, M.O.M., **On the design of ejectors for deep hole machining**, International Journal of Machine Tools & Manufacture, vol. 36, no. 2, p.155-171, Elsevier Science Ltd., London, 1996.
- Astakhov, V.P., Osman, M.O.M., Hayajneh, M.T., Re-evaluation of the basic mechanics of orthogonal metal cutting: velocity diagram, virtual work equation and upper-bound theorem, International Journal of Machine Tools & Manufacture, vol. 41, p.393-418, Elsevier Science Ltd., London, 2001.
- Astakhov, V.P., Shvets, S.V., **A system concept in metal cutting**, Journal of Materials Processing Technology, vol. 79, p.189-199, Elsevier Science Ltd., London, 1998.
- Astakhov, V.P., Gundrilling: systems outlook (gundrilling system coherence assures process stability and reliability), taken from http://gundrilling.tripod.com
- Astakhov, V.P., Why gundrills?, taken from http://gundrilling.tripod.com
- Astakhov, V.P., **Basics of cutting tool geometry**, taken from http://gundrilling.tripod.com
- Astakhov, V.P., **Gundrilling: very sharp points**, taken from http://gundrilling.tripod.com
- Astakhov, V.P., What is the meaning of 'self-piloting'?, taken from http://qundrilling.tripod.com
- Astakhov, V.P., Cutting fluids (coolants) and their application in deep-hole machining, taken from http://gundrilling.tripod.com
- catalog Roterende gereedschappen, Sandvik-Coromant, 2001.
- catalog Sartorius, der Werkzeugkatalog 2002/03, H. Sartorius Nachf. GmbH, Ratingen.
- Chin, J.-H., Hsieh, C.-T., Lee, L.-W., **The shaft behavior of BTA deep hole drilling tool**, International Journal of Mechanical Science, vol. 38, no. 5, p.461-482, Elsevier Science Ltd., 1996.
- De Chiffre, L., **Function of cutting fluids in machining**, Lubrication Engineering, vol. 44, p.514-518.
- Deckers, J.W., Schellekens, R., Verspaningstechnologie, Stam Techniek, Houten, 2000.

- Deng, C.-S., Huang, J.-C., Chin, J.-H., Effects of support misalignments in deep-hole drill shafts on hole straightness, International Journal of Machine Tools & Manufacture, no. 41, p.1165-1188, Elsevier Science Ltd., 2001.
- Dingemans, P., **IS, MRP, JIT of OPT? Keuzes in productiebesturing**, graduation thesis at the Erasmus University Rotterdam, Rotterdam, 1999.
- Economist, The, The World Measurement Guide, The Economist Newspaper Ltd., London, 1980.
- Elhachimi, M., Torbaty, S., Joyot, P., Mechanical Modelling of High Speed Drilling. 1: Predicting Torque and Thrust, International Journal of Machine Tools & Manufacture, nr. 39, p.553-568, Elsevier Science Ltd., 1999.
- Gao, C.H., Cheng, K., Kirkwood, D., **The investigation on the machining process of BTA deep hole drilling**, Journal of Materials Processing Technology, no. 107, p.222-227, Elsevier Science B.V., 2000.
- Giancoli, D.C., Physics for scientists & engineers, Prentice Hall, Upper Saddle River (NJ), 2000.
- Kolbe, G., The making of a rifled barrel, 1995 Precision Shooting Annual, 1995.
- Schneider, G., Chapter 8 Drills & drilling operations, taken from http://www.toolingandproduction.com
- Kalpakjian, S., Manufacturing Engineering and Technology (third edition), Addison-Wesley, Reading (Mass.), 1995.
- Kals, H.J.J., Van Luttervelt, C.A., Moulijn, K.A., **Industriële productie**, Ten Hagen & Stam B.V., Den Haag, 1998.
- Koelsch, J.R., **Productive deep-hole drilling**, Machine Shop guide web archive, july-august 2001. Taken from: http://gundrilling.tripod.com
- Langereis, F., Werkplaatsmeettechniek (richtlijnen voor het passen en meten van de geometrie van werkstukken), Den Boer Middelburg/uitgevers B.V., 1980.
- McDonald, K., Deep hole drilling for the rear endplate of the BaBar drift chamber, taken from ******website!!******
- Kluin Wijhe BV gaat diep, Metaalbewerking, nr.11-12, dec.2003, Uitg. Ten Hagen & Stam, Deventer
- Langgatboren, Polytechnisch Tijdschrift, editie Werktuigbouw 32, nr. 9, 1977.
- Normen voor werktuigbouwkundig tekenen NEN-Bundel 16, Nederlands Normalisatie Instituut, Delft, 1993.
- Theis, W., Webber, O., Modellierung der Bohrgüte in Abhängigkeit von den Fertigungsparametern beim BTA-Tiefbohren, Technical Report Reihe des SFB 475, Technical Report 48, 2002. (source: http://www.statistik.uni-dortmund.de/sfb475/berichte/tr48-02.ps)
- Tiefbohren auf Bearbeitungszentren, Werkzeug Technik, nr. 79, p. 50, (www.werkzeugtechnik.com)
- Multifunktion auch im Tiefbohren, Werkzeug Technik, nr. 68, p. 40, (www.werkzeugtechnik.com)
- Van Gemerden, J., **Technische informatie voor werktuigbouwkundigen**, Educatieve Partners Nederland B.V., Houten, 2000.
- Verein Deutscher Ingenieure, **VDI-Richtlinie 3208 Richtlinie für das Tiefbohren mit Einlippenbohrern**, VDI-Handbuch Betriebstechnik Teil 2, Beuth-Verlag, Berlin, 1996.
- Verein Deutscher Ingenieure, VDI-Richtlinie 3209 Tiefbohren mit äußerer Zuführung des Kühlschmierstoffes (BTA- und ähnliche Verfahren), VDI-Handbuch Betriebstechnik Teil 2, Beuth-Verlag, Berlin, 1996.
- Verein Deutscher Ingenieure, **VDI-Richtlinie 3210 Tiefbohrverfahren**, VDI-Handbuch Betriebstechnik Teil 2, Beuth-Verlag, Berlin, 1974.
- Verne, J., From the Earth to the Moon...and...Round the Moon, Project Gutenberg Etext version, filename = 'moon10.txt', taken from http://promo.net
- Weinert, K., Webber, O., Hüsken, M., Mehnen, J., Theis, W., Analysis and Prediction of Dynamic Disturbances of the BTA Deep Hole Drilling Process, Proceedings of the 3rd CIRP

