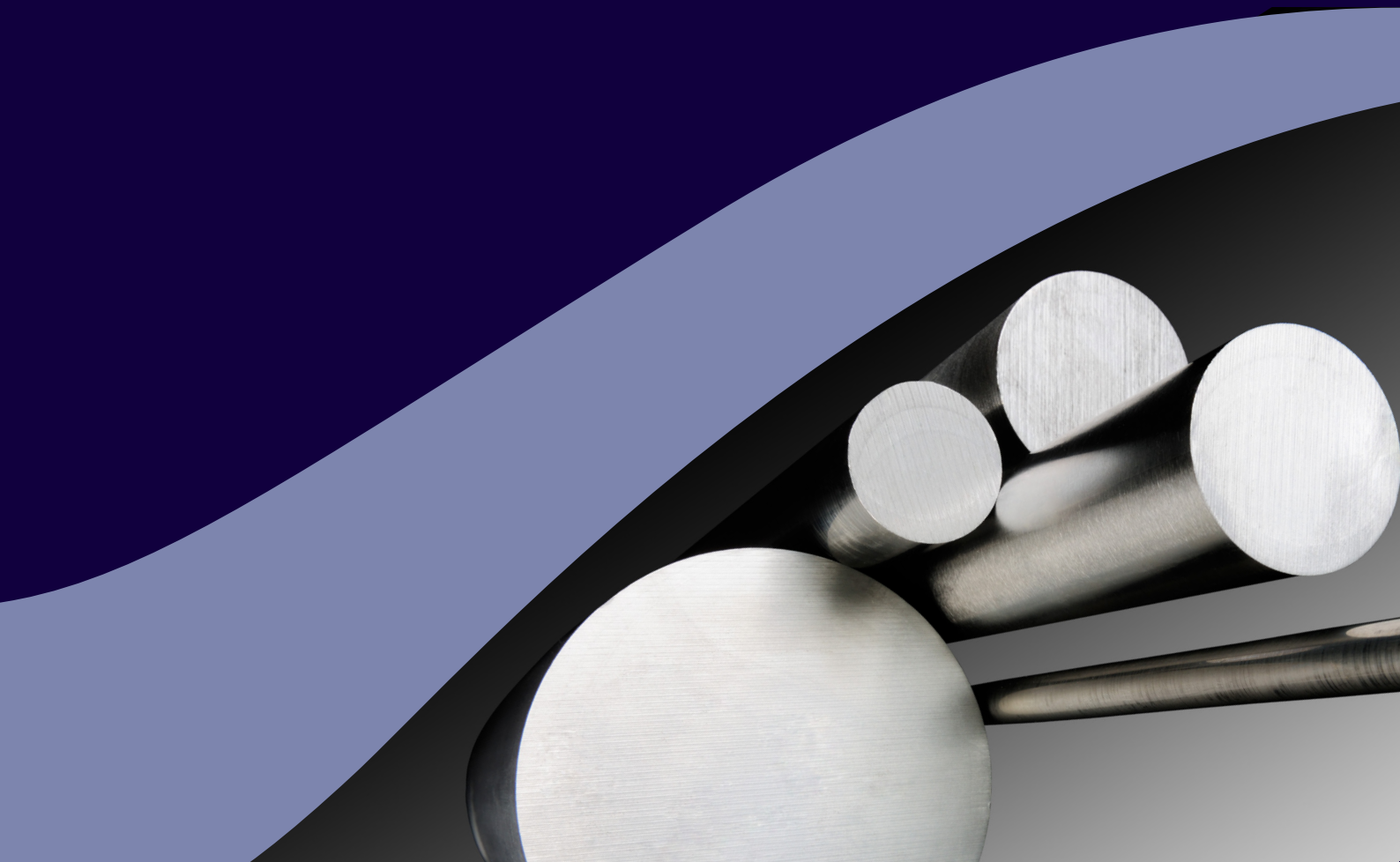ERASTEEL

GRINDING
of High-Speed Steels

INTRODUCTION

High-speed steel (HSS) has been used in cutting tools for more than one-hundred years. Its high alloy content gives it a high-performance combination of toughness and wear resistance, but also makes it more difficult to grind than conventional low-alloy steel. This poses special challenges when aiming to achieve both high quality and high productivity.

Consequently, achieving consistent, successful results requires an in-depth knowledge of grinding fundamentals and the skills necessary to apply this knowledge to grinding of HSS.

This brochure provides detailed explanations and information on grinding of HSS. It is divided into three sections. The first gives fundamentals: a description of the constituents of a grinding wheel, an explanation of the wheel marking nomenclature, and a description of the mechanisms of abrasion and wheel wear and how they affect grinding performance. The second section discusses grinding of high-speed-steel: HSS composition and its effect on grinding and grindability; the differences between PM and conventionally produced HSS and how they affect grinding and the economics of grinding; thermal damage, how to detect and measure it and its effect on tool performance; and how the quality of the ground surface affects tool performance. The third section gives information on improving grinding performance: wheel truing and dressing; CBN and ceramic abrasives and how to use them to achieve higher productivity; and cutting fluid, burr formation, wheel choice, grit-size selection and troubleshooting. The brochure also provides information on reducing cycle times, wheel consumption and grinding costs.

Archives TNATP, Collection Meillassoux

Modern grinding is now a high-tech, state-of-the-art operation. Nevertheless, grinding is as much a skill today as it was in the past. This early Parisian knife-grinder knew that proper grinding gave a longer tool life and a sharper edge.

TABLE OF CONTENTS

PART 1: FUNDAMENTALS

Saw Grinders, Sheffield, England. London News, 6 Jan, 1866.

GRINDING WHEEL BASICS

A grinding wheel consists of three basic components:

- *Abrasive*
- *Bond*
- *Porosity*

The abrasive (referred to as grits or grains) is the hard material that does the cutting. It is held in place by the bond material. The porosity is simply the air pores trapped within the wheel. Porosity is important for delivering coolant to the grit-workpiece interface and for providing space for chip formation. Vitrified-bonded wheels have a high natural porosity. Resin-, rubber- and metal-bonded wheels have almost no natural porosity.

Abrasive grain

Bond bridge
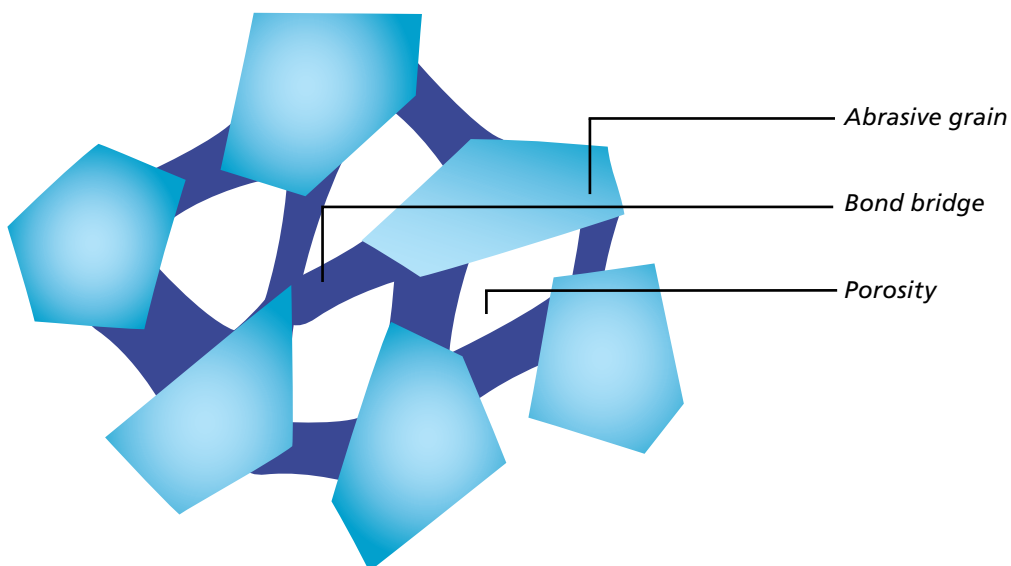
Porosity

*The three components of a grinding wheel: abrasive, bond and porosity.*

COMPOSITION

The composition of the grinding wheel and the relative percentages of the three components determine how the wheel behaves during use. Details about a particular wheel can be found printed on it and follow the standard *wheel marking system*. The notation given here is for wheels using conventional abrasives. For superabrasive wheels, the notation is somewhat different and is given on page 32.

ABRASIVE TYPE (I)

This letter denotes the type of abrasive used.

A	Aluminium Oxide (Al_2O_3)
C	Silicon Carbide (SiC)
B	Cubic Boron Nitride (CBN)
D	Diamond

Aluminium Oxide and *Silicon Carbide* are referred to as *conventional abrasives*. *Cubic Boron Nitride (CBN)* and *Diamond* are referred to as *superabrasives*. The particular type of abrasive used depends on the application. *Aluminium oxide* is commonly used for grinding of high-speed steel. *Silicon carbide*, although somewhat harder, is now seldom used for grinding HSS. *Cubic Boron Nitride,* with its high hardness and good conductivity, performs well on HSS, particularly on higher-alloy grades. However, it is significantly more expensive than conventional abrasives and has more demanding machine requirements. *Diamond*, in spite of its high hardness, is not suitable for grinding of HSS because of its poor thermal resistance and chemical reactivity to iron.
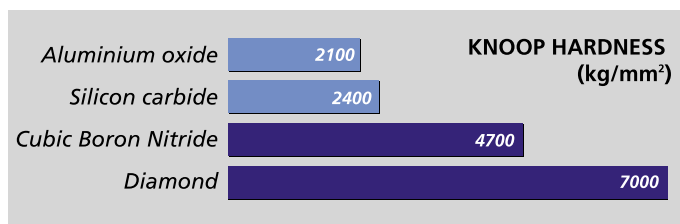
Hardness of abrasive grains

The numbers preceding the letter denote the exact variety of the abrasive used and are different for each manufacturer. For example, there are numerous varieties of aluminium oxide. *White Al_2O_3* is hard and 'friable', meaning that it fractures and 'self-sharpens' during grinding, exposing fresh cutting edges. *Brown Al_2O_3* is tough, meaning that it fractures less easily. 'Seeded-gel' or 'sol-gel' abrasives have recently gained popularity. They have a crystal structure that micro-fractures during use, maintaining sharpness yet keeping wheel wear to a minimum.
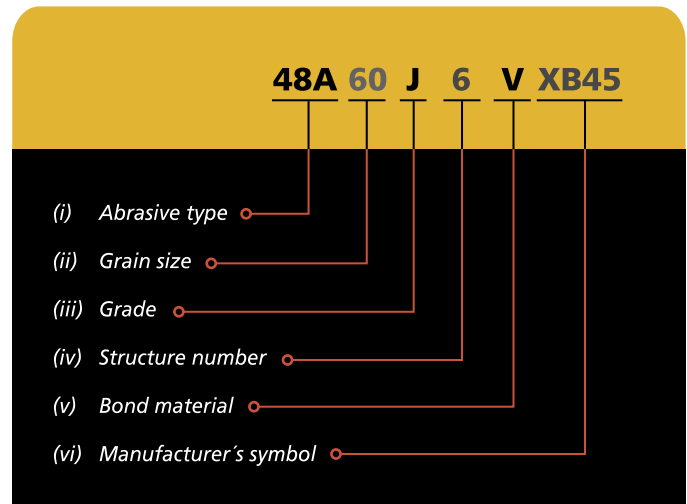

Grinding wheel notation for conventional abrasives.

GRAIN SIZE (II)

The grain size number denotes the size of the grits in the wheel. Because it is related to the number of screens per inch used during sieving, *a larger number corresponds to a smaller grit*. In general, doubling the grain size number will halve the mean diameter of the grits, resulting in approximately four times the number of grits per unit area at the grinding surface.

Coarser grits are used for higher stock-removal rates, when grinding softer materials, and when the contact area is large. They produce a rougher surface finish and the minimum form radius that can be achieved is larger. Finer grains are used for high-precision grinding, when grinding harder materials, and when the contact area is small. They achieve a finer finish and a smaller minimum form radius.
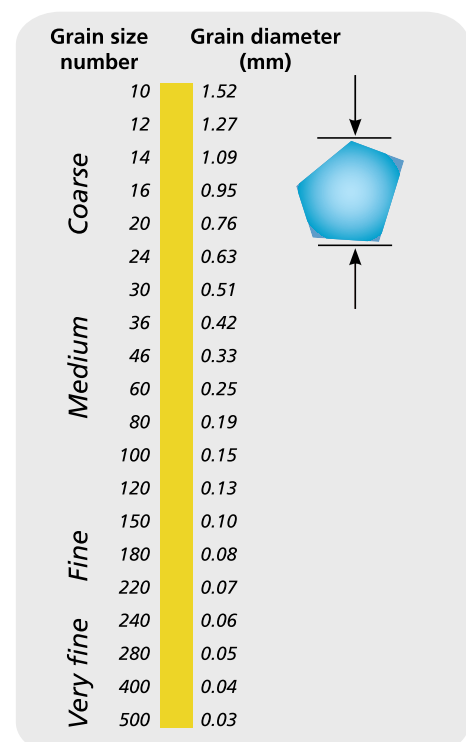
GRADE (III)

The grade indicates the 'strength' of the wheel, or how tightly the bond material holds the grits. It is sometimes referred to as the 'wheel hardness', which can be misleading as it is *not related to the hardness of the abrasive*. For vitrified-bonded wheels, the grade refers to the relative fraction of bond material and porosity in the wheel for a fixed abrasive content. Higher-graded wheels have *more bond and less porosity*, making them act 'harder'. Lower-graded wheels have *less bond and more porosity*, making them act 'softer'. For resinoid-bonded and metal-bonded wheels, which have almost no natural porosity, the grade is determined by the bond formulation.

Harder-graded wheels tend *to maintain form well* but are *more prone to burning* because the grits are not released upon dulling. Softer-graded wheels tend *to lose form but are less prone to burning* because the grits release upon dulling, maintaining a 'self-sharpening' or 'free-cutting' wheel.

The correct choice of wheel grade will depend on numerous variables. Materials that are more difficult to grind cause rapid blunting of the wheel. Therefore, they require a softer grade to keep the wheel sharp. Grinding operations that have a longer length of the *arc-of-cut* [page 36] tend to use softer-graded wheels because of the larger surface area available to distribute the forces on the grits.

The optimum wheel for a particular job needs to strike a balance between strength and sharpness: it should be hard enough to maintain form but soft enough to release dull grits.
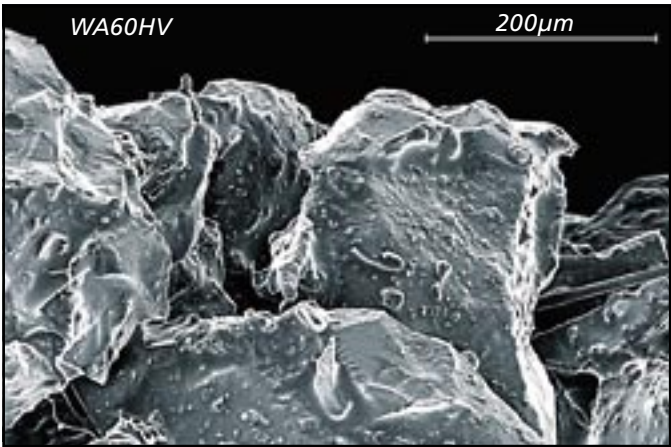
Grits in a grinding wheel. Freshly dressed wheels are sharp, but they become dull during use. Choosing a softer-graded wheel means less bond material and more porosity, so the grits break away after becoming dull, creating a 'self-sharpening' wheel.

Hardness scales are not standardised: they are different for each manufacturer. However, within each family of products and wheel type the grade indicates the relative strength of the wheel from one grade to another.

soft	medium	hard	very hard

E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W

Wheel grades. Higher-graded vitrified-bonded wheels have more bond material and act 'harder'.

STRUCTURE NUMBER (IV)

The structure indicates *the spacing of the abrasive within the wheel*, often defined by the volumetric concentration of abrasive in the wheel. A smaller number indicates a higher percentage of abrasive and a more 'closed' structure. A larger number indicates a lower percentage of abrasive and a more 'open' structure. This number is often omitted if it is the default value of the manufacturer. Open-structured wheels are used to facilitate chip formation and in applications where cooling is more important, such as in creep-feed grinding.

closed		regular		open		very open

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15

Wheel Structure. Open-structured wheels have a greater spacing between grits.

BOND MATERIAL (V)

The purpose of the bond is to hold the abrasive grits in place. The most common types of bond are:

V	**Vitrified**
B	**Resinoid**
R	**Rubber**
M	**Metal**

Vitrified-bonded wheels are the most common and are used with both conventional abrasives and superabrasives. They are stiff (good for precision grinding), have a porous structure and are not sensitive to high temperatures. **Resin**-bonded wheels are non-porous, less stiff (good for finer surface finishes), tough (less brittle, good for heavy-duty operations, high operating speeds and handling side-forces) and more temperature-sensitive than vitrified-bonded wheels. **Rubber**-bonded wheels are used on wet cutting-off operations and to create a very fine surface finish. **Metallic**-bonded wheels are often used with superabrasives.

MANUFACTURER'S SYMBOL (VI)

Additional numbers and/or letters describe the particular type of bond used and are different for each manufacturer. Other digits may provide further information about the wheel.

HOW GRINDING WORKS

Grinding is a process of abrasive cutting where the grit acts as a cutting tool and the bond material serves as a tool holder. Similar to turning and milling, grinding is a process of chip formation. However, the chips produced are extremely small and the cutting edges are numerous, irregularly shaped and 'self-sharpening', with negative cutting angles.

During grinding, three primary interactions occur at the grit-workpiece interface: *Cutting, Ploughing* and *Rubbing*. All three generate heat.

CUTTING

Cutting is the formation of chips to the sides of the grit.

PLOUGHING

Ploughing is the pushing of material to the sides and to the front of the grit. No material is removed, but ploughing facilitates chip formation.

RUBBING

Rubbing is the sliding of the workpiece against the grit. No material is removed.

During grinding, all three interactions occur to varying degrees. A sharp wheel operates efficiently, having a higher proportion of cutting – generating less heat. A dull wheel operates inefficiently, having a higher proportion of ploughing and rubbing – generating more heat.

20 μm

Above: Grinding swarf. Grinding is a chip-formation process (grinding of M9V with WA46HV wheel, 1000X).

chip formation (cutting)

front ploughing

side ploughing

chip formation (cutting)

side ploughing

rubbing

Right: A soft material after a hard, pyramid-shaped abrasive has been pushed through it, simultaneously showing the three types of abrasive interaction: cutting, ploughing and rubbing.
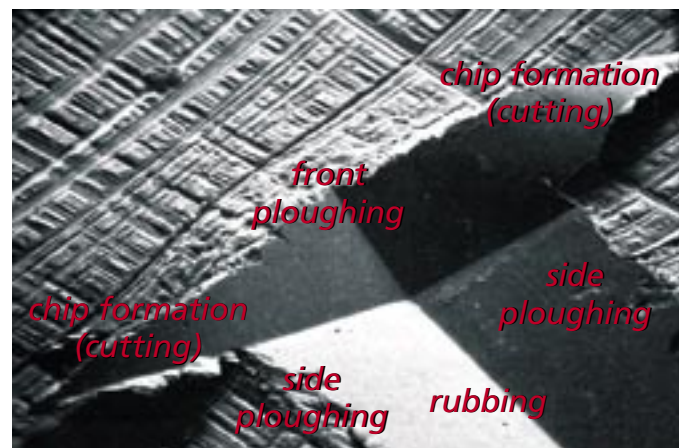
WHEEL WEAR

Immediately after dressing, the grinding wheel is sharp and acts efficiently, resulting in a high proportion of cutting. As grinding continues, however, the tips of the grits become blunt. This leads to a higher degree of ploughing and rubbing and results in higher power consumption, which is directly related to increased heat generation, higher temperatures, and grinding burn.

