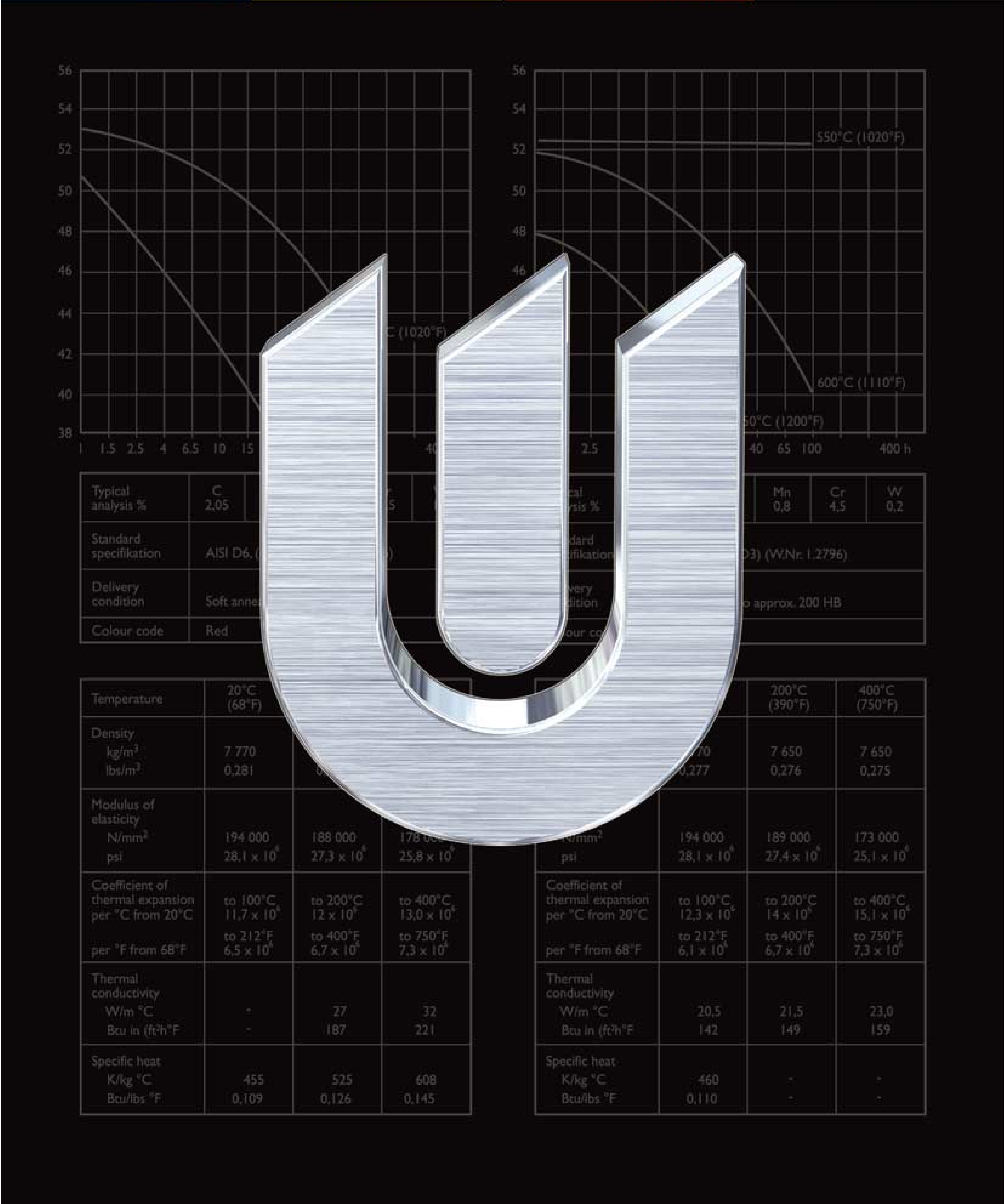
Grinding of tool steel

COLD WORK | **PLASTIC** MOULDING | **HOT** WORK | **HIGH** PERFORMANCE STEEL



Contents

Introduction

The high alloy content of tool steels means that such steels are often more difficult to grind than conventional structural steels.

In order to achieve successful results when grinding tool steels, it is necessary to choose the grinding wheel with care. In turn, choosing the right grinding wheel and grinding data requires an understanding of how a grinding wheel works.

This brochure provides a quite detailed description of the make-up of the wheel, of how it works when grinding and of the parameters that determine the final result. It also includes recommendations for grinding wheels for use with Uddeholm tool steels.

Grinding wheel design

In principle, a grinding wheel consists of the following components:

- **Abrasive**
- **Binder**
- **Air pores.**

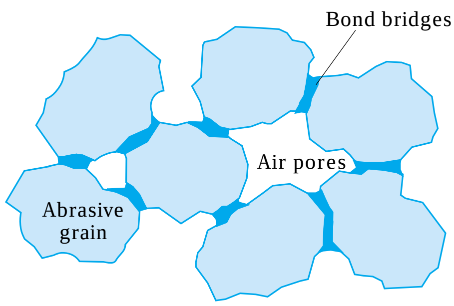
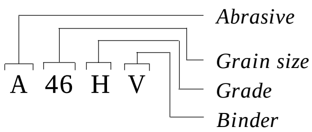


Figure 1. The arrangement and proportions of abrasive grains, air pores and bond bridges (made up of binder) determine grinding wheel characteristics.

Certain special grinding wheels, such as metallically bonded diamond wheels, contain no air pores.

It is the composition and variation of the above components that determines the characteristic of a grinding wheel. An identification system, which has now been ratified as an international standard by ISO, indicates the composition of grinding wheels. The identification consists of numerals and letters in a particular sequence, defining the abrasive, grain size, grade and binder.

Example:



ABRASIVE

It is important that the abrasive fulfils requirements in respect of:

- **Hardness**
- **Sharpness**
- **Thermal resistance**
- **Chemical stability.**

Today, the following four main groups of abrasives (all synthetic) are used, fulfilling the above requirements to greater or lesser extents:

1. Aluminium oxide	*designation:*	A (SG)
2. Silicon carbide	„	C
3. Boron nitride	„	B
4. Diamond	„	SD

Abrasives have different application areas, depending on their particular characteristics, as shown partially in the table below.

Abrasive	**Hardness Knoop** kp/mm²	**Thermal durability in air** °C
Aluminium oxide	2100	2000
Silicon carbide	2500	1200
Boron nitride	4700	1400
Diamond	7000	650

1. Aluminium oxide is the abrasive most commonly used for grinding steel, and is available in several variants. It can be alloyed with other oxides, of which the most common is titanium oxide. The table below shows how the characteristics of aluminium oxide abrasive can be varied by alloying it.

Abrasive	**Colour**	**Properties**
Normal corundum	Brown, grey	Harder ↓ / Tougher ↑
Mixed corundum	Yellowbrown	
Red alumina	Red	
White alumina	White	

Unfortunately, the colour of a grinding wheel does not always necessarily indicate the type of abrasive used in it, due to the fact that some grinding wheel manufacturers colour their abrasives and binders.

In recent years, a new type of aluminium oxide has been developed, having a fine crystalline structure, which means that the grains retain their sharpness better. However, its use requires higher grinding pressure. A typical application for it is grinding tool steels in rigid grinding machines. An example of this abrasive is Norton SG (Seeded Gel).