International Seminar on Intelligent Computation in Manufacturing Engineering (ICME 2002), 2002

- Weinert, K., Webber, O., Busse, A., Hüsken, M., Mehnen, J., Stagge, P., Experimental Investigation of the Dynamics of the BTA Deep Hole Drilling Process, taken from Univ. of Dortmund Dept. of Machining technology website.
- Weinert,K., Webber, O., Busse, A., Hüsken, M., Mehnen, J., Stagge, P., **In die Tiefe: Koordinierter Einsatz von Sensorik und Statistik zur Analyse und Modellierung von BTATiefbohrprozessen**, taken from Univ. of Dortmund Dept. of Machining technology website
 (zwf2001.pdf)
- Weinert, K., Webber, O., Hüsken, M., Mehnen, J., **Statistics and Time Series Analyses of BTA Deep Hole Drilling**, International Conference "Non-linear Dynamics in Mechanical Processing", Universität Dortmund, Germany, 2001.
- Weinert, K., Peters, C., Mehnen, J., Analyse der Prozessdynamik beim Einlippen-Tiefbohren (Prozessdatenaufnahme und -analyse für die Reglerentwicklung beim Einlippen-Tiefbohren), Werkstattstechnik, p.510-513, Institut für Spanende Fertigung, Universität Dortmund, 2001.
- Weinert, K., Löbbe, H., Peters, C., FEM-Analyse von Einlippen-Tiefbohrwerkzeugen (FEM-Analyse der Werkzeugverlagerung und -belastung beim Einlippenbohren), Werkstattstechnik, p.352-356, Institut für Spanende Fertigung, Universität Dortmund, 2001.
- Wijeyewickrema, A.C., Keer, L.M., Ehmann, K.F., **Drill wandering motion: experiment and analysis**, International Journal of Mechanical Science, vol. 37, no. 5, p.495-509, Elsevier Science Ltd., London, 1995.
- author unknown, History of the single flute gundrill, taken from http://www.starcutter.com/html/sec02_con01_history.htm
- I have been unable to find and use this source, which is so far the only book dealing (partly) with qundrilling:
- Bloch, F., Self-piloting Drilling, Trepanning and Deep Hole Machining. Manufacturing Data, ASTME, Dearborn (MI), 1967.

Some websites that have been used as source of information:

- http://www.titek.com
- http://www.deephole.com
- http://viktorastakhov.tripod.com (website dr. V.P. Astakhov)
- http://gundrilling.tripod.com (Astakhov; many scientific articles)
- http://www.jarvie.com.au (Jarvie Engineering Pty. Ltd.)
- http://www.rifleshootermag.com/gunsmithing/RSgunsmith1/
- http://www.gundrillingsolutions.com
- http://www.starcutter.com/html/sec02_con01_history.htm
- http://www.drillmasters.com
- http://www.tiefbohren.info ('vocabulary of deephole drilling', in German)
- http://www.isf.de (Institut für spanende Fertigung)
- http://www-isf.maschinenbau.uni-dortmund.de
- http://www.tbt-usa.com (TBT, a major deephole machine manufacturer)
- http://www.technidrillsystems.com
- http://www.hammco.com
- http://www.americanheller.com
- http://www.botekusa.com (Botek, a major gundrill manufacturer)
 http://www.hypertool.com (an American gundrill manufacturer)

Appendix B

Source of images

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                       Sandvik-Coromant catalog
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p. 27 bottom:
                       V.P.Astakhov
                       www.tiefbohren.info
p. 28 top:
                       www.tiefbohren.info
p. 28 bottom:
                       www.titek.com
p. 29 top:
                       www.tiefbohren.info
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Appendix C

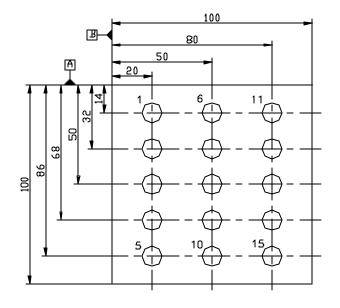
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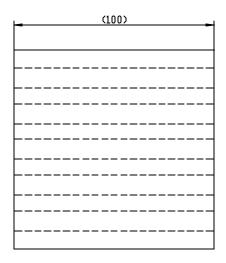
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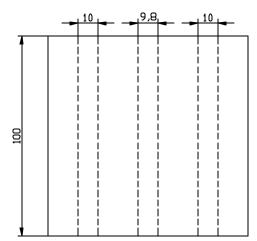
source: www.drillmasters.com

Appendix D

Specimen Spiraldrilling





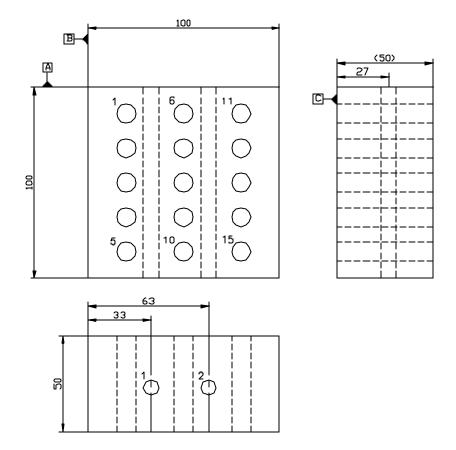


Material: Free cutting aluminium (AMgSi1) Material: Free cutting steel (9SMn28K)

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Appendix E

Specimen Gundrilling



Material: Free cutting aluminium (AlMgSi1)
Material: Free cutting steel (9SMn28K)

N/A	N/A	N/A			N/A	N/A			
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Appendix F

Machining parameters spiraldrilling

Below are the machining parameters as they were determined for the spiraldrilling of the samples. These are based on the data of the book of Schellekens & Deckers. Machining parameters were chosen conservatively in order to get an 'as fair as possible' view of the capability of spiraldrilling. When productivity would be an issue, more aggressive machining conditions could be used. However, during the drilling process, feed rate had to be reduced to about 30-40% of the values given here. Despite correction of feed rates for the depth of the holes, the values were much too high.