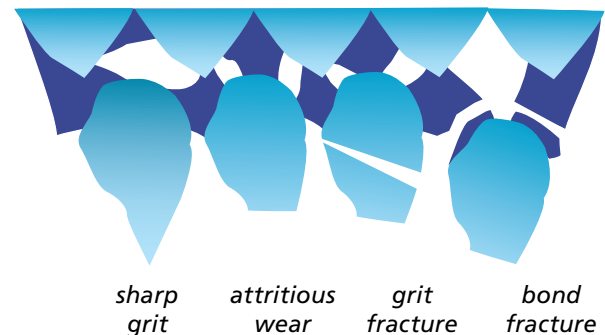The three types of wheel wear are:

ATTRITIOUS WEAR (I)

Attritious wear occurs at the tips of the grits. Although it accounts for only a tiny fraction of overall wheel wear, it adversely affects performance as it leads to a higher degree of heat generation. It is often referred to as the development of *wear flats* or as *blunting, dulling* or *glazing* of the wheel. CBN wheels, because of their high hardness, have a much slower rate of attritious wear.

GRIT FRACTURE (II)

Grit fracture is the wear of the wheel by fracture of the abrasive grit. It occurs when the stresses acting on the grit exceed its strength. Friable abrasives, such as *white alumina*, are more prone to grit fracture. The 'seeded-gel' abrasives have a high degree of grit fracture, which occurs along their microscopic fracture planes.

BOND FRACTURE (III)

Bond fracture is the wear of the wheel by fracture of the bond post. It occurs when the stresses on the grit exceed the strength of the bond bridges. Softer-graded wheels are more prone to bond fracture because they have less bond material to hold the grits.

sharp grit   attritious wear   grit fracture   bond fracture

Above: The three types of wheel wear. Attritious wear leads to greater heat generation and higher temperatures. It should be balanced by the right degree of grit fracture and bond fracture to create a self-sharpening wheel.


10μm
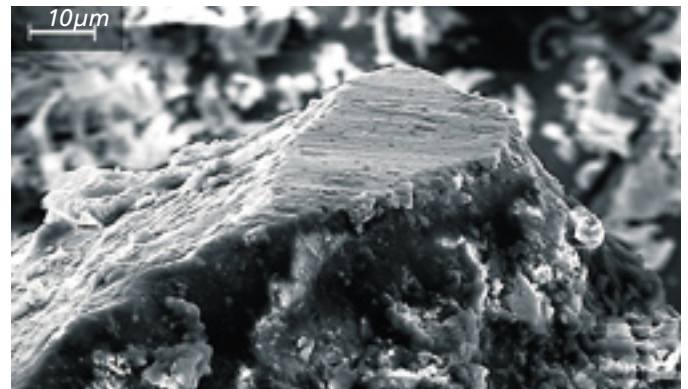
Right: A dull grit. Severe wheel dulling leads to high temperatures and grinding burn. This 46-grit, N-grade, vitrified-bonded wheel was too hard for the job.

In a properly functioning grinding wheel, the increased stresses acting on the dull grits (*type I* wear) are balanced by the strength of the abrasive and the strength of the bond bridges, so that dull grits break free, exposing new, sharp cutting edges. This is accomplished by either fracture of the abrasive (*type II* wear) or fracture of the bond (*type III* wear). This type of wheel is referred to as 'self-sharpening' or 'free-cutting'. For wheels that wear too quickly, the rate of grit fracture and bond fracture can be decreased by decreasing the chip thickness [page 38].
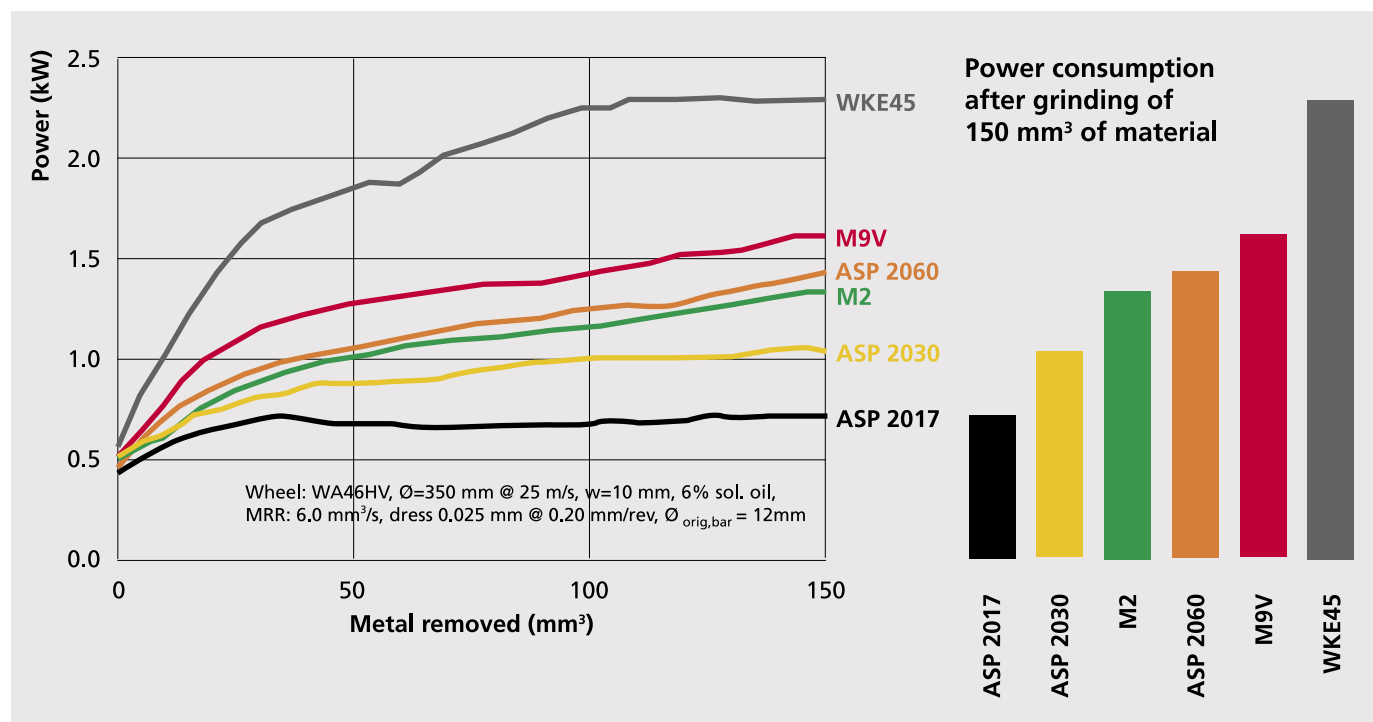
Under mediocre self-sharpening conditions, the forces acting on the grits reach a critical point and wheel wear becomes extreme and unsteady (see side bar). At this point the wheel 'collapses' and loses its *roundness*, resulting in machine vibration and unstable grinding. Grinding operations should not be allowed to reach this point. Higher-alloy grades dull the wheel at a faster rate and reach the 'collapse stage' earlier. In addition, grinding operations with severe wheel 'loading' (clogging) are particularly prone to this phenomenon.

STEEL COMPOSITION AND GRINDING

The rate of wheel wear is affected by the grinding conditions, but also by the composition of the steel. Grinding of high-alloy steels, with their increased hardness and large number of hard carbides, leads to rapid blunting of the wheel and increased power consumption. For example, high-alloy grades begin with approximately the same power consumption as low-alloy grades, as seen in the figure. As grinding progresses, however, the power consumption of the high-alloy grades increases much more rapidly. After some time, the power consumption of one grade may be several times greater than that of another grade.

'COLLAPSE' OF GRINDING WHEEL

POWER CONSUMPTION

Newly dressed wheel

Stable grinding   *Unstable grinding*
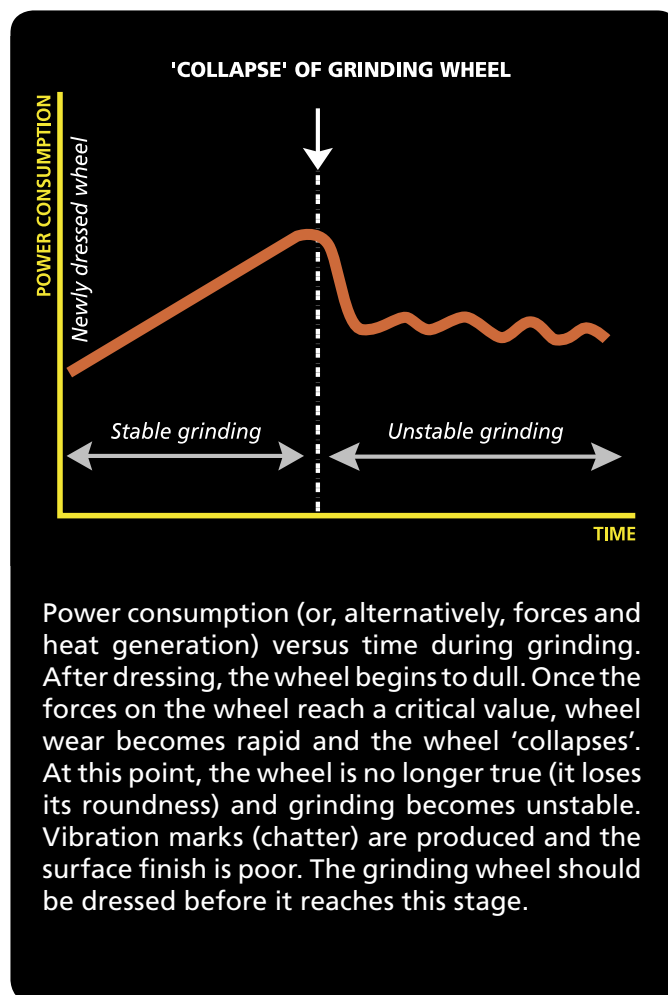
TIME

Power consumption (or, alternatively, forces and heat generation) versus time during grinding. After dressing, the wheel begins to dull. Once the forces on the wheel reach a critical value, wheel wear becomes rapid and the wheel 'collapses'. At this point, the wheel is no longer true (it loses its roundness) and grinding becomes unstable. Vibration marks (chatter) are produced and the surface finish is poor. The grinding wheel should be dressed before it reaches this stage.

Power consumption after grinding of 150 mm³ of material

Power (kW)

WKE45
M9V
ASP 2060
M2
ASP 2030
ASP 2017

Wheel: WA46HV, Ø=350 mm @ 25 m/s, w=10 mm, 6% sol. oil, MRR: 6.0 mm³/s, dress 0.025 mm @ 0.20 mm/rev, Ø$_{orig,bar}$ = 12mm

Metal removed (mm³)

ASP 2017   ASP 2030   M2   ASP 2060   M9V   WKE45

Almost 100% of the power used in grinding is converted to heat at the wheel-workpiece interface, leading to higher temperatures. High-alloy steel and low-alloy steel generate approximately the same amount of power and heat with a sharp wheel. As grinding proceeds, however, high-alloy steel blunts the wheel more quickly. This results in excessive wheel wear and, as shown here, increased power consumption. Consequently, the risk of grinding burn increases.

PART II:
GRINDING OF
HIGH SPEED STEEL

Der Scherenschleifer. Etching by French; from painting by Weenix.

HSS COMPOSITION
AND GRINDING

High-speed steel is composed of two primary components: the alloyed iron-carbon matrix and the carbides. Tungsten, molybdenum and vanadium combine with carbon to form hard carbides. As shown in the figure on the following page, these carbides can be of the same hardness or even harder than the abrasive grits, leading to dulling and grit/bond fracture. In general, a higher alloying content means more carbides and decreased grindability.
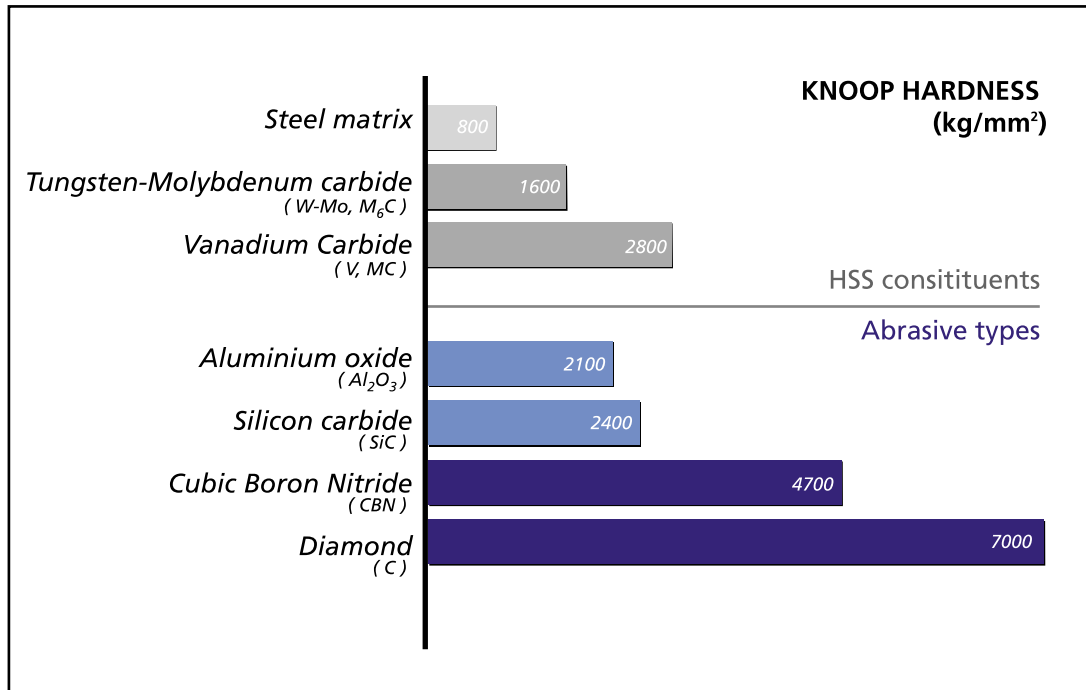

Vanadium carbide

Tungsten-molyb-
denum carbide
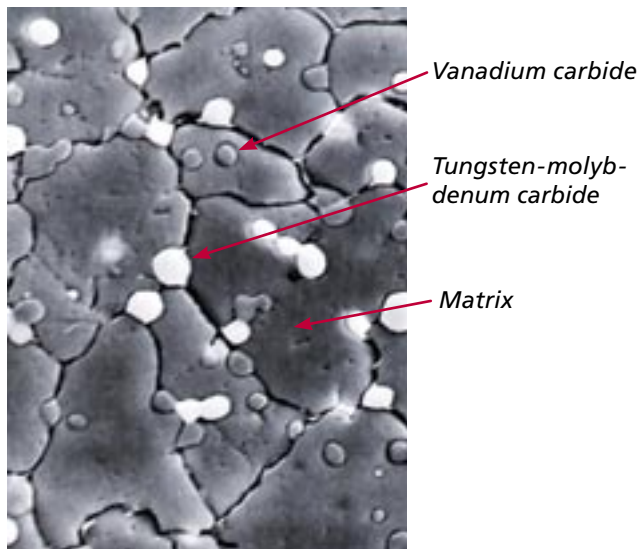
Matrix

Carbides and matrix in ASP 2030 PM steel.

The edge of a knife made of ASP 2053. The carbides give the knife its wear resistance, but also make it more difficult to grind.

Grinding of low-alloy steels tends to be much easier: the wheel maintains sharpness for a longer period of time. Grinding of high-alloy steels, with their high percentage of hard carbides, poses special challenges. Therefore, the correct choice of grinding wheel, dressing conditions, coolant and grinding parameters is extremely important in order to achieve high production rates with minimum heat generation. Nevertheless, even well-optimised grinding operations are pushed to the limit for productivity, which can lead to *thermal damage*, often referred to as *grinding burn*.

KNOOP HARDNESS (kg/mm²)

Material	Value
Steel matrix	800
Tungsten-Molybdenum carbide (W-Mo, M_6C)	1600
Vanadium Carbide (V, MC)	2800
Aluminium oxide (Al_2O_3)	2100
Silicon carbide (SiC)	2400
Cubic Boron Nitride (CBN)	4700
Diamond (C)	7000

HSS consitituents

Abrasive types

Hardness values of HSS constituents and various types of abrasives.

'Softer'-graded wheel   **'Harder'-graded wheel**

porosity

grit

bond

A softer-graded wheel and a harder-graded wheel. Harder-graded vitrified-bonded wheels have more bond material.

Wheel Grade: A common misconception in grinding is that a harder-graded wheel contains a harder abrasive. This is not true. For vitrified-bonded wheels, a harder-grade simply means that the wheel has more bond material. Consequently, the bond does not fracture as easily when the grits become dull, and the grits are retained in the wheel longer before popping out. Harder-graded wheels tend to hold form better and produce a finer surface finish, but generate more heat and have an increased risk of chatter. For resin-bonded wheels, which have almost no porosity, the hardness is determined by the strength of the bond material rather than the amount.

GRINDABILITY

The term 'grindability' is used to describe the relative ease at which a material can be ground. Because of the differences in composition and hardness, different grades of HSS can vary significantly in terms of how easy or how difficult they are to grind.

Grindability can encompass the *sensitivity* of the material to thermal damage at high temperatures due to its metallurgical properties. More importantly, the *grindability* is best described in terms of the *G-ratio*, particularly when grinding with *conventional abrasives*. The *G-ratio* is defined as *the volume of material removed during grinding divided by the volume of wheel lost*.

The significance of the G-ratio is not the cost of the consumed wheel, but rather the effect of the steel composition on the cutting properties of the abrasive grits. High-alloy steels, with their numerous hard carbides, tend to blunt the wheel quickly, resulting in increased heat generation and wheel wear. This gives a *lower G-ratio* and a *poorer grindability*. Materials with low G-ratios require *lower speeds and feeds* and frequent dressing (to maintain sharpness and keep form). This results in longer cycle times. Low-alloy steels have higher G-ratios: they can use *higher speeds and feeds* because of the slow rate of blunting and wheel wear. They require less frequent dressing. This results in shorter cycle times and better quality control of the workpiece.

For these reasons, *CBN wheels* are often used for high-alloy materials with low grindability. The CBN grits are significantly harder than the carbides in the steel, resulting in a wheel that maintains sharpness. In addition, CBN has a higher thermal conductivity. Therefore, heat is conducted away from the workpiece and into the wheel, further reducing the risk of thermal damage.

The chart at the end of this brochure shows the relative grindability of Erasteel grades based on G-ratio tests, power measurements, production tests and practical experience. Because G-ratio is a *process parameter*, it depends on numerous variables. However, under pratical conditions the relative ranking of grindability among grades will generally remain consistent. Therefore, grindability values are given relative to that of M2. This ranking is for grinding with *conventional abrasives*. When grinding with *superabrasives*, the practical difference in grindability between grades is smaller.
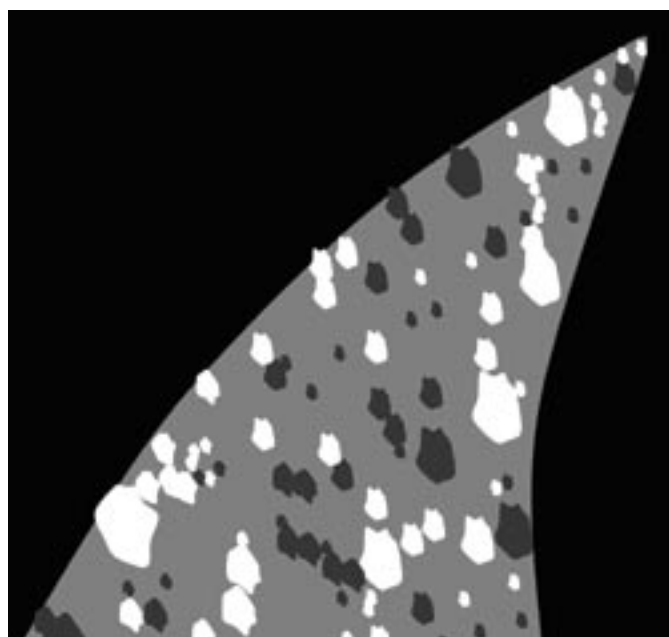
*Schematic of cutting edge in HSS.*

GRINDING OF PM STEEL

The differences in metallurgical characteristics between steel produced by the conventional method and steel produced by the PM method mean significant differences in how they behave during grinding.