2. Silicon carbide is an abrasive that is used primarily for grinding cast iron and austenitic stainless steels, although it can also be used for hardened tool steels. It occurs in two main variants: the black silicon carbide and a somewhat harder green variant, which is more brittle than the black material.

3. Boron nitride is produced in approximately the same way as synthetic diamond, and is an abrasive that is used primarily for grinding hardened high-carbide tool steels and high-speed steels. A drawback of boron nitride is its high price—almost twice that of synthetic diamond.

4. Diamond is seldom used, despite its high hardness, for grinding tool steels as a result of its low thermal resistance. Diamond is used primarily for grinding cemented carbide and ceramic materials.

ABRASIVE GRAIN SIZE

The grain size of the abrasive is an important factor in selecting the correct grinding wheel. Grain sizes are classified in accordance with an international mesh size in mesh/inch, ranging from 8 (coarse) to 1200 (super-fine).

Grain sizes for grinding tool steels are generally in the range 24–100 mesh. Coarse grain sizes are used for rapid rate of removal, when grinding large workpieces, grinding softer materials or when the contact surface of the grinding wheel is large. Fine grain sizes are used to produce high surface finish, when grinding hard materials or when the contact surface of the grinding wheel is small.

The surface smoothness of the ground part depends not only on the grain size of the grinding wheel. The sharpness of the wheel, the bonding material used and the hardness of the wheel also play a considerable part in determining the surface finish produced.

In the case of diamond and boron nitride grinding wheels, European grinding wheel manufacturers indicate grain size by the diameter of the abrasive grains in microns, while American and Japanese manufacturers indicate it in mesh size.

GRINDING WHEEL GRADE

The grade of a grinding wheel refers to its hardness, i.e. how securely the abrasive grains are held by the binder. It does not, therefore, depend on the hardness of the abrasive used in the wheel.

The grade of a grinding wheel is determined primarily by the quantity of binder used in the wheel. A higher proportion of binder reduces the amount of air pores and produces a harder wheel.

The grade of a wheel is indicated by a letter, indicating the hardness in alphabetical order:

E = very soft composition
Z = very hard composition.

For tool steels, the most commonly encountered compositions are within the hardness range G–K. Indication of the grade is sometimes followed by a numeral, which indicates the spread of the abrasive particles in the wheel.

GRINDING WHEEL BINDERS

The following binders are used to bind the grains in a grinding wheel:

- **Vitrified** *designation:* V
- **Resinoid** „ B
- **Rubber** „ R
- **Metal** „ M

Vitrified grinding wheels are those most commonly used for grinding tool steels.

Resinoid is used as a binder in grinding wheels intended for high peripheral speeds, such as certain boron nitride wheels.

Rubber-bonded wheels are used for high specific grinding pressures, such as for control wheels in centreless grinding.

Metallic binders are used for diamond and certain boron nitride wheels. Such wheels can withstand very high peripheral speeds.

Photo 1. The difference between a boron nitride wheel and a conventional grinding wheel.
As a result of the high price of boron nitride, wheels made from it consist of a thin layer of abrasive applied to a central hub, usually of aluminium.

How the grinding wheel works

Grinding is a cutting process in which the cutting edges are formed by the grains of abrasive. The same principles apply for grinding as for other chip-cutting methods, although various factors mean that it is necessary to consider the theory of grinding somewhat differently. Conditions that are special for grinding are:

- The cutting tool has an irregular cutting geometry. The grains of abrasive are irregularly placed.
- The cutting geometry can change. The method of working of an abrasive tool includes a certain degree of "self-sharpening", which means that grains of abrasive break or are replaced as they wear.
- Negative cutting angles. The irregular "blunt" shapes of the grains mean that the rake angles are often negative.
- A very large number of cutting edges.
- Very high cutting speed. The most common cutting speed for precision grinding (35 m/s = 2100 m/min.) is far above what is normal for other cutting processes.
- Very small chips, i.e. very small cutting depth for each cutting edge.

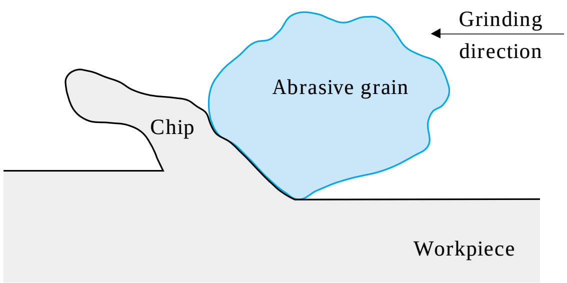


Figure 2. Chip formation when grinding (highly schematic). Cutting angles are generally negative.

GRINDING FORCES

The grinding forces that act on each individual grain of abrasive are referred to as **specific forces**. A mean value of the specific forces can be obtained by dividing the total force by the number of cutting edges, which depends on the size of the contact area and the number of cutting edges in the grinding path. The specific forces determine various effects, including the degree of self-sharpening of the grinding wheel, i.e. its "working hardness". **The total force** is the force arising between the grinding wheel and the workpiece.

GRINDING WHEEL WEAR

The grains of abrasive are initially sharp, but in the same way as with all other cutting edges they wear down in use and become blunt. Finally, the grains will have become so blunt that they have difficulty in penetrating into the material of the workpiece. They cease to remove material and generate only heat. The grinding wheel is then said to be burning the material, which can cause cracks in it.

For a grinding wheel to work correctly, the stresses in the binder and the strength of the binder must be so balanced that, as the grains become as blunt as can be accepted, they are pulled out of the binder and are replaced by new, sharp grains. The grinding wheel, in other words, **sharpens itself**. Self-sharpening also occurs through the grains cracking, so forming new cutting edges.

The degree of self-sharpening, i.e. whether the grinding wheel is hard or soft, is affected by the composition of the wheel (its design hardness) and by the conditions under which it is working.

AVERAGE CHIP THICKNESS

Although the chips removed by grinding are small and irregular, the mean value of their thickness at any time is relatively constant. This value varies, depending on the type of grinding operation and in response to the changes in grinding data.

If a grinding wheel is cutting larger chips, this means two things:

1. Higher loading on each cutting edge, i.e. higher specific forces. This increases the self-sharpening characteristic of the wheel and gives it the characteristics of a softer wheel.

2. The surface of the part being ground is coarser, see Figure 3.

A reduction in the average chip thickness represents the opposite. It is therefore important to understand how changes in grinding data and other conditions affect the average chip thickness.

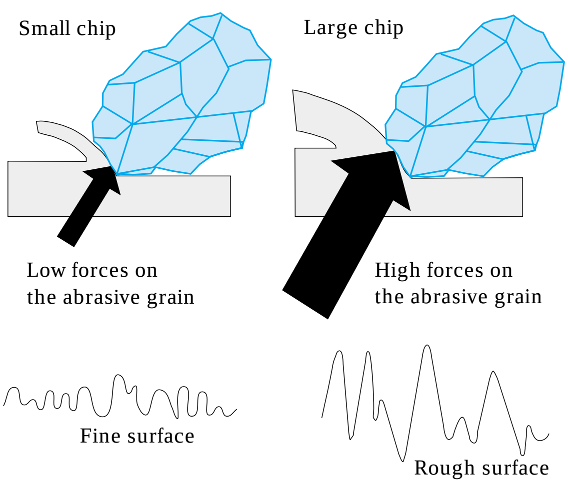


Figure 3. A large chip size results in a rougher surface finish on the workpiece.