Spiraldrilling steel:

```
D = 9.5 \text{ mm}
V_c = 19 \text{ m/min}
n = 600 \text{ RPM}
f = 0.2 \text{ mm/rev}.
```

Spiraldrilling aluminium:

```
D = 9,5 \text{ mm} V_c = 48 \text{ m/min} n = 1500 \text{ RPM} f = 0,32 \text{ mm/rev}.
```

3-flute spiraldrilling steel:

Since no info was found regarding machining parameters, the same parameters as in spiraldrilling were used, taking into account that much less material has to be removed in 3-flute drilling, much less power will be needed, and that chip removal should be easier.

```
D = 9,75 \text{ mm} V_c = 19 \text{ m/min} n = 600 \text{ RPM} f = 0,2 \text{ mm/rev}.
```

3-flute spiraldrilling aluminium:

Since no info was found regarding machining parameters, the same parameters as in spiraldrilling were used, taking into account that much less material has to be removed in 3-flute drilling, much less power will be needed, and that chip removal should be easier.

```
D = 9,75 \text{ mm}

V_c = 48 \text{ m/min}

n = 1500 \text{ RPM}

f = 0,32 \text{ mm/rev}.
```

Reaming steel:

Reaming was done with a HSS reamer.

```
D = 10H7
V_c = 7 \text{ m/min}
n = 400 \text{ RPM}
f = 0.3 \text{ mm/rev}.
```

Reaming aluminium:

Reaming was done with a HSS reamer.

```
D = 10H7

V_c = 12 \text{ m/min}

n = 400 \text{ RPM}

f = 0.5 \text{ mm/rev}.
```

Appendix G

Measurement results spiraldrilled aluminium sample

In the table below are all the measurements that were made with the 3D-measuring machine on the aluminium spiraldrilled sample. These are the raw measurements, without any editing, directly taken from the print-outs of the measuring machine.

spiraldrilled all values measured with Mitutoyo 3D measuring machine (Mitutoyo MXF 203 & Micropak 120) roundness mid bottom diameter bottom mid bottom remark bore top mid top 85,962 20,086 85,916 19,982 85,828 19,848 10,137 10,089 10,052 0,107 0,067 2fluted 2 67,890 20,093 67,962 20,032 67,920 19,980 10,204 10,068 10,053 0,052 0,030 0,043 2fluted 3 49,969 20,093 49,913 20,014 49,840 19,953 10,138 10,091 10,013 0,024 0,033 0,059 2fluted 4 31,971 20,148 31,903 20,163 31,832 20.230 10,123 10,077 10,025 0.06 0,035 0.053 2fluted 5 13,970 20,128 13,885 20,165 13,831 20,250 10,138 10,102 10,032 0,043 0,047 0,055 2fluted 85,995 50,052 86,029 49,988 86,057 49,949 9,971 10,143 9,811 0,037 0,035 0,057 2fl + 3fl (9,8mm) 68,000 50,043 68,028 49,96 68,136 49,835 9,993 10,635 9,802 0,015 0,063 0,057 2fl + 3fl (9,8mm) 8 50,010 50,087 50,072 50,015 50,176 49,978 10,169 10,341 9,904 0,031 0,037 0,052 2fl + 3fl (9,8mm) 9 32,006 50,156 32,011 50,174 32.042 50,245 9,923 10,272 9.962 0,013 0,019 0.069 2fl + 3fl (9,8mm) 10 14,004 50,163 14,044 50,187 14,103 50,282 9,884 10,079 9,837 0,033 0,038 0,063 2fl + 3fl (9,8mm) 11 86,025 80,073 86,087 80,045 N/A 9,854 10,273 0,048 0,047 drill broken 12 68,041 80,107 68,215 80,026 68,434 79.965 7,327 7,415 7,004 0,019 0,041 0.048 7 mm! 13 50,021 80,123 50,138 80,181 50,233 80,237 10,038 10,255 9,986 0,037 0,043 0,040 2fl+3fl+reamed (10H7) 14 31,979 80,120 32,045 80,210 32,107 80,278 10,023 10,272 9,990 0,071 0,068 0,040 2fl+3fl+reamed (10H7) 14,032 80,107 14,103 80,147 14,162 80,183 10,217 10,228 10,042 0,075 0,024 0,045 2fl+3fl+reamed (10H7)

table G.1

In the tables below, the raw data from the two tables above are grouped, edited and calculations are performed, in order to turn the raw data in meaningful information. Graphs are included to simplify interpreting the results.

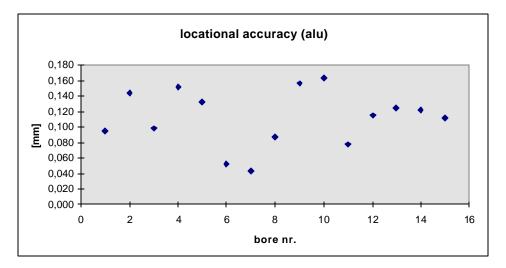
Locational accuracy

Locational accuracy is determined by the distance between the center of the drilled hole and the center of an imaginary hole at the exact target (X,Y)-location. The (X,Y)-location of the hole is measured at the top, i.e. where the drill entered the workpiece.

$$loc._accuracy = \sqrt{(X_{top} - X_{target})^2 + (Y_{top} - Y_{target})^2}$$

Aluminium	1	Location (n	nm)			
	[measur	ed, top]	tar	get	loc.accuracy	
bore	Χ	Υ	Χ	Υ	(difference)	remark
1	85,962	20,086	86,000	20,000	0,094	2fluted
2	67,890	20,093	68,000	20,000	0,144	2fluted
3	49,969	20,093	50,000	20,000	0,098	2fluted
4	31,971	20,148	32,000	20,000	0,151	2fluted
5	13,970	20,128	14,000	20,000	0,131	2fluted
6	85,995	50,052	86,000	50,000	0,052	2fl + 3fl
7	68,000	50,043	68,000	50,000	0,043	2fl + 3fl
8	50,010	50,087	50,000	50,000	0,088	2fl + 3fl
9	32,006	50,156	32,000	50,000	0,156	2fl + 3fl
10	14,004	50,163	14,000	50,000	0,163	2fl + 3fl
11	86,025	80,073	86,000	80,000	0,077	drill broken
12	68,041	80,107	68,000	80,000	0,115	7 mm!
13	50,021	80,123	50,000	80,000	0,125	2fl+3fl+reamed
14	31,979	80,120	32,000	80,000	0,122	2fl+3fl+reamed
15	14,032	80,107	14,000	80,000	0,112	2fl+3fl+reamed

table G.2



graph G.1

Attitude and straightness

Attitude was determined by taking the (X,Y)-location at the top and the (X,Y)-location at the bottom, and calculating the absolute size of their difference:

$$attitude = \sqrt{(X_{top} - X_{bottom})^2 + (Y_{top} - Y_{bottom})^2}$$

Straightness was determined by first calculating a mathematical (X,Y)-location halfway through the bore (depth of 50 mm), followed by comparison of this 'fictional' location (but corrected for attitude) with the true (X,Y)-location of the bore:

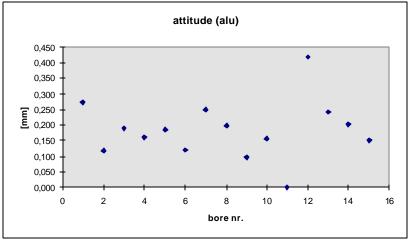
$$X_{corrected} = \frac{X_{top} + X_{bottom}}{2}$$

$$Y_{corrected} = \frac{Y_{top} + Y_{bottom}}{2}$$

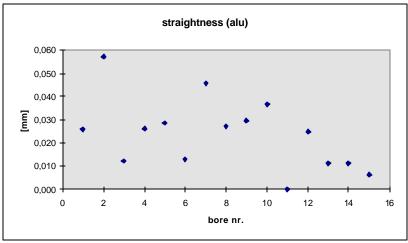
$$straightness = \sqrt{(X_{corrected} - X_{mid})^2 + (Y_{corrected} - Y_{mid})^2}$$

Aluminium	1			
	[all dimen	sions in mm]		
bore	attitude	straightness	remark	
1	0,273	0,026	2fluted	
2	0,117	0,057	2fluted	
3	0,190	0,012	2fluted	
4	0,161	0,026	2fluted	
5	0,185	0,029	2fluted	
6	0,120	0,013	2fl + 3fl	
7	0,249	0,046	2fl + 3fl	
8	0,199	0,027	2fl + 3fl	
9	0,096	0,030	2fl + 3fl	
10	0,155	0,037	2fl + 3fl	
11	N/A	N/A	drill broken	
12	0,418	0,025	7 mm !	
13	0,241	0,011	2fl+3fl+reamed	
14	0,203	0,011	2fl+3fl+reamed	
15	0,151	0,006	2fl+3fl+reamed	

table G.3



graph. G.2



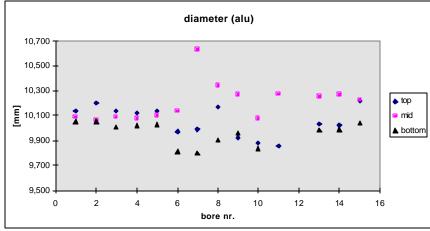
graph G.3

Diameter

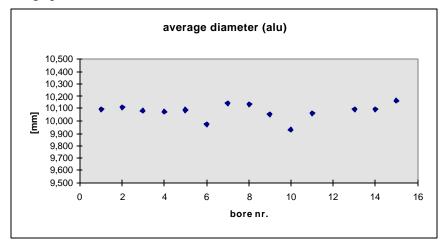
Aluminium	1	Diameter (mm)			
		measured]		[calcu	lated]	
bore	top	mid	bottom	average	range	remark
1	10,137	10,089	10,052	10,093	0,085	2-fluted
2	10,204	10,068	10,053	10,108	0,151	2fluted
3	10,138	10,091	10,013	10,081	0,125	2fluted
4	10,123	10,077	10,025	10,075	0,098	2fluted
5	10,138	10,102	10,032	10,091	0,106	2fluted
6	9,971	10,143	9,811	9,975	0,332	2fl + 3fl (9,8mm)
7	9,993	10,635	9,802	10,143	0,833	2fl + 3fl (9,8mm)
8	10,169	10,341	9,904	10,138	0,437	2fl + 3fl (9,8mm)
9	9,923	10,272	9,962	10,052	0,349	2fl + 3fl (9,8mm)
10	9,884	10,079	9,837	9,933	0,242	2fl + 3fl (9,8mm)
11	9,854	10,273		10,064	0,419	drill broken
12	7,327	7,415	7,004	7,249	0,411	7 mm, not to end diameter
13	10,038	10,255	9,986	10,093	0,269	2fl+3fl+reamed (10H7)
14	10,023	10,272	9,990	10,095	0,282	2fl+3fl+reamed (10H7)
15	10,217	10,228	10,042	10,162	0,186	2fl+3fl+reamed (10H7)

table G.4

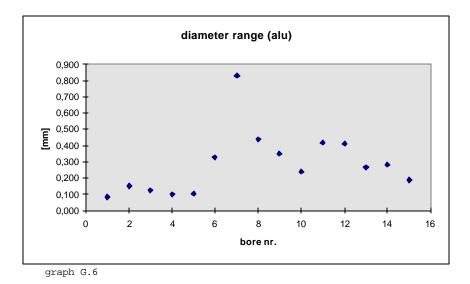
The average diameter was calculated by averaging the 3 measured diameters (top, mid and bottom). The range is the difference between the largest and the smallest diameter, per bore.



graph G.4



graph G.5



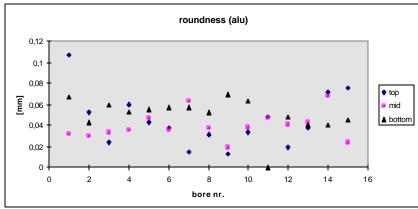
84

Roundness

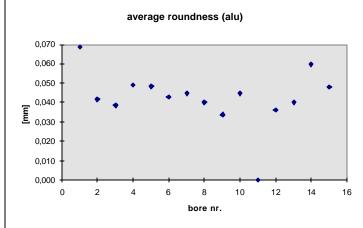
The values for average roundness and range were calculated in the same way as those for diameter, in the paragraph above, except for bore nr. 11, where the average was calculated by only using the two values.