When produced by conventional methods, HSS contains large carbides that dull the wheel. This problem is made worse by segregation, a condition where the carbides cluster together in large groups during cooling.

When produced by the powder metallurgy (PM) method, HSS contains much smaller carbides. During grinding, this results in a wheel that remains sharper and wears less. In addition, the rapid solidification rate of the PM method ensures that no segregation occurs in the steel, resulting in a homogeneous carbide distribution.

This means that, for a given alloying content, HSS produced by the PM method is easier to grind than HSS produced by the conventional method. The relative advantage increases as alloy content increases. The benefit is much more pronounced when grinding with conventional abrasives than with superabrasives.
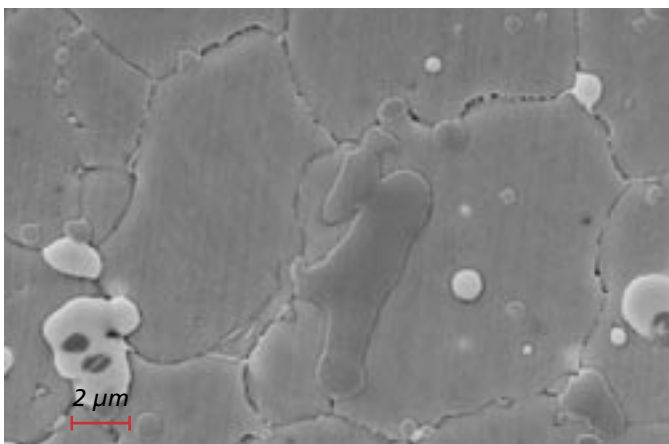
Conventionally manufactured high-speed steel has large carbides that cluster together.
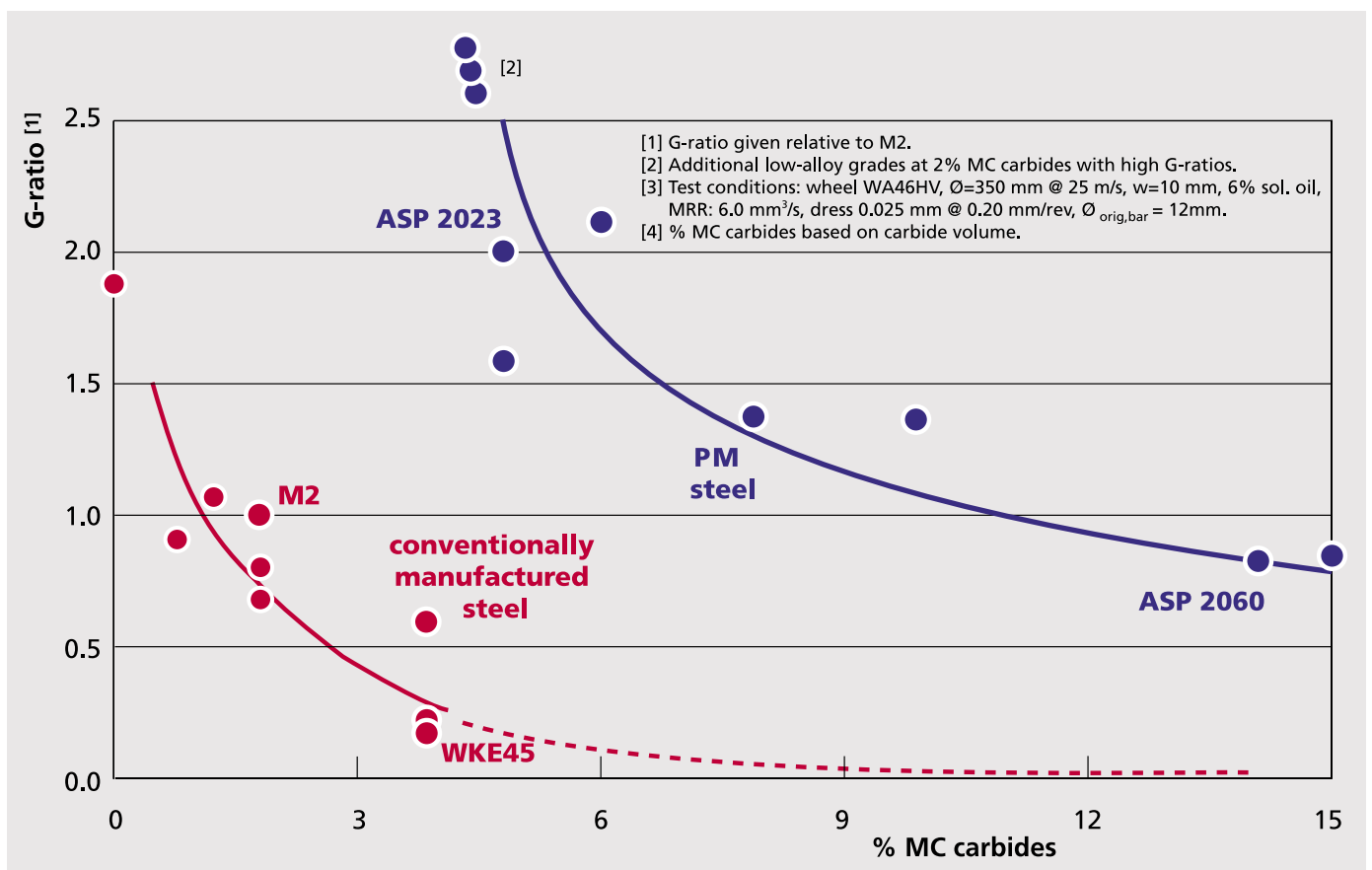
2 μm
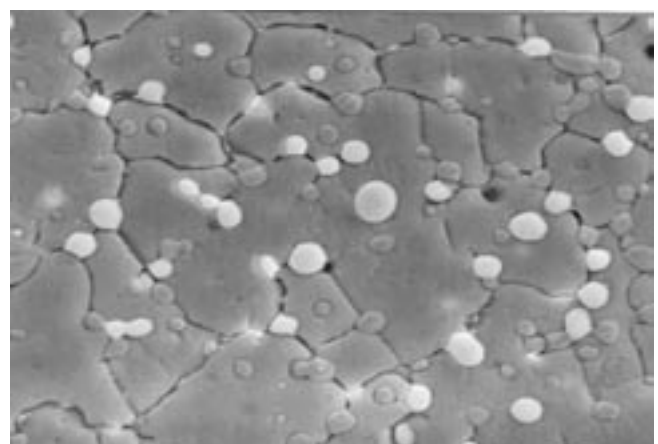
PM steel has small, evenly distributed carbides.
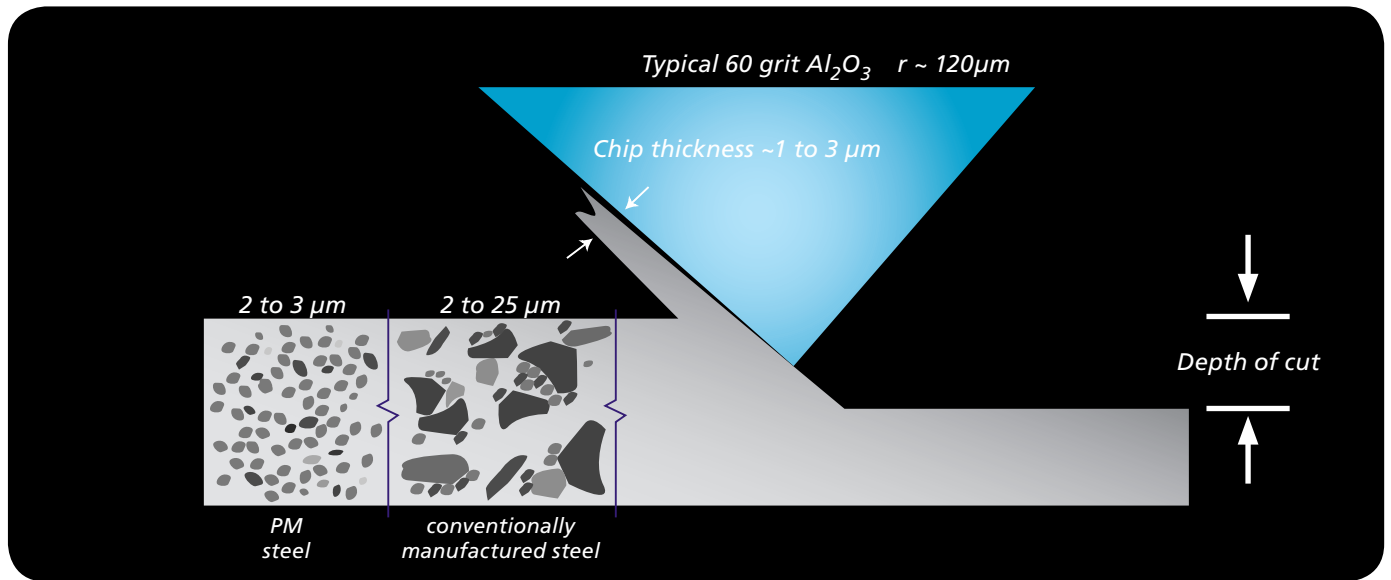
Grit, carbide and chip sizes when grinding of PM steel and conventionally manufactured steel.

With the development of the PM process, steel grades can now be produced with a higher alloy content, taking advantage of the increased wear resistance due to the carbides, yet still maintain toughness. Grindability decreases as alloy content increases for both cases. However, PM steel has better grindability compared to conventionally manufactured steel for a given alloy content. The chart below shows the effect of alloy content on G-ratio for both PM and conventionally manufactured steel. For example, ASP 2023 is often used as an upgrade to M2. It has a much higher carbide content than M2, particularly the harder vanadium carbides. In spite of this, ASP2023 is still easier to grind than M2.

[1] G-ratio given relative to M2.
[2] Additional low-alloy grades at 2% MC carbides with high G-ratios.
[3] Test conditions: wheel WA46HV, $\varnothing$=350 mm @ 25 m/s, w=10 mm, 6% sol. oil, MRR: 6.0 mm^3/s, dress 0.025 mm @ 0.20 mm/rev, $\varnothing_{orig,bar}$ = 12mm.
[4] % MC carbides based on carbide volume.

G-ratio versus percentage of hard MC (vanadium) carbides. For a given carbide content, PM steel is always easier to grind than conventionally manufactured steel.

COST SAVINGS IN PM

Grades with high grindability can be ground at higher feedrates, resulting in shorter cycle times and higher productivity. This benefit is particularly pronounced in PM HSS. In spite of the higher cost of PM steel, its better grindability can be used to decrease overall production costs.

The raw-material cost of HSS is some fraction of the total production cost. As the tool diameter increases, this fraction increases exponentially. This mean that, at small diameters, the raw-material cost – i.e., the cost of the blank – is extremely small.

However, at small diameters the grinding costs are not small. In fact, the blank cost at small diameters are insignificant compared to the grinding costs. Consequently, any improvement in grindability that can result in a reduction in cycle time will result in a decrease in overall tool cost.

Using a PM grade instead of a conventional grade increases the blank cost. However, the grinding costs in PM can be reduced due to its better grindability. This is usually accomplished via shorter cycle times, but can also be accomplished through less grinding-wheel consumption and less scrap.

By combining the blank cost and the grinding costs we get the total cost. Since the blank cost at small diameters is so small (on the order of € 0.02 for a 3mm-diameter tool), any reduction in grinding costs, even a nominal reduction, will result in a lower total cost. At a certain diameter there will be a break-even point – at larger diameters the overall cost will be higher, at smaller diameters the overall cost will be lower. The break-even range is usually between 6 mm and 14 mm, depending on the tool.

By switching to PM in small-diameter tools, not only will the tool performance be better due to the better material properties of PM, but the overall production costs will be lower.
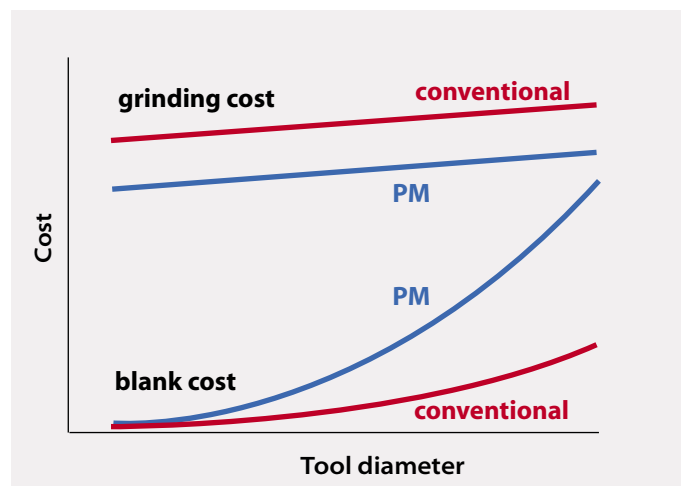

Although both grinding costs and blank costs increase with tool diameter, grinding costs increase only linearly, whereas blank costs increase exponentially. At small diameters, the increased blank cost of PM is very small.
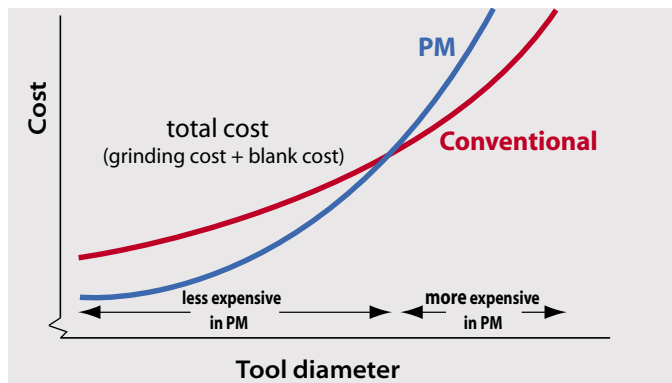
Overall tool cost vs. diameter. At smaller diameters, producing a tool in PM is less expensive due to its better grindability.
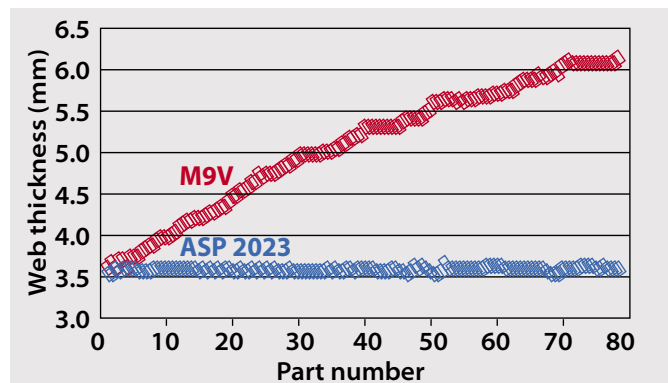
Web thickness vs. part number for large batch in flute grinding of 10-mm-diameter tools. After switching from M9V to ASP 2023, the in-feed was increased 127%, reducing the total cycle time by 46%. The dressing frequency was also cut from every tool to every other tool. ASP 2023 held form throughout the 80 tools; M9V lost form almost immediately.
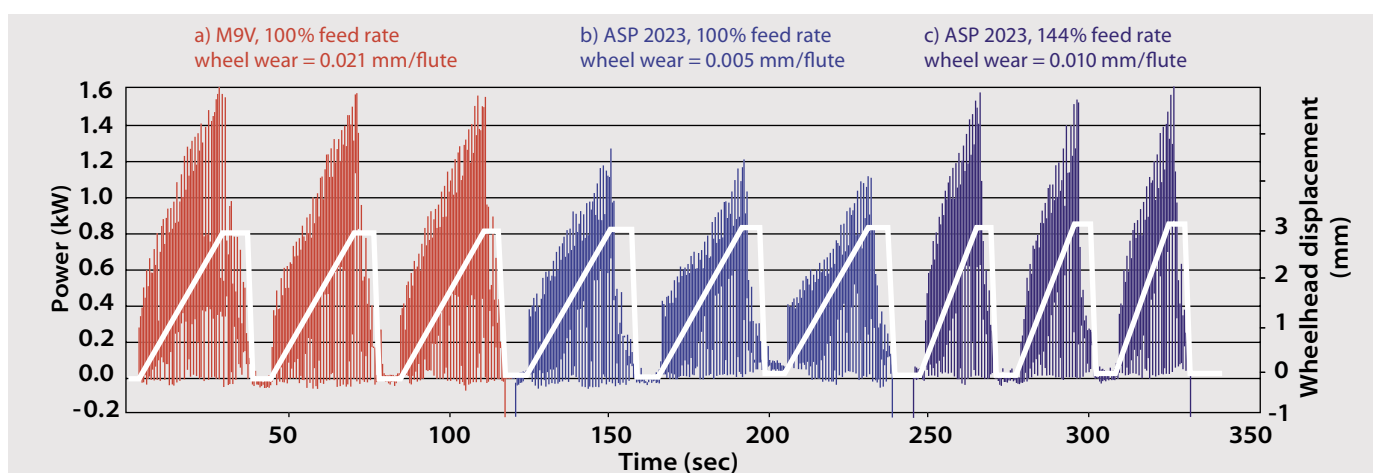
Power generated and wheel wear for flute grinding of 10-mm-diameter taps in M9V and ASP2023. M9V (a) generated a maximum power (and heat) of 1.6 kW, with 0.021 mm of wheel wear per flute. Using the exact same parameters but grinding ASP2023 (b) resulted in much less power (1.25 kW) and wheel wear (0.005 mm). This enabled the operator to increase the feedrate and reduce cycle time in ASP2023 (c). Even with the increased feedrate (44% higher), power generation was about the same (1.6 kW) as M9V and wheel wear was less (0.010 mm, 52% lower). Consequently, cycle time was reduced from 122 s to 88 s (28%) without any increase in the risk of burn or form loss.

INCREASING PRODUCTIVITY WITH HIGH-GRINDABILITY GRADES.

Care must be taken when switching to an easier-to-grind grade. Under the same grinding conditions – i.e., speeds and feeds – the easier-to-grind grade will not wear the wheel as much, increasing the risk of grit dulling and wheel clogging. The solution is to grind more aggressively – through a faster table speed and/or a deeper cut. Also, a softer wheel grade or a more friable grit may be used to ensure self-sharpening, but this will not result in any increase in productivity.

REDUCING CYCLE TIMES

In the effort to reduce cycle times, often too much emphasis is placed on choosing a better wheel and grinding faster. Improvements by this method are usually small and hard-won. Much greater reductions can be achieved by a clear, step-by-step methodology of: i) mapping out the entire cycle, taking into account the time spent part-changing, dressing, grinding, cycling back, air-grinding, idle, etc.; ii) assessing wheel wear; iii) documenting grinding parameters and correlating grinding behaviour with parameters and wheel wear; and iv) developing a comprehensive strategy to reduce cycle times based on this information. This often means eliminating air-grinding, unnecessary part-cycling and other anomalies and then eliminating a dressing pass or a grinding pass. It can also mean rough grinding and finish grinding with two different sets of dressing parameters. Whatever option is chosen, it is a much more useful method of reducing cycle times than simply 'grinding faster'.

THERMAL DAMAGE AND 'GRINDING BURN'

'Grinding burn' is a term that is used loosely to describe any type of thermal damage that occurs to the workpiece during grinding. In fact, there are several types of thermal damage, and each occurs within a different temperature range and affects the quality of the workpiece in a different way.

THE FOUR TYPES OF THERMAL DAMAGE ARE:

    Type 1: Oxidation Burn

    Type 2: Thermal Softening

    Type 3: Residual Tensile Stress

    Type 4: Rehardening Burn

Most types of thermal damage do not show visual evidence on the workpiece.

