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Definition of cylindrical grinding process standard for aeronautical gears

Relatore
Prof. Luca Iuliano

Co-relatore
Ing. Ivano Moretto (GE Avio S.r.l.)

Candidato
Davide Brandino

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Introduction

Grinding is a key technology in metal manufacturing process because it can ensure required surface finish where other manufacturing process may have difficulty meeting product requirements. Grinding is applied in finishing stages of product manufacturing cycle when the value of the machined part is already significant and where mistakes can be very expensive. Besides accuracy of dimensions and surface finish, grinding also influences physical layer properties such as residual stress, hardness and microstructure during the material removal process leading to high risk of a thermal damage of the part surface layer.

Grinding is a high-added value manufacturing process. In today's global manufacturer competition, companies that deliver high value in manufacturing have strong financial performance also because of their high quality recognition.

However they must constantly improve their performances first of all in terms of quality and delivering time to maintain leadership in their business.

This becomes possible only innovating, inventing, investing in Research and Development and last but not least investing in people knowledge.

This thesis has been developed in collaboration with Avio Aero, Global Supply Chain in Rivalta plant.

Avio Aero is a GE Aviation business that designs, manufactures and maintains components and systems for mechanical transmissions, turbines and combustors.

Through continuous investment in research and development and a consolidated network of relationships with major Universities and international Research Centers, Avio Aero has developed a technological and manufacturing excellence globally acknowledged.

The aim of this thesis was to define a cylindrical grinding process standard for aeronautical gears in particular for grinding of case hardened steel bearing race.

The study has been conducted mainly on four phases, that means my gradual growth in "grindology".

The first was a deepened study of grinding process and in the meantime the knowing of aeronautical product in particular gears, the second was a meticulous data collection of current grinding process from the company, the third was a careful analysis of gathered data, and the fourth was a multiple approach to improve the current process looking at the grinding in itself but also at the technologists needs, supporting them in the grinding parameters definition.

This Thesis is divided in 8 sections. The first Chapter explores from literature all the aspects of the grinding process, including chips formation theory, grinding methods, abrasive wheels and dressing, damages due to grinding abuses.

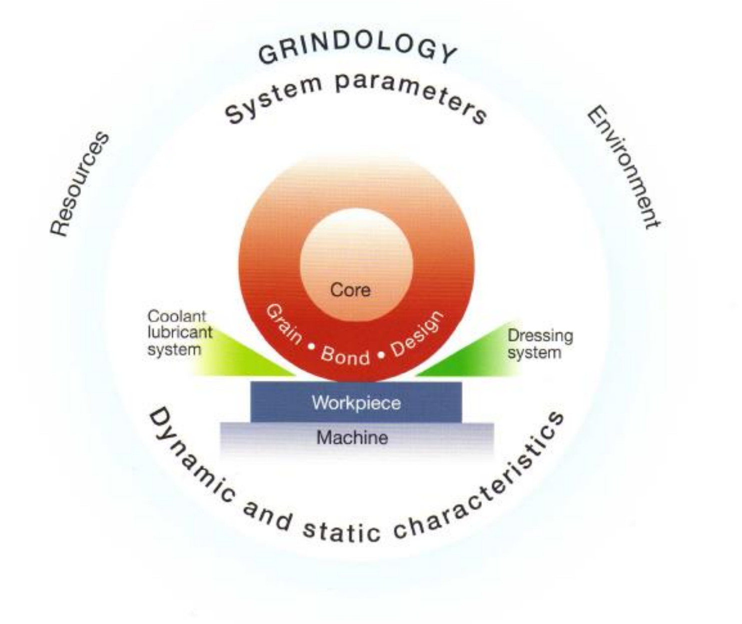
The second Chapter shows all process control methods to detect grinding abuses.

The third Chapter introduces cylindrical grinding application to aeronautical gearshafts with case hardened steel bearing race. Chapter 4 aims to gather all process data relevant to the above gearshafts from the Company's Product Data Management (PDM). Chapter 5 carefully analyzes current process, using correlations between input and control parameters. This analysis shows in several ways with aggregated data an uneven current process. Thus, the need of a process standard definition. This chapter outlines also the power model, that is a new control parameter to strengthen process control. Chapter 6 is crucial for optimizing the grinding process by means of two spreadsheet tools. The first one is a sort of driven choice to avoid unsafe grinding input parameters, the second is a decision-making solver that gives as a result the grinding input parameters in order to maximize productivity within limits to ensure workpiece integrity.

I wrote this tool in excel using Excel Solver VBA putting as decision variables feed rate and workpiece speed, as constraint variables the depth of cut, the speed ratio, the aggressiveness and the chip thickness and as a target the productivity indicator Qw'.

Chapter 7, as further improving step, includes the drawing up of a grinding test plan (DOE) to be developed within a research project in collaboration with a University or a technology development center. The preliminary DOE plan is enclosed in this Thesis.

Finally, in Chapter 8 there are some considerations on the benefits achievable applying the process standard defined in this Thesis.



1. The grinding process

The use of abrasives for shaping goes back to more than 2000 years. Abrasive stones were used for sharpening early knives, tools, and weapons. From early times, abrasives have been used to cut and shape rocks and stones for construction of buildings and edifices such as the pyramids. Abrasives were also used for cutting and polishing gems. Abrasives continue to be used in increasingly various applications today, and much of modern mechanical parts relies on the abrasives industry for its manufacturing. Even in the early days grinding was a finishing process applied to products approaching the most valuable stage in their production.

Grinding was developed as a metal manufacturing process in the 19th century and it played an important role in the development of tools, in the production of steam engines, internal combustion engines, bearings, transmissions, and ultimately jet engines, astronomical instruments, and micro-electronic components.

The term grinding is used in modern manufacturing practice to describe machining with high-speed abrasive wheels, pads and belts. Grinding wheels come in a wide variety of shapes, sizes, and types of abrasive.

In the second half of the 20th century, it was recognised grinding as a strategic process for high-technology applications. It was realized, for example, by manufacturers of aero-engines and missile guidance systems that grinding was the key to achieve the necessary quality. This caused a rapid development in the last part of the 20th century. Modern technology has also seen a trend towards hard ceramic materials that bring new challenges for manufacturing.

Abrasive processes are the natural choice for machining very hard materials. It is a general rule that the tool used for machining should be harder than the material being machined. Suitable abrasives to grind hardened steels and aerospace alloys include aluminium oxide, silicon carbide, and cubic boron nitride. A diamond abrasive is used to grind hardened ceramics. Hard ceramics are difficult to machine because they are not only very hard but also brittle. Grinding is well suited to coping with the challenges presented by new engineering materials such as silicon nitride.

In recent decades, grinding has been evolved both for producing very high quality parts and for fast economic production. Owing to modern developments, grinding has a large role in efficient manufacturing industry in terms of both volume and value. This allows to get high removal rate jointly with high accuracy.

In particular, grinding allows high accuracy to be achieved and close tolerances can be held for size, shape, and surface texture. Roughness can be reduced down to mirror finishes and optical quality of flatness. The achievement of this quality depends on the roughness of the abrasive, the quality of the grinding machine, and the removal rates applied.

Grinding can carefully ensure good quality where other processes may have difficulty meeting specifications. Quality is a term that includes all aspects required for parts to operate correctly. Accuracy of dimensions and surface finish are obvious aspects of quality. The integrity of the material at the machined surfaces is vitally important. For instance, the ground surface of a hardened part shall not be softened or cracked. It may also be important to avoid tensile residual stress that reduces strength and shortens service life. All the aspects of quality require careful design and control of the grinding process, that's the reason of cut-up studies.

The speed of manufacturing process depends on the material being machined and the accuracy required. Alternatives processes such as hard turning may be feasible in some cases, but often grinding is the least expensive process to achieve the quality and productivity required.

Grinding is usually done towards the end of product manufacturing when the value of the part is already significant and where mistakes can be expensive. As illustrated in Fig. 1, the product gains value thru the completion of production cycle. The increase in cost and lead time with the number of operations is not linear but exponential. Grinding operations tend to govern the accuracy of the parts produced and are often the key to the required quality.

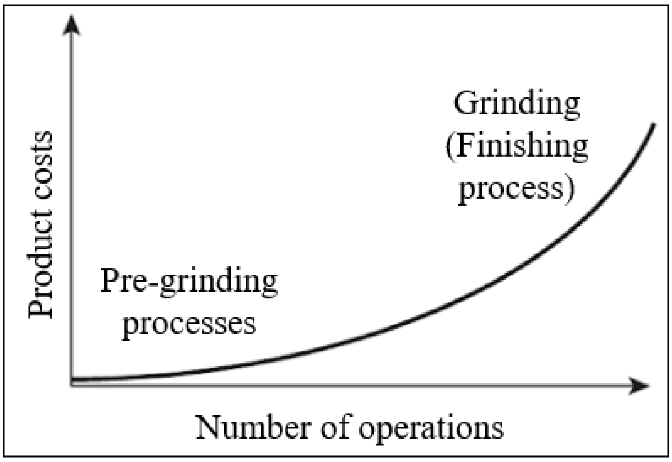


Fig. 1 Product cumulated cost trendline

1.1. The cutting in grinding process

How does the grinding work? Grinding is a process of material removal where the abrasive grains act as tools, while the grinding wheel binder serves as a tool holder. Like milling and turning, grinding is a chip removal process. However, the chips produced are extremely small and the cutting edges are numerous, of irregular geometry, characterized by negative cutting angles and having "self-sharpening" ability.

In the abrasive-to-piece interface during grinding, there are three primary interactions: sliding, displacement and cutting.
The cutting is the formation of chips (Fig. 2) on the sides of the abrasive grain.

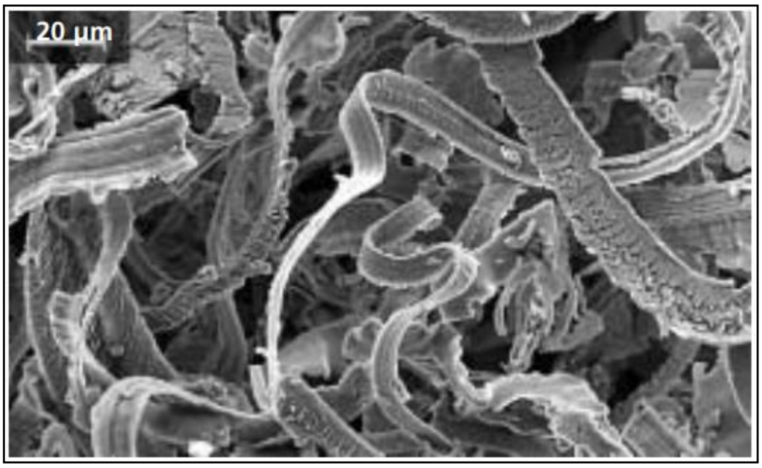


Fig. 2 Grinding chips (zoom 1000X)

The displacement and the sliding of material on the front and on the side of the single abrasive grain don't cause removal of material but contribute to chip formation.
During grinding all the three interactions (Fig. 3) mentioned above occur, but in a variable way in three times. At the beginning the abrasive grain slides the superficial material, then the ridge formation begins and at the end the chip is detached from the workpiece. This sequence is repeated and multiplied in a unit of time by the multitude of abrasive grains in a continuous flowing process.

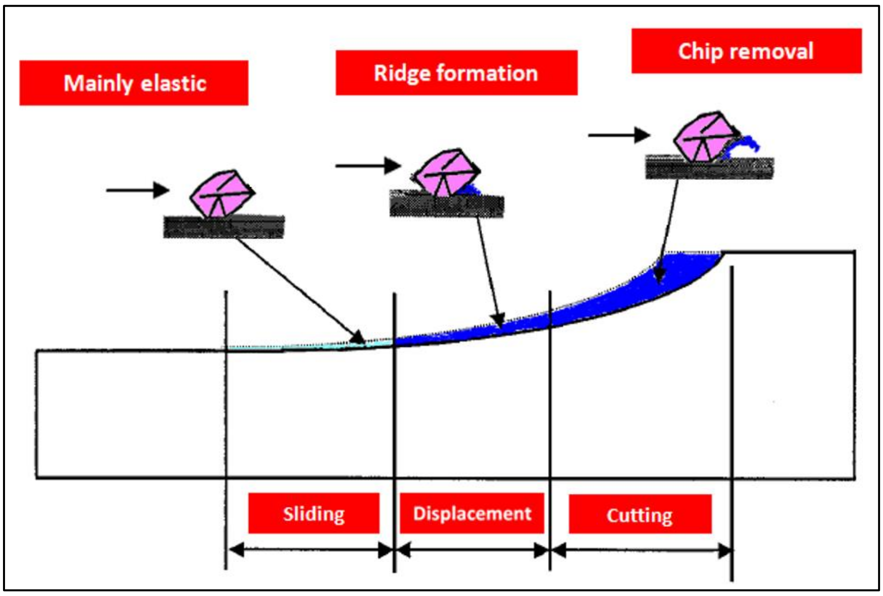


Fig. 3 Grinding interactions: sliding, displacement and cutting

A sharp cutting wheel operates efficiently and gives a prevailing cutting action causing less heat. A non-cutting grinding wheel operates in a non-efficient way with a higher displacing and sliding action, thus causing more heat.