STOCK REMOVAL RATE

When grinding, the amount of chips removed per unit of time can most easily be expressed as mm^3/s. This is often referred to as the stock removal rate, and depends on the machine feed, the composition of the grinding wheel, its cutting speed (peripheral speed) and (in certain cases) on the dimensions of the workpiece.

It is often more meaningful to talk about stock removal rate rather than about table feed speed, feed depth etc., and it is also quite easy to calculate. Cost considerations often dictate that the stock removal rate should be as high as possible. If the stock removal rate is increased without increasing the number of grains of abrasive performing the work, e.g. by greater infeed depth, the chip size will also naturally be increased.

CUTTING SPEED

The peripheral speed of a grinding wheel has a direct effect on the number of cutting edges that actually perform the machining work. If, for example, the cutting speed is doubled, twice as many grains of abrasive will pass the workpiece per unit of time. If the workpiece speed is not increased, the mean chip thickness will decrease, thus also reducing the cutting forces on each grain. Self-sharpening will be less effective, i.e. the grinding wheel will be effectively harder, producing a finer surface finish, but with greater risk of burning the surface.

Conversely, reducing the speed of the wheel will increase the chip thickness, with the result that the grinding wheel behaves as a softer wheel.

Generally, both peripheral velocity and workpiece speed are increased in order to increase the total rate of removal.

THE G-RATIO OF A GRINDING WHEEL

The *G-ratio* of a grinding wheel refers to the relationship between the amount of material removed and the amount of grinding wheel consumed. The G-ratio is a measure of how effectively a grinding wheel works with the particular workpiece material.

GRINDING WHEEL CONTACT SURFACE

It is at the contact surface between the grinding wheel and the workpiece that the actual cutting operation occurs. A large contact surface means that a greater number of cutting edges participate in the process, thus reducing the chip size and specific forces. Similarly, a reduced contact surface area results in greater chip size and higher specific forces.

In principle, the contact surface is in the shape of a rectangle. Its extent in the cutting direction is referred to as the *contact length* or *contact arc*, while its extent perpendicular to the cutting direction is referred to as the *contact width*.

The contact length depends primarily on the type of grinding operation. In addition, it depends on the diameter of the grinding wheel, the cutting depth and in all cases—except for surface grinding—the dimensions of the workpiece. Differences in the contact length are the main reason for having to select different grinding wheel compositions for different grinding operations.

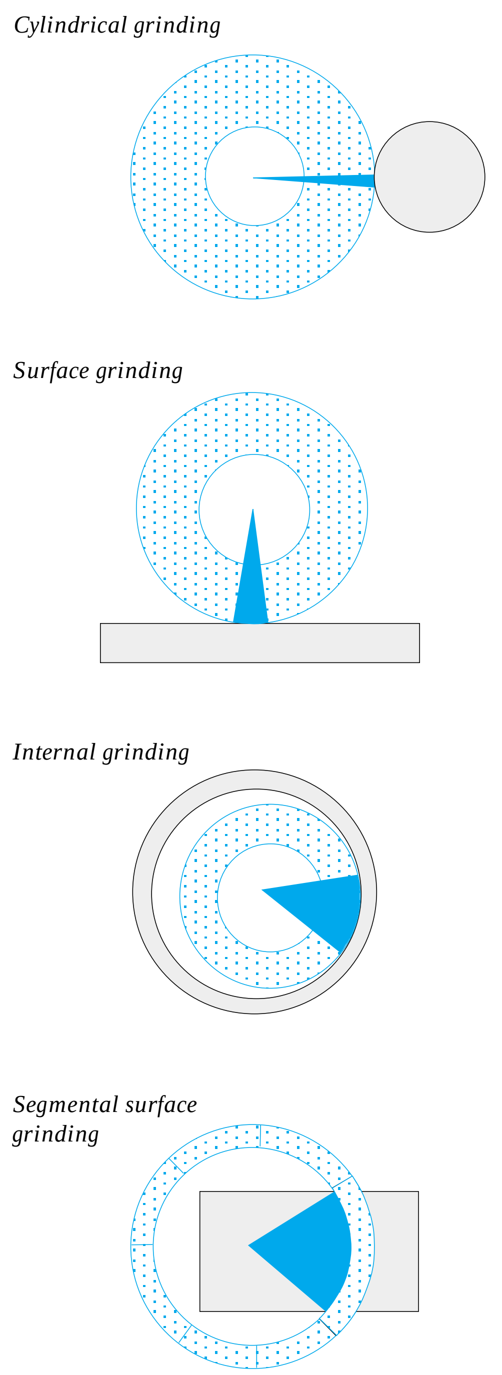


Figure 4. Differences in contact length for different grinding operations.

If, when performing internal grinding, a grinding wheel is used that has a diameter only a little less than that of the ground hole, the contact length will be very large, resulting in low cutting force per grain.

If the wheel is to sharpen itself properly, it must be of a softer composition than one intended for external cylindrical grinding of a similar part. In this latter case, the contact length is shorter, which means that there are higher cutting forces on each grain.

The contact width may be equal to the width of the grinding wheel as, for example, in plunge grinding. However in operations such as surface grinding with a moving table, only part of the grinding wheel is actually cutting and this part changes as the wheel wears down. It is sometimes possible to reduce the contact width, if this is required, by truing of the grinding wheel. This reduces contact surface area, resulting (as described above) in a greater chip thickness, higher loading on the abras-ive grains and an effectively softer grinding wheel.

THE NUMBER OF CUTTING EDGES IN THE CONTACT AREA

The number of cutting edges in the contact area is a factor that has a considerable effect on the chip thickness and thus on the grinding process.

A large number of cutting edges per unit area means that the work of removing material is spread over a larger number of grains, reducing the chip thickness and the specific forces.

The grain size of the abrasive also affects the number of cutting edges, which is the reason for the common observation that fine-grained cutting wheels seem to be harder.

DRESSING AND TRUING GRINDING WHEELS

Dressing and truing of a grinding wheel are often considered to be the same thing because they are often performed as one operation.

Truing is made to produce any profile which may be required on the face of the wheel and to ensure concentricity.

Dressing is a conditioning of the wheel surface to give the desired cutting action. Dressing the wheel exposes sharp cutting edges. One and the same grinding wheel can be given completely different grinding characteristics through application of different dressing tools or different dressing methods. Dressing is therefore a particularly important parameter in achieving good grinding performance.

Dressing resulting in a smooth surface on the wheel results in the cutting edges of the grains of abrasive being close together, while dressing resulting in a rough surface of the wheel gives the wheel a more open structure. Dressing provides a means of making the same grinding wheel give completely different grinding results.

The degree of self-sharpening affects the structure of the grinding wheel surface, i.e. the number of cutting edges per unit of area. A grinding wheel that has a high self-sharpening performance has a different, more open structure than one having poorer self-sharpening performance.

There are many different tools available for dressing and truing grinding wheels, e.g. crushing rolls and diamond tools. Boron nitride wheels are best dressed using a diamond coated roller.

Certain types of grinding wheels, e.g. resinoid bonded boron nitride wheels, need to be “opened” after dressing. This reveals the abrasive particles and creates space for chip formation.