Aluminium		Roundnes	s (mm)			
		measured]	[calcu	lated]	
bore	top	mid	bottom	average	range	remark
1	0,107	0,032	0,067	0,069	0,075	2fluted
2	0,052	0,030	0,043	0,042	0,022	2fluted
3	0,024	0,033	0,059	0,039	0,035	2fluted
4	0,06	0,035	0,053	0,049	0,025	2fluted
5	0,043	0,047	0,055	0,048	0,012	2fluted
6	0,037	0,035	0,057	0,043	0,022	2fl + 3fl
7	0,015	0,063	0,057	0,045	0,048	2fl + 3fl
8	0,031	0,037	0,052	0,040	0,021	2fl + 3fl
9	0,013	0,019	0,069	0,034	0,056	2fl + 3fl
10	0,033	0,038	0,063	0,045	0,030	2fl + 3fl
11	0,048	0,047	N/A	N/A	0,001	drill broken
12	0,019	0,041	0,048	0,036	0,029	7 mm !
13	0,037	0,043	0,040	0,040	0,006	2fl+3fl+reamed
14	0,071	0,068	0,040	0,060	0,031	2fl+3fl+reamed
15	0,075	0,024	0,045	0,048	0,051	2fl+3fl+reamed

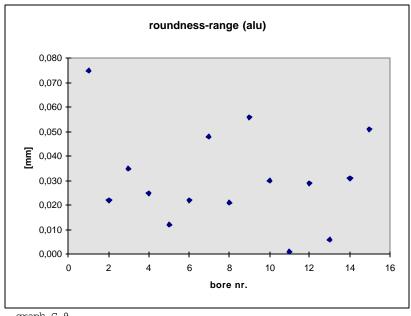
table G.5



graph G.7



Graph G.8



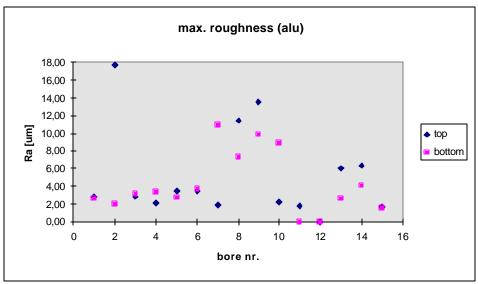
graph G.9

Roughness

In the table below are the results of the roughness measurements, as made with the Mitutoyo Surftest 301. The sample block was measured in two places, at the the top, i.e. where the drill entered the material, and at the bottom, where it exited. At each of these places, at least two measurements were made. In cases where there was a large difference between the two, one or two extra measurements were made. The measurements (per bore, per location (top/bottom)) are numbered m.1 to m.4. The last column of each block gives the maximum roughness of these measurements. It is this value that is used in the rest of the analysis as being 'the' $R_{\rm a}$, since the surface quality is, at least at one location, of that value. Note that there is quite a large range in $R_{\rm a}$ values per bore, which means that if more measurements were made, in several cases the resulting max. \boldsymbol{R}_{a} could be worse...

Aluminium)	Spiraldrille	ed	all values n	neasured w	ith Mitutoyo	roughness	tester (Mitu	toyo Surfte	st 301)
		top of s	ample; [Ra	a in um]		bott	om of sam	ple; [Ra in	um]	
bore	m.1	m.2	m.3	m.4	max.	m.1	m.2	m.3	max	remark
1	1,60	2,84			2,84	2,12	2,67		2,67	2fluted
2	4,13	17,64	3,41	4,59	17,64	2,05	1,87		2,05	2fluted
3	2,83	2,04	1,12		2,83	3,18	1,05	2,47	3,18	2fluted
4	2,11	1,53			2,11	3,35	2,04		3,35	2fluted
5	3,04	3,47			3,47	2,78	2,64		2,78	2fluted
6	3,51	2,78			3,51	3,75	2,16		3,75	2fl + 3fl
7	1,88	1,26			1,88	10,27	10,86		10,86	2fl + 3fl
8	11,40	5,23	5,80	6,93	11,40	2,13	7,31	4,83	7,31	2fl + 3fl
9	13,59	5,88	11,53		13,59	3,02	9,81	3,85	9,81	2fl + 3fl
10	1,95	2,20			2,20	2,21	5,03	8,85	8,85	2fl + 3fl
11	1,84	1,75			1,84	N/A	N/A	N/A	N/A	drill broken
12	N/A	N/A			N/A	N/A	N/A	N/A	N/A	7 mm !
13	4,07	6,03			6,03	0,51	2,68	1,08	2,68	2fl+3fl+reamed
14	6,31	2,04	1,59		6,31	0,74	4,08	0,77	4,08	2fl+3fl+reamed
15	0,90	1,71			1,71	1,57	0,52		1,57	2fl+3fl+reamed

table G.6



Appendix H

Measurement results spiraldrilled steel sample

In the table below are all the measurements that were made with the 3D-measuring machine on the aluminium spiraldrilled sample. These are the raw measurements, without any editing, directly taken from the print-outs of the measuring machine.

Steel	spiraldrilled		all values m	neasured wi	th Mitutoyo	3D measurii	ng machine	(Mitutoyo N	1XF 203 & N	/licropak 120)			
	to	0	m	id	bot	ttom		diameter			roundness		
bore	Х	Υ	Х	Υ	Х	Υ	top	mid	bottom	top	mid	bottom	remark
1	85,920	20,034	86,002	20,057	86,047	20,064	10,143	10,159	10,139	0,057	0,026	0,032	2fluted
2	67,917	20,034	68,032	20,005	68,089	19,953	10,189	10,069	10,177	0,052	0,041	0,034	2fluted
3	49,923	20,047	49,971	20,007	50,018	19,984	10,172	10,246	10,144	0,084	0,036	0,032	2fluted
4	31,890	20,044	31,939	19,988	31,982	19,926	10,201	10,193	10,223	0,071	0,030	0,018	2fluted
5	13,894	20,095	13,937	20,119	13,945	20,158	10,058	10,177	10,177	0,085	0,024	0,025	2fluted
6	85,901	50,068	86,003	50,084	86,084	50,084	9,813	9,854	10,004	0,057	0,028	0,020	2fl + 2fl (9,8mm)
7	67,895	50,059	67,982	50,048	68,036	50,015	9,822	9,864	9,870	0,024	0,024	0,025	2fl + 2fl (9,8mm)
8	49,888	50,074	49,938	50,105	49,991	50,120	9,835	9,863	9,798	0,042	0,031	0,011	2fl + 2fl (9,8mm)
9	31,913	50,078	31,958	50,103	32,024	50,131	9,835	9,845	9,892	0,066	0,040	0,008	2fl + 2fl (9,8mm)
10	13,903	50,074	13,949	50,082	14,019	50,081	9,839	9,844	9,956	0,037	0,022	0,015	2fl + 2fl (9,8mm)
11	85,905	80,079	85,997	80,096	86,091	80,086	9,997	10,016	10,010	0,030	0,030	0,026	2fl+2fl+reamed
12	67,904	80,093	67,995	80,132	68,041	80,174	9,993	10,018	10,036	0,036	0,026	0,036	2fl+2fl+reamed
13	49,893	80,073	49,956	80,092	50,024	80,080	9,995	10,018	10,004	0,024	0,020	0,029	2fl+2fl+reamed
14	31,901	80,086	31,950	80,123	N/A	N/A	9,836	9,889	N/A	0,025	0,038 N	I/A	2fl + 2fl (9,8mm)
15	13,985	80,070	13,960	80,081	14,044	80,057	10,003	10,012	10,004	0,049	0,040	0,038	2fl+2fl+reamed