It is important to know the parameters that have influence in the grinding process, as well as choosing the appropriate grinding wheel. It is very important to understand the grinding process in detail in order to optimize the result. Chip formation determines whether the grinding process is efficient or inefficient. Therefore, it is extremely important to know how to control the grinding process.

The selection of the grinding wheel depends on the material properties of the part to be machined and on the surface roughness requirement. The characteristics of the grinding wheel include the type of abrasive, the size of the grain, the hardness grade and the structure of the grinding wheel. The number of sharp edges, their distribution and the ability to self-dress the grains have a decisive influence on the removal capability and on the efficiency of the wheel.

The heat production in grinding process is one of the K-factors: a better grinding process implies a good control of temperature, if you consider that a temperature up to 1800 degrees can be reached on the cutting edges, higher than that of casting steel, you can easily imagine the stress suffered by the grain and the workpiece (Fig. 4).

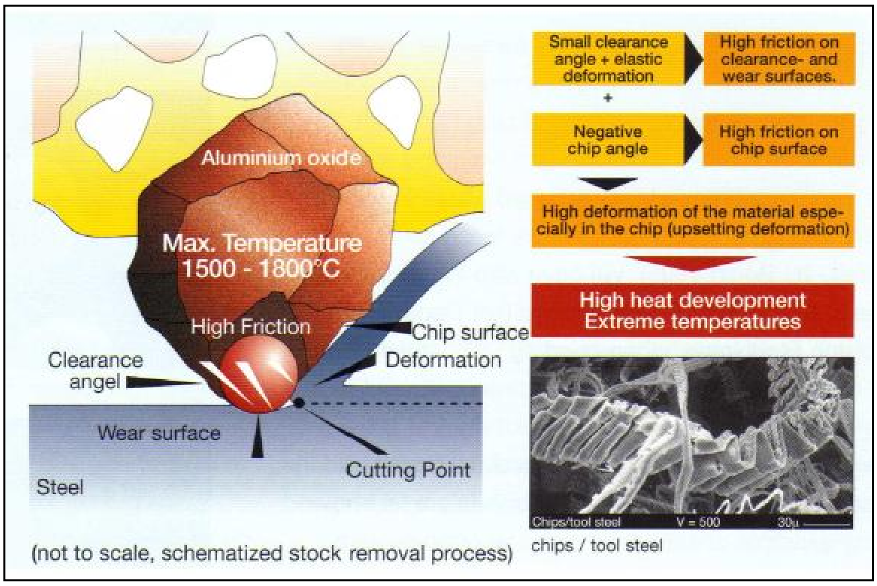


Fig. 4 High temperature generated during the grinding process

This phenomenon takes place several times per second for each revolution of the grinding wheel, which means heating up to 1800 degrees and cooling to room temperature for each cycle. Friction is generated during digging and rubbing, where the workpiece surface is deformed without chip formation. As a result, the surface of the piece becomes tender and the edges of the grain are covered with metal.

Furthermore, the surface of the piece can oxidize. The grains coated with metal no longer have sharp edges and generate additional heat, since they cannot longer form chips in the contact area. The outside of the grinding wheel becomes clogged with metal and results "kneaded" according to the most common definition. Under these conditions the grinding wheel can continue to work well only if it has been dressed. To obtain optimized grinding chips, the generated heat shall be within process limits. This is made possible by varying the grinding parameters that affect chip formation (Fig. 5).

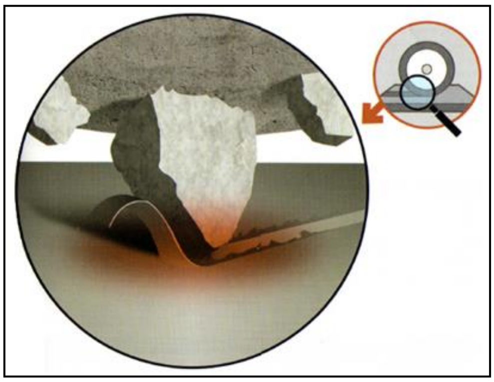


Fig. 5 Chip formation

Grinding machining parameters could be classified in independent parameters (Tab. 1) and calculated parameters (Tab. 2).
This chapter includes an explanation of each grinding parameter.

INDEPENDENT PARAMETERS		
PARAMETER	SYMBOLOGY	UNIT MEASURE
Peripheral wheel speed	Vc	m/s
Peripheral workpiece speed	Vw	m/s
Depth of cut	Feed/rev	mm/rev

Tab. 1 Independent working parameters

Independent parameters are the input parameters such as the peripheral wheel speed, the peripheral workpiece speed and the depth of cut.
First of all, the chips formation depends on the abrasive grit number (mesh) and the peripheral speeds, therefore if you consider a grinding wheel with a certain mesh, the chip size can be changed by varying the grinding parameters. One of these, the peripheral wheel speed (Vc), has a very important influence on the dynamic hardness. The dynamic hardness is the result of the measurement of the chips produced. With smaller peripheral wheel speed, larger chips are obtained, on the contrary higher peripheral wheel speed produces smaller chips. As a result, large chips produce higher pressures on the wheel grain, so the grinding wheel is consumed rapidly and has a

tender action. On the opposite, smaller chips generate less pressure on the grain and the grinding wheel is consumed less quickly and has a harsh action.
The interaction between wheel grain and the chips determines the behaviour of the grinding wheel. Big chips increase grain crushing, small chips reduce grain crushing.
Explanation of this parameters interaction is shown in Fig. 6.

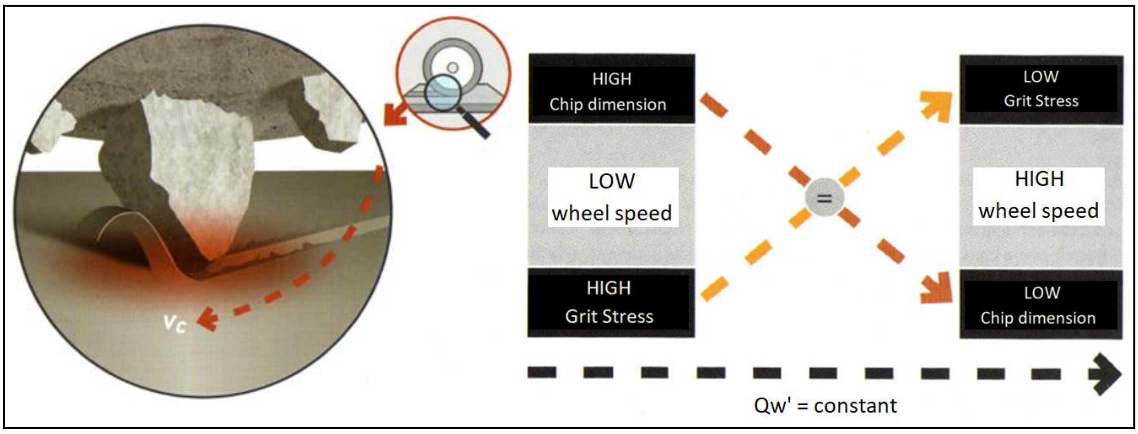


Fig. 6 Wheel cutting phenomenon and properties

Next parameter is the peripheral workpiece speed (Vw), see Fig. 7.
The formation of the chips has highly dependence to the workpiece speed (Vw) because it influences the efficiency of the grinding wheel and the depth of cut. For a certain feed rate [mm/min] high Vw produces smaller chips because of a smaller depth of cut and the grinding wheel has a hard behaviour, while low workpiece speed produces larger chips and the grinding wheel has a soft behaviour with the risk to burn the part.

$$\text{Depth of cut [mm/rev]} = \frac{\text{Feed rate [mm/min]}}{\text{RPM workpiece [rev/min]}}$$

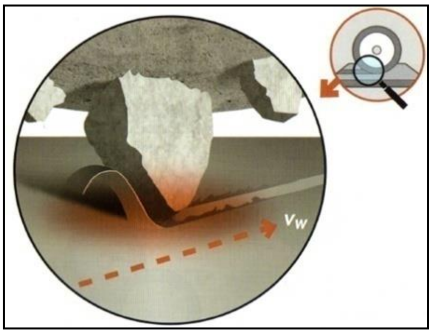


Fig. 7 Workpiece peripheral speed

The feed rate can be calculated as follows:

$$\text{Feed rate [mm/min]} = \text{RPM workpiece [rev/min]} \times \text{depth of cut [mm/rev]}$$

The material removed per workpiece revolution defines the depth of cut or penetration of the grinding wheel in the workpiece. According to the Fig. 8 the variation of the depth of cut is similar on both plane and cylindrical grinding process.

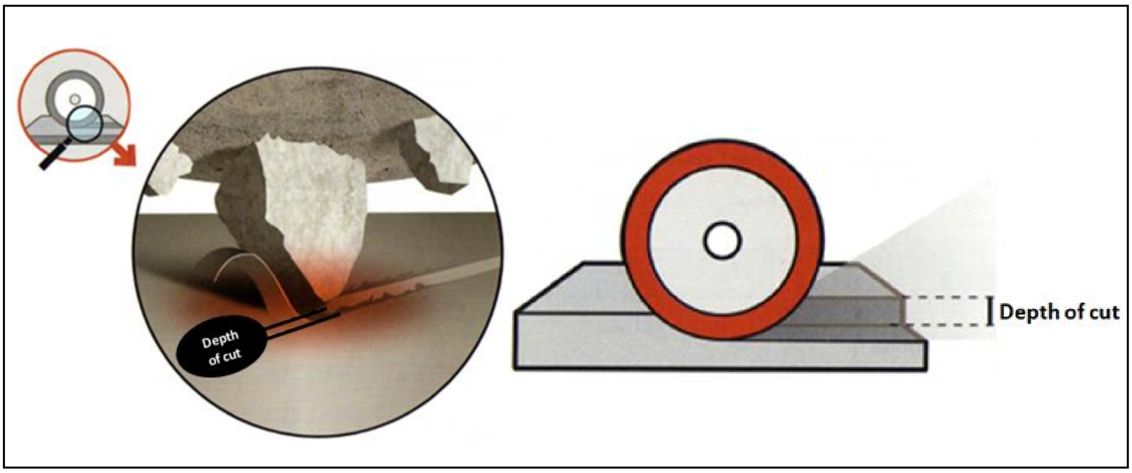


Fig. 8 Depth of cut

For very high depth of cut values (more than 0,1 mm) the grinding is defined as "creep-feed" grinding. This is the typical depth of cut for CBN grinding wheel and obviously affects the characteristic of the chips.
Some useful indicators are the following calculated parameters: the speed ratio (q) and the Specific Material Removal Rate (Qw'). See Tab. 2.

CALCULATED PARAMETERS		
PARAMETER	SYMBOLOGY	UNIT MEASURE
Speed ratio	q	-
Specific Material Removal Rate	Qw'	mm3/s*mm
G ratio	G	-

Tab. 2 Calculated machining parameters

The actual chip size is estimated between 1-2,5 µm for roughing and < 1 µm for finishing. More than the actual size of the chips, it is important to understand the effects produced in the efficiency of the grinding wheel by changing the above calculated parameters.
The speed ratio "q" is the relationship between the peripheral speeds of the grinding wheel and the workpiece. It's calculated as follows:

$$q = \frac{Vc\ [m/s]}{Vw\ [m/s]}$$

The q value has a strong correlation with the workpiece surface roughness.
Fig. 9 clearly shows how, by increasing the q value, the roughness channels produced by the abrasive grains are getting closer and closer.
The R_t parameter in Fig. 9 is the height of the single "tallest" peak to the depth of the "deepest" valley in a surface trace. While the b_k is the active cutting length of the grit abrasive.