The grinding machine

The type of grinding operation and the machine available has a considerable effect on the choice of appropriate grinding wheel composition. A grinding machine should be as rigid as possible, in order to allow it to work at high grinding pressures. This is because it is the rigidity of the grinder and the method of clamping the workpiece that determine the permissible grinding pressure and therefore
restrict the choice of wheels. If the machine is not sufficiently rigid, a softer grinding wheel composition or a smaller contact area between the grinding wheel and the workpiece should be chosen, in order to achieve the required degree of self-sharpening performance.

The speed of the grinder also affects the choice of grinding wheel. Boron nitride wheels often require peripheral speeds of 45 m/s in order to provide good cutting performance.

Grinding fluid

When grinding, as with all other cutting operations, a cutting fluid is used primarily to:

- cool the workpiece
- act as a lubricant and reduce friction between the chips, workpiece and grinding wheel
- remove chips from the contact area.

There are three main types of cutting fluids that can be used when grinding:

- *Water solutions.* These are liquids that consist of water with synthetic additives in order to increase its wetting performance and prevent corrosion. Such fluids contain no oil and provide good cooling performance but poorer lubrication performance.
- *Emulsions.* These consist of water with an admixture of 2–5% of oil in an extremely finely distributed form. Sulphur or chlorine additives may also be used as EP additives.
- *Cutting oils.* These are composed of a mineral oil base with EP-type additives. Cutting oils provide effective lubrication but poorer cooling.

Water solutions are most suitable when grinding with diamond wheels.

Emulsions are used nowadays for the majority of grinding operations because they are ecologically beneficial and perform adequately.

Cutting oils give the best results for profile and plunge grinding with fine grained wheels, e.g. when grinding threads. Cutting oil also provides the longest life for resinoid bonded boron nitride wheels, although high-oil emulsions are often chosen in the interests of pollution reduction.

The tool steel

The alloying constituents of a tool steel have a considerable effect on its ease of grinding.

The Uddeholm range of tool steels extends from low-alloy steels, such as *UHB 11*, to high-alloy steels, such as *VANADIS 10*.

There is seldom any problem in grinding low-alloy tool steels. At the other end of the scale, however, the high-alloy carbide-rich steels can cause problems when being ground, and require a careful choice of grinding wheel and operating parameters.

The higher the wear resistance of a steel, the more difficult it is to grind. The wear resistance of a steel, and thus also its ease of grinding, are determined by its basic hardness and by the size, hardness and quantity of the carbides in it.

In order to enhance the wear resistance of a tool steel, the steel is alloyed with carbide-forming alloying elements, of which the most important are chromium and vanadium. The steel must also have a high carbon content if carbides are to be formed.

The diagram (fig. 5) shows the hardness of the basic phases found in a tool steel, the hardness of the most common carbides found in tool steels and the hardness of commonly used grinding abrasives.

As can be seen in Figure 5, it is only diamond and boron nitride that are harder than all the carbides that are found in a tool steel. However, as mentioned earlier, diamond is unsuitable for grinding steel.

The quantity and the size of carbides in a steel has a very considerable effect on the ease of grinding of the material. The greater the number of, and the larger the carbides, the more difficult the material is to grind. This is the reason why a tool steel produced by powder metallurgy processes, having smaller carbides, is easier to grind than a conventionally produced steel having a similar composition.

In practice, powder metallurgy is employed to increase the quantity of carbide in a tool steel, i.e. such steels are more highly alloyed than conventional steels, which generally means that they are more difficult to grind.

The effect of hardness on ease of grinding is also dependent on the quantity of carbide-forming alloying elements in the steel.

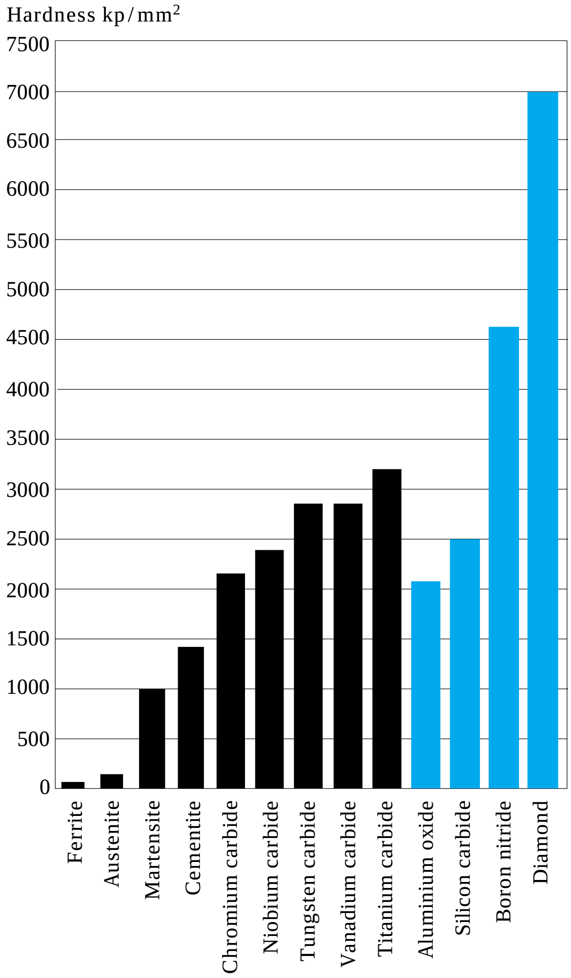


Figure 5.
The hardness of grinding abrasives, basic phases found in a tool steel and carbides found in tool steels.

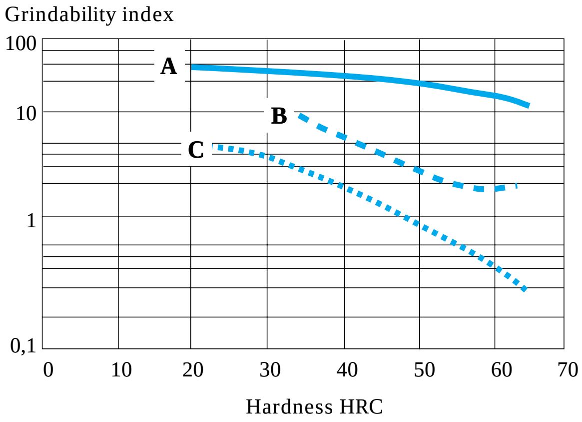


Figure 6. The effect of hardness on grindability for:
A – a low-alloy tool steel of ARNE type
B – a material of SVERKER type
C – material of VANADIS 10 type.

As can be seen in Figure 6, hardness has a greater effect on grindability for high-carbide steels.

In order to obtain good grinding performance with high-alloy carbide-rich tool steels, it is important to select the correct grinding wheel. Materials in the Vanadis range, for example, contain a large quantity of vanadium carbides. To cut through a vanadium carbide requires an abrasive that is harder than aluminium oxide or silicon carbide. Boron nitride wheels are therefore recommended as first choice for grinding this material. The fact that, despite this, material can be removed from *VANADIS* steels by grinding with aluminium oxide or silicon carbide is due to the fact that it is the material enclosing the carbides that is ground away, so that the carbides are torn out of the basic material of the steel. However, this occurs at the price of high wear of the grinding wheel and a risk of poor grinding performance.

GRINDING CRACKS AND GRINDING STRESSES

The wrong choice of grinding wheels and grinding parameters results in a considerable risk of causing cracks in the workpiece.