table H.1

In the tables below, the raw data from the two tables above are grouped, edited and calculations are performed, in order to turn the raw data in meaningful information. Graphs are included to simplify interpreting the results.

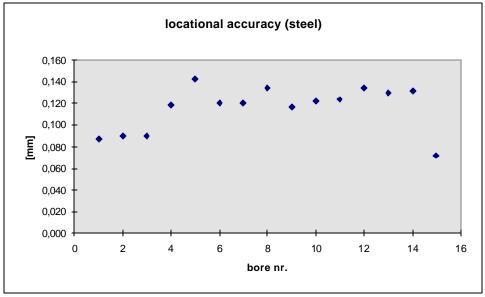
Locational accuracy

Locational accuracy is determined by the distance between the center of the drilled hole and the center of an imaginary hole at the exact target (X,Y)-location. The (X,Y)-location of the hole is measured at the top, i.e. where the drill entered the workpiece. The target locations of the holes are shown in Appendix D.

$$loc._accuracy = \sqrt{(X_{top} - X_{targ\ et})^2 + (Y_{top} - Y_{targ\ et})^2}$$

Steel		Location (r	nm)			
	[measure	ed, top]	tar	get	loc.accuracy	
bore	Х	Υ	Χ	Y	(difference)	remark
1	85,920	20,034	86,000	20,000	0,087	2fluted
2	67,917	20,034	68,000	20,000	0,090	2fluted
3	49,923	20,047	50,000	20,000	0,090	2fluted
4	31,890	20,044	32,000	20,000	0,118	2fluted
5	13,894	20,095	14,000	20,000	0,142	2fluted
6	85,901	50,068	86,000	50,000	0,120	2fl + 2fl (9,8mm)
7	67,895	50,059	68,000	50,000	0,120	2fl + 2fl (9,8mm)
8	49,888	50,074	50,000	50,000	0,134	2fl + 2fl (9,8mm)
9	31,913	50,078	32,000	50,000	0,117	2fl + 2fl (9,8mm)
10	13,903	50,074	14,000	50,000	0,122	2fl + 2fl (9,8mm)
11	85,905	80,079	86,000	80,000	0,124	2fl+2fl+reamed
12	67,904	80,093	68,000	80,000	0,134	2fl+2fl+reamed
13	49,893	80,073	50,000	80,000	0,130	2fl+2fl+reamed
14	31,901	80,086	32,000	80,000	0,131	2fl + 2fl (9,8mm)
15	13,985	80,070	14,000	80,000	0,072	2fl+2fl+reamed

table H.2



graph H.1

Attitude and straightness

Attitude was determined by taking the (X,Y)-location at the top and the (X,Y)-location at the bottom, and calculating the absolute size of the difference:

$$attitude = \sqrt{(X_{top} - X_{bottom})^2 + (Y_{top} - Y_{bottom})^2}$$

Straightness was determined by first calculating a mathematical (X,Y)-location halfway through the bore (depth of 50 mm), followed by comparison of this 'fictional' location (but corrected for attitude) with the true (X,Y)-location of the bore:

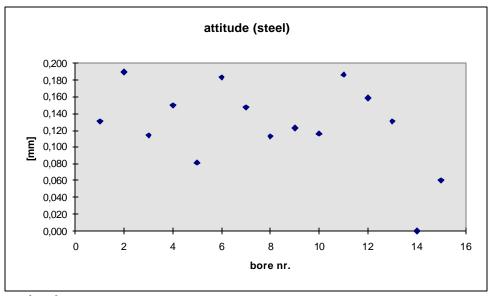
$$X_{corrected} = \frac{X_{top} + X_{bottom}}{2}$$

$$Y_{corrected} = \frac{Y_{top} + Y_{bottom}}{2}$$

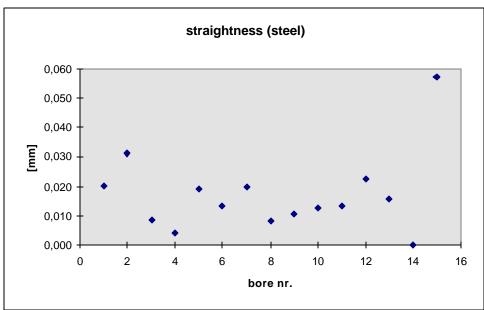
$$straightness = \sqrt{(X_{corrected} - X_{mid})^2 + (Y_{corrected} - Y_{mid})^2}$$