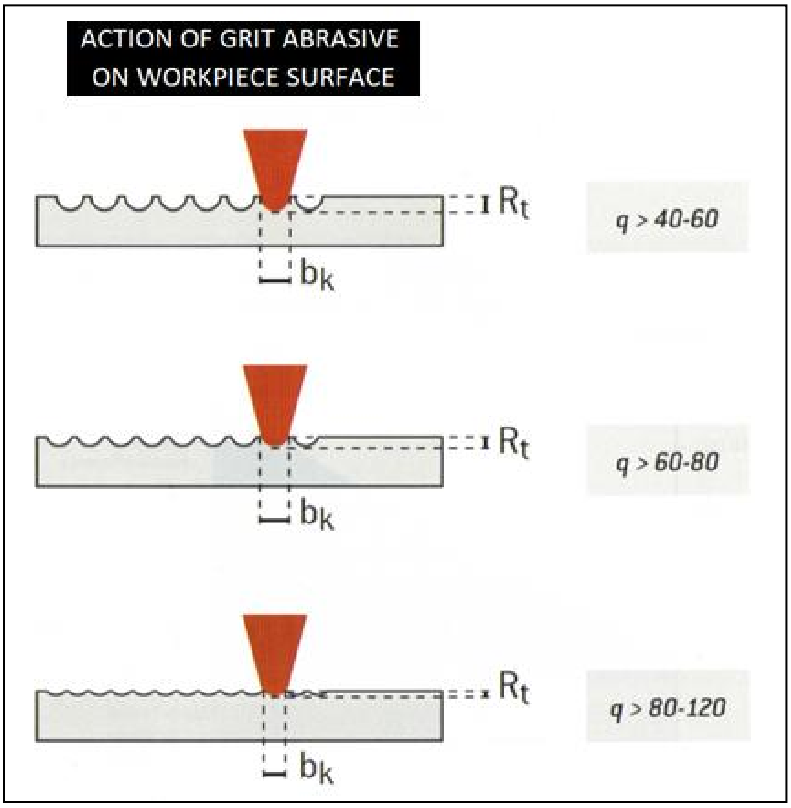


Fig. 9 Action of abrasive grain on workpiece surface

Consequently different speed ratio is recommended for rough, semi-finish and finish grinding. Recommended values of the speed ratio (q) are included in Tab. 3.

Speed ratio (q)		
Roughing	Semi-finishing	Finishing
40-60	60-80	80-120

Tab. 3 Speed ratio reference values

There are limits on the q value.
For conventional grinding the safe values are below 200. Highest q values are allowed only with advanced process such as High Efficiency Deep Grinding (HEDG).

The specific material removal rate (Qw') is a productivity indicator of the grinding process. This is the volume of material per unit width of wheel contact removed each unit of time.

$$Qw' \left[\frac{\text{mm}^2}{sec}\right] = a_e \times v_w = a_e \times \frac{RPM_w \times \pi \times \text{Ø}_\text{w}}{60} = \frac{\pi \times \text{Ø}_\text{w} \times Feed\ rate}{60}$$

The increase of Qw’ may result in faster consumption of the grinding wheel. A cost trade-off between productivity and tool wear is one of the keys to optimize removal rate parameter. High removal rate can significantly reduce the cost of the process, even in the presence of higher wheel consumption.

Workpiece speed can vary within the limits shown in Fig. 10 with respect to depth of cut limits depending on grinding process type; it is clearly highlighted the thermal damage area where no grinding process is available without risk of burn.

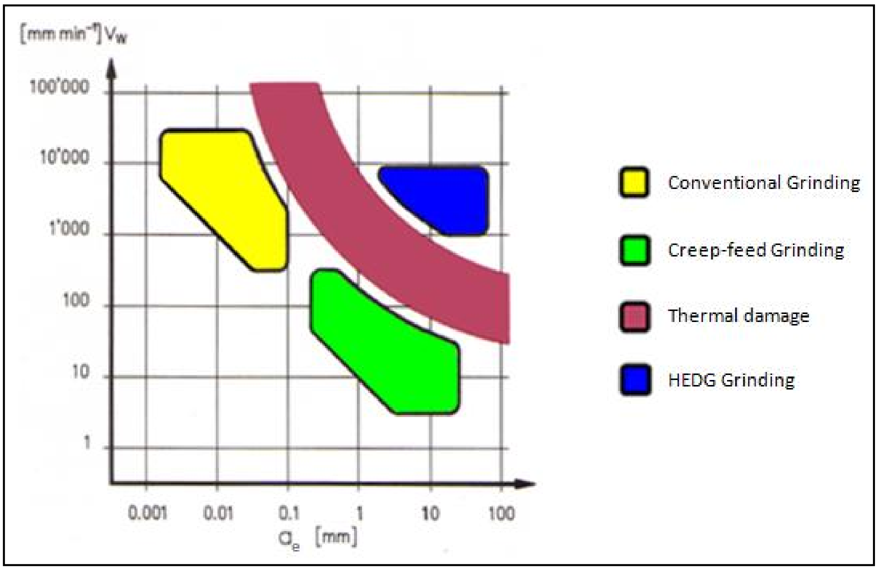


Fig. 10 Workpiece speed and depth of cut limits

Grinding wheel life is a very important aspect in the grinding process. The G ratio measures the grinding wheel wear.

It is equal to:

$$G = \frac{\text{Volume of workpiece material removed}}{\text{Volume of wheel consumed}}$$

The G factor is the ratio between the volume of the removed material and the consumed volume of the grinding wheel. High values of the G ratio indicate long-lasting wheels. Low values of the G ratio are related to short life grinding wheels.

Compared to conventional wheels, diamond and CBN wheels have very high G factors.

Generally conventional wheels have a G ratio minor than 1, while CBN and diamond wheels have 100000.

INFLUENCE OF GRINDING PARAMETERS ON ACHIEVED RESULTS										
	↑Vw	↓Vw	↑Vc	↓Vc	↑Feed	↓Feed	↑wheelØ	↓wheelØ	Coolant	Dry
Chip size	↑	↓	↓	↑	↑	↓	≈	≈	≈	≈
Grit stress	↑	↓	↓	↑	↑	↓	↓	↑	↓	↑
Feed rate	↑	↓	≈	≈	↑	↓	≈	≈	≈	≈

Tab. 4 Influence of grinding parameters on achieved results

Tab. 4 shows some relations between working parameters and output results. For instance you could say that chip dimension becomes larger increasing workpiece speed or reducing peripheral grinding wheel speed; hence, you can conclude that chip dimension increases if q ratio decreases. Obviously, chip dimension is directly influenced by the feed rate. While diameter of the grinding wheel and coolant efficiency have weak influence on it.

Looking at the grit stress, it rises up decreasing q factor, increasing the feed rate or decreasing the grinding wheel diameter and has correlation to coolant efficiency.

The feed rate has positive correlation with workpiece speed and feed per revolution, not on grinding wheel speed, wheel diameter and coolant.

In the following figures is explained how workpiece speed and/or grinding wheel speed affect grinding process efficiency.

A clear understanding of all correlations between input machining parameters and critical output of the grinding process is necessary to obtain a well performing grinding process. As you can see on the left of the Fig. 11 to 16 there are the correlations between workpiece speed and output parameters, in the center in the same way correlations are referred to grinding wheel speed, on the right these correlations are combined.

The workpiece speed increase has a positive correlation to Qw'. This means an increase in productivity level considering the correlated increase of feed rate maintaining the same depth of cut. Consequently we have machining time reduction. Furthermore, since workpiece run-out, surface roughness and thermal stress increase, a clever selection of v_W has to be done in order to get high productivity level complying with surface roughness, shape and thermal constraints.

The central diagrams of Fig. 11 to 16 show correlations between wheel speed and output process parameters but considering the strong relation between workpiece speed and wheel speed are only reported to explain better the diagrams on the right.

The right diagrams of Fig. 11 to 16 highlight the combined effect of peripheral speeds. In Fig. 11 the effect on productivity is unaffected by wheel speed, q ratio does not affect productivity.

Fig. 12 shows an option to maintain constant wheel consumption rate if q ratio is optimized.
In Fig. 13 the wheel speed has no correlation to machining time, however it should be changed to maintain q ratio within limits.
In Fig. 14 an optimized q ratio allows to increase productivity preserving the shape within product requirements, the same happens in Fig. 15 with regard to roughness.
In Fig. 16 the increase of speeds to improve productivity causes high thermal stress, this effect should be mitigated by coolant (dotted line).

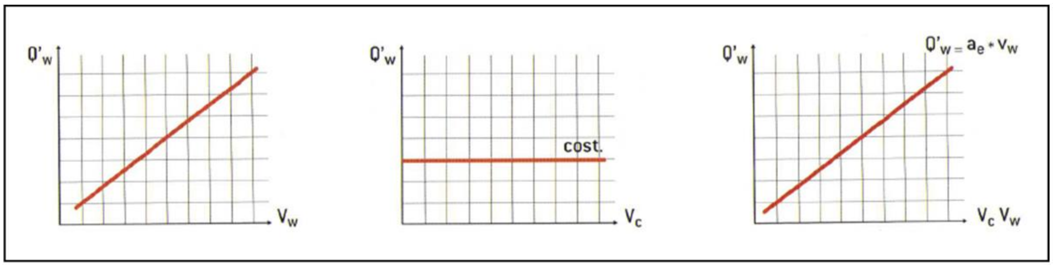


Fig. 11 Specific Material Removal Rate (Qw') correlations

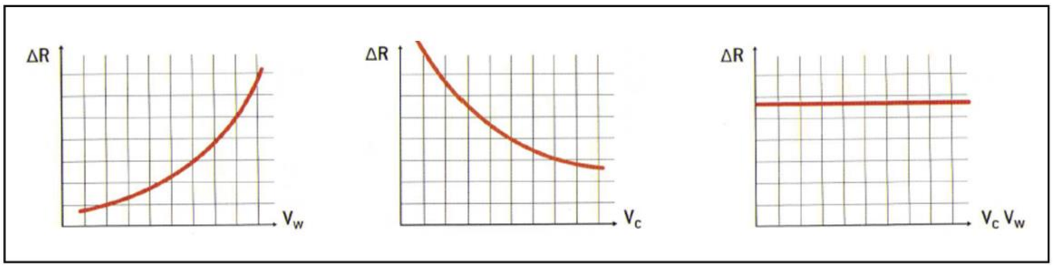


Fig. 12 Wheel consumption rate (ΔR) correlations

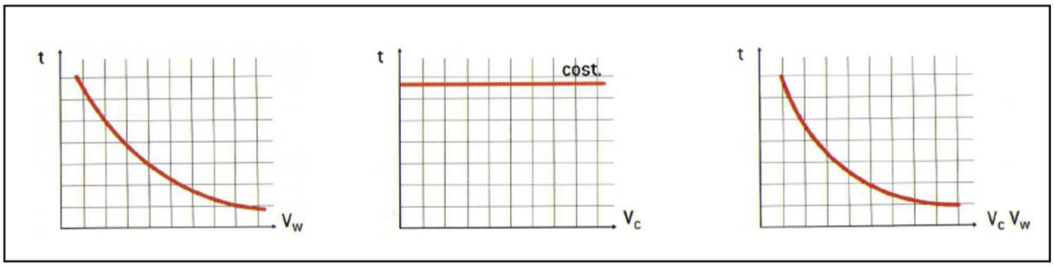


Fig. 13 Machining time (t) correlations

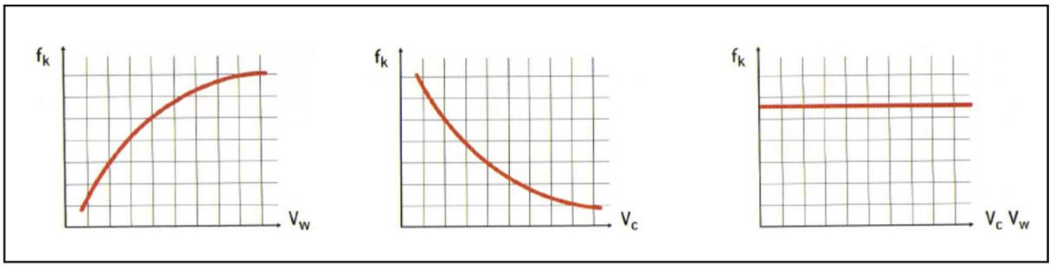


Fig. 14 Shape deviation (f_k) correlations

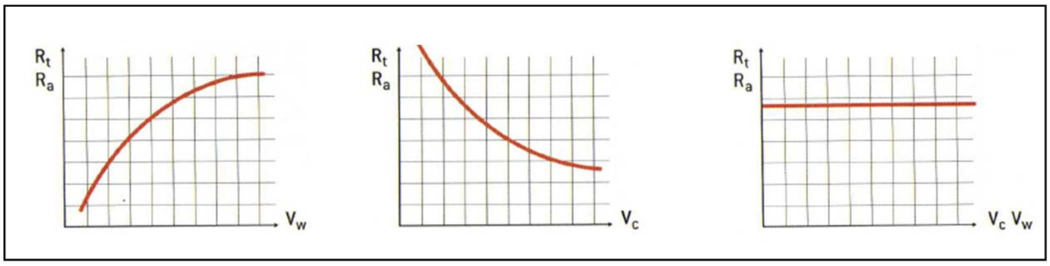


Fig. 15 Surface roughness (Ra) correlations

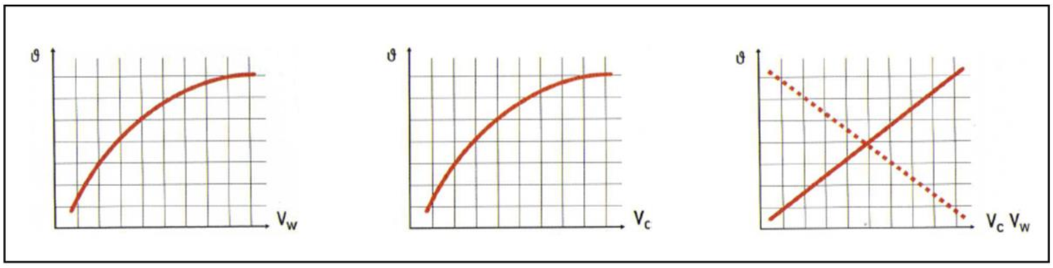


Fig. 16 Thermal stress (ϑ) correlations

The Specific Energy is an important output parameter useful to control the grinding process. The Specific Energy could be explained as the heat generated per unit of volume of material removed and it is expressed in J/mm3. It depends on the efficiency of the grinding process.