Generally, grinding cracks are not as easy to see as in Photo 2. It is usually necessary to examine the part under a microscope, or with magnetic powder inspection, in order to see the cracks.

The formation of grinding cracks, which tend to occur perpendicular to the direction of grinding, usually means the tool has to be scrapped. Hardened steels are more sensitive to grinding cracks than non-hardened steels. A material that has been only hardened, and not tempered, must never be ground: hardened materials should always be tempered before grinding.

Formation of grinding cracks can be explained as follows:

Almost all the energy used in grinding is converted into heat, partly through pure friction and partly as a result of deformation of the material. If the correct grinding wheel has been chosen, most of the heat will be removed in the chips, with only a smaller part heating up the workpiece.

Photo 2. Grinding cracks.

Incorrect grinding of a hardened tool steel can result in such a high temperature at the ground surface that the tempering temperature of the material is exceeded. This results in a reduction in the hardness of the surface. If the temperature is allowed to rise further, the hardening temperature of the material can be reached, resulting in rehardening. This produces a mixture of non-tempered and tempered martensite in the surface layer, together with retained austenite, as shown in Photo 3. Very high stresses arise in the material, often resulting in the formation of cracks.

Photo 3. Re-hardened layer in an incorrectly ground tool.

The diagram below shows the hardness profile through the surface of a tool steel, incorrectly ground in such a way as to produce re-hardening.

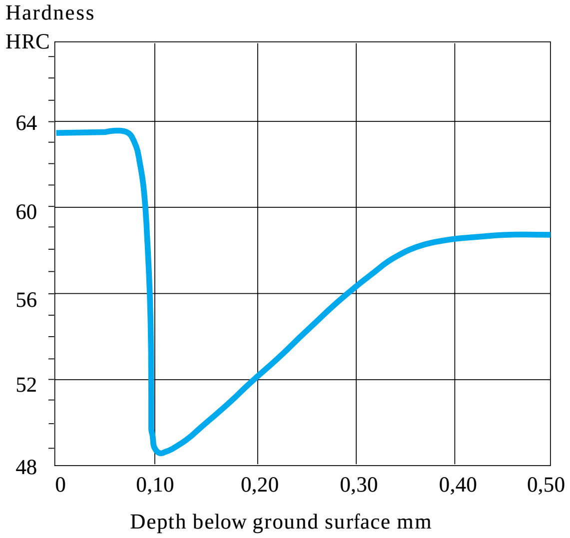


Figure 7. Hardness profile through the surface layer of an incorrectly ground tool.

The surface exhibits a high hardness due to the untempered martensite. An overtempered zone occurs just below the surface, where the hardness is lower than the basic hardness of the workpiece.

Incorrect grinding, resulting in a modified surface layer, often reveals itself through burn marks—discoloration of the ground surface. In order to avoid burning and grinding cracks, it is necessary to keep down the temperature of the ground part, e.g. by means of good cooling, and to employ properly dressed grinding wheels that cut the material with sharp cutting edges instead of simply generating heat through friction.

A simple example of how incorrect grinding can cause cracks is shown in figure 8. A hardened punch with a head is to be cylindrical-ground, with the head (*b*) being ground flat in the same operation.

Alternative A shows the use of a grinding wheel trued with a 90° edge. The grinding wheel, which is suitable for cylindrical grinding of the surface *a* produces a good result on surface *a*. Here the contact surface is small so the self sharpening performance is good. The head, on the other hand, which is to be ground flat, presents a larger contact surface to the grinding wheel. The specific forces on the abrasive grains is low so that the wheel does not self-sharpen. Instead, surface *b* is subjected mainly to rubbing and the heat generated can cause grinding cracks.

Alternative B shows a better way to grind the punch. In this case, the side of the grinding wheel has been trued as shown so that the contact surface at *b* is smaller. This results in improved self-sharpening and “cooler” grinding.

Case C shows the preferred way to grind this part. The grinding wheel is set at an angle, so that the two contact surfaces are of approximately the same size.

The retained austenite content of a hardened material can also affect the grinding result. High retained austenite levels increase the risk of crack formation when grinding.

The majority of grinding operations leave residual stresses in the ground surface. These stresses are usually at a maximum close to the surface, and can cause permanent deformation of the ground part when grinding thin materials.

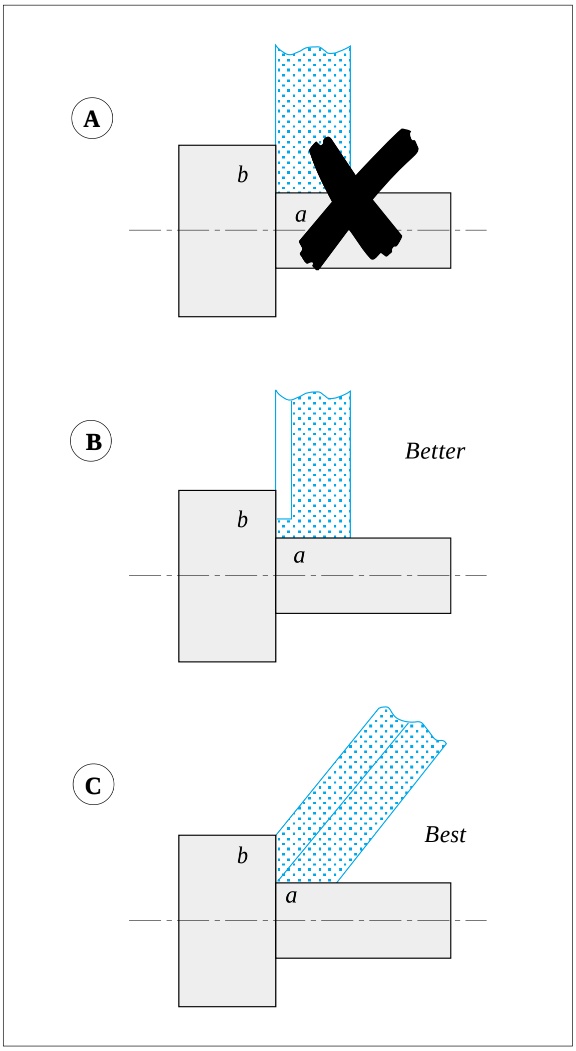


Figure 8. Incorrect grinding can often result in grinding cracks.

Of the three examples shown in Figure 9, *Example 1* is most at risk in respect of crack formation. It exhibits tensile stresses in the surface which can, if they exceed the material's ultimate tensile strength, result in the material cracking. *Examples 2* and *3* are not as dangerous—the surface stresses are compressive stresses, which result in improved fatigue strength of the ground parts.

It is, unfortunately, very difficult to produce a simple check to determine the stress pattern set up in the ground part unless the stresses are so high that grinding cracks are visible.

Grinding stresses can be reduced by stress-relief tempering after grinding. The tempering temperature should be about 15°C below the previous tempering temperature in order to avoid any risk of reducing the hardness of the workpiece. Another way of reducing grinding stresses is to tumble or blast the ground parts.