The four types of thermal damage and the relative temperature ranges where they occur.
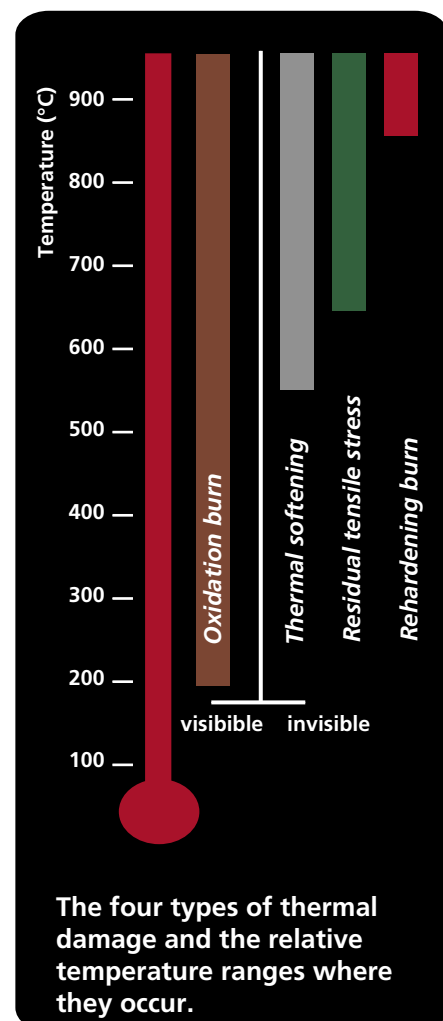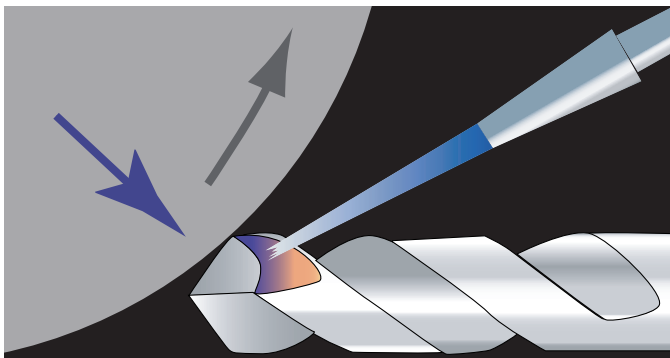
TYPE 1: OXIDATION BURN

Oxidation burn is caused by oxidation of the workpiece and/or coolant and leaves a thin, discoloured layer on the ground surface. It can also occur on the unground surface near the grinding region where temperatures are high due to conduction. Oxidation burn is sometimes strictly cosmetic and often occurs without any metallurgical damage to the part, although this thin layer can inhibit any later surface coatings. Although it usually becomes more severe at higher temperatures, it does not indicate whether other types of thermal damage have occurred.

Oxidation burn on a tap. The surface is discoloured due to heat conduction from the thread-grinding operation.
It does not indicate whether other types of thermal damage are present.


Heat conduction during point grinding often causes oxidation burn on the unground surface. Because this oxidation burn can not be ground away, it is difficult to remove. An extra coolant nozzle directed at the oxidizing region will cool it and starve it of oxygen, thus reducing or eliminating the oxidation burn.

TYPE 2: THERMAL SOFTENING

Thermal softening (overtempering) occurs when the temperature of the workpiece exceeds the tempering temperature. It results in a layer of overtempered material with reduced hardness. This can adversely affect the strength and performance of the tool.

The figure shows how the hardness of the workpiece is affected by thermal damage with increasing depth into the material. It shows two types of thermal damage. First, in the top 0.1 mm (red) is a region of rehardening burn (type 4) with increased hardness. Then, from 0.1 mm to 0.4 mm depth (grey) is a region of thermal softening (type 2) with reduced hardness. Beyond 0.4 mm depth (black), the hardness of the workpiece is unaffected. Although *both thermal softening* and *rehardening* thermal damage are visible here, *thermal softening often occurs without the presence of rehardening,* because thermal softening begins to occur at a lower temperature.
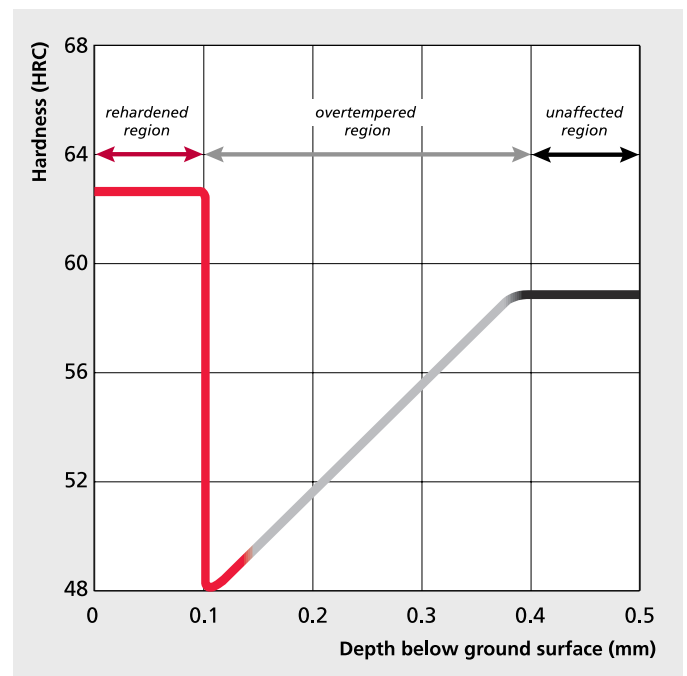
Hardness versus depth showing Type 4 and Type 2 thermal damage. At the surface is a layer of rehardening burn; below that is a layer of overtempered material.
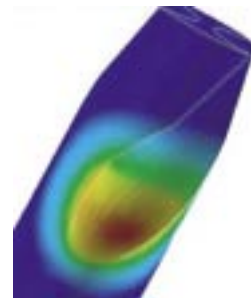

Courtesy of Darren Walsh.

Finite-element analysis of temperatures in flute grinding. The flute run-out is most susceptible to thermal damage because, un-like the rest of the flute, the hot-spot is not ground away.

TYPE 3: RESIDUAL TENSILE STRESS

During gentle grinding, the plastic deformation of the workpiece due to the action of the abrasive grits leaves the surface in a state of *residual compressive stress*. Like shot-peening, this can enhance the material properties of the workpiece, most notably fatigue life. However, as production rates are increased, temperatures increase and *residual tensile stresses* begin to emerge.

Residual tensile stresses are caused by restricted thermal expansion of the surface during grinding. After cooling, the surface is in a state of tension. In moderate cases, residual tensile stress negatively affects tool life. In extreme cases it results in cracking of the tool after grinding. The depth and the severity depend on the temperature reached and the material properties of the workpiece. Assuming that no immediate cracking is present, residual stresses can be alleviated by a post-tempering operation after grinding.
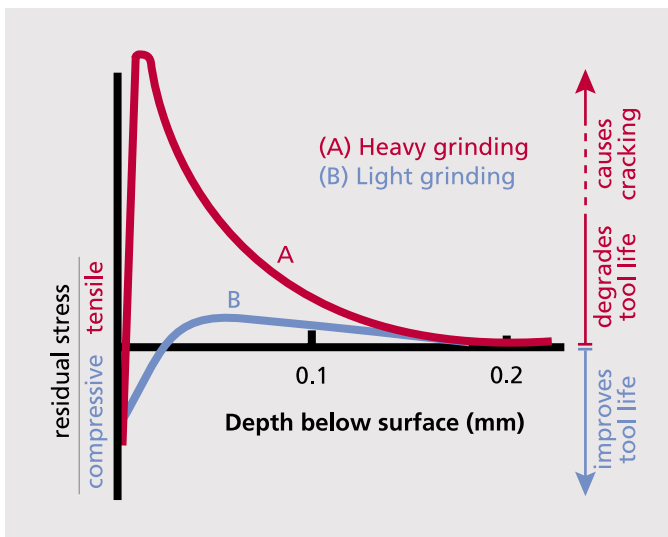
Residual stress versus depth into the workpiece. Residual stresses are present in all ground specimens. Residual compressive stress improves tool life. Residual tensile stress degrades tool life and can cause immediate cracking.

TYPE 4: REHARDENING BURN

Rehardening burn occurs when the temperature of the workpiece exceeds the austenising temperature, causing a metallurgical phase change in the material upon cooling. The result is a thin layer of *hard, brittle, untempered martensite*. This condition is further exacerbated by secondary residual stresses, which occur with the change in density of the newly formed material. It is the most severe form of thermal damage and often leads to cracking of the tool.
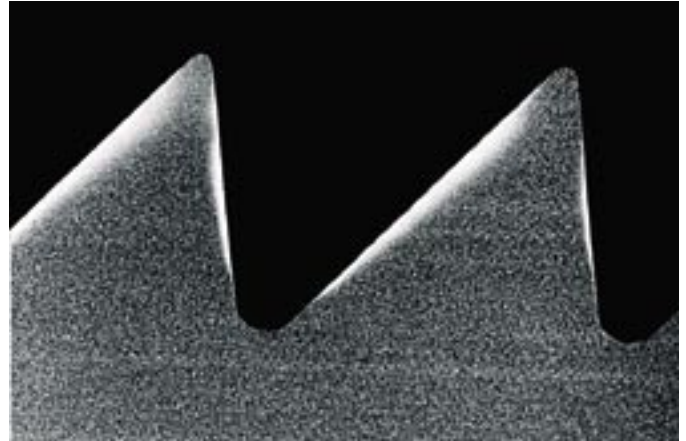
Rehardening burn in a thread milling cutter. The white sections show where a phase change in the material occurred.

ALLEVIATING THERMAL DAMAGE

Even under well-optimised grinding conditions, the pursuit of high production rates means that thermal damage is always a risk. The challenge lies in achieving high production rates and consistent quality while keeping temperatures down. Reduced temperatures can be achieved by either *(i) reducing the heat generation*, or by *(ii) reducing the amount of heat entering the workpiece*, for example by effective cooling.
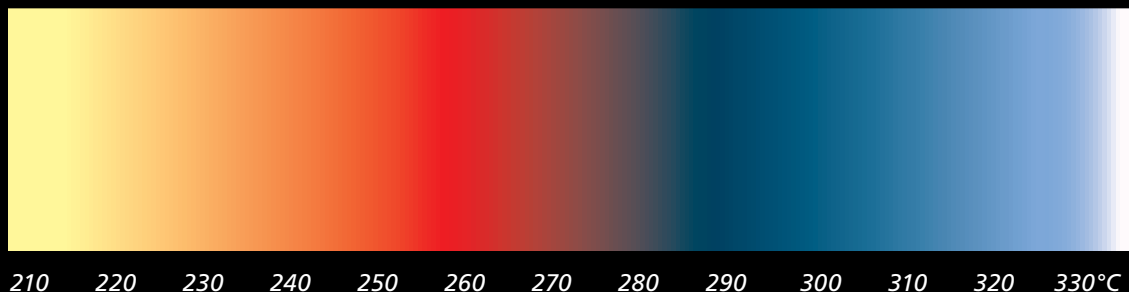
'Temper colours' caused by oxidation of the workpiece, with approximate corresponding temperatures. The colour of the burned tool gives some indication of the temperature reached. However, the temperatures where oxidation burn begins are much lower than the temperatures where genuine thermal damage occurs. Therefore, care must be taken if trying to assess based on 'temper colours' if the tool has suffered genuine thermal damage from grinding.

TESTING FOR THERMAL DAMAGE

Thermal damage can lead to poor tool performance or even catastrophic failure. Because the dangerous type of thermal damage – thermal softening, residual tensile stress and rehardening burn – cannot be seen with the naked eye, it is necessary to test workpieces in the laboratory to determine if they have suffered damage. There is no single robust, quantifiable method to test for all types of thermal damage. However, the following can be used:

A) NITAL ETCHING
to detect *overtempering* and *rehardening burn*

This test involves taking a section of the tool and cutting and polishing it. The polished section is dipped in a solution of nitric acid (HNO_3, usually 4-15%) at room temperature for less than a minute, followed by cleaning in an alcohol solution. It is examined under a microscope. Areas that have experienced thermal softening appear grey and those that have experienced rehardening burn appear white.

Rehardening burn in a drill detected by nital etching.
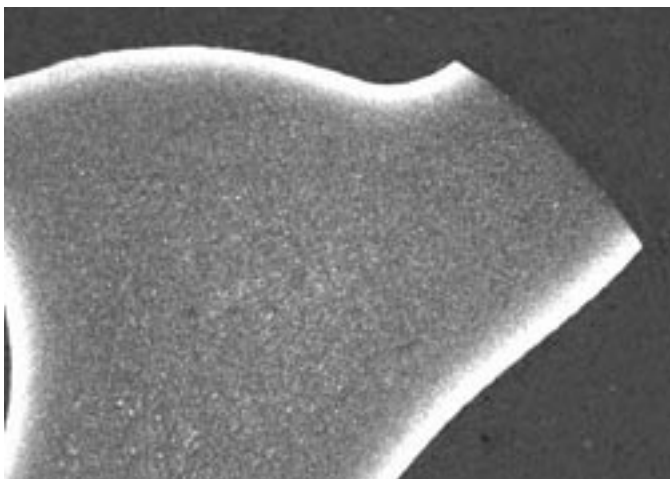
B) HOT HYDROCHLORIC ACID ETCHING
to detect *residual tensile stresses*

The entire tool is soaked in a high-temperature bath of hydrochloric acid and then etched in nitric acid. The surface is examined with the naked eye. A clean surface means little or no stress. A surface with fissures perpendicular to the direction of grinding indicates moderate stress. A surface with a spider-web-like pattern indicates severe stress. Several possible variations exist. A typical method is to soak the tool in a 30% solution of HCl which is suspended in a hot-water bath at 100°C for 30 to 90 minutes, followed by cleaning in a 36% nitric-acid solution.

A common misconception is that this method *exposes* cracks underneath the surface. This is not the case. By a process of hydrogen embrittlement, the acid *induces* fissures to form in areas where residual tensile stresses are high. This method may also reveal thermal softening and rehardening burn in a similar manner to *Nital Etching*, but is less reliable. Although qualitative rather than quantitative, this method is the quickest, most robust and best suited for the shop floor.

c) HARDNESS MEASSUREMENTS
to detect *thermal softening* and *rehardening burn*

Thermal softening and rehardening burn can be detected to some extent by measuring the hardness of the work-piece, with a decrease in hardness indicating thermal softening and an increase indicating rehardening burn. Hardness measurements can be performed either (I) directly on the ground surface, or (II) by taking a section of the tool and measuring hardness at increasing depths from the ground surface. In practice it can be difficult to achieve accuracy in either method, as the depth of the damaged layer may be very thin and the hardness inden-ter may penetrate into the undamaged layer. This can be remedied by using a smaller load. However, this is less accurate as hard carbides or grinding scratches near the surface can distort the measurements.

d) OTHER TECHNIQUES

X-ray diffraction can be used for measuring residual stresses. Although accurate and quantifiable, this method is cumbersome, time-consuming and expensive, and is not suitable for a production environment. *Barkhausen Noise*, which measures changes in magnetic domains in magnetised ferromagnetic materials, can be used to detect residual stresses and may also indicate thermal softening and rehardening burn. However, due to restrictions posed by complex tool geometries and because the output signal depends on numerous other factors, it can be very difficult to implement.
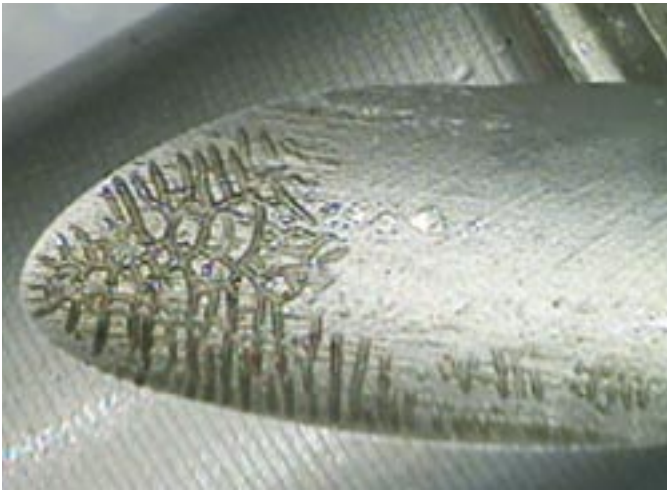
Hot hydrochloric acid etching induces fissures to form in areas where residual tensile stresses are high. The flute run-out region is particularly susceptible to residual tensile stress.

Tap after thread grinding (left) and after hot-hydrochloric-acid etching (right). The region exhibiting oxidation burn is on the unground surface. However, this is not a region with genuine, severe thermal damage. The thread-ground surface suffered the highest residual stress. However, this surface is clean – i.e., shows no oxidation burn – due to 'cleaning up' of the thin oxide layer.

Early grinding wheels: Millstones on Stanage Edge. Peak District, England.
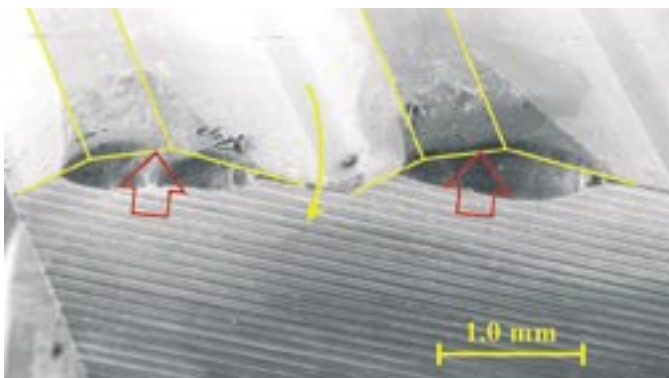
SURFACE QUALITY AND TOOL PERFORMANCE

The quality of the ground surface impacts the performance of the tool. Surfaces with large grinding scratches and/or grinding burn at the cutting edge are prone to fracture. Therefore, it is important to understand how the surface quality affects tool performance and where a good surface is needed.

GRINDING SCRATCHES

The impact strength of a tool depends both on the toughness of the material and the size of the largest defect. Often, the largest defect is a large grinding scratch. This acts as a crack-initiation point, causing fracture of the tool.

The milling cutter below, with the original geometry given in yellow and the direction of the forces during use given in red, fractured during use. The cause was large grinding scratches.

At the cutting edge there are two sides: the rake face – or cutting edge face – and the clearance face. The direction of the force acting on the tool causes the scratches on rake face to 'open up', while causing the scratches on the flank to 'close down'.

In addition, there are two types of scratches: scratches in the 'good direction' and scratches in the 'bad direction'. Scratches in the 'good direction' run parallel to the direction of the applied force. Scratches in the 'bad direction' run perpendicular to the applied force. When the scratches are on the 'bad side' in the 'bad direction', the tool is particularly prone to fracture.

The impact strength depends on the orientation of these scratches. When these scratches are in the 'good direction',
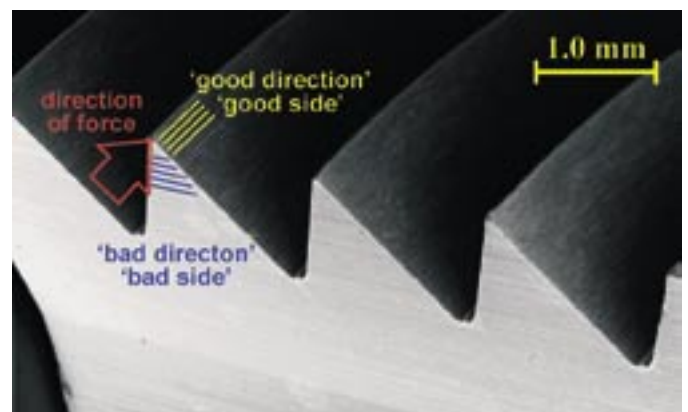
Thread-grinding scratches and flute-grinding scratches in tap grinding. The flute-grinding scratches are on the rake face in the 'bad direction', whereas the thread-grinding scratches are on the clearance face on the 'good side' in the 'good direction'. Therefore, a good surface at the cutting edge – imparted by the flute-grinding operation – is very important.