Grinding with low specific energy is an efficient process and generates little heat.

Sharp cutting wheels, with their high cutting ability and low rate of displacement and sliding on workpiece removal material, absorb lower specific energy generating less heat.

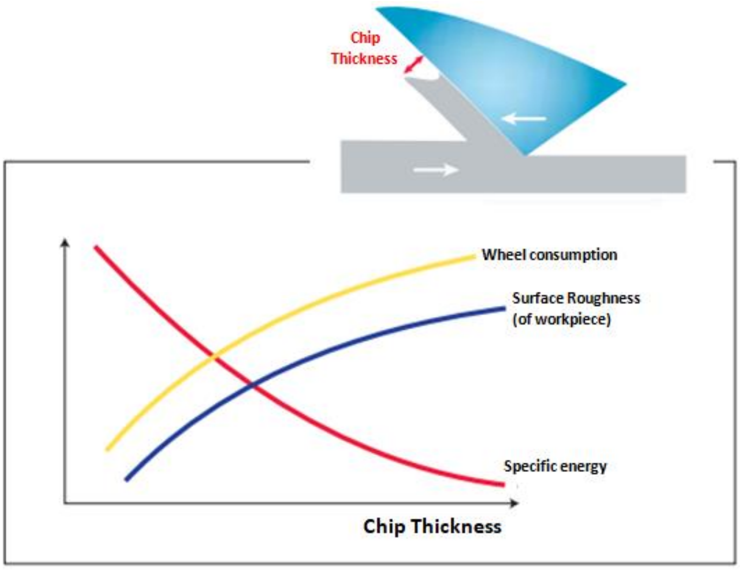


Fig. 17 Chip thickness and Specific Energy

The chip thickness has an important influence on grinding and it can be modified to achieve the desired result (Fig. 17).

In general, a larger chip thickness involves:

- higher surface roughness on the piece
- higher wear of the grinding wheel and rapid alteration of its geometry
- better self-dressing of the grinding wheel itself
- minor energy consumption

Therefore, the heat induced to the workpiece during grinding can be decreased by reducing the specific energy (with larger chip thickness, gentler grinding, more energetic dressing, etc).

For example, reducing the peripheral speed of the grinding wheel leads to a larger chip thickness and consequently to a lower specific energy and less heat generation. However, there is also an increase in grinding wheel wear (with the effect of self-dressing) and a less good surface finish on the piece.

Grinding is a very complex process characterized by numerous interdependent variables. The correct grinding parameters are very important but also the right choice of the grinding wheels is fundamental to obtain the desired result. For example, hard grade wheels tend to keep the shape longer, but give an increased risk of overheating burns (Fig. 18).

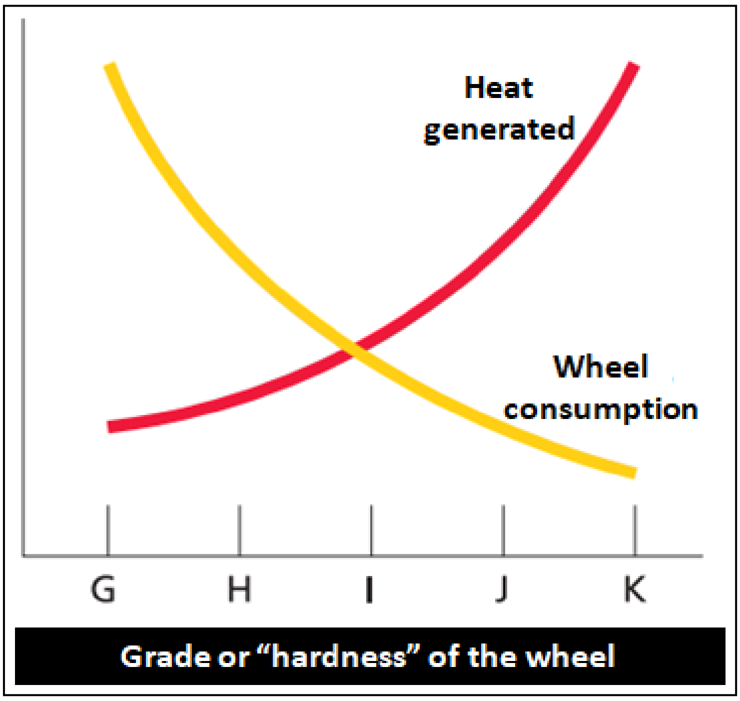


Fig. 18 Wheel grade

Tab. 5 is a complete guideline or best practice collection to avoid problems frequently encountered in grinding. For each detected issue it provides the possible cause and the possible solution along with comments and potential side effects that the technicians should know.

<table>
<tr><th>ISSUE</th><th>POSSIBLE CAUSES</th><th>POSSIBLE SOLUTIONS</th><th>COMMENTS AND POTENTIAL UNDESIRED EFFECTS</th></tr>
<tr><td rowspan="10">Traces of vibrations on the piece, vibrations on the machine.</td><td>Worn bearings</td><td>Replace the bearings</td><td></td></tr>
<tr><td>Poor rigidity of the grinding machine and system</td><td>Switch to stiffer bearings, use stiffer fixture, use a stiffer spindle</td><td></td></tr>
<tr><td>Unbalanced grinding wheel</td><td>Balance the wheel</td><td></td></tr>
<tr><td>Eccentric grinding wheel</td><td>Dress the grinding wheel</td><td>The wheel may have reached the "collapse" phase (to be substituted)</td></tr>
<tr><td rowspan="3">Grinding wheel too hard</td><td>Use a softer wheel</td><td>Risk: worse surface finish, loss of shape</td></tr>
<tr><td>Switch to a less brittle abrasive</td><td>Risk: minor surface finish, loss of shape</td></tr>
<tr><td>Increase specific material removal rate (in particular the peripheral speed of the piece)

Increase the chip thickness to create a self-dressing of the grinding wheel</td><td>Risk: overheating, minor surface finish, loss of shape, higher forces due to the higher material removal rate</td></tr>
<tr><td>Excessive specific material removal rate</td><td>Reduce the specific material removal rate
Lower speeds and feed rates ("gentle" grinding to reduce the energy involved)</td><td>Risk: Wheel too soon worn</td></tr>
<tr><td rowspan="2">Grinding wheel surface too smooth (too dull)</td><td>Switch to a more "open" dressing, change the dressing diamond</td><td>Risk: worse surface finish, loss of shape</td></tr>
<tr><td>Switch to an abrasive with a higher granulometry</td><td>Risk: worse surface finish, wheel cutting loss (larger grains can make the wheel "harder")</td></tr>
</table>

ISSUE	POSSIBLE CAUSES	POSSIBLE SOLUTIONS	COMMENTS AND POTENTIAL UNDESIRED EFFECTS
Burns, Thermal damage, Stress cracks	Excessive specific material removal rate	Reduce specific removal rate. Reduce peripheral speeds and feed ("gentle" grinding)	Risk: wheel cutting loss
	Grinding wheel with surface too smooth	Switch to a more "open" dressing, change the dressing diamond	Risk: worse surface finish
		Switch to an abrasive of higher granulometry	Risk: worse surface finish, loss of shape
	Wheel too "hard"	Switch to a softer wheel	Risk: worse surface finish, loss of shape
		Use less brittle abrasive	Risk: worse surface finish, loss of shape
		Increase specific material removal rate (in particular the peripheral speed of the piece) Increase the chip thickness to induce self-dressing of the grinding wheel, in particular with brittle abrasives.	Risk: thermal stress due to excessive removal rate, worse surface finish, loss of shape
	Insufficient cooling	Increase the pressure of coolant flow	Check the cooling system
		Improve the nozzle position	Direct the coolant flow over the contact arc and in the hot-spot area
		Reduce the nozzle section	Larger nozzles can cause pressure drop in the circuit and lower flow velocity
	Refrigerant too hot	Check the cooling system	
Traces of burns on surfaces not ground	Oxidised burns	Improve cooling, direct an extra nozzle on the area with altered color (burned)	Purpose: to cool the oxidised surface directly and reduce contact with oxygen Risk: the additional nozzle can reduce the flow available for the main contact arc

ISSUE	POSSIBLE CAUSES	POSSIBLE SOLUTIONS	COMMENTS AND POTENTIAL UNDESIRED EFFECTS
Insufficient surface roughness finish	Rough dressing	Perform a finer dressing	Risk: overheating, thermal alterations, vibrations
		Switch to a minor grit size (less microns = major mesh)	Risk: thermal damage, vibrations, loss of shape
	Wheel too much "soft"	Switch to a harder grinding wheel	Risk: thermal damage, vibrations
		Switch to a more tenacious abrasive	Risk: thermal damage due to insufficient self-dressing of the non-brittle abrasive
	Excessive chip thickness	Reduce the chip thickness by decreasing depth of cut or workpiece speed or increasing the speed of the grinding wheel	Risk: insufficient self-sharpening of the grinding wheel, in particular with brittle abrasives Excessive energy with thermal damage associated
Workpiece shape out of tolerance	Wheel too soft	Switch to a harder grinding wheel	Risk: thermal changes, vibrations
		Switch to a higher grit mesh	An abrasive with bigger granulometry makes the grinding wheel harder and reduces its wear
		Switch to an abrasive with different binder	Risk: thermal alterations due to insufficient self-dressing of the non-brittle abrasive
		Reduce the chip thickness	Risk: small chips reduce the self-dressing of the grinding wheel, especially with brittle abrasives
	Excessive granulometry of the grinding wheel	Switch to a smaller grit mesh and a harder grinding wheel	Risk: overheating

Tab. 5 Frequent issues in grinding process

The burns are one of the worst issues because if they happen the workpiece could be unrepairable and so scrapped.
Grinding process as explained generates heat, thus the coolant has a very important role to dissipate heat, reducing the temperature generated by the grinding operation and lubricating the cutting area. In addition, the lubricant-cooling liquid performs the action of cleaning the working area and the surface of the grinding wheel from the chips.
There are two different types of coolant: whole oil or emulsion.
Based on their characteristics, the oils perform an excellent lubricating action while they have poor cooling properties. For these reasons they are used in grinding processes with materials that can withstand the high operating temperatures.
The emulsions consist of oils (2-6%) diluted in water (94-98%), in which the oil is mixed in form of very small particles. The emulsions produce an excellent cooling action but have a low lubricating action and are used in grinding operations on materials that are highly sensitive to high temperatures.
The latest technical research has led to the development of new type of polymer-based lubricant-cooling liquid which combines good lubrication properties with good cooling capacity. The coolant shall be conforming with machine equipment, to avoid its damage caused for instance by corrosive action.
The operating parameters must be balanced on the type of liquid used. The use of an oil or an emulsion generates a different behaviour on the grinding process.
The continuous control of the percentage of oil in the emulsion and its purity (zero chips) is essential to obtain constant working conditions during process. In Fig. 19 you can see the trajectory of the coolant steered toward the surface of the grinding wheel.

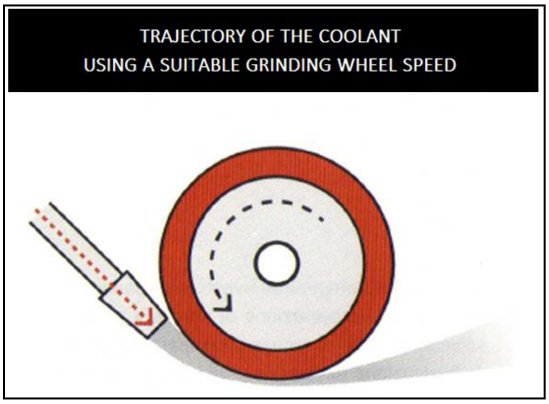


Fig. 19 Grinding coolant

The flow pressure/speed should not be too high or too low to avoid coolant performance compromised. Additional nozzles can improve the result of cooling. In high-efficiency grinding operations, using wheels with peripheral speeds > 80 m/s, high-pressure jets are used to clean the surface of the grinding wheel and cool the workpiece.