Steel					
	[all dime	ensions in mm]			
bore	attitude	straightness	remark		
1	0,130	0,020	2fluted		
2	0,190	0,031	2fluted		
3	0,114	0,009	2fluted		
4	0,150	0,004	2fluted		
5	0,081	0,019	2fluted		
6	0,184	0,013	2fl + 2fl (9,8mm)		
7	0,148	0,020	2fl + 2fl (9,8mm)		
8	0,113	0,008	2fl + 2fl (9,8mm)		
9	0,123	0,011	2fl + 2fl (9,8mm)		
10	0,116	0,013	2fl + 2fl (9,8mm)		
11	0,186	0,014	2fl+2fl+reamed		
12	0,159	0,023	2fl+2fl+reamed		
13	0,131	0,016	2fl+2fl+reamed		
14	N/A	2fl + 2fl (9,8mm)			
15	0,060	0,057	2fl+2fl+reamed		

table H.3



graph H.2



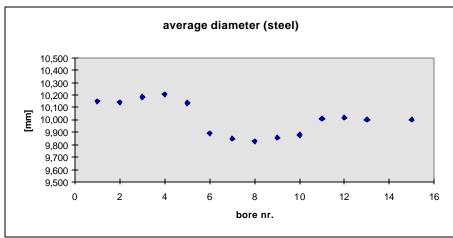
graph H.3

Diameter

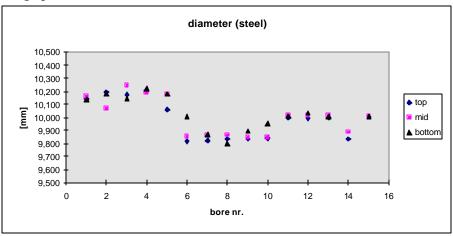
The average diameter was calculated by averaging the 3 measured diameters (top, mid and bottom). The range is the difference between the largest and the smallest diameter, per bore.

Steel		Diameter (mm)			
		measured]		[calcu	lated]	
bore	top	mid	bottom	average	range	remark
1	10,143	10,159	10,139	10,147	0,020	2fluted
2	10,189	10,069	10,177	10,145	0,120	2fluted
3	10,172	10,246	10,144	10,187	0,102	2fluted
4	10,201	10,193	10,223	10,206	0,030	2fluted
5	10,058	10,177	10,177	10,137	0,119	2fluted
6	9,813	9,854	10,004	9,890	0,191	2fl + 2fl (9,8mm)
7	9,822	9,864	9,870	9,852	0,048	2fl + 2fl (9,8mm)
8	9,835	9,863	9,798	9,832	0,065	2fl + 2fl (9,8mm)
9	9,835	9,845	9,892	9,857	0,057	2fl + 2fl (9,8mm)
10	9,839	9,844	9,956	9,880	0,117	2fl + 2fl (9,8mm)
11	9,997	10,016	10,010	10,008	0,019	2fl+2fl+reamed
12	9,993	10,018	10,036	10,016	0,043	2fl+2fl+reamed
13	9,995	10,018	10,004	10,006	0,023	2fl+2fl+reamed
14	9,836	9,889	N/A	N/A	0,053	2fl + 2fl (9,8mm)
15	10,003	10,012	10,004	10,006	0,009	2fl+2fl+reamed

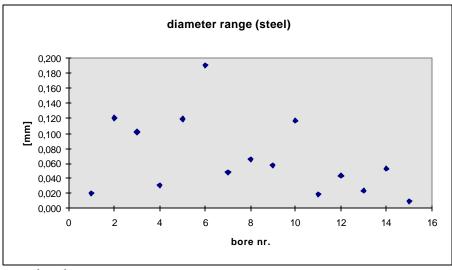
table H.4



graph H.4



graph H.5



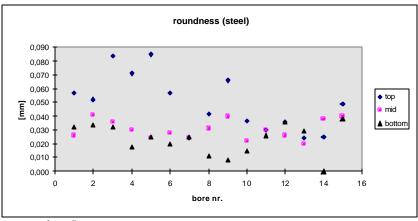
graph H.6

Roundness

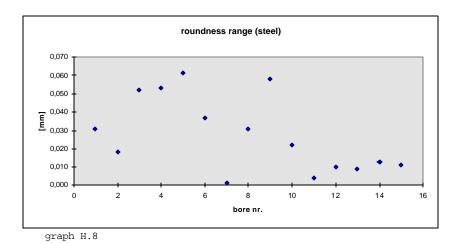
The values for average roundness and range were calculated in the same way as those for diameter, in the paragraph above.

Steel	Roundness (mm)					
	[measured]			[calcu	lated]	
bore	top	mid	bottom	average	range	remark
1	0,057	0,026	0,032	0,038	0,031	2fluted
2	0,052	0,041	0,034	0,042	0,018	2fluted
3	0,084	0,036	0,032	0,051	0,052	2fluted
4	0,071	0,030	0,018	0,040	0,053	2fluted
5	0,085	0,024	0,025	0,045	0,061	2fluted
6	0,057	0,028	0,020	0,035	0,037	2fl + 2fl (9,8mm)
7	0,024	0,024	0,025	0,024	0,001	2fl + 2fl (9,8mm)
8	0,042	0,031	0,011	0,028	0,031	2fl + 2fl (9,8mm)
9	0,066	0,040	0,008	0,038	0,058	2fl + 2fl (9,8mm)
10	0,037	0,022	0,015	0,025	0,022	2fl + 2fl (9,8mm)
11	0,030	0,030	0,026	0,029	0,004	2fl+2fl+reamed
12	0,036	0,026	0,036	0,033	0,010	2fl+2fl+reamed
13	0,024	0,020	0,029	0,024	0,009	2fl+2fl+reamed
14	0,025	0,038	N/A	N/A	0,013	2fl + 2fl (9,8mm)
15	0,049	0,040	0,038	0,042	0,011	2fl+2fl+reamed

table H.5



graph H.7



average roundness (steel) 0,060 0,050 0,040 0,030 0,020 0,010 0,000 12 14 0 2 6 8 10 16 bore nr.

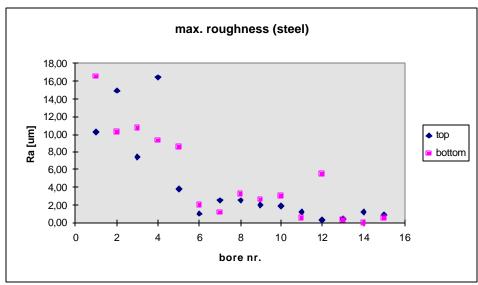
graph H.9

Roughness

In the table below are the results of the roughness measurements, as made with the Mitutoyo Surftest 301. The sample block was measured in two places, at the the top, i.e. where the drill entered the material, and at the bottom, where it exited. At each of these places, at least two measurements were made. In cases where there was a large difference between the two, one or two extra measurements were made. The measurements (per bore, per location (top/bottom)) are numbered m.1 to m.4. The last column of each block gives the maximum roughness of these measurements. It is this value that is used in the rest of the analysis as being 'the' R_a , since the surface quality is, at least at one location, of that value. Note that there is quite a large range in R_a per bore, which means that if more measurements were made, in several cases the resulting max. R_a would be worse...