A milling cutter. Fracture was caused by large grinding scratches.

26

the impact strength is high and largely independent of the roughness of the surface (figure). When the scratches are in the 'bad direction', the impact strength decreases drastically with poorer surface finish.
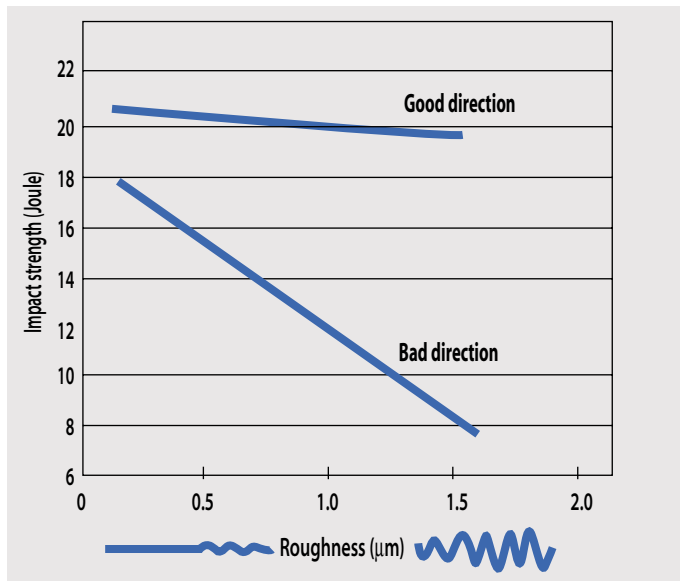

Impact strength vs. surface roughness.
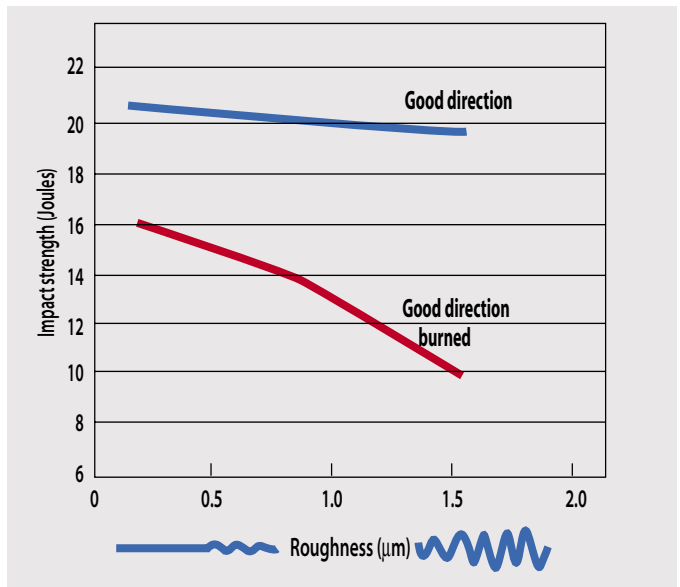
Impact strength vs. surface roughness. The presence of grinding burn also has a negative impact on tool performance. Even when the grinding scratches are in the 'good direction', if the tool has thermal damage (type 4: rehardening burn), the impact strength is much lower, regardless of the depth of the grinding scratches.

Consequently, it is important to know where a good surface is needed. In the step-drill below, the outer-diameter surface quality is very good, the flute surface quality is mediocre, and the quality from the two point-grinding operations is poor. Considering the way the tool is loaded, particularly how the scratches are orientated in the 'bad direction', it is the point-grinding operation that is most important – and the one that was neglected. The result was a fracture at the tool tip.
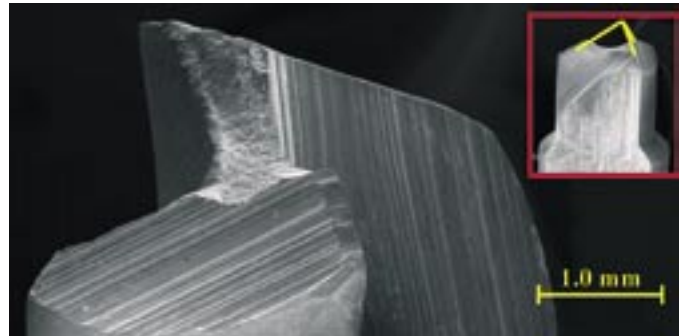
Step drill. Failed due to large grinding scratches.

In tap production, many toolmakers pay close attention to the quality of the thread-grinding operation, considering this to be a delicate, fine-grinding operation, and pay less attention to the flute-grinding operation. Considering the orientation of the scratches, it is obvious that it is the scratches imparted by the flute-grinding operation are just as important to tool performance.

The figure below is a worn tap that had a very long life. Here we see a surface from thread-grinding that is actually quite poor – and a surface from the flute-grinding that is reasonably good. The result was a tool that didn't fracture, but enjoyed a long life and gradually wore away through abrasion. However, the thread surface should not be negleated, particularly if the tool will be coated.

A worn tap.

PART III: IMPROVING PERFORMANCE
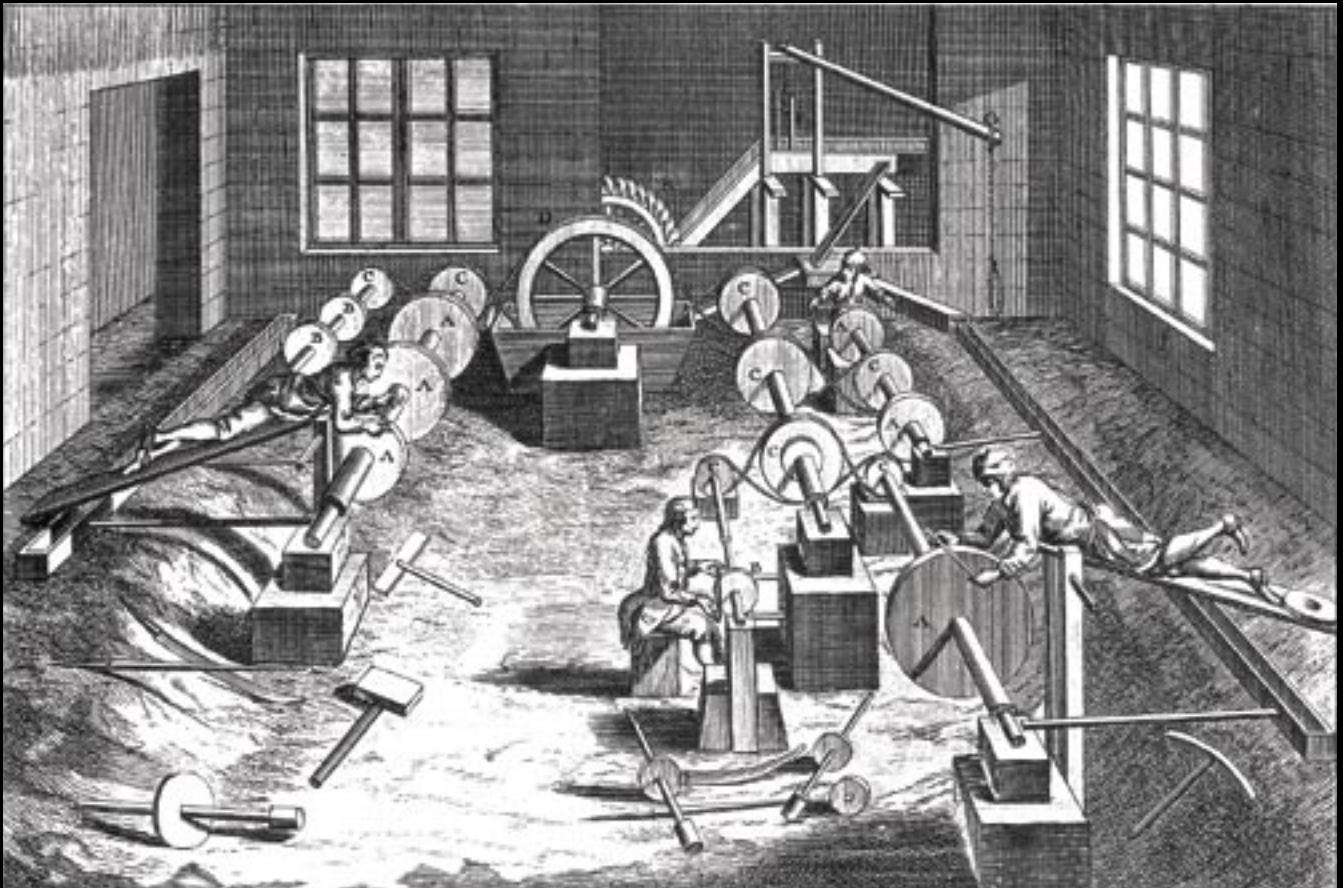
From Diderot Pictorial Encyclopaedia of Trades and Industry.

WHEEL DRESSING
AND TRUING

Preparation of the wheel prior to grinding includes truing and dressing. Truing refers to the removal of material so that the spinning wheel is round, that it runs 'true'. It may also include profiling the wheel to create a desired shape. Dressing refers to the process of creating a specific topography on the active surface of the wheel to achieve the desired grinding behaviour.
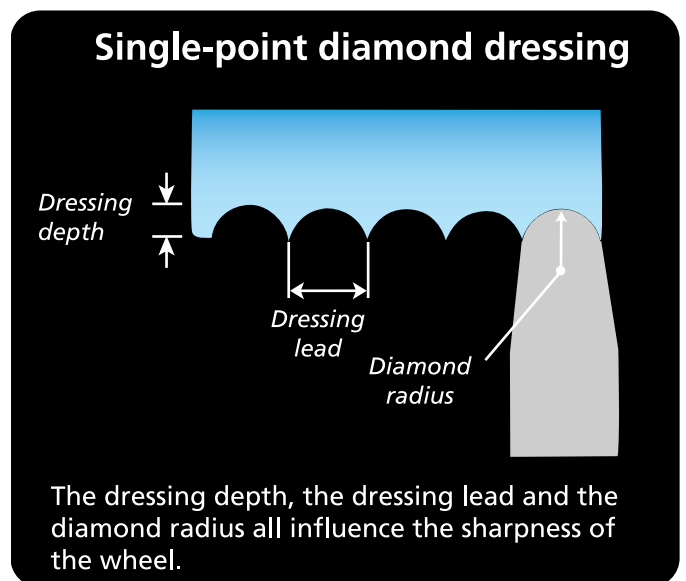
SINGLE-PONT DRESSING

For resinoid-bonded superabrasive wheels, truing and dressing are normally performed separately. In most other cases, they are performed by the same process, where it is usually referred to simply as dressing. There are several different methods for dressing. The two most common are *single-point diamond* dressing and *rotary diamond* dressing.

In *single-point diamond dressing*, the *dressing depth*, the *dressing lead* and the *diamond radius* all affect the final topography. A larger *dressing depth* and a larger *dressing lead* both create a rougher wheel surface. However, the *dressing lead* often has a more significant effect and is frequently overlooked. When used appropriately it can also create a *helix on the wheel*, which facilitates coolant flow. The dressing *diamond radius* is also important and often neglected. After repeated use, the diamond becomes dull, resulting in a larger radius. This leads to a duller wheel. Therefore, the dressing diamond should be rotated frequently to maintain sharpness. Alternatively, multi-point diamonds (blade, cluster, etc.) are often advantageous and better suited for automated production.

ROTARY-DIAMOND DRESSING

Rotary diamond dressing consists of a roll of diamond particles impregnated in a metal matrix. It is often used for generating profiles. There are numerous parameters that affect performance. They are the *dressing depth*,

Single-point diamond dressing

Dressing depth

Dressing lead

Diamond radius

The dressing depth, the dressing lead and the diamond radius all influence the sharpness of the wheel.

the *in-feed per wheel revolution*, the *dwell time* and the *speed ratio*. A larger *in-feed per revolution*, also called the *plunge speed*, produces a coarser wheel. The *dwell time* acts in the same way as a finishing pass during grinding, producing a finer wheel. The *speed ratio* is the ratio of the dresser surface speed to the grinding wheel surface speed. A positive value means that they are moving in the same direction. A value of +1 means that the velocities match, producing a *crushing effect*. Tests have shown that, in many cases, an optimum dress occurs at a speed ratio of +0.8, producing a coarse wheel.
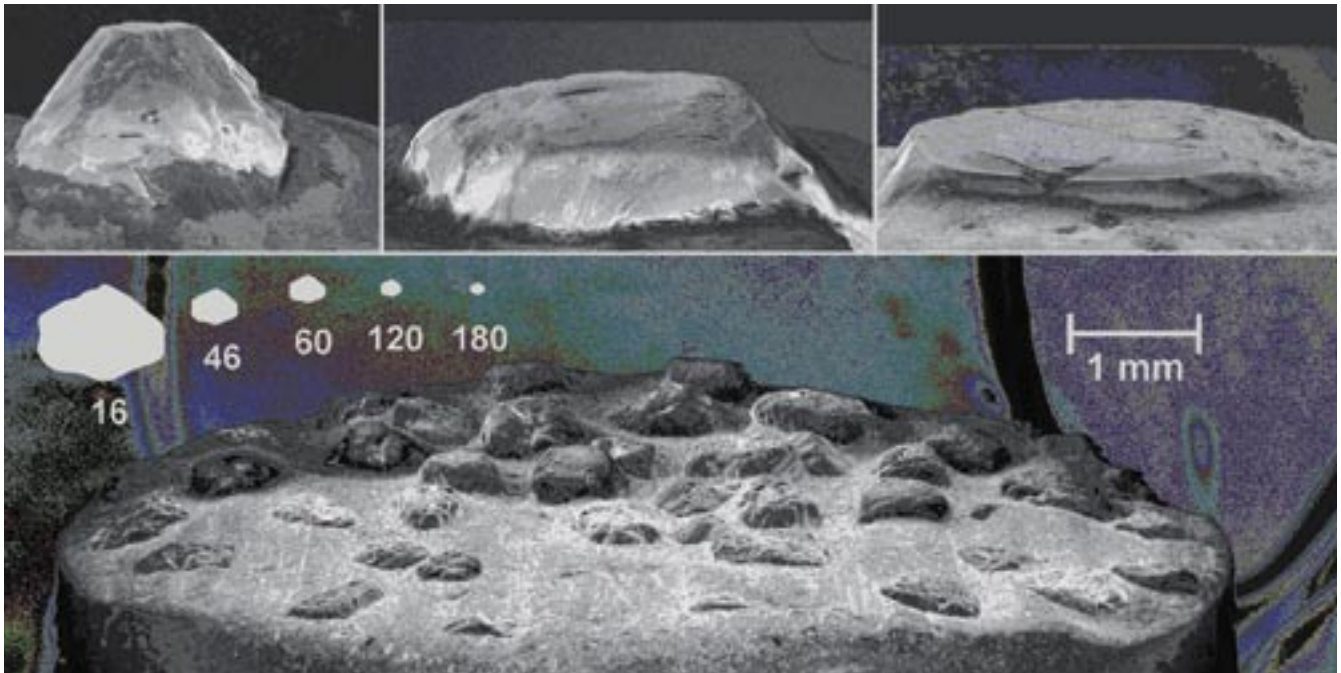
New, worn and dull single-point diamonds and a worn diamond cluster, all on same scale. Single-point diamonds that aren't rotated become flat. Notice the sizes of abrasive grits (in yellow) relative to the dull diamond. Diamond clusters do not need to be rotated and give a more consistent dress. However, a diamond cluster must traverse the wheel at a faster speed, otherwise it will dull the wheel.

$$\text{Ratio} = \frac{v_{dresser}\ (m/s)}{v_{wheel}\ (m/s)} = \frac{RPM_{dresser}\ x\ diameter_{dresser}}{RPM_{wheel}\ x\ diameter_{wheel}} = +0.8$$

Synchronous or uni-directional same direction (+)

Asynchronous or anti-directional opposite direction (−)

surface roughness

power generated

+1.0 +0.8 +0.6 +0.4 +0.2 0 −0.2 −0.4 −0.6 −0.8 −1.0
synchronous   asynchronous
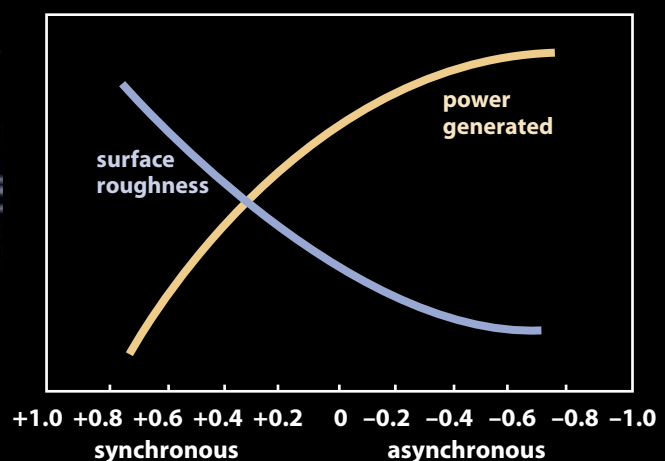
When the grits in the grinding wheel are moving in the same direction as the grits in the dressing wheel, the motion is synchronous or uni-directional. This type of dressing produces an open, sharp wheel. When they are moving in the opposite direction, the motion is asynchronous or anti-directional. The highest metal-removal rates in grinding are achieved by dressing in the synchronous mode when the dresser surface velocity is 80% of the wheel surface velocity.

WA60HV, ø=200 mm, EN31 @ 740 Rc, diamond blade, s_d=0.2 mm/rev, V_s=31 m/s, a_d=5 µm V_w=0.11 m/s, 4% sol.oil.

Dressing depth = 5 µm   **Dressing depth = 30 µm**
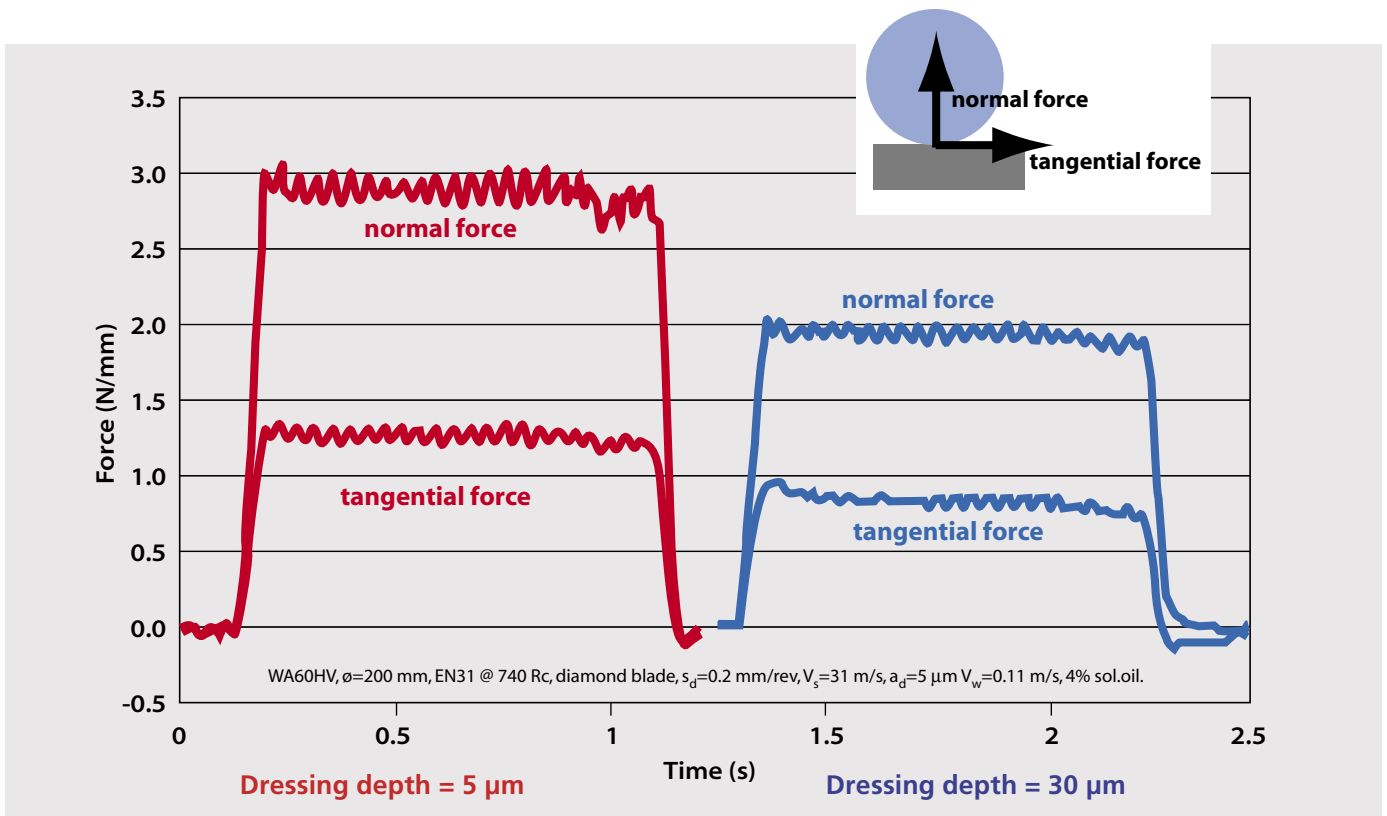
Normal and tangential forces for two different sets of single-point dressing conditions. By increasing the dressing depth from 5 µm to 30 µm, the wheel became sharper. This resulted in a 30% decrease in the normal force – meaning less risk of chatter – and a 40% decrease in the tangential force – meaning less heat generation, lower temperatures and less risk of burn. The trade-off was a rougher surface finish.