1.2. Grinding machine types

A grinding machine is a precise industrial equipment that uses an abrasive wheel for cutting metallic workpiece. There are many grinding machine types, varying for each different purpose.

We could identify four grinding machine types as illustrated in Fig. 20:

- Surface Grinder
- Cylindrical Grinder
- Centerless Grinder
- Advanced 5 Axis Grinder

Fig. 20 Grinder classification

A surface grinder (Fig. 20) is a machine used to obtain precision ground surfaces such as features with critical size and very good surface finish. The typical precision achievable on most surface grinders is ± 0,002 mm. A surface grinder has a table with a chuck (a workpiece holding device) that traverses both longitudinally and across an abrasive wheel rotating on a spindle moved by an electrical motor. The longitudinal feed is usually powered by hand, hydraulic or electrical motor. Depending on the workpiece material, the piece is generally held by the use of a magnetic, electromagnetic or manually operated chuck. The surface grinder has a coolant device with the aim of lubricating the cutting area as well as the extraction of metal dust (chips) and heat generated during cutting process.

Modern surface grinders can be controlled by a computer (CNC).

A cylindrical grinder (Fig. 20) is used to machine outside or inside diameters. These machines are able to grind workpieces in a variety of shapes around an axis. In a cylindrical grinder, both the workpiece and grinding wheel are simultaneously rotated. Cylindrical grinder has the following movements:

1. The workpiece rotates with constant speed
2. The grinding wheel rotates with constant speed
3. The grinding wheel moves toward and away from the workpiece
4. The workpiece and the grinding wheel move transversely one to the other

As the surface grinder a Numerical Control interface could be used to drive the cylindrical grinder.

A centerless grinder (Fig. 21) is a grinder used to grind workpiece diameters.

It differs from cylindrical grinder in that the workpiece is not mechanically constrained in a spindle, but two rotary wheels are used to keep the workpiece in place using a work-blade to support it. The workpiece is driven by a regulating wheel smaller and slower with respect the high speed grinding wheel (grinding tool).

Obviously with centerless grinding collet or a pair of centers on workpiece are not used. The work-blade is angled slightly toward the moving wheel, with the workpiece centerline a little above the centerlines of the moving and grinding wheel.

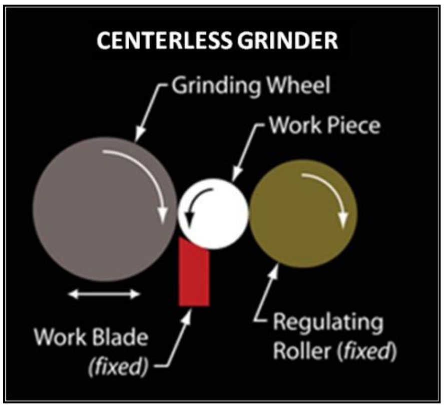


Fig.21 Centerless grinder scheme

The advanced 5 axis grinder (Fig. 20) is a high precision grinder using the best state-of-the-art technology with up to 5 axis and automatic grinding wheels change.
The advanced 5 axis grinder uses CNC technology to enhance the quality and versatility of grinding process. The benefits include:

- Faster and versatile grinding (this grinder is a perfect robot that provides extremely flexible solutions for any grinding with the ability to reduce cycle time with respect to conventional grinding)
- Multi-tool grinding (possibility to merge grinding operations saving cycle time)
- Multi-part grinding (possibility to grind two different workpieces simultaneously)
- Adaptive control (it is an automatic monitoring of process conditions to compensate any variation in operation performance such as tool wear, coolant efficiency, spindle torque and avoid workpiece or machine itself damage)
- Smart machine tending (thanks to all best state-of-the-art technology included, this machine reaches a significant step in developing unmanned machining techniques)

1.3. Grinding methods

The grinding process consists in the removal of stock material in very small chips using tools called grinding wheels made by abrasive grains held by a binder.
It allows a high dimensional and shape accuracy. It is the only process that can be carried out after case hardening and it is used to remove only a few stock material and to finish a machined feature after other previous surface machining processes.
This process has some specific characteristics that are:

- Very high cutting speed
- High temperature in the contact area between tool and workpiece
- Projection of incandescent chips for fusion and solidification in contact with oxygen
- Frequent workpiece thermal damage if it is not properly cooled (grinding abuse). The machined surface shows transformations, cracks, tensions and burn marks

You could classify grinding methods of production depending on how the grinding wheel is used for working:

- If the grinding wheel is used to work a surface of revolution, the grinding production method is classified as circular grinding, using a grinding wheel with a rotation axis parallel to that of the revolution surface to be machined
- If the grinding wheel is used to work a plan surface, the grinding production method is classified as plane grinding, using a grinding wheel with a rotation axis parallel to the surface to be machined. The axis can also be perpendicular to the work surface if a cup wheel is used

In particular, it's possible to distinguish the main motions within production methods.
In circular grinding main motions are:

- Cutting motion: continuous tool rotation, grinding wheel rotation
- Workpiece motion: continuous workpiece rotation with a straight movement parallel to the grinding wheel axis
- Feed motion: rectilinear grinding wheel spindle movement to approach the workpiece, better known as feed

In plane grinding main motions are:

- Cutting motion: continuous tool rotation
- Workpiece motion: workpiece movement tangential and parallel or perpendicular to the wheel axis
- Feed motion: rectilinear grinding wheel spindle motion to approach the workpiece

Moreover, circular grinding can be classified in five different types:

- outside diameter (OD) grinding
- inside diameter (ID) grinding
- plunge grinding
- traverse feed grinding
- centerless grinding

OD grinding (Fig. 22) occurs on external cylindrical surface of an object between the centers. The centers usually are added features at the ends of the workpiece used to allow the object rotation on a center axis. The grinding wheel and the workpiece rotations are usually in the same direction, this means the two surfaces are moving in opposite direction in the cutting area.

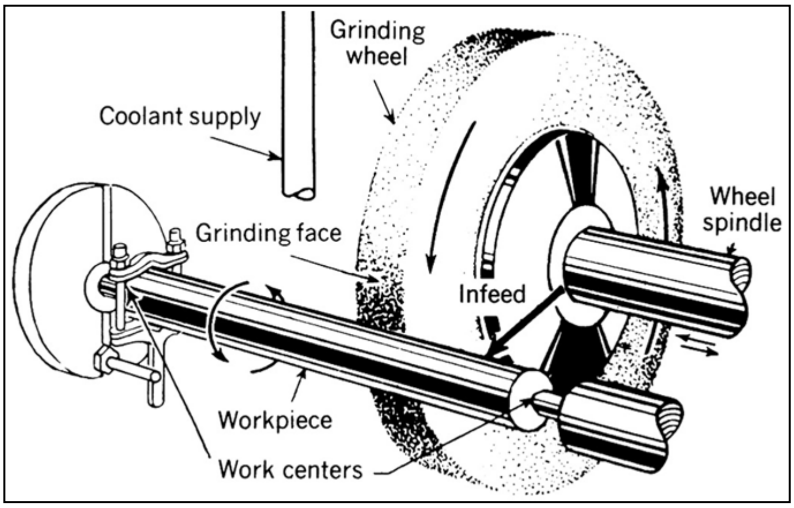


Fig. 22 Outside diameter grinding

ID grinding (Fig. 23) occurs inside of an object. The grinding wheel is always smaller than the inner diameter of the object. The workpiece is held in place by a collet, clamped in a self centering chuck, the workpiece axis and the grinding wheel axis are properly displaced. The grinding wheel and the workpiece rotations are usually in opposite direction, so to have the surfaces movement in opposite direction in the cutting area.

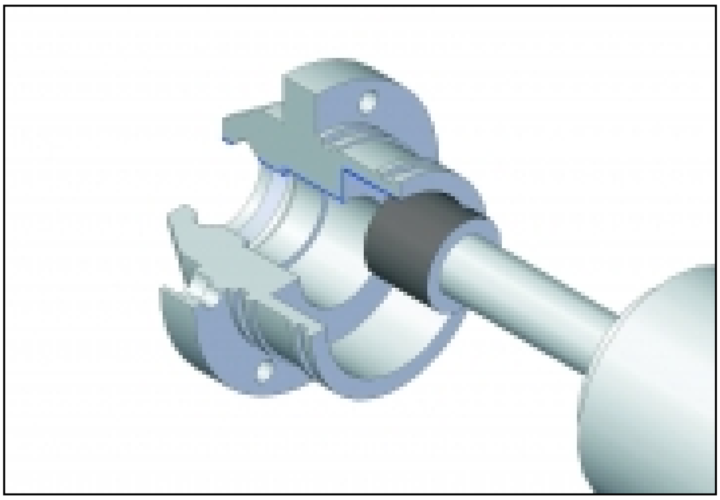


Fig. 23 Inside diameter grinding

Plunge grinding (Fig. 24) is a particular cylindrical grinding, where the grinding wheel has not traverse movement, typical of Traverse feed grinding.

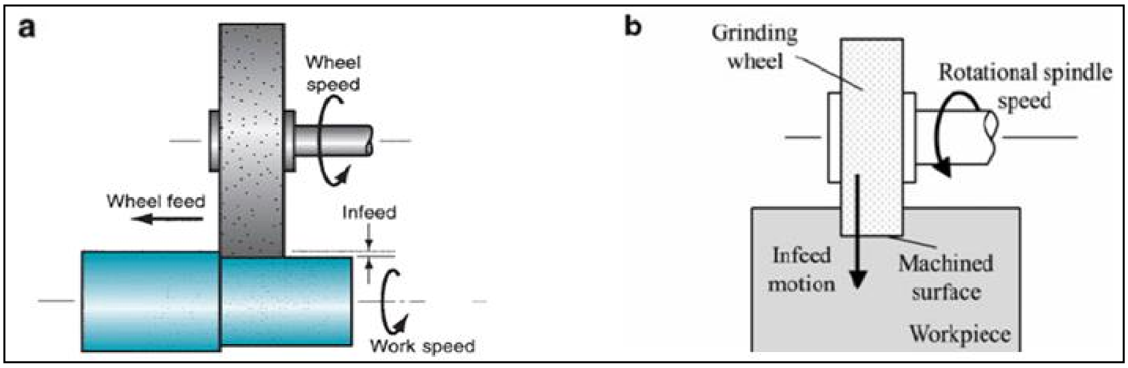


Fig. 24 Traverse feed grinding (a) vs Plunge grinding (b)

Centerless grinding (Fig. 25) is a particular circular grinding where the workpiece is not mechanically constrained in a spindle but two rotary wheels are used to keep the workpiece in place using a work-blade to support it. The workpiece is driven by a regulating wheel smaller and slower with respect the high speed grinding wheel (grinding tool).

Centerless grinding is typically used rather than other grinding processes in high volume production, in fact centerless grinding is virtually a continuous process because, compared to other grinding between centers, the loading time is very small and the setup simplified. For those reasons is preferred to grind large quantities of small parts, for instance various types of pins including shaped pins, and even long length particulars that can be ground continuously, for instance long precision bars.

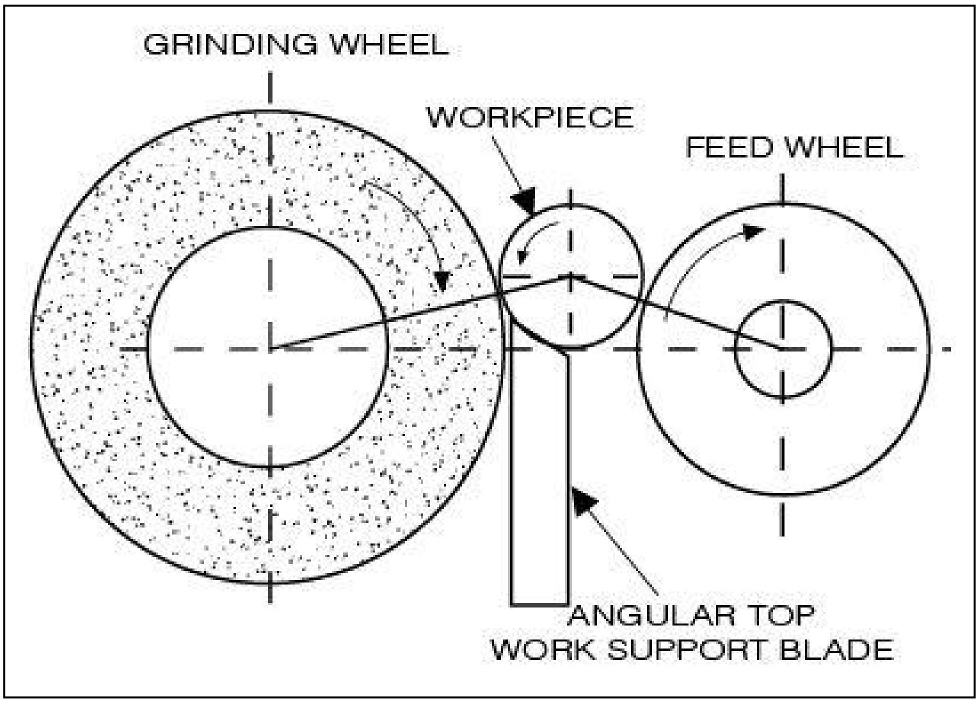


Fig. 25 Centerless grinding

Another classification could be based on the depth of cut.
It's possible to distinguish between conventional grinding and creep-feed grinding, with only a glance at High Efficiency Deep Grinding.
Conventional grinding has generally a depth of cut up to 0,1 mm, while creep-feed has depth of cut between 0,1 to 30 mm. Creep-feed grinding is perfect for difficult-to-machine materials, easily it holds precision tolerances, and leaves few burrs.
Creep-feed (Fig. 26) grinding could perform a full depth of cut in a single pass grinding. Creep-feed grinding is much like a milling process but using a grinding wheel instead of a milling cutter. Wheels using cubic boron nitride (CBN) superabrasives make possible the high efficiency deep grinding (HEDG). These wheels don't require wheel dressing.
Tab. 6 shows the main difference between grinding processes, take into account that productivity has positive correlation to specific material removal rate.