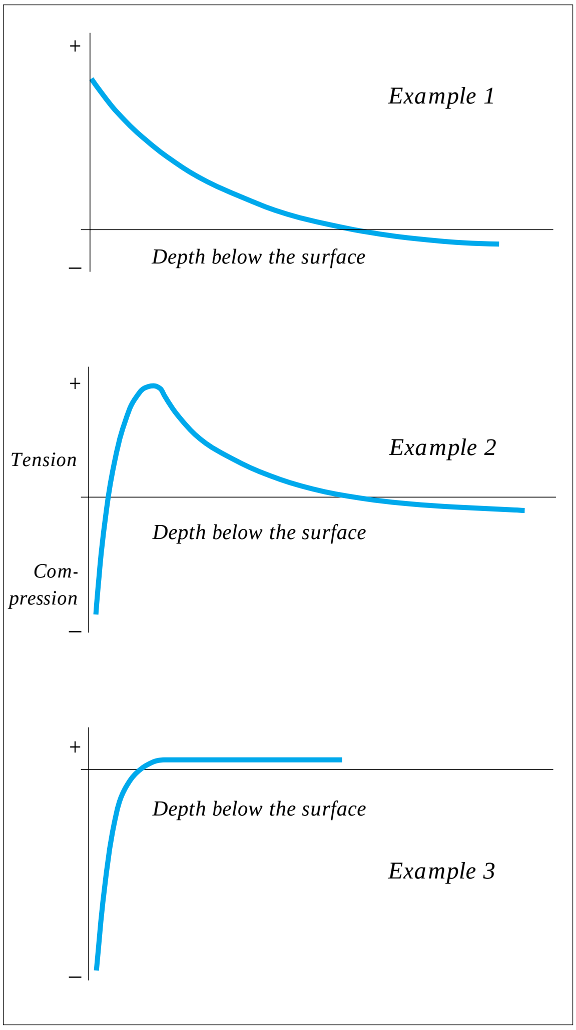


Figure 9. Three typical examples of stress distribution in a ground surface.

Recommendations for grinding of Uddeholm tool steels

GRINDING OF HIGH-CARBIDE TOOL STEELS

The high carbide content of high-carbide tool steels gives them excellent wear resistance, and requires special recommendations in respect of grinding operations and selection of grinding wheels. Steels in this group are the *SVERKER*, *ELMAX* and *VANADIS* types. For the majority of grinding operations, boron nitride wheels are the best choice for such steels.

Figure 10 shows the results of surface grinding trials on *VANADIS 10* with aluminium oxide, fine crystalline aluminium oxide and boron nitride grinding wheels.

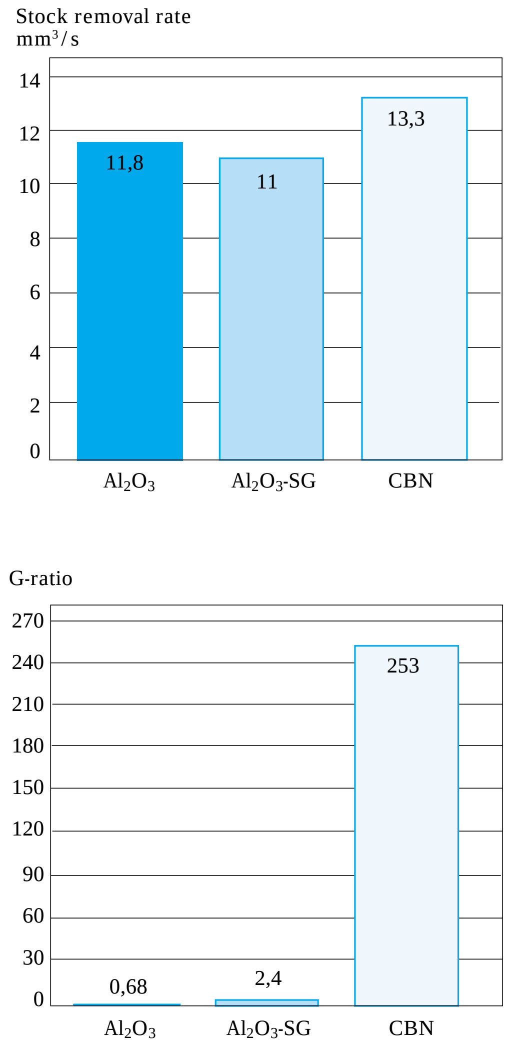


Figure 10. Surface grinding of VANADIS 10 with various grinding wheels. (Grinding wheel width: Al_2O_3 40 mm, CBN 20 mm.)

As can be seen in Figure 10, material is removed more quickly, and the G-ratio is higher, using boron nitride wheels. These wheels have a "colder" cut, with less risk of "burning" the surface.

If the material is to be profile-ground, bear in mind that a considerable quantity of heat will be generated. Experiments have shown that vitrified boron nitride wheels are preferable for this application. These wheels also operate well for other grinding operations, provided that a high peripheral speed can be maintained.

Where boron nitride wheels cannot be used, the type of grinding wheel must be chosen with care. White aluminium oxide or green silicon carbide wheels are recommended. Fine-crystalline aluminium oxide wheels, such as the Norton SG, give good results if the grinding set-up is rigid.

When grinding high-carbide steels, the grinding wheel should always be somewhat softer in order to ensure good self-sharpening performance.

In addition, the following points must be borne in mind:

- The grinder must be vibration-free, rigid and in good condition.
- The workpiece must be securely clamped. Use a steady rest when grinding long, thin work pieces.
- Use sharp conical diamonds when dressing Al_2O_3 and SiC wheels. The dressed finish must be rough.
- Maintain a high peripheral speed of grinding wheels.
- Ensure an adequate supply of coolant to the grinding zone.
- If grinding is carried out without a coolant, select a grinding wheel that is one grade softer than would have been used if grinding was performed with coolant.
- Never grind a hardened workpiece before it has been tempered.

GRINDING OF CONVENTIONAL TOOL STEELS

This group covers all the other conventionally produced tool steels. Providing that common grinding recommendations are followed, problems are seldom encountered when grinding these tool steels. For these steels, ordinary aluminium oxide grinding wheels are perfectly suitable. Boron nitride wheels can also be used if the steels are to be ground in the hardened and tempered condition.

GRINDING OF PRECIPITATION HARDENING STEELS

Precipitation hardening steels, such as *CORRAX*, behaves in a little different way than other tool steels when grinding. It tends to clog the grinding wheel, especially if the grinding wheel is hard and has a close structure. The clogging can cause problems like low material removal rate and rough surface finish. To prevent the clogging, observe following recommendations:

- The wheel should have an open and porous structure
- Use a softer wheel grade (hardness) than for other types of tool steels
- The wheel dressing should be done frequent and rough
- The coolant concentration should be high (≥5%) for efficient lubrication.

Conventional Al_2O_3 wheels are recommended, but SiC wheels can be a better choice for high surface finish when a small amount of material is to be ground. No particular difference in grindability between solution treated and aged condition. In the table with recommended grinding wheels, suitable standard type of grinding wheels are recommended. However, if a lot of grinding is to be done in this type of steels, it is recommended to select a wheel with a more open structure than a standard wheel type.

Cutting speed and feed

GRINDING WHEEL SPEED (CUTTING SPEED)

When using small grinding machines, the spindle speed often restricts choice of cutting speed.

A common safety limit for vitrified grinding wheels is 35 m/s. However, some grinding wheels are approved for peripheral speeds of 125 m/s.