Dwell is when the rotary diamond dresser is in contact with the wheel without any in-feed. If the dwell is not long enough the wheel may not be completely true or may have a topography that is too open. If the dwell is too long the wheel may close down and become dull. A common mistake is to dwell too long. Typically 20 to 40 revolutions of the grinding wheel are enough to produce a true, open wheel in the synchronous mode; 10 to 20 revolutions in the asynchronous mode. At 3000 RPM, 20 revolutions are achieved in only 0.4 s.

Optimum results in grinding are often achieved by using different dressing parameters. For example, if the work-piece is dressed aggressively before rough grinding, then higher metal-removal rates can be achieved without increased risk of burn or chatter. Then, a fine dress can be used to close down the wheel and the last few finishing passes can be done at small depth-of-cut to produce a finer surface finish.
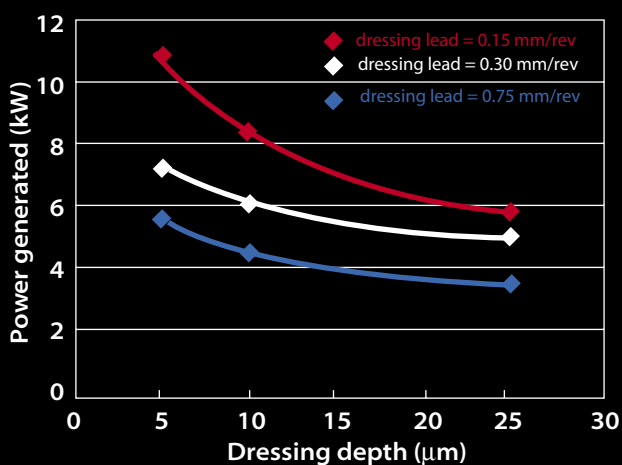
Dressing more aggressively creates a sharper, more open wheel. For single-point dressing, the dressing lead (the speed at which the diamond traverses the wheel) has a greater impact on wheel sharpness than the dressing depth. For example, when dressing with a lead of 0.15 mm per wheel revolution (red), dressing 5 µm generates 11 kW of power in grinding. Increasing the depth to 25 µm decreases the power generation to just below 6 kW, at the expense of wheel consumption. However, keeping a 5 µm dressing depth and increasing the dressing lead to 0.75 mm/rev decreases the power generation to 5.5 kW, while still keeping wheel consumption to a minimum. Since the power consumption has been cut in half, a much higher metal-removal rate can be used (either by increasing the table speed or the depth of cut) without increasing the risk of grinding burn. The trade-off is a poorer surface finish.

CUBIC BORON NITRIDE (CBN)

Cubic Boron Nitride (CBN) is much harder than aluminium oxide (hardness of 4700 vs. 2100 Knoop). Consequently, CBN wheels stay sharp longer, generate less heat and hold form better, and they can be used at higher metal-removal rates. However, they are much more expensive and have more demanding machine requirements.

Grinding wheel notation for superabrasives

500 B 91 N 100 V 78 6 40 3

Manufacturer's symbol indicating particular variety of abrasive

Abrasive type
  B cubic boron nitride (CBN),
    hardness = 4700 Knoop
  D diamond
    hardness = 7000 Knoop

Grit size

Wheel grade

Concentration (50 to 150)
  50 corresponds to a small percentage
  of abrasive grit (often around 12.5%)
  150 corresponds to a high percentage
  of abrasive grit (often around 37.5%)

Additional manufacturer-specific details about wheel

Depth of abrasive layer, in inches or mm

Manufacturer-specific notation for bond

Bond material
  V   vitrified
  B   resin
  R   rubber
  M   metal
  E   electroplated

US mesh	FEPA
30/40	B602
35/45	B502
40/50	B427
45/60	B357
50/60	B301
60/80	B252
80/100	B181
120/140	B126
140/170	B107
170/200	B91
200/230	B76
230/270	B64
270/325	B54

FACTS ABOUT CBN

1. CBN wheels cannot be dressed effectively with a single-point diamond or a diamond cluster. Rotary-style dressers are typically used.

2. CBN wheels are too expensive to be 'dressed to form'. Wheels that require a specific form must be custom-made. Consequently, in grinding operations that require many wheels to accommodate numerous different part geometries, switching to CBN can be both impractical and cost prohibitive.

3. After mounting a CBN wheel, it should be dressed 'true'. Consequently, in small-batch operations, frequent dressing leads significant wheel consumption. The exception is electroplated wheels, which can be mounted and used directly.

4. The advantage of CBN over Al_2O_3 is most pronounced on grades with low grindability.

5. CBN wheels perform better on stiff machines at high spindle speeds.

6. The life of CBN wheels can vary greatly, but is typically 20 to 2000+ times that of Al_2O_3 wheels.

7. The cost of CBN wheels can vary greatly, but is typically 20 to 100 times that of Al_2O_3 wheels.

8. Electroplated CBN wheels contain only a single layer of abrasive and do not need truing/dressing.

TECHNICAL TERMS

ANGULAR VS. BLOCKY (I)

Angular grits have high aspect ratios, penetrate at sharper angels and cut more efficiently. However, their geometry makes them more likely to fracture, resulting in greater wheel wear. Blocky grits are somewhat round-shaped and can absorb larger forces without fracturing, but cut less efficiently and are prone to dulling. Blocky grits produce a finer surface finish.
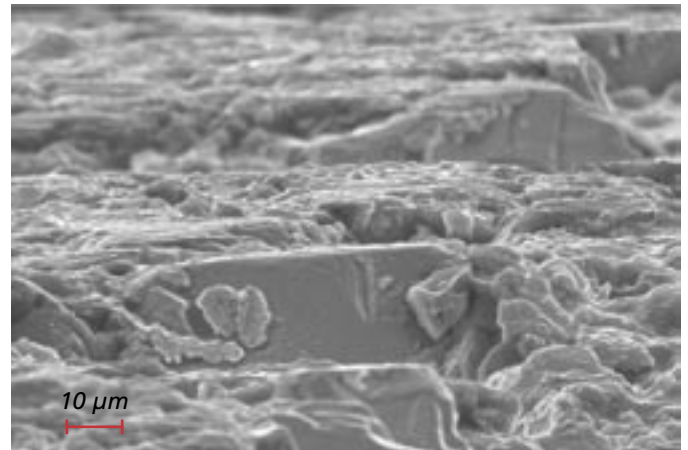
TOUGH VS. FRIABLE (II)

Tough grits can absorb large loads without fracturing, which decreases wheel wear but makes them prone to dulling. Friable (or brittle) abrasives tend to fracture, resulting in greater wheel wear yet better self-sharpening. Tough grits produce a finer surface finish.

MICRO- VS. MACRO-FRACTURE (III)

Micro-fracturing grits tend to fracture into small pieces. Macro-fracturing grits tend to fracture to large chunks.

COATINGS (IV)

Grits are sometimes coated in order to improve their retention in the bond. The coating is not used to affect cutting properties.

Power generation vs. metal-removal rate for Al_2O_3 and CBN. In most cases, CBN will generate less heat than Al_2O_3, so higher metal-removal rates can be used. However, the surface finish is often rougher, requiring smaller grit sizes with CBN.


Resin-bonded CBN wheels have almost no natural porosity. After truing, they must be 'opened up' with a dressing stick to clear away the bond material. At least two mesh sizes smaller should be used for the dressing stick. This 107-FEPA grit size resin-bonded CBN fluting wheel requires a 220-grit dressing stick [grit mesh number = 15600/ FEPA grit size (μm)].

CERAMIC ABRASIVE

Ceramic abrasive is a special type of aluminium oxide with a finer microstructure. It is often referred to as sintered, seeded-gel, sol-gel or microfracturing abrasive or by the trade name Norton/Saint-Gobain SG or 3M Cubitron.

HOW CERAMIC Al_2O_3 WORKS

Ceramic grits have a much finer microstructure than conventional Al_2O_3 grits. Instead of becoming dull – causing excessive heat generation – or fracturing into large chunks – causing excessive wheel wear – they fracture into tiny pieces, maintaining sharpness and minimizing wheel wear.
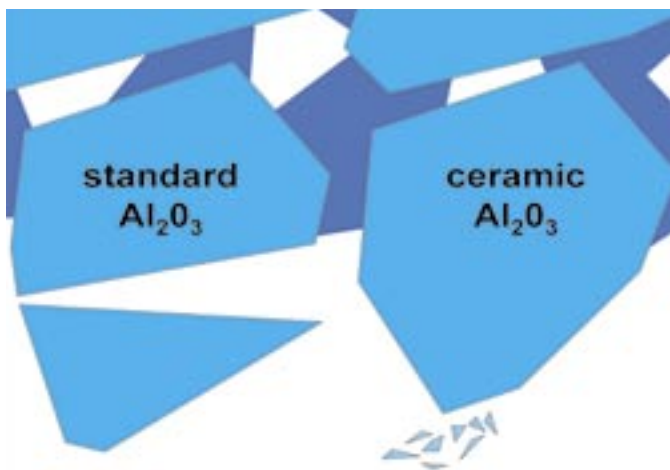

Standard Al_2O_3 grits fracture into large chunks, whereas ceramic Al_2O_3 grits fractures into tiny pieces.

HOW TO USE CERAMIC Al_2O_3 CORRECTLY

Because of their fine microstructure, ceramic grits are tough. This means that they need large forces to fracture. If the workpiece is ground too gently, the grits simply become dull and the wheel performs poorly, resulting in excessively large forces and heat generation and eventual bond fracture instead of grit fracture. In other words, the grit needs to be 'pushed hard'.

A more aggressive grind can be achieved by:

- **a higher table speed**
- **a deeper cut**
- **a slower wheel speed.**
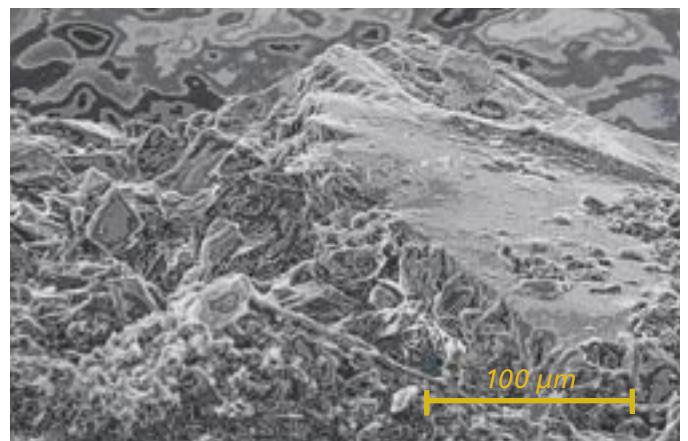
A worn ceramic grit. Notice the top of the grit, although worn, has not become dull. It has fractured into small pieces, staying sharp.

WHEN TO USE CERAMIC-GRIT WHEELS

- small-diameter fluting (under 6 mm):   **perhaps**

- medium-diameter fluting (6 – 12 mm):   **yes**

- large-diameter fluting (above 12 mm):   **definitely yes**

- single-rib threading with resin-bonded wheel: **probably**

- multi-rib threading with vitrified-bonded wheel: **probably not**

FACTS ABOUT CERAMIC-GRIT WHEELS

- Most wheels use a mixture of ceramic grit (10% - 30%) and conventional Al_2O_3.

- Wheel price is typically double to four times a conventional Al_2O_3 wheel.

- Wheel life is typically 25% to 300% longer.

- If used properly, higher metal-removal rates can be achieved.

- Most beneficial on materials with low grindability.

- Tends to produce greater wear on diamond dressing tools.

- Works better on rigid machines.
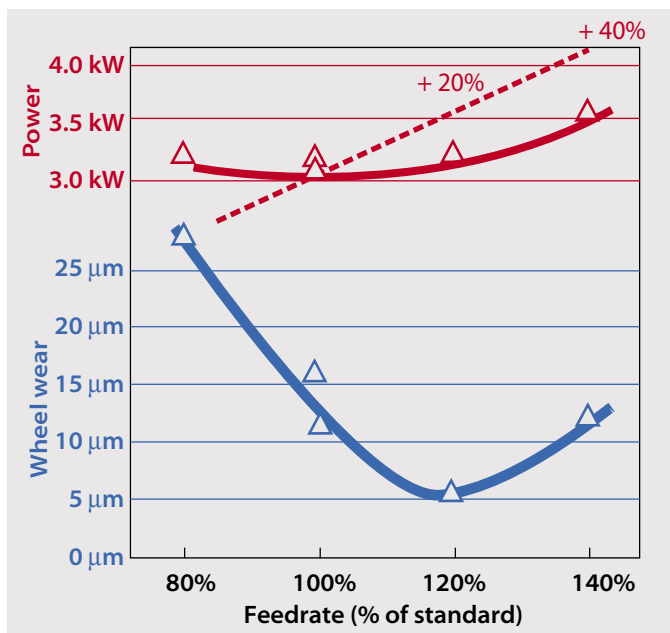
Wheel wear and power generation vs. feedrate for flute grinding of 12 mm drill in M35. As the feedrate is increased, the wheel wear decreases due to better microfracture of the ceramic grits. After a 20% increase, wheel wear begins to increase again due to excessive bond fracture. In addition, power generation does not increase proportionately to feedrate. This is due to better self-sharpening of the wheel (at 120% feedrate only a 5% increase instead of a 20% increase). At low feedrates the situation is least efficient, with excessive wheel wear and power generation. Here grinding is too 'gentle' and the wheel is dulling.
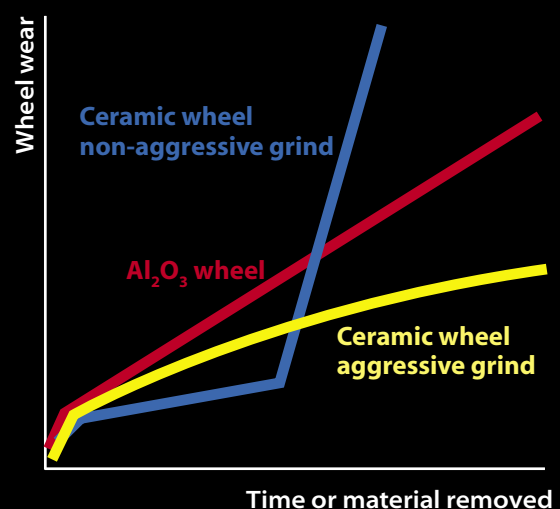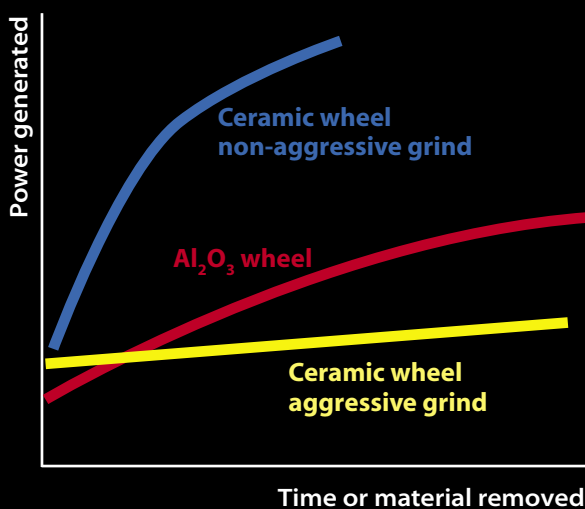
Power generation and wheel wear in ceramic-grit and conventional-grit Al_2O_3 wheels. The ceramic wheel begins with slightly higher power generation. If it is not used aggressively, the grits become dull instead of fracturing and power generation increases rapidly. The wheel also experiences rapid wear, or 'collapse' [page 10]. If the ceramic wheel is 'pushed hard', the grits will self-sharpen and power generation and wheel wear will remain low and steady, realizing the full benefit of the ceramic grits.

CUTTING FLUID

**The three primary purposes of the cutting fluid are to:**
- **Cool the workpiece**
- **Provide lubrication at the grit-workpiece interface**
- **Flush away grinding chips**

In general, *water-based emulsions* provide *good cooling but poor lubrication*, whereas *cutting oils* provide *good lubrication but poorer cooling*. Emulsions are often favoured because of health and ecological considerations.

The effectiveness of cooling depends largely on the length of the arc-of-cut. Grinding operations with a *longer arc-of-cut*, such as creep-feed grinding, have a larger contact area available for convection of heat directly to the cutting fluid. Therefore, the cutting fluid absorbs a large fraction of the heat. These operations benefit greatly from effective cooling. Operations with a *shorter arc-of-cut*, such as

outer-diameter grinding, have a smaller contact area available for convection. Thefore, the cutting fluid absorbs only a small fraction of the heat. These operations do not benefit as much from effective cooling. Here the primary benefit of the cutting fluid is lubrication.

Operations with a longer arc-of-cut benefit greatly from efficient cooling. In addition, the length of the arc-of-cut greatly affects the optimum wheel grade. A longer arc-of-cut distributes the forces over a larger contact area. This means smaller forces per grit – so a softer-graded wheel can be used.

Cylindrical grinding

Surface grinding

Creep-feed grinding

Internal grinding
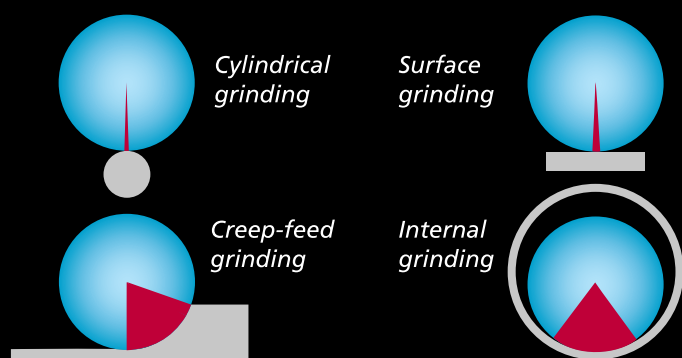
The hot-spot is the region at the wheel-workpiece interface where temperatures are highest. The effectiveness of cooling depends on the coolant breaking the *air barrier* surrounding the wheel and getting into the *hot-spot* at the contact area. This is accomplished by having a coolant velocity that approaches the surface velocity of the wheel, so the coolant penetrates the air barrier. This means that a well-aimed nozzle with a high coolant exit velocity is more important than a high coolant flowrate. Higher surface velocities require higher pressures (figure). Therefore, it is important that the coolant nozzle is well designed. It must have an orifice that is sized appropriately. An orifice opening that is too large will result in a pressure drop in the system, which leads to low exit velocities.