	Conventional grinding	Creep-Feed grinding	High Efficiency Grinding (HEDG)
Depth of cut	LOW (0,0002 – 0,1 mm)	HIGH (0,1 - 30 mm)	HIGH (0,5 - 30 mm)
Work speed	HIGH (1 - 30 m/min.)	LOW (0,05 – 0,5 m/min.)	HIGH (0,5 - 10 m/min.)
Wheel speed	LOW (20 - 50 m/s)	LOW (20 - 50 m/s)	HIGH (80 - 200 m/s)
Specific Material Removal Rate	LOW 0,25 – 10,7 mm3/ sec*mm	LOW 0,25 – 10,7 mm3/ sec*mm	HIGH >50 mm3/ sec*mm

Tab. 6 Grinding types comparison

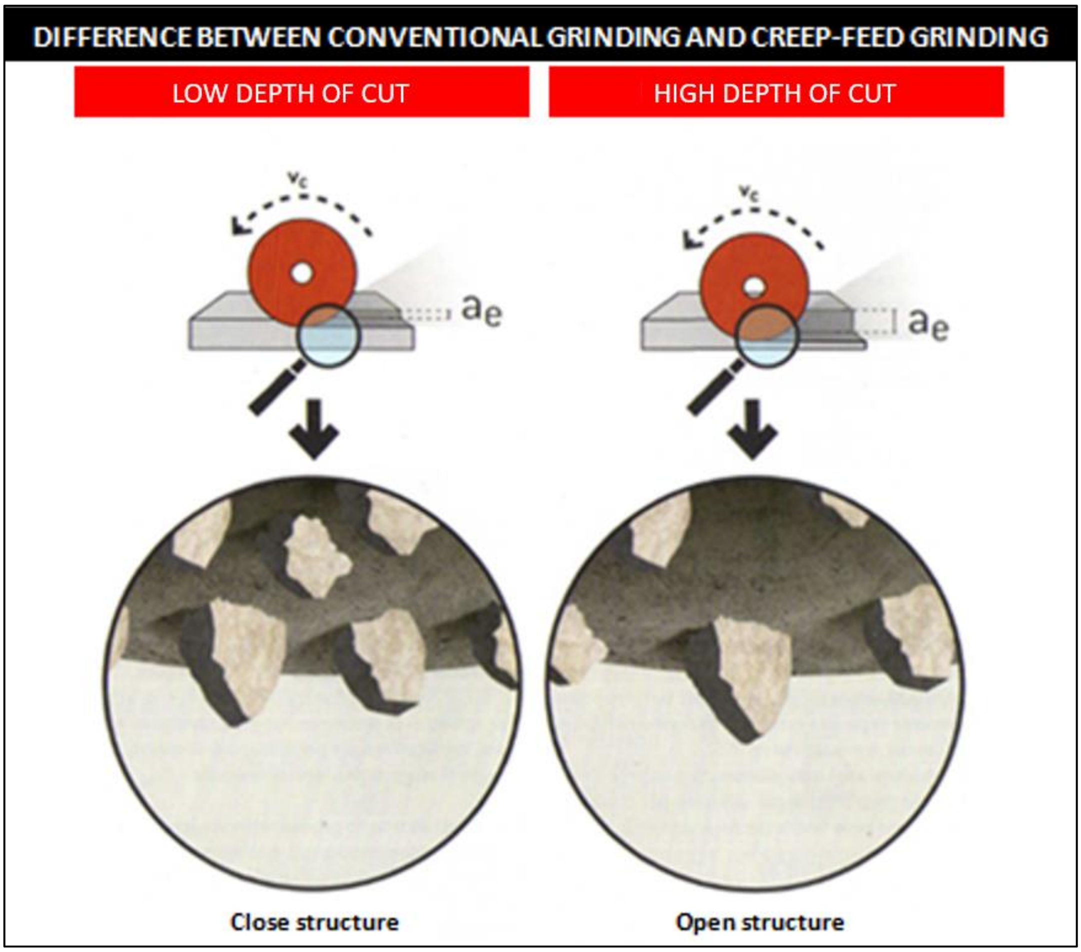


Fig. 26 Conventional grinding vs Creep-feed grinding

1.4. Grinding wheels

A grinding wheel consists of three basic elements (Fig. 27):

- abrasive
- binder (bond and filler)
- pore

The abrasive (with reference to the single grains) is the material of great hardness that carries out the material removed (chips). It is held in place in the agglomerated mass by means of a "binder". The porosity is simply constituted by pores of the abrasive mass: this lack of material is important because it allows the refrigerant to reach the wheel-piece cutting area working like a sponge and it ensures space for chips formation. The vitrified bonded wheels have a high natural porosity. Those with a resinoid or metal binder, on the other hand, are almost free of natural porosity.

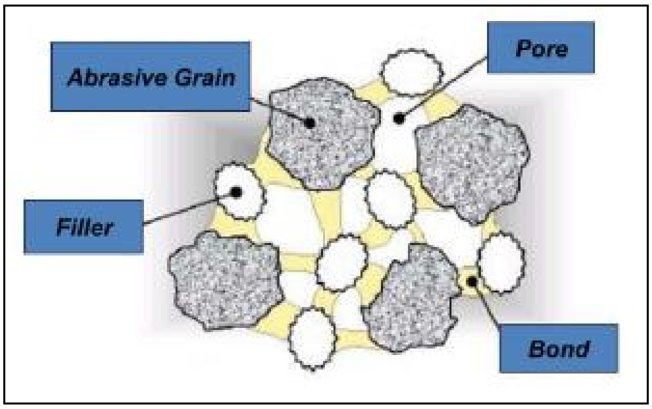


Fig. 27 Basic elements of a grinding wheel

The type of the wheel abrasive and the relative percentages of its three components determine the behaviour of the grinding wheel itself. Additionally, specific fillers are sometimes included depending on the wheel abrasive type.

The indications in Fig. 28 give the standard nomenclature according to ISO Norton method for conventional abrasive wheels. For super-abrasives this classification is not applicable.

Marking classification includes 7 items for the grinding wheel characterization:

1. *Prefix*: a manufacturer's symbol, indicating exact type of abrasive (use optional)
2. *Abrasive type*: for instance A means Aluminium oxide
3. *Abrasive grain size:* really important to select wheel depending on surface roughness needed
4. *Grade*: Hardness scale from A (Soft) to Z (Hard)
5. *Structure*: it specifies the density of the grain size in the wheel matrix (affecting the capability to hold back coolant during working operation)

6. *Bond type*: it's referred not to cutting grain but to the matrix in which cutting grains are concentrated. For instance B (resinoid)
7. *Manufacturer's record*: it's the manufacturer's code number

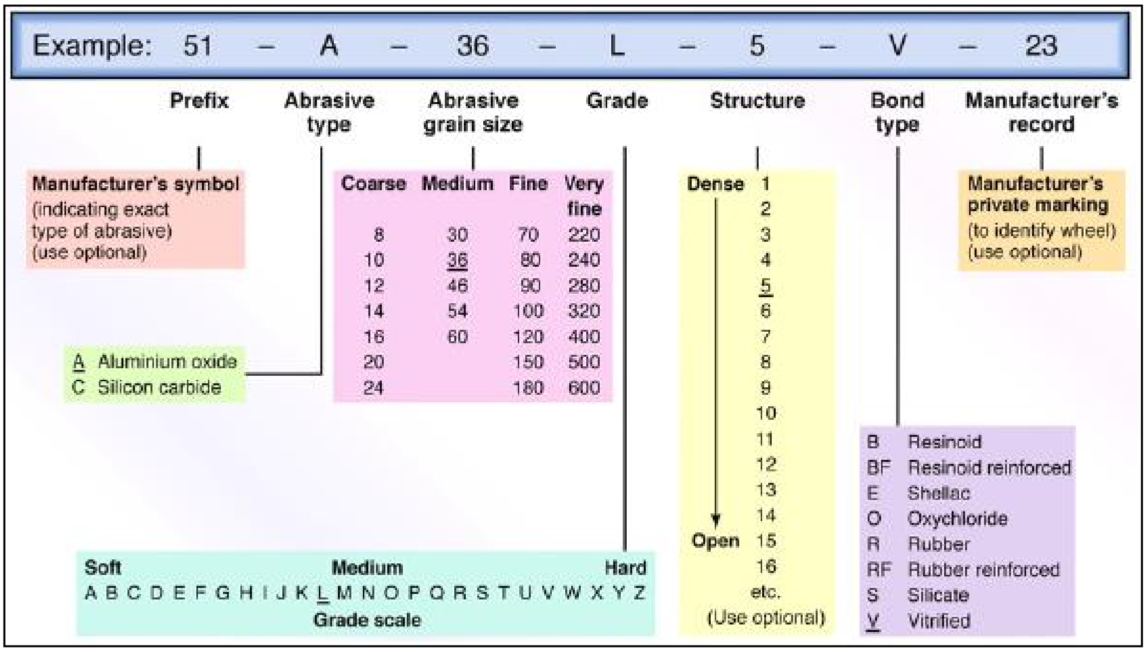


Fig. 28 ISO Norton method

Tab. 7 includes a classification based on origin of abrasives with specific letters assigned.

TYPE OF ABRASIVES	
NATURAL ABRASIVES	**ARTIFICIAL / SYNTHETIC ABRASIVES**
Obtained from nature	Obtained by chemical synthesis
D = Diamond	**A** = Aluminium Oxide (Al_2O_3) **B** = Cubic boron nitride (CBN) **C** = Silicon Carbide (SiC)

Tab. 7 Type of abrasives

Aluminium oxide and silicon carbide are conventional abrasives. Cubic boron nitride (CBN) and diamond are super-abrasives. The kind of abrasive to be used depends on the application: the type of material to be machined determines the abrasive or the different mixtures of abrasives to be used. The aluminium oxide is commonly used for grinding of super-rapid steels. Silicon carbide, although of higher hardness, is rarely used for super-fast steels. Cubic boron nitride with its great hardness and good conductivity provides good performance on super-fast steels, especially high-alloy steels. However, it is significantly more expensive than conventional abrasives and imposes more constraints on the grinding machine characteristics. The diamond (Fig. 29), in spite of its very high hardness, is not suitable for the grinding of super-rapid steels due to its limited resistance to heat and the tendency to react chemically with iron.