A common cutting speed for surface and cylindrical grinding is 20–35 m/s. Varying the peripheral speed of the wheel makes it possible to modify its grinding performance. Increasing the peripheral speed of the wheel while retaining the same workpiece speed means that the wheel behaves as if it was harder. Reducing the peripheral speed makes the wheel seem softer.

A suitable peripheral speed for resinoid boron nitride wheels is 30–40 m/s. For vitrified boron nitride wheels, a cutting speed >45 m/s is often necessary.

When grinding high-carbide tool steels, the peripheral speed of the grinding wheel should be high. Tests on cylindrcal grinding of *ELMAX* have shown that the G-ratio of the grinding wheel dropped from 127 to 28 when the peripheral speed was dropped from 60 m/s to 30 m/s. Cutting speed, in other words, has a considerable effect on the economics of grinding.

WORKPIECE SPEED

For surface grinding, the speed of the workpiece should be 10–20 m/min. For conventional cylindrical grinding, this speed should be 15–20 m/min. This speed should be reduced for smaller workpieces, for which 5–10 m/min is suitable.

Varying the workpiece speed also provides a means of modifying the grinding performance of the wheel. Increasing the speed of the workpiece makes the wheel seem softer, while reducing its speed produces a harder wheel.

CROSS-FEED

The cross- feed speed of a grinding wheel, i.e. its sideways motion, is higher for rough grinding than for fine grinding.

In the case of cylindrical grinding, the cross-feed should be about 1/3–1/2 of the width of the wheel for each revolution of the workpiece. For fine surface finish, this ratio should be reduced to 1/6–1/3 of the width of the grinding wheel per revolution of the workpiece.

If a very high standard of surface finish is required, cross feed can be further reduced to 1/8–1/10 of the grinding wheel width.

When surface grinding with a straight wheel, choose a transverse feed of 1/6–1/3 of the width of the grinding wheel for each stroke. Again, reduce this feed for high surface finish requirements.

Note that when the cross-feed is increased, the active contact surface area between the grinding wheel and the workpiece becomes larger, resulting in an apparent increase in hardness of the grinding wheel.

INFEED

The infeed of the grinding wheel depends on the type of wheel and the rigidity of the grinder and/or workpiece clamping.

Guide values for cylindrical grinding using conventional grinding wheels are:

Rough finish ~0.05 mm/pass.
Fine finish ~0.005–0.010 mm/pass.

The above feeds should be halved for cylindrical grinding using boron nitride wheels.

For surface grinding using a straight grinding wheel, the feed depths for conventional wheels are:

Rough finish ~0.025–0.075 mm/pass.
Fine finish ~0.005–0.010 mm/pass.

The feed depths when using boron nitride wheels are:

Rough finish ~0.010–0.040 mm/pass.
Fine finish ~0.005–0.010 mm/pass.

When using grinding wheels having fine-crystalline aluminium oxide abrasive, such as the Norton SG type, feed depth should be increased somewhat over the above values in order to achieve higher grinding pressure and hence good self-sharpening performance.

Grinding wheel dressing

During dressing a helix along the wheel periphery is made. The lead of helix which the dressing tool is being fed affects the structure of the grinding wheel. The lead of helix depends both of the r.p.m. of the grinding wheel and the speed of the dressing tool.
The following are rules of thumbs for grinding wheel dressing with single point diamonds and similar tools.

	Rough dressing	Fine dressing
Diamond infeed (mm)	0.02–0.04	0.01–0.02
Diamond transverse rate (mm/wheel rev.)	0.15–0.30	0.05–0.10

Diamond is sensitive for high temperatures. Therefore, dressing with diamonds should always be carried out with plenty of coolant. The coolant should always be turned on before the diamond touches the wheel. Single point diamond dressing tool should be systematically rotated to maintain the sharpness.

GRINDING PROBLEMS—REMEDIES

The following shows the most important actions to solve different grinding problems.

Symptom	Remedy
Chatter marks	Check the wheel balance. Ensure that the diamond is sharp. Ensure that the diamond is fixed.
Finish too coarse	Use fine, slow traverse dress. Decrease work speed. Use finer grit wheel. Use harder grade wheel.
Burning, grinding cracks	Ensure that the diamond is sharp. Use coarse dress. Ensure that the coolant reaches the contact point. Use softer grade wheel.
Short wheel life	Ensure that the cutting speed is sufficient. Reduce depth of cut and feed. Use harder grade wheel.
Flecking on surface finish	Check coolant filtration. Flush wheel guard.

Recommended grinding wheels

The recommendations in the following table have been made in consultation with grinding wheel manufacturers, and are based on our own and others' experience. However, it must be emphasised that the choice of grinding wheel is strongly dependent on the type of grinding machine, rigidity of clamping and the size of the workpiece, which means that the recommendations below should be seen as starting points, from which each particular process should be optimized.

The grinding wheels are of SlipNaxos1) ,Tyrolit2), Norton3) and Unicorn4) type. The designations, however, essentially comply with international standards.

Steel grade	Condition	Centerless	Surface grinding straight wheel	Surface grinding segment
Conventional steels: *UHB 11* *UHB 20* *FORMAX* *ARNE* *GRANE* *ORVAR 2 M* *ORVAR SUPREME*	Soft annealed	1)33A 60 LVM 2)89A 60 2 K5A V217 3)SGB 60 MVX 4)51A 601 L5V MRAA	1)43A 46 HVZ 2)91A 46 2 I 8 V111 3)SGB 46 G10 VXPM 4)WA 46 HV	1)43A 24 FVZ 2)88A 36 H8A V2 3)86A 30 G12 VXPM 4)WA 24 GV
VIDAR SUPREME *THG 2000* *QRO 90 SUPREME* *CALMAX* *STAVAX ESR* *REGIN 3* *ALVAR 14* *HOTVAR* *DIEVAR*	Hardened	1)62A 60 LVX 2)89A 60 2 K5A V217 3)SGB 60 MVX 4)48A 601 L8V LNAA	1)48A 46 HVZ 2)93A 46 H8A V217 3)SGB 46 G10 VXPM 4)WA 46 GV	1)48A 46 FVZP 2)89A 30 1 I 10A V237 P20 3)86A 36 F12 VXPC 4)WA 36 GV
IMPAX SUPREME *HOLDAX* *CARMO* *RAMAX S*	Prehardened	1)33A 60 LVM 2)89A 60 2 K5A V217 3)SGB 60 MVX 4)51A 601 L5V MRAA	1)43A 60 HVZ 2)91A 46 2 I 8 V111 3)SGB 46 G10 VXPM 4)WA 46 HV	1)43A 24 FVZ 2)88A 36 H 8A V2 3)86A 36 F12 VXPC 4)WA 24 GV
	Hardened	1)62A 60 LVX 2)89A 60 2 K5A V217 3)SGB 60 MVX 4)48A 601 L8V LNAA	1)48A 46 HVZ 2)91A 46 2 I 8 V111 3)SGB 46 G10 VXPM 4)WA 46 GV	1)48A 46 FVZP 2)88A 36 H 8A V2 3)86A 36 E12 VXPC 4)WA 36 GV
Precipitation hardening steels: *CORRAX*	Solution-treated, Aged	1)33A 60 KVM 2)89A 60 2 K5A V217 3)SGB 60 KVX 4)48A 601 J8V LNAA	1)43A 46 GVZ 1)15C 46 HVM 2)91A 46 2 H 8 V111 3)SGB 46 G10 VXPM 4)WA 46 GV	1)43A 36 FVZ 1)15C 36 GVM 2)89A 30 1 I 10A V 237 P20 3)1TGP 36 F12 VXPC 4)WA 24 GV
High-carbide steels: *SVERKER 3* *SVERKER 21* *RIGOR* *VANADIS 4* *VANADIS 6* *VANADIS 10* *VANADIS 23* *VANADIS 30* *VANADIS 60* *ELMAX* *SLEIPNER*	Soft annealed	1)33A 60 LVM 2)89A 60 2 K5A V217 3)SGB 60 LVX 4)51A 601 L5V MRAA	1)43A 46 HVZ 2)91A 46 2 I 8 V111 3)SGB 46 G10 VXPM 4)WA 46 HV	1)43A 36 FVZ 2)89A 30 1 I 10A V237 P20 3)53A 30F12 VBEP 4)WA 24 GV
SVERKER 21 *RIGOR* *VANADIS 23* *VANADIS 30* *SLEIPNER*	Hardened	1)48A 60 LVZ 1)820A 60 LVQ 2)89A 60 L5 V217 3)SGB 60 LVX 4)48A 601 L8V LNAA 4)43A 601 L8V LNAA	1)B151 R50 B3 1)420A 46 H12VQP 2)B126 C 50 B54 BA 2)93A 46 H8A V217 3)SGB 46 HVX 3)3SG 46 G10 VXPM 4)B126 V18 KR237 4)27A 46 HV	1)420A 46 FVQP 2)89A 30 1 I 10A V237 P20 3)3SG 36 HVX 4)WA 36 HV
SVERKER 3 *VANADIS 4* *VANADIS 6* *VANADIS 10* *VANADIS 60* *ELMAX*	Hardened	1)48A 60 LVZ 1)820A 60 LVQ 2)89A 60 L5 V217 3)SGB 60 LVX 4)48A 601 L8V LNAA 4)43A 601 L8V LNAA	1)B151 R50 B3 1)420A 46 H12VQP 2)B126 C 50 B54 BA 2)93A 46 H8A V217 3)SGB 46 HVX 3)3SG 46 G10 VXPM 4)B126 V18 KR237 4)27A 46 HV	1)420A 46 FVQP 2)89A 30 1 I 10A V237 P20 3)3SG 46 FVSPF 4)WA 46 FV