An alternative technique is to force coolant into the porosity of the wheel, so that the wheel drags it into the arc-of-cut at the wheel velocity. However, this can be difficult to implement and requires additional machine power to accelerate the coolant.
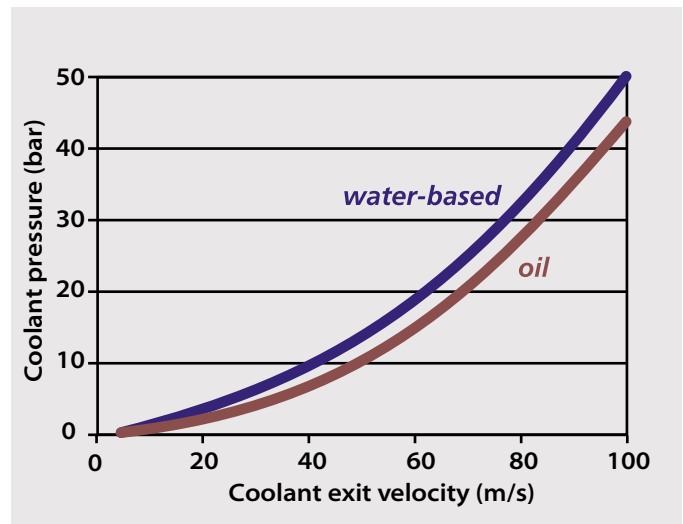
Coolant pressure versus coolant exit velocity. For effective cooling, the coolant exit velocity should match the wheel surface velocity.
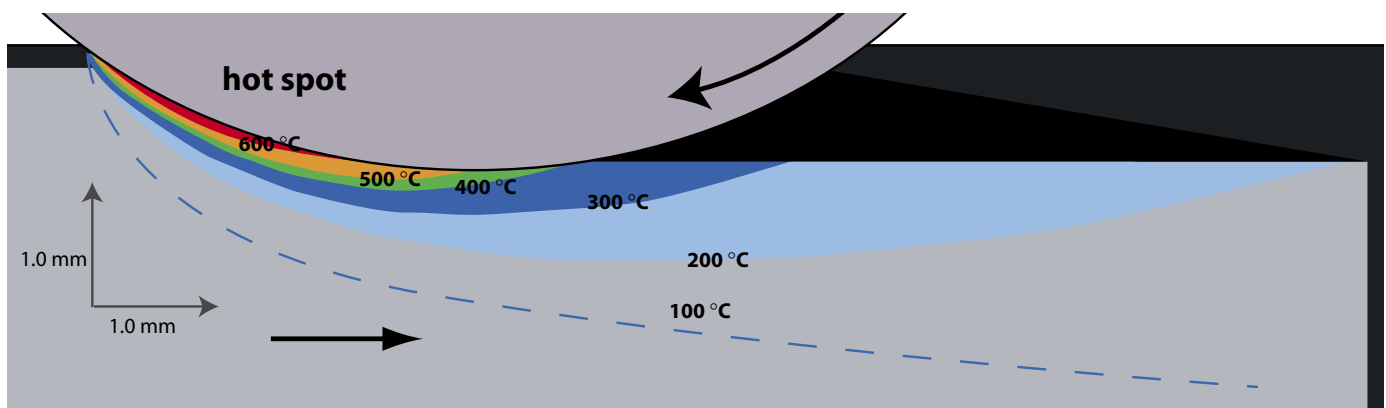
The hot-spot is the region where temperatures are highest. Effective cooling requires penetration between the grits, allowing the wheel to drag the cutting fluid to the hot-spot.
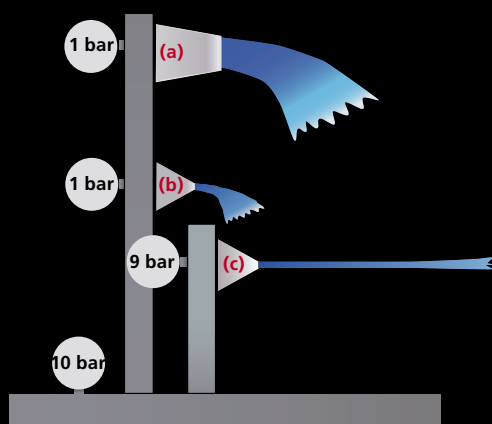
The coolant exit velocity is directly related to the pressure at the outlet. However, a large pressure drop will occur if the orifice opening is too large (a). In general, a small, well-aimed nozzle that maintains back pressure but gives low flow (c) is far superior to a large orifice that gives high flow but low pressure. However, if the small nozzle is fed off the same line as a large-orifice, high-flow outlet, it will cause a pressure drop, even if the nozzle orifice is small (b). The solution is to keep the other orifices small or to feed the small nozzle from the mains off of a separate line (c).

METAL REMOVAL RATE
AND CHIP THICKNESS

The metal removal rate, also called the stock removal rate, refers to the amount of material removed per unit time (expressed in mm³/s). Increasing the depth-of-cut, the workpiece velocity or the width-of-cut means an increased metal removal rate. In practice, the metal removal rate is increased as high as possible to achieve higher production rates.

The metal removal rate is often given per unit wheel width, and is referred to as the *specific metal removal rate* (expressed in mm³/mm/s). Increasing the *specific metal removal rate* increases the chip thickness.

The *chip thickness* is the average thickness of the chips being formed. Although the chips removed in grinding are irregularly shaped, the average chip thickness will remain relatively constant for a given set of conditions. A larger chip thickness is achieved by:

* increasing the *depth-of-cut*
* increasing the *workpiece velocity*
* decreasing the *wheel speed*

The chip thickness has an important effect on grinding and can be changed to achieve a desired result.

In general, a *larger chip thickness corresponds to*:

* **A rougher surface finish**
* **Increased wheel wear and loss of form**
* **Better self-sharpening of the wheel**
* **A lower specific energy**

The *specific energy* is the heat generated per unit volume of removed material (expressed in Joules/mm³). Grinding operations with a low specific energy act efficiently and generate less heat. Sharp wheels, with their high proportion of *cutting* and low proportion of *rubbing* and *ploughing*, produce lower *specific energies* and lower heat generation.

The power (and heat) generated during grinding is a product of the removal rate and the *specific energy*.

Power (W) = metal removal rate (mm³/s) X specific energy (J/mm³)

Therefore, the heat dissipated into the workpiece during grinding can be decreased by

(1) Decreasing the *specific metal removal rate* (a gentler grind)

(2) Decreasing the *specific energy* (with a larger chip thickness, a sharper wheel, a coarser dress, etc.)

For example, decreasing the wheel speed produces a larger chip thickness and, consequently, a lower specific energy and less heat generation. The trade-off is increased wheel wear (and self-sharpening) and a rougher surface finish. In contrast, a slower *workpiece velocity* produces a smaller chip thickness and a finer surface finish.

BURR FORMATION

Burr formation is caused by repeated ploughing (page 8), where material is continually pushed in front of the grits until a burr forms on the edge of the grinding area.

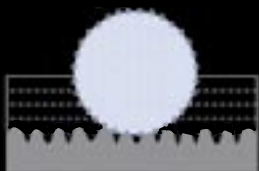Most burr simply flakes off when the tool is used. However, burr can cause premature microfracture of the cutting edge when the burr snags on the workpiece. Also, tools that are coated are particularly vulnerable when burr is present. If there is sufficient burr, the layer of coating will adhere to the burr instead of to the workpiece. When the burr flakes off, the coating also flakes off, leaving an uncoated surface at the cutting edge. In many investigations into poor tool performance, the culprit is often burr in coated tools.

A common misconception is that burr can be 'eliminated' by choosing a better grinding wheel or by changing grinding and dressing parameters. This is not true, as all grinding operations will experience some ploughing and, consequently, some burr. Even finer and finer grinding operations on adjacent sides do not eliminate burr, they simply reduce it to a negligible level. Burr can also be reduced to a negligible level by a post-grinding operation, such as blasting.

However, burr can be reduced considerably in grinding. The primary cause of excessive burr is a dull, closed wheel. By dressing more aggressively burr can be reduced. Also, grinding too gently can result in excessive burr for two reasons: first, the grits do not penetrate as deeply into the workpiece, resulting in excessive ploughing; second, the less aggressive grind results in less self-sharpening of the wheel, and the duller grits cause more ploughing. A softer-graded wheel or a more friable abrasive also help to reduce burr.

1. Dress wheel sharp, then rough grind **2. Dress wheel dull, then finish grind**

In most cases, the trade-off of reduced burr formation via coarser dressing is a rougher surface finish. One solution is to dress the wheel coarsely (large depth of and fast diamond traverse) and then remove most of the stock via rough grinding. This will give less burr, but a poorer surface. Then, finish-dress the wheel (small depth of cut and slow diamond traverse) to close it up and make it dull, and take the last few passes at low depths of cut. The result will be a smoother surface with minimal burr.

20 µm
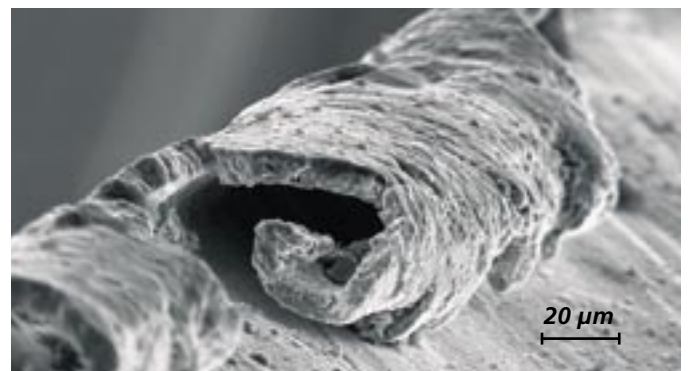
Burr.

USEFUL INFORMATION

APPROXIMATE GRIT SIZE REQUIRED TO ACHIEVE
A GIVEN SURFACE FINISH
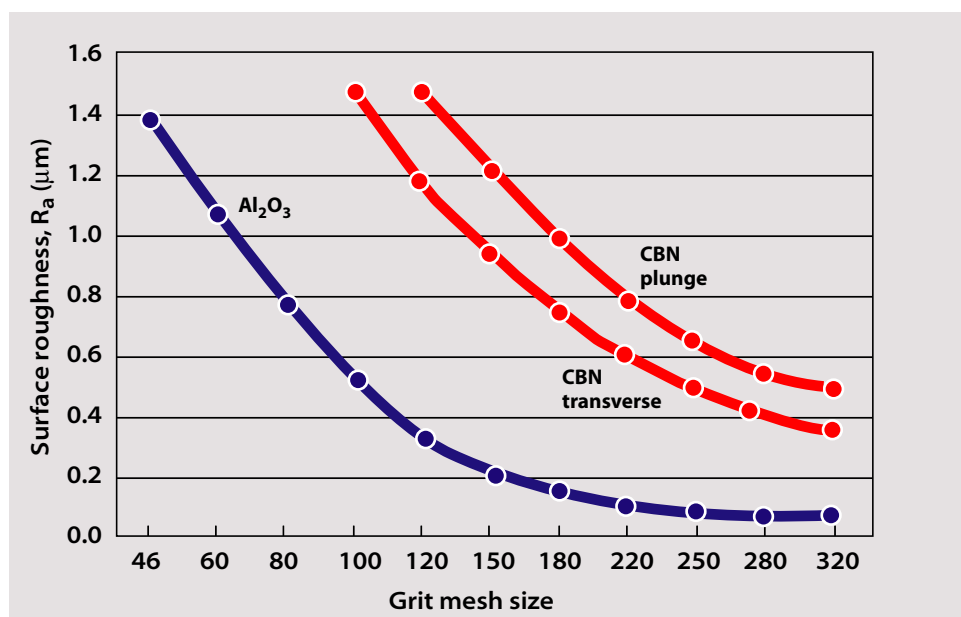
THREAD GRINDING. APPROXIMATE GRIT SIZE REQUIRED
TO ACHIEVE A GIVEN THREAD PITCH

APPROXIMATE GRIT MESH NUMBER REQUIRED TO ACHIEVE A GIVEN CORNER RADIUS, FOR CONVENTIONAL ABRASIVES

Coolant pressure

coolant pressure required at outlet

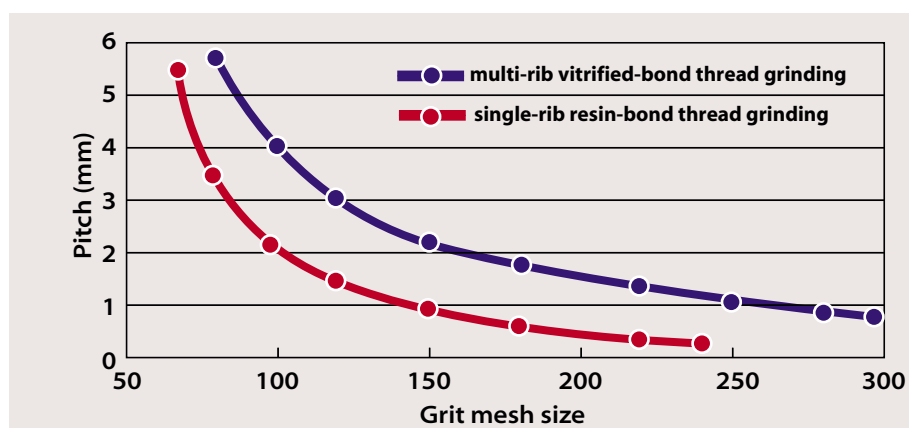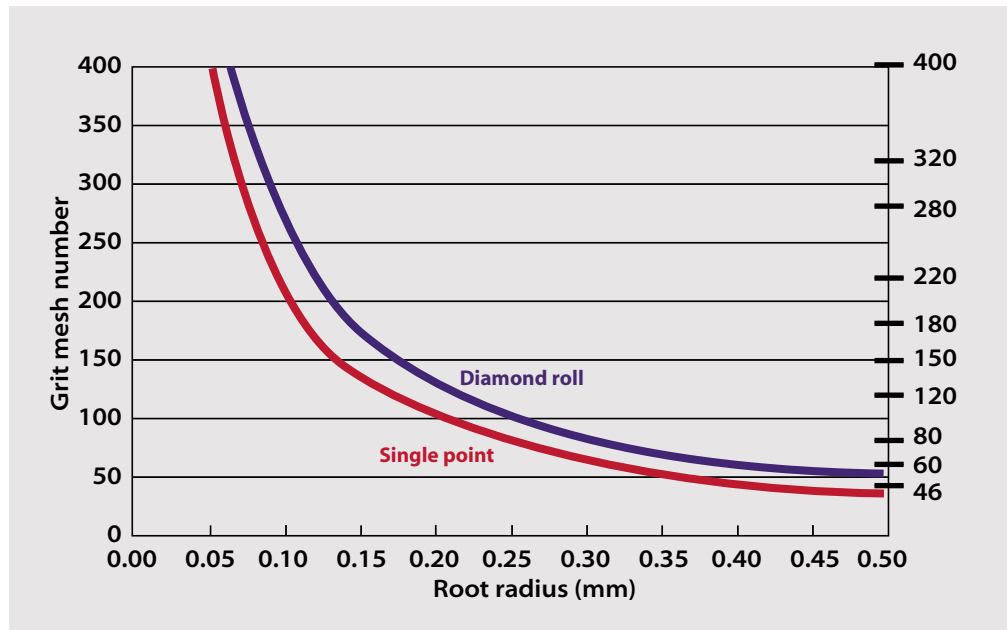| wheel speed	water-based	oil
10 m/s	0.5 bar	0.5 bar
12 m/s	0.7 bar	0.7 bar
14 m/s	1.0 bar	0.9 bar
16 m/s	1.3 bar	1.2 bar
18 m/s	1.6 bar	1.5 bar
20 m/s	2.0 bar	1.8 bar
22 m/s	2.4 bar	2.2 bar
24 m/s	2.9 bar	2.6 bar
26 m/s	3.4 bar	3.1 bar
28 m/s	3.9 bar	3.6 bar
30 m/s	4.5 bar	4.1 bar
32 m/s	5.1 bar	4.7 bar
34 m/s	5.8 bar	5.3 bar
36 m/s	6.5 bar	6.0 bar
38 m/s	7.2 bar	6.6 bar
40 m/s	8.0 bar	7.4 bar
42 m/s	8.8 bar	8.1 bar
44 m/s	9.7 bar	8.9 bar
46 m/s	10.6 bar	9.7 bar
48 m/s	11.5 bar	10.6 bar
50 m/s	12.5 bar	11.5 bar
52 m/s	13.5 bar	12.4 bar
54 m/s	14.6 bar	13.4 bar
56 m/s	15.7 bar	14.4 bar
58 m/s	16.8 bar	15.5 bar
60 m/s	18.0 bar	16.6 bar
62 m/s	19.2 bar	17.7 bar
64 m/s	20.5 bar	18.8 bar
66 m/s	21.8 bar	20.0 bar
68 m/s	23.1 bar	21.3 bar
70 m/s	24.5 bar	22.5 bar
72 m/s	25.9 bar	23.8 bar
74 m/s	27.4 bar	25.2 bar
76 m/s	28.9 bar	26.6 bar
78 m/s	30.4 bar	28.0 bar
80 m/s	32.0 bar	29.4 bar

Further reading

1. *Abrasives Magazine*. Grindability of High-Speed Steel, by J. Badger. (Dec/March 2003).
2. *Cutting Tool Engineering*. Question/Answer column 'Ask The Grinding Doc'. Ongoing.
3. Influence of the Composition and Structure of Steels on Grinding Process, by König and Messer. *Annals of CIRP*, Vol. 30, p547-552, February 1981.
4. Factors Affecting the Grindability of Highly Alloyed Steels, by L. P. Tarasov. *International Conference of Manufacturing Technology*, p.689, ASTM, 1967.
5. Some Metallurgical Aspects of Grinding, by L. P. Tarasov. *Machining – Theory and Practice*, p. 409-464, ASM, 1950.
6. On the grindability of AISI T-15 Tool Steel produced by the Consolidation of Atomized Metal Powder, by Komanduri and Shaw. p.281, Carnegie Press, Pittsburgh PA, 1975.
7. Grindability of Tool Steels, by L. P. Tarasov. *Trans. Amer. Soc. Metals*, Vol. 43, 1951.
8. *ASM Metals Handbook: Machining*. American Society for Metals.
9. *Principles of Abrasive Processing*, by M. C. Shaw. Oxford University Press, 1996

WHEEL CHOICE

A suitable choice of grinding wheel for a particular process will depend on numerous variables, such as the workpiece material, the size of the workpiece, the rigidity of the set-up, the speeds and feeds, the dressing conditions, the coolant application, the surface finish and tolerance requirements, etc.

The wheels given in the following table are based on recommendations from grinding wheel manufacturers. These recommendations should be seen as a starting point. Further optimisation should be made in collaboration with the wheel supplier, taking into account the specific characteristics of the individual grinding process. The wheel suppliers listed in the table are SlipNaxos[1], Norton[2] and Tyrolit[3].