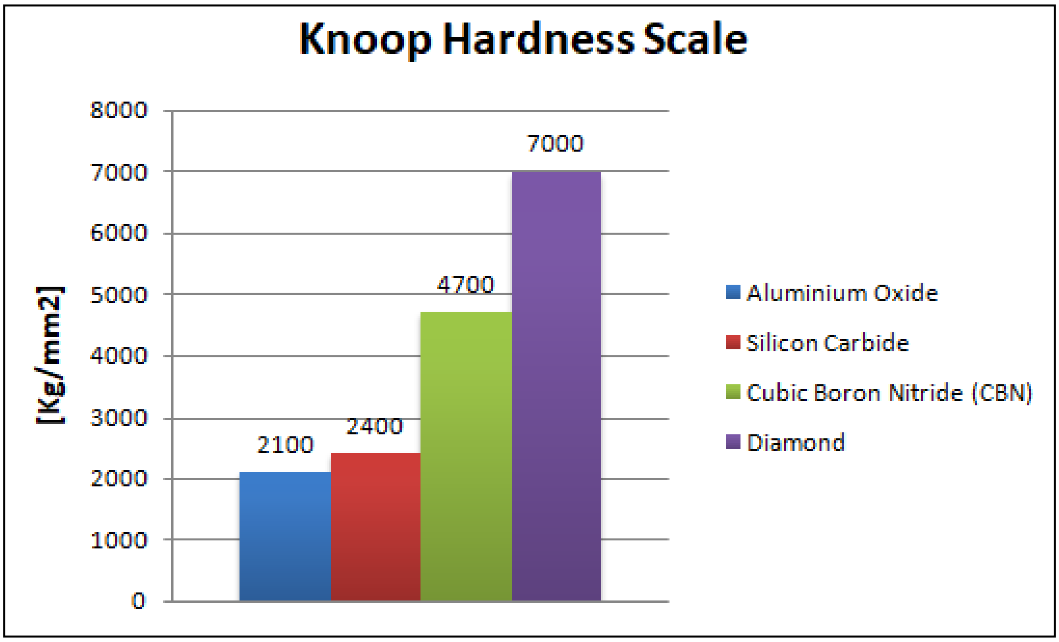


Fig. 29 Knoop Hardness scale

For ductile materials that produce long chips, such as steels and alloy steels, aluminium oxide and CBN are used. Materials that produce brittle and small chips, such as metal carbides and sintered materials, are processed with Silicon Carbide or Diamond.
Most of the abrasives are artificially produced in industrial processes.
Generally, aluminium oxide and silicon carbide are called conventional abrasives, while CBN and diamond are called super-abrasives, to emphasize their higher hardness.
The number of the abrasive grain size indicates the number of holes per inch square (25,4 mm^2) in a wire sieve that permits the grit to pass through. This number is called Mesh (Fig. 30).
The coarse abrasives are used for strong removal (rough grinding). They produce a rough surface finish and as a consequence don't allow complex profile with small radii. The fine abrasives are used instead for high precision grinding. They provide better roughness and allow smaller radii with fine and complex shape.

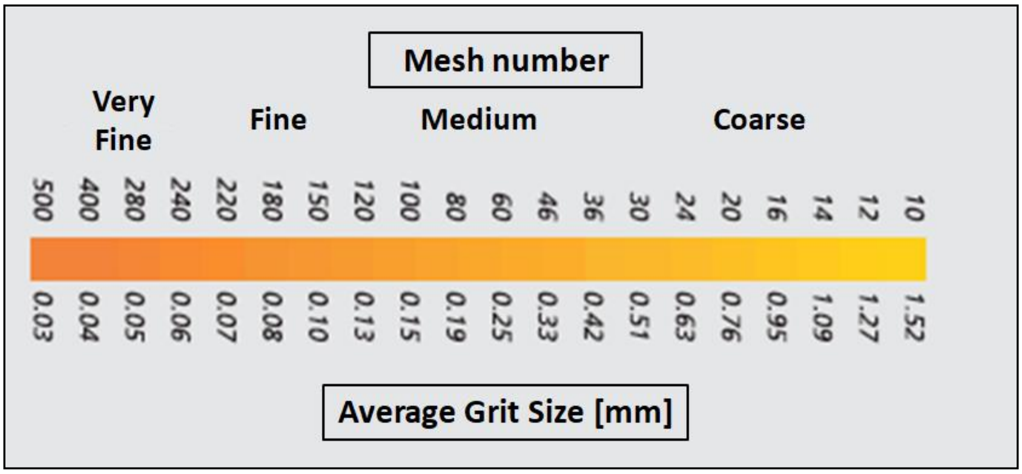


Fig. 30 Mesh to Grit size conversion

The conversion from Mesh number to abrasive grain size [mm] (Fig. 31) is:

$$Average\ abrasive\ grit\ size\ [mm] = \frac{15.2}{Mesh}$$

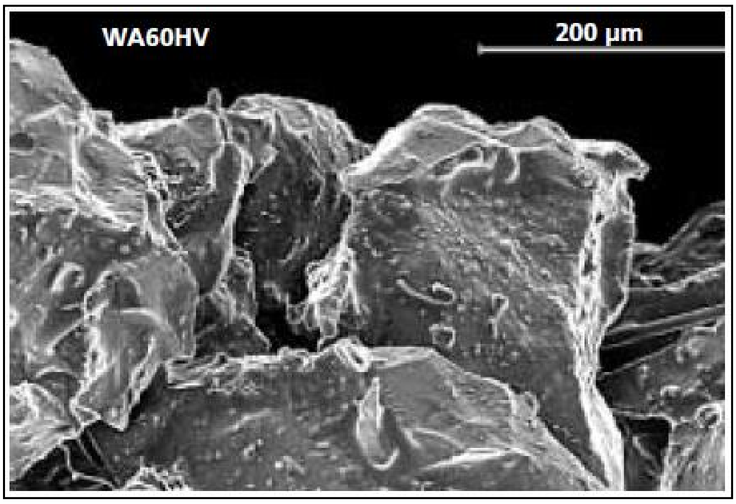


Fig. 31 Abrasive grains in a grinding wheel

Tab. 8 highlights grit mesh number in relation to achievable surface finish.

Grinding operation	Mesh
Rough grinding	36-60
Finish grinding	60-120
Super-finishing	120-320 mesh (or finer)

Tab. 8 Mesh range suggested for different grinding operations

The result of the grinding operation, i.e. the chip formation in the cutting area, is strongly influenced by the size of the abrasive grain and its hardness. Large grains produce large chips, fine grains produce small chips.
The grinding wheel grade indicates the "resistance of the grinding wheel", this means how tenaciously the binding material retains the abrasive grains. It is sometimes called the "hardness" of the grinding wheel, which can lead to misunderstanding because it does not indicate the hardness of the abrasive. The grade of a grinding wheel depends on the amount of binder present in the grinding wheel body. Wheels containing a lot of binder are classified as hard, while wheels with less binder are soft. The grade is indicated with letter from A to Z. In this range the soft wheels have letters E or F, while the hardest wheels S or T.
For grinding wheels with vitrified binder the aforementioned grade is obtained varying the fraction of binder material related to the porosity of the grinding wheel for a fixed abrasive content. High grade wheels are characterized by a higher quantity of binder and less porosity, which makes them more "hard". Low grade wheels have less binder and more porosity, which makes them "soft".
For resinoid and metal binder wheels (which are virtually free of natural porosity) the grade is determined by the formulation of the binder.
High-grade wheels tend to keep the shape well but are more prone to burns on the contrary wheels with lower grade tend to lose shape but are less prone to burns because the single abrasive grains are easily removed, ensuring a self-dressing effect. The correct choice of the grinding wheel depends on numerous variables.
The grinding of difficult to grind material quickly causes the wear of the grinding wheel if this choice is not appropriate. Grinding operations with a high cutting arc length require the use of low grade wheels given the availability of a large area to distribute forces on individual grains. The optimum grinding wheel for a specific processing is a compromise between strength and cutting: it must be hard enough to keep the shape but tender enough to allow the replacement of worn grains (self-dressing).
High grit size wheels are used to grind workpieces with high stock material, the high porosity (Fig. 32) allows high quantity of chip that can be easily removed. In high grit size wheels, the ductility is a beneficial factor because it provides a high strength in heavy-duty. Finally wheels with high grit size are not recommended for finishing because of poor capability to achieve high surface finish.

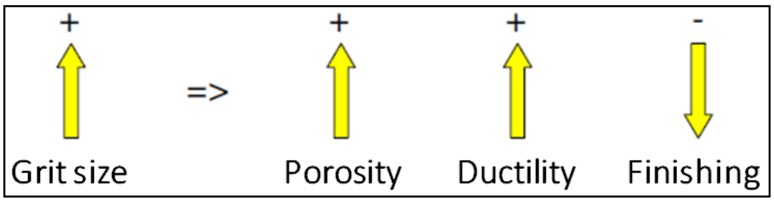


Fig. 32 Grit size properties

Different surface roughness on the workpiece can be achieved depending on grit mesh used. This means that specific curves of surface roughness in function of Mesh need to be considered for the right selection of the grinding wheel.

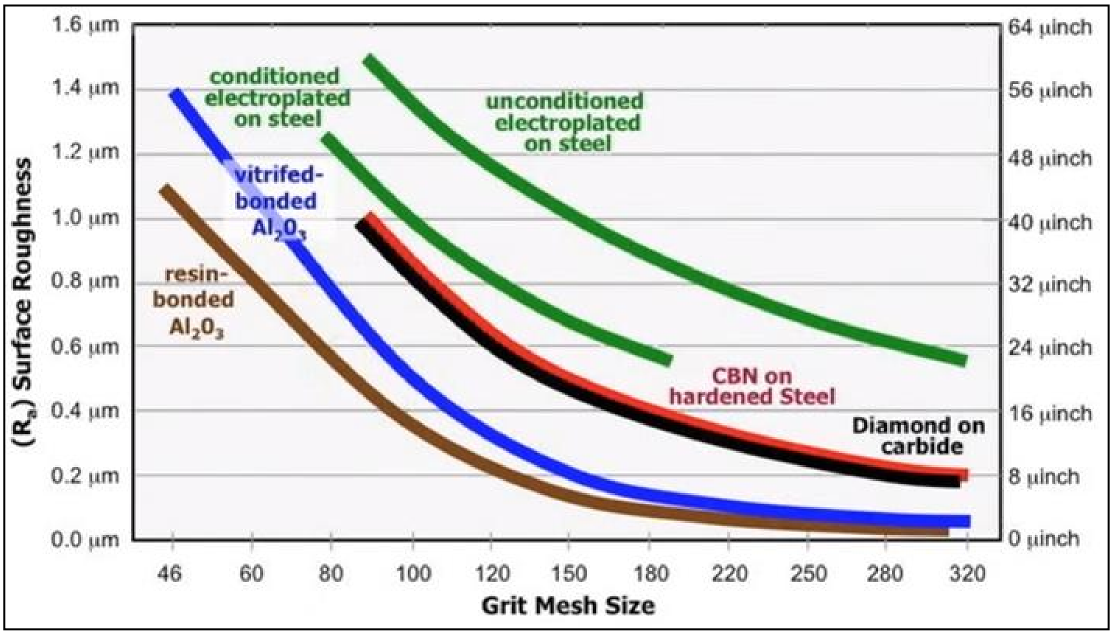


Fig. 33 Grit Mesh and abrasives relation to Surface Roughness

The diagram in Fig. 33 is an excellent guideline to take decision on which grit mesh is better to use for specific surface roughness constraint for a certain wheel type. To choose a wrong grit size wheel and try to adjust it by dressing is the worst option, because this could lead to burn the workpiece, in other words, try to adapt a not suitable grinding wheel by changing the dressing parameters is not the right way to proceed.

Fig. 34 shows the abrasive spacing in the grinding wheel, also called "volumetric concentration of abrasive". A small number indicates a higher percentage of abrasive, namely "close" structure. A big number indicates instead a lower percentage of abrasive, therefore "open" structure. The open structure is used in process where cooling is very important, such as rough grinding and creep-feed grinding. In open structures the distance between grains is high and facilitates the chips removal from the wheel and workpiece cutting area, it reduces friction that is the primary cause of heat release. Furthermore, the porosity improves the cooling and lubricating action of the coolant, where it is intended to be used. The size of the pores should respect the dimensional scale of the abrasive grains.

Through the combination of structure, hardness and porosity, 100% of the volume is achieved.

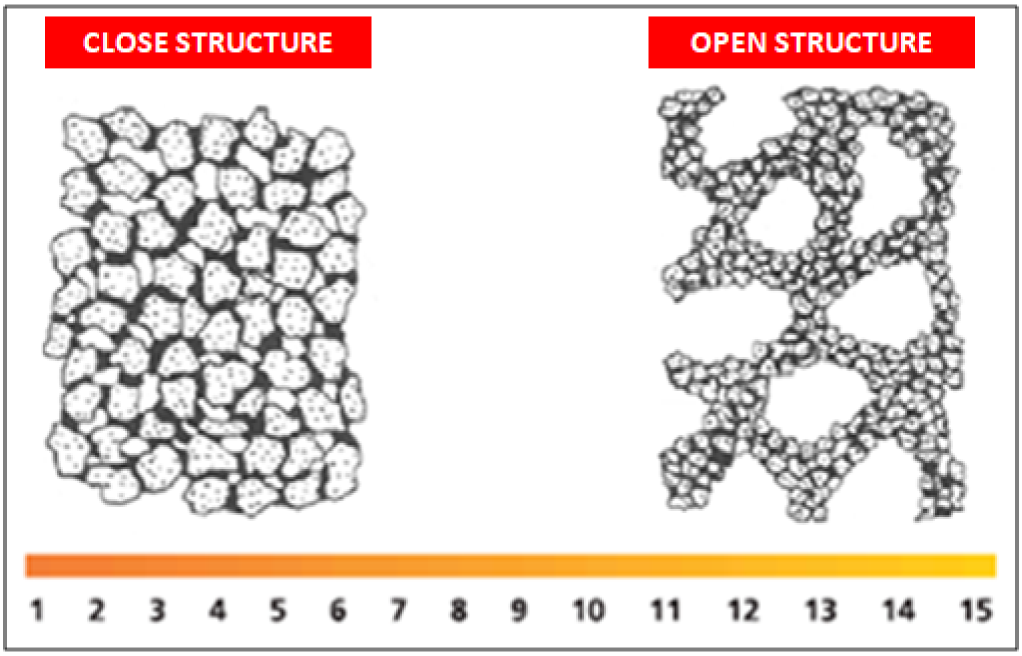


Fig. 34 Structure classification

Tab. 9 summarizes the influence of open and close structure on wheel properties.