Steel grade	Condition	Cylindrical grinding	Internal grinding	Profile grinding
Conventional steels: *UHB 11* *UHB 20* *FORMAX* *ARNE* *GRANE* *ORVAR 2 M* *ORVAR SUPREME*	Soft annealed	[1]33A 46 KVM [2]89A 60 2 K 5A V217 [3]19A 60 KVS [4]48A 46 LV	[1]77A 60 K9VX [2]89A 60 2 J6 V111 [3]32A 46 L5 VBE [4]WA 46 JV	[1]42A 100 IVZ [2]89A 60 2 I 6 V111 [3]32A 100 KVS [4]WA 100 LV
VIDAR SUPREME *THG 2000* *QRO 90 SUPREME* *CALMAX* *STAVAX ESR* *REGIN 3* *ALVAR 14* *HOTVAR* *DIEVAR*	Hardened	[1]48A 60 KVZ [2]89A 60 2 J 5A V217 [3]SGB 60 KVX [4]WA 60 JV	[1]77A 80 K9VX [2]C 60 H 5 V15 [3]32A 60 K5 VBE [4]WA 60 IV	[1]42A 1003 HVZ [2]97A 60 1 G10 A V257 P23 [3]32A 100 KVS [4]WA 120 JV
IMPAX SUPREME *HOLDAX* *CARMO* *RAMAX S*	Prehardened	[1]33A 46 KVM [2]89A 60 2 K 5A V217 [3]19A 60 KVS [4]48A 46 LV	[1]77A 60 K9VX [2]89A 60 2 J6 V111 [3]32A 46 L5 VBE [4]WA 46 JV	[1]42A 100 IVZ [2]89A 60 2 I 6 V111 [3]32A 100 KVS [4]WA 100 LV
	Hardened	[1]48A 60 KVZ [2]89A 60 2 K 5A V217 [3]SGB 60 KVX [4]WA 60 JV	[1]77A 80 K9VX [2]89A 60 2 J6 V111 [3]32A 60 K5 VBE [4]WA 60 IV	[1]42A 1003 HVZ [2]89A 60 2 I 6 V111 [3]32A 100 KVS [4]WA 120 JV
Precipitation hardening steels: *CORRAX*	Solution-treated, Aged	[1]77A 60 JVX [1]15C 60 IVM [2]89A 60 2 J 5A V217 [3]SGB 60 JVX [4]77A 461 K7V LNAA	[1]77A 60 J9 VX [1]15C 60 IVM [2]89A 60 2 I6 V111 [3]32A 46 K5 VBE [4]25A 601 J85VP MCNN	[1]42A 100 HVZ [2]89A 60 2 H 6 V111 [3]32A 100 JVS [4]77A 100 J8V LNAA
High-carbide steels: *SVERKER 3* *SVERKER 21* *RIGOR* *VANADIS 4* *VANADIS 6* *VANADIS 10* *VANADIS 23* *VANADIS 30* *VANADIS 60* *ELMAX* *SLEIPNER*	Soft annealed	[1]62A 60 KVX [2]89A 60 2 K 5A V217 [3]SGB 60 KVX [4]48A 46 LV	[1]77A 60 K9 VX [2]89A 60 2 J6 V111 [3]32A 46 L5 VBE [4]WA 46 JV	[1]42A 100 IVZ [2]89A 60 2 I 6 V111 [3]32A 100 KVS [4]WA 100 LV
SVERKER 21 *RIGOR* *VANADIS 23* *VANADIS 30* *SLEIPNER*	Hardened	[1]B151 R50 B3 [1]420A 54 JVQ [2]B126 C75 B54 BA [2]92A 60 1 J5A V237 [3]SGB 60 KVX [3]3SGP 70 JVX [4]B126 V18 KR191 [4]27A 60 JV	[1]B151 R75 B3 [1]420A 80 K9 VQ [2]B126 C75 B54 BA [2]91A 60 1 J6 V111 [3]3SG 60 JVX [4]B126 V24 KR237 [4]27A 60 HV	[1]B126 R100 B6 [1]820A 1003 GVQ [2]B126 C75 B53 [2]F13A54 FF22V STRATO [3]5SG 80 KVX [4]B126K V24 KR237 [4]27A 100 JV
SVERKER 3 *VANADIS 4* *VANADIS 6* *VANADIS 10* *VANADIS 60* *ELMAX*	Hardened	[1]B151 R50 B3 [1]420A 54 JVQ [2]B126 C75 B54 BA [2]92A 60 1 J5A V237 [3]SGB 60 KVX [3]3SGP 70 JVX [4]B126 V18 KR191 [4]27A 60 IV	[1]B151 R75 B3 [1]420A 80 K9 VQ [2]B126 C75 B54 BA [2]91A 60 1 J6 V111 [3]3SG 60 JVX [4]B126 V24 KR237 [4]27A 60 HV	[1]B126 R100 B6 [1]820A 1003 GVQ [2]B126 C75 B53 [2]F13A54 FF22V STRATO [3]5SG 80 KVX [4]B126K V24 KR237 [4]27A 100 IV