	LOW-ALLOY (M50) (ASP 2017)	MEDIUM-ALLOY (M2) (ASP 2030)	HIGH-ALLOY (WKE 45) (ASP 2060)
Flute grinding	B91 R100 B3[1] 57A 100U B[2] M10A 802S 8 B25[3]	B91 R100 B3[1] 23A 100U B[2] M10A 802S 8 B25[3]	B91 R100 B3[1] SG 100U B[2] M10A 802S 8 B25[3]
Clearance grinding	B91 R100 B3[1] M10A 802S 8 25[3]	B91 R100 B3[1] M10A 802 S8 B25[3]	B91 R100 B3[1] M10A 802 S8 B25[3]
Thread grinding	48A 100 G VZ[1] 430A 100 G VQP[1]* 38A 100L V[2] 86A 100L V[2] 89A 1802 J2 V112[3]	48A 100 G VZ[1] 430A 100 G VQP[1]* 32A 100L V[2] 89A 1802 J2 V112[3]	48A 100 G VZ[1] 430A 100 G VQP[1]* SG or TG 100L V[2] 89A 1802 J2 V112[3]
Point grinding	B91 R100 B6[1] 57A 100U B[2]	B91 R100 B6[1] 23A 100U B[2]	B91 R100 B6[1] SG 100U B[2]
Centreless grinding	53A 60 L VZ[1] 820A 60 L VQ[1]* 57A 60L V[2] 64A 60L V[2]	53A 60 L VZ[1] 820A 60 L VQ[1]* 23A 60L V[2] 53A 60L V[2]	53A 60 L VZ[1] 820A 60 L VQ[1]* SG or SGP 60L V[2]
Cylindrical grinding	48A 54 J VZ[1] 420A 54 J VQ[1]* 99A 802 K5 V121[3]	48A 54 J VZ[1] 420A 54 J VQ[1]* 99A 802 K5 V121[3]	48A 54 J VZ[1] 420A 54 J VQ[1]* 99A 802 K5 V121[3]
Internal grinding	48A 80 J9 VZ[1] 420A 80 J9 VZ[1]* 32A 100K V[2] 32AA 100K V[2] 51B 91C 75 B75[3]	48A 80 J9 VZ[1] 420A 80 J9 VZ[1]* SG 100K V[2] 51B 91C 75 B75[3]	48A 80 J9 VZ[1] 420A 80 J9 VZ[1]* SG or TG 100K V[2] 51B 91C 75 B75[3]
Surface grinding	48A 46 G VZ[1] 420A 46 G12 VQP[1]* 53A 60J V[2] 51B 126 C50 B54 VIB[3]	48A 46 G VZ[1] 420A 46 G12 VQP[1]* 32A or 32AA 60J V[2] 51B 126 C50 B54 VIB[3]	48A 46 G VZ[1] 420A 46 G12 VQP[1]* SG or TG 60J V[2] 51B 126 C50 B54 VIB[3]

* for use with rigid machines
For some operations, wheel manufacturers have given more than one choice

[1] SlipNaxos
[2] Norton
[3] Tyrolit

TYPICAL TRENDS

(with all other parameters remaining constant)

wheel speed (faster) ↑

- wheel wear ↓↓
- temperatures/burn ↑↑
- wheel self-sharpening ↓↓
- wheel blunting ↑↑
- surface finish ↑ (gets better)
- risk of chatter ↑↑ (higher risk)

wheel speed (slower) ↓

- wheel wear ↑↑
- temperatures/burn ↓↓
- wheel self-sharpening ↑↑
- wheel blunting ↓↓
- surface finish ↓ (gets worse)
- risk of chatter ↓↓ (lower risk)

wheel grade "harder wheel" (H to J, J to L) ↑

- wheel wear ↓
- temperatures/burn ↑
- wheel self-sharpening ↓
- wheel blunting ↑
- surface finish ↑ (better)
- risk of chatter ↑ (higher risk)

wheel grade "softer wheel" (L to J, J to H) ↓

- wheel wear ↑
- temperatures/burn ↓
- wheel self-sharpening ↑
- wheel blunting ↓
- surface finish ↓ (worse)
- risk of chatter ↓ (lower risk)

grit size larger (ex: 120 to 100) ↑

- wheel wear ↓
- temperatures/burn ↓
- wheel self-sharpening ↓
- wheel blunting ↑ (usually)
- surface finish ↓ (worse)
- risk of chatter ↓ (lower risk)

grit size smaller (ex: 100 to 120) ↓

- wheel wear ↑
- temperatures/burn ↑
- wheel self-sharpening ↑
- wheel blunting ↓ (usually)
- surface finish ↑ (better)
- risk of chatter ↑ (higher risk)

wheel sharpness (sharper) ↑

- wheel wear ↑↓ (conditional)
- temperatures/burn ↓
- surface finish ↓ (worse)
- risk of chatter ↓ (lower risk)

wheel sharpness (less sharp) ↓

- wheel wear ↑↓ (conditional)
- temperatures/burn ↑
- surface finish ↑ (better)
- risk of chatter ↑ (higher risk)

- single-point dressing diamond: depth of dress (mm) ↑ → wheel sharpness ↑
- single-point dressing diamond: speed of diamond traverse (mm/rev or mm/s) ↑ → wheel sharpness ↑↑
- rotary diamond roll in-feed (mm/s or mm/rev) ↑ → wheel sharpness ↑↑
- rotary diamond roll dwell (s or revolutions) ↑ → wheel sharpness ↓
- rotary diamond disk: depth of dress (mm) ↑ → wheel sharpness ↑
- rotary diamond disk: speed of traverse (mm/rev or mm/s) ↑ → wheel sharpness ↑

TROUBLESHOOTING

Grinding is an extremely complex process with numerous interdependent variables. The table given below serves as a guide for addressing common problems that are encountered during grinding. It gives the symptom, the possible cause, and the remedy, along with comments and possible side-effects that the engineer must consider. In fact, there is often more than one cause for a particular problem, and several possible solutions.

The correct choices in grinding often involve striking a balance between parameters. For example, harder-graded wheels tend to hold form better, but run an increased risk of burning due to excessive heat generation.
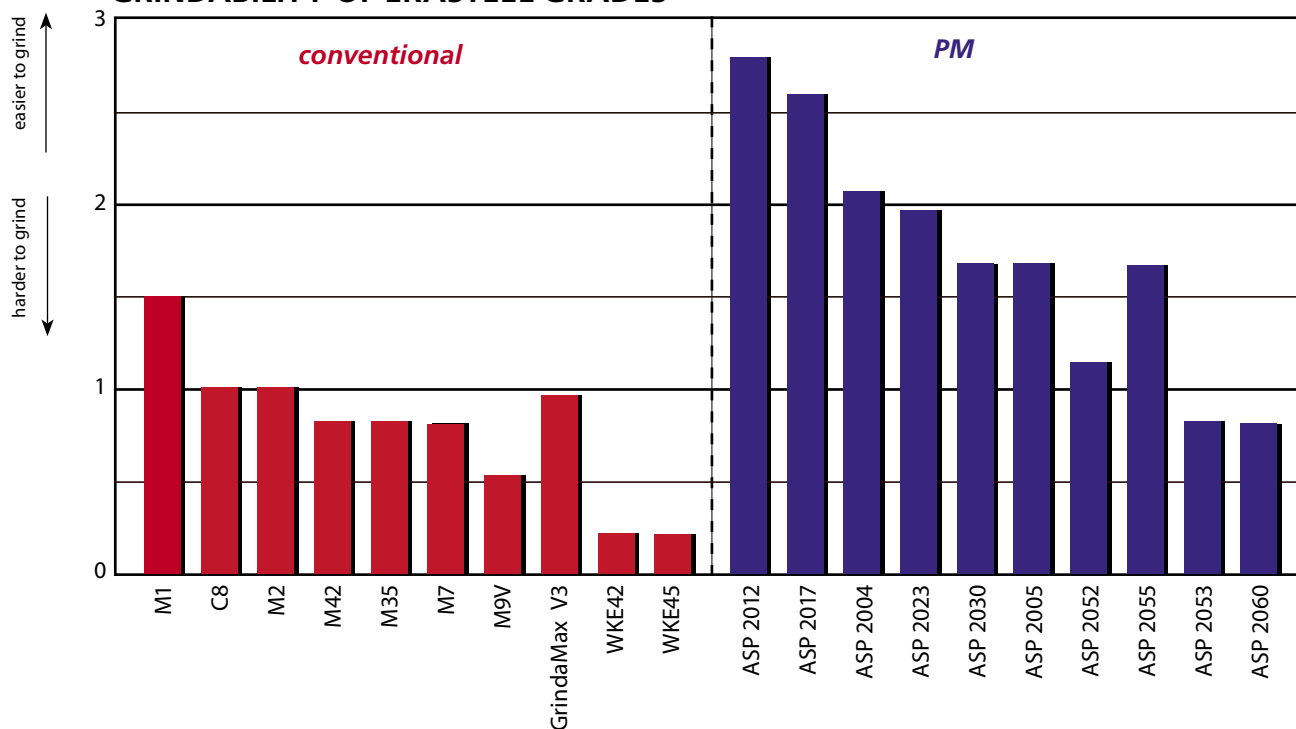

heat generated

wheel wear

| G | H | I | J | K |

WHEEL GRADE OR 'HARDNESS'
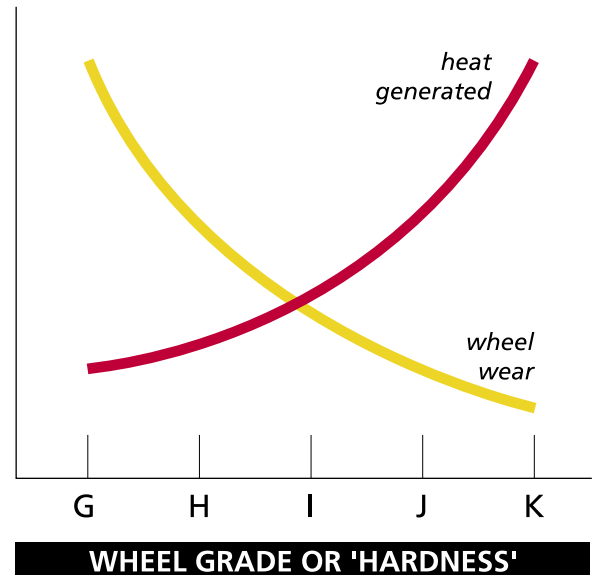
SYMPTOM	POSSIBLE CAUSE	REMEDY	COMMENTS, POSSIBLE SIDE-EFFECTS
Chatter marks, machine vibration	Worn bearings	Replace bearings.	
	Poor machine stiffness	Switch to a stiffer bearing, more rigid machine set-up, more rigid tool-holder.	
	Wheel out of balance	Balance wheel.	
	Wheel out of true	Dress wheel.	Wheel may have reached the 'collapse' stage.
	Wheel too 'hard'	Switch to a lower-graded 'softer' wheel.	Risk: Poorer surface finish, loss of form.
		Switch to a more friable abrasive.	Risk: Poorer surface finish, loss of form.
		Increase *specific metal removal rate* (particularly workpiece velocity).	Increases the chip thickness to induce self-sharpening of the wheel. Risk: Thermal damage, surface finish, loss of form, larger forces due to increased metal remove rate.
	Stock removal rate too high	Decrease the *metal removal rate.*	Smaller speeds and feeds (a 'gentler' grind) to decrease forces. Risk: Blunting of the wheel.
	Wheel surface too fine	Switch to a more open dress, rotate or change the dressing diamond.	Risk: Surface finish, loss of form.
		Switch to a larger grit size.	Risk: Surface finish, blunting of the wheel (larger grits can make the wheel act 'harder').

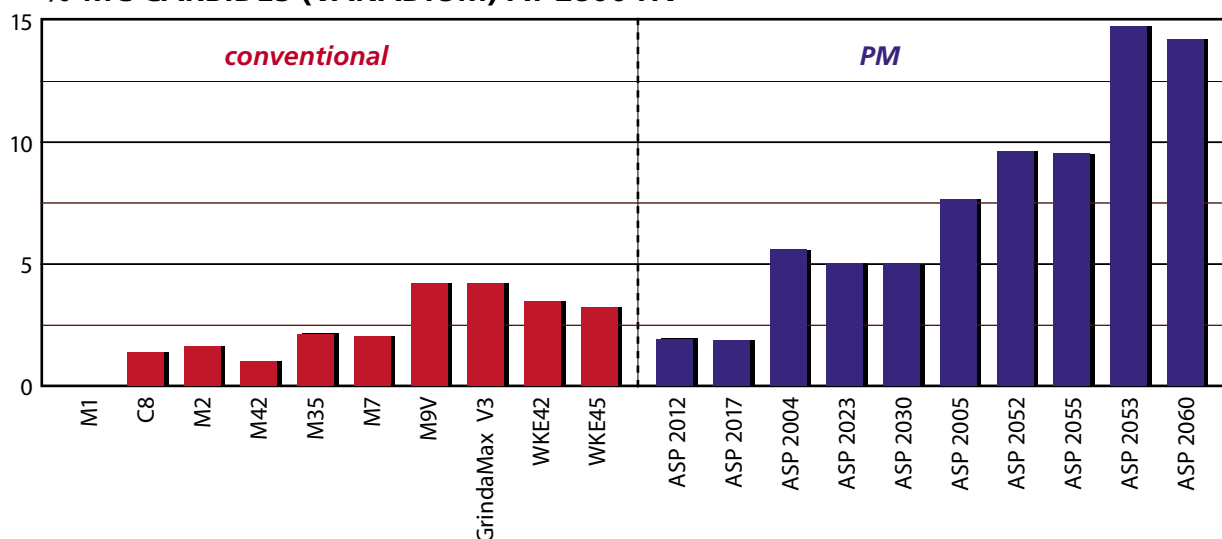| SYMPTOM	POSSIBLE CAUSE	REMEDY	COMMENTS, POSSIBLE SIDE-EFFECTS
Burning, thermal damage, stress cracking	Stock removal rate too high	Decrease the *specific metal removal rate*	Smaller speeds and feeds (a 'gentler' grind) Risk: Blunting of the wheel
	Wheel surface too fine	Switch to a more open dress, rotate or change the dressing diamond	Risk: Poorer surface finish
		Switch to a larger grit size	Risk: Poorer surface finish, minimum form radius
	Wheel too 'hard'	Switch to a lower-graded 'softer' wheel	Risk: Poorer surface finish, loss of form
		Switch to a more friable abrasive	Risk: Poorer surface finish, loss of form
		Increase *specific metal removal rate* (particularly workpiece velocity)	Increases the chip thickness to induce self-sharpening of the wheel, particularly with friable and seeded-gel abrasives Risk: Thermal damage due to excessive stock removal, poorer surface finish, loss of form
	Poor cooling	Increase coolant pressure	See section on Cutting Fluid
		Improve nozzle position	Get coolant into the *arc-of-cut hot-spot*
		Reduce nozzle orifice size	Large orifice causing pressure drop in the system and low coolant exit velocity
	Coolant too hot	Check coolant capacity, refrigeration	Higher temperatuers also mean lower viscosities for oil
Coloured burn marks on non-ground surface	Oxidation burn	Improve overall cooling, apply extra nozzle directly at coloured region	To directly cool oxidising surface and starve of oxygen Risk: Extra coolant nozzle may cause deprivation of main *arc-of-cut* cooling
Poor surface finish	Wheel too coarse	Switch to a finer dress	Risk: Thermal damage, chatter
		Switch to a smaller grit size	Risk: Thermal damage, chatter, loss of form
	Wheel too 'soft'	Switch to a higher-graded 'harder' wheel	Risk: Thermal damage, chatter
		Switch to a tougher abrasive	Risk: Thermal damage caused by poorer self-sharpening of the non-friable grits
	Chip thickness too large	Decrease the chip thickness	Chip thickness decreased by decreasing depth-of-cut or workpiece velocity, or increasing wheel speed Risk: Thermal damage caused by poorer self-sharpening of the wheel, particularly with friable and seeded-gel abrasives; larger specific energy. see section on chip thickness
Loss of form	Wheel too 'soft'	Switch to a higher-graded 'harder' wheel	Risk: Thermal damage, chatter
		Switch to a larger grit size	Larger grits make the wheel act 'harder', reducing wheel wear
		Switch to a tougher abrasive	Risk: Thermal damage caused by poor self-sharpening of the non-friable grits
		Decrease the chip thickness	Risk: Smaller chip thickness inhibits self-sharpening of the wheel, particularly with friable and seeded-gel abrasives
	Grit size too large to achieve form radius	Switch to a smaller grit size and higher-graded 'harder' wheel	Smaller grits can achieve a smaller form radius Risk: Thermal damage

Grinding of PM steel is akin to sailing in a sea of ice cubes – as opposed to a sea of ice bergs.
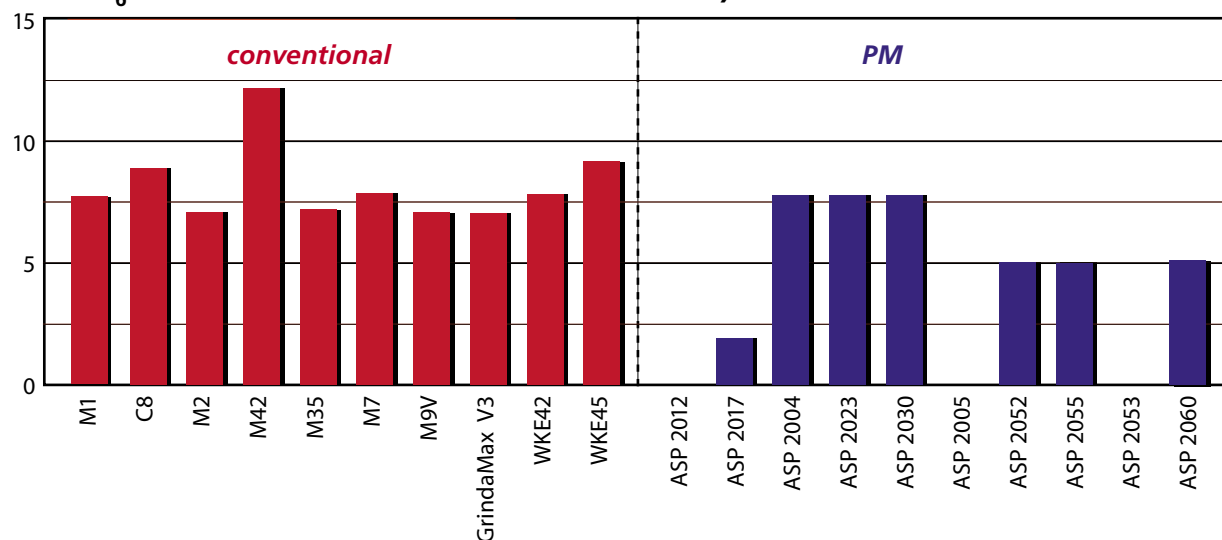
GRINDABILITY OF ERASTEEL GRADES

conventional

PM

easier to grind

harder to grind

3

2

1

0

M1 · C8 · M2 · M42 · M35 · M7 · M9V · GrindaMax V3 · WKE42 · WKE45 · ASP 2012 · ASP 2017 · ASP 2004 · ASP 2023 · ASP 2030 · ASP 2005 · ASP 2052 · ASP 2055 · ASP 2053 · ASP 2060

% MC CARBIDES (VANADIUM) AT 2800 HV

conventional

PM

15

10

5

0

M1 · C8 · M2 · M42 · M35 · M7 · M9V · GrindaMax V3 · WKE42 · WKE45 · ASP 2012 · ASP 2017 · ASP 2004 · ASP 2023 · ASP 2030 · ASP 2005 · ASP 2052 · ASP 2055 · ASP 2053 · ASP 2060

% M_6C CARBIDES TUNGSTEN-MOLYBDENUM) AT 1600 HV

conventional

PM

15

10

5

0

M1 · C8 · M2 · M42 · M35 · M7 · M9V · GrindaMax V3 · WKE42 · WKE45 · ASP 2012 · ASP 2017 · ASP 2004 · ASP 2023 · ASP 2030 · ASP 2005 · ASP 2052 · ASP 2055 · ASP 2053 · ASP 2060

Grindability ranking for grinding with conventional abrasives. Based on G-ratio tests and practical experience.
When grinding with superabrasives, the differences between grades will generally be less pronounced.

47

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