INFLUENCE OF THE GRINDING WHEEL STRUCTURE ON ITS PROPERTIES		
STRUCTURE-PROPERTIES	OPEN STRUCTURE	CLOSE STRUCTURE
Porosity	↑	↓
Hardness	↓	↑
Heat generation	↓	↑
Grain stress	↑	↓
Distance between grains	↑	↓
Precision of shape	↓	↑

Tab. 9 Open and close structure effects

Another characteristic marked on the grinding wheel is the type of bond.

The purpose of the binder is the retention of the individual abrasive grains. The most common types of binder are:

- V = vitrified
- B = resinoid
- R = rubber (elastic)
- M = metallic

Vitrified bonded wheels are the most common and are used both with conventional abrasives and with superabrasives. They are rigid (therefore suitable for precision grinding) and are porous and less sensitive to high temperatures.

The resinoid bonded wheels are not porous, they are less rigid, tenacious (i.e. less brittle, which is favourable for use in heavy operations, at high peripheral speeds and in presence of lateral forces) but they are more sensitive to high temperature.
The rubber-bonded grinding wheels are used for operations with really strong surface finish like polishing.
Metal binder wheels are often used with super-abrasives and obviously are very precise in shape but they don't allow dressing.
The different wheel binder type influences wheel properties and its operational behaviour as shown in Tab. 10.

	GRINDING WHEEL PROPERTIES					
BINDER	HARDNESS	SHAPE MAINTENANCE	TOUGHNESS	IMPACT ABSORPTION CAPACITY	THERMAL CONDUCTIVITY	HEAT RESISTANCE
Vitrified	++	++	– –	– –	–	++
Resinoid	+	+	+	+	–	– –
Metallic	++	+	– –	– –	++	++

	OPERATION RESULT		
BINDER	SURFACE ROUGHNESS	REMOVAL RATE CAPACITY	WORKPIECE GEOMETRY
Vitrified	–	++	++
Resinoid	+	+	–
Metallic	–	+	++

Tab. 10 Binder properties and its influence on grinding results

For safety reason the grinding wheel has a certain maximum operational speed limit specified by its constructor, obviously the grinding wheel needs to turn balanced (Fig. 35).

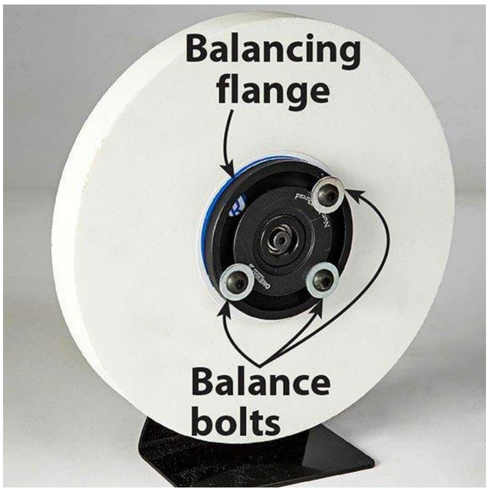


Fig. 35 Grinding wheel balancing flange

1.5. Dressing

Grinding wheels are consumable tools. During grinding process the sharp edges of the abrasive grains become more or less quickly dull losing their cutting ability.
It would be perfect if the time of the consumption of the binder were the same to the time of the consumption of the grains, basically what happens is that bond fracture releases worn grains, this action is called self-dressing for which an emerging layer of new sharp grains restores the cutting ability of the grinding wheel.
The presence of more blunt grains (Fig. 36) leads to high grinding temperatures and typical "burns".

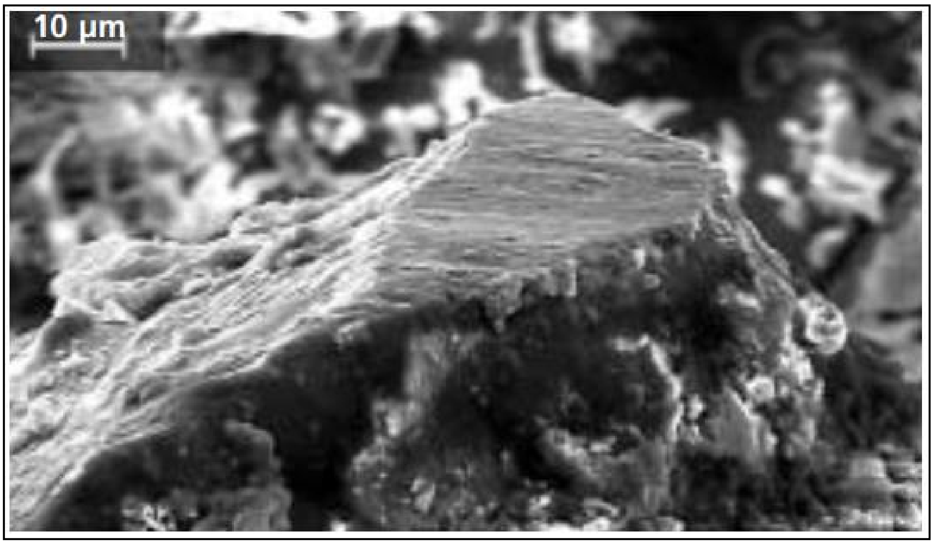


Fig. 36 A blunt abrasive grain

The three types of wear on the grinding wheel are: friction wear, grape fracture and binder fracture (Fig. 37).
Friction wear occurs on the top of individual abrasive grains. Although it is only responsible for a small fraction of the overall wear of the grinding wheel, it negatively affects its performance as it leads to a strong heat development: this phenomenon is called "wear flattening".
Grape fracture of the grains is a kind of wear due to the break of the single abrasive grains. It occurs when the stresses acting on the grain exceed its breaking limit. Friable abrasives, such as white alumina, are prone to these breaks.
Binder fracture occurs on the grinding wheel by fracture of the binder which retains the individual abrasive grains. It occurs when grain stress exceeds the strength of the binder. The "soft" grade wheels binder is easier to break, because they have a smaller amount of binder material around the individual grains.

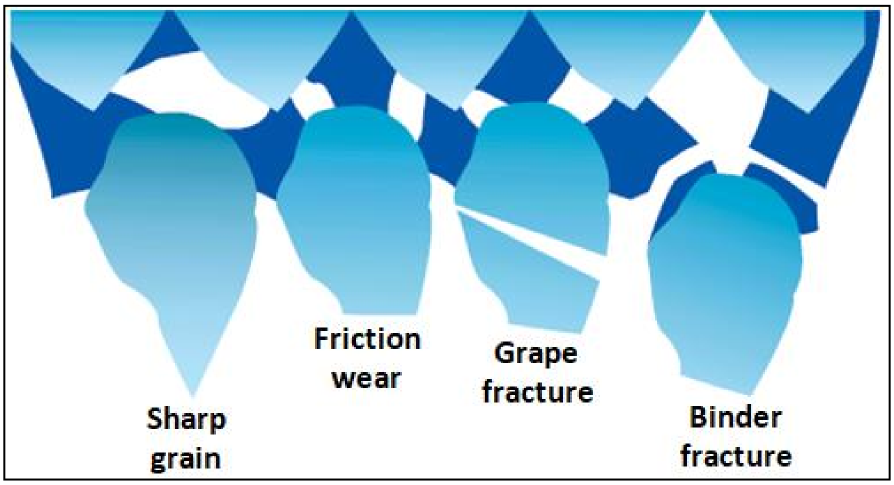


Fig. 37 Three types of grinding wheel wear

Dressing is a very important operation for the right behaviour of the grinding wheel.
It can be described as a calibration process of the wheel with a tool (usually diamond) to obtain the desired shape and restore the cutting ability of the wheel.
The usual reasons for dressing a wheel are: slow removal rate, grinding vibration, workpiece burn, poor surface texture and loss of form-holding.
Conventional grinding wheels made from aluminium oxide and silicon carbide are almost exclusively dressed with diamond tools.
Dressing tools are fixed diamond or diamond roller dresser.
Single point diamond dressing is commonly used for precision grinding, while diamond impregnated rolls are used for large batch sizes and shaped profiles. The diamond roll extends to the full width of the grinding wheel, making wheel dressing fast, however diamond rolls are expensive due to the large quantity of diamond required and for shaped wheels a dedicated roll is needed for each shape.
The fixed diamond dressing process has some critical parameters:

- Dressing depth [mm]
- Number of dressing passes
- Traverse feed [mm/min]
- Peripheral wheel speed [m/s]
- Width of diamond [mm]

The dressing depth is the depth of cut of the dressing diamond with respect the grinding wheel. The wheel consumed during dressing depends on the number of dressing passes, sometimes dressing shall be repeated to remove completely the worn grains or the kneaded binder.

Recommended dressing depth shall be calculated with the following formula:

$$Dressing\ Depth\ [mm] = 0.1 \times Average\ Grit\ Size$$

A 60 Mesh grinding wheel has an average grit size of 0,25 mm, thus the recommended dressing depth is 0,025 mm. Tab. 11 includes dressing depth recommended values.

Mesh Number	10	20	36	46	54	60	80	100	120	150	180	220	240	280	400	500
Dressing Depth	0,152	0,076	0,042	0,033	0,028	0,025	0,019	0,015	0,013	0,010	0,008	0,007	0,006	0,005	0,004	0,003

Tab. 11 Dressing Depth recommended values

Try to adapt a not suitable grinding wheel by changing the dressing parameters is not the better way to proceed, however it's possible within limits to obtain change in grinding wheel behaviour by increasing or decreasing the recommended Whack Ratio.
Whack Ratio (%) is the ratio between the dressing depth and the abrasive Grit size.
It is a control parameter calculated as follows:

$$\text{Whack Ratio} = \frac{Dressing\ Depth\ [\mu m]}{Average\ Grit\ Size\ [\mu m]} \times 100 = \%$$

For 36 to 220 Mesh wheels a safe Whack Ratio range is between 5 and 15 %.
The values of the Whack Ratio are shown in Tab. 12.

	Whack Ratio %
Standard dressing	9% - 11%
Dull dressing	5% - 9%
Sharp dressing	11% - 15%

Tab. 12 Whack Ratio values

For instance, a 60 Mesh wheel has a recommended Dressing Depth of 0,025 mm that means a Whack Ratio of about 10%. Then if the wheel needs to be dressed sharp the Whack Ratio shall be increased up to 15%, while if it needs as dull it shall be decreased up to 5%. Note that with Whack Ratio over 15%, no problems occurred but the wheel has quick wear because too much dressed, while with a Whack Ratio below 5% the wheel loses its cutting ability because of an excessive blunt of abrasive grain with associated risk of workpiece burns.

Dressing Overlap Ratio is a very important control parameter of dressing operation. Dressing Overlap Ratio (U_d) is the number of times each abrasive grain touches the dressing diamond (see Fig. 38). This depends on the traverse feed of the diamond across the face of the wheel.

For single point dressing, max diamond flat width b_d is 0,5 mm.

v_{fd} is the axial feed of the tool across the grinding wheel.

Recommended traverse feed (v_{fd}) is given by the following formula:

$$v_{fd}\left[\frac{mm}{min}\right] = \frac{b_d \times Wheel\ RPM}{U_d}$$

As the traverse feed increases, the dressing pitch increases and also the sharpness of the wheel, but machining precision gets worse. Vice versa, as the speed decreases, machining precision improves but it becomes more prone to knead and cutting ability decreases.

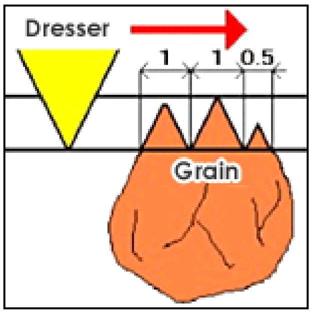


Fig. 38 Dressing traverse feed (rough grinding wheel)

Fig. 39 shows the relations between dressing depth (a_{ed}) and traverse feed (v_{fd}) and the resultant wheel surface.