Steel	spiraldrilled all values measured with Mitutoyo roughness tester (Mitu					itoyo Surfte	st 301)			
	top of sample; [Ra in um]					bottom of sample; [Ra in um]				
bore	m.1	m.2	m.3	m.4	max.	m.1	m.2	m.3	max	remark
1	10,22	10,05			10,22	10,36	6,68	16,51	16,51	2fluted
2	14,95	9,20	7,00		14,95	5,51	10,31		10,31	2fluted
3	7,39	7,31			7,39	10,69	8,12		10,69	2fluted
4	16,44	12,99			16,44	9,30	6,43		9,30	2fluted
5	3,60	3,81			3,81	4,77	8,57		8,57	2fluted
6	0,52	1,09			1,09	1,95	1,99		1,99	2fl + 2fl (9,8mm)
7	2,58	1,17			2,58	0,48	1,20		1,20	2fl + 2fl (9,8mm)
8	1,59	2,52			2,52	0,87	3,26	1,31	3,26	2fl + 2fl (9,8mm)
9	1,99	2,00			2,00	0,32	2,64	1,00	2,64	2fl + 2fl (9,8mm)
10	1,93	0,88			1,93	3,05	2,21		3,05	2fl + 2fl (9,8mm)
11	0,13	1,28			1,28	0,29	0,56		0,56	2fl+2fl+reamed
12	0,31	0,34			0,34	5,53	4,53		5,53	2fl+2fl+reamed
13	0,25	0,43			0,43	0,30	0,11		0,30	2fl+2fl+reamed
14	1,27	1,22			1,27	N/A	N/A	N/A	N/A	2fl + 2fl (9,8mm)
15	0,98	0,37			0,98	0,58	0,22		0,58	2fl+2fl+reamed

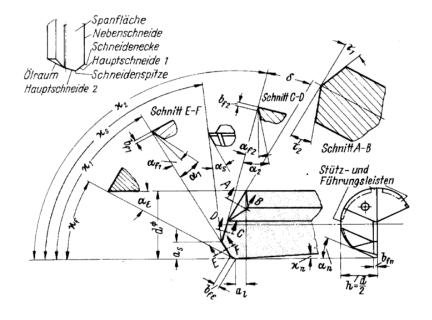
table H.6



graph H.10

Appendix I

Gundrill geometry, angles and terms



Schneidengeometrie und Bezeichnungen des Einlippen-

und Bezeichnungen des Einlippen-Vollbohrwerkzeuges bezugnehmend auf VDI – Richtlinie 3208

_	
×1 ×2	Einstellwinkel der Hauptschneiden
α_1 α_2	Freiwinkel der Hauptschneiden
b _{f1} , b _{f2}	Schneidenfasenbreiten
α_{f1} α_{f2}	Schneidenfasenfreiwinkel
bts	Breite der Eckenfase
×f' (×1f)	Einstellwinkel der Schneidecken- fasen
αe	Freiwinkel der Schneideckenfasen
×n	Einstellwinkel der Nebenschneide (Konizität)
b _{fn}	Nebenschneidenfasenbreite
αn	Nebenschneidenfasenfreiwinkel
as	Abstand der Schneidspitze von der Nebenschneide
αs	Freiwinkel der Schneidspitze
×s	Einstellwinkel der Schneidenspitze
αs	Freiwinkel der Schneidspitze
a ₁	Abstand der Stützleiste von der Schneidecke
8. Tr. To	Ölraumwinkel

Durchmesser d mm	Freiwinkel $\alpha_{1'}\alpha_{2}$	Span- winkel Y1' Y2	Breite der Rund- schliffase b _f mm
2,5 bis 6,3 6,3 bis 12,5 12,5 bis 20 20*) bis 63	15° 14° 13° 13° bis 10°	0° 0° 0°	0,3 bis 0,1 0,4 bis 0,1 0,5 bis 0,1 0,5 bis 0,1

*) ab d = 20 mm im allgemeinen hartmetallbestückter Bohrkopf.

Appendix J

Abstract

This thesis deals with the subject of deephole drilling, with an emphasis on gundrilling, both in theory and in application. An overview is given of the various kinds of holes and the seven most important qualities of a (deep) hole: diameter, roundness, straightness, roughness, location, attitude and hardness. A short overview of the various processes of deephole drilling (gundrilling, BTA/STS drilling and Ejector drilling) is given. The importance of various aspects, like tool forces, coolant, whipguides and starting bushing is dealt with, like the various possible tool/workpiece situations (rotating workpiece, rotating tool and counterrotation) and their consequences. A model for the determination of the process parameters of gundrilling is explained, along with the attainable quality levels of the hole. A short explanation is given of the typical deephole deficiencies. The second part of the thesis compares the performance of the common spiraldrilling process with gundrilling. Performance is measured with respect to the seven qualities of a bore. Spiraldrilling is the reference process, to which gundrilling is compared. Holes that are drilled with multi-fluted spiral drills and/or are reamed are also compared to this reference, both in free cutting aluminium (AlMgSil) and free cutting steel (9SMn28K). The performance on the seven bore qualities of the spiraldrilled holes are compared with those of gundrilled holes, with sometimes surprising outcomes.

Appendix K

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Appendix L

About the author

Peter Dingemans was born in 1973 in Bergen Op Zoom (The Netherlands) and grew up in Hoogerheide. After elementary school he attended the Gymnasium Juvenaat H.Hart in Bergen Op Zoom, where he graduated in 1992. He then went to study Business Economics at the Erasmus University in Rotterdam where he graduated in 1999, specialising in Internal Organisation with emphasis on Quality Management. The subject of his graduating thesis was Manufacturing Planning and Control, a comparison of Just In Time (JIT), Manufacturing Resources Planning (MRP-2) and Optimised Production Theory (OPT), including a model to help determine which system a company should use. Besides his interest in electronics (analog and RF) and metalworking he also finished a course as glider technician during his study. After starting to work as an Industrial Engineer at Philips he attended a one-year course at the Vlerick School of Management in Leuven. In 2000 he started evening school at the



Hogeschool Brabant in Breda to become a Mechanical Engineer, with special interest in Manufacturing and Materials Technologies. This thesis on gundrilling is the graduating thesis for that course.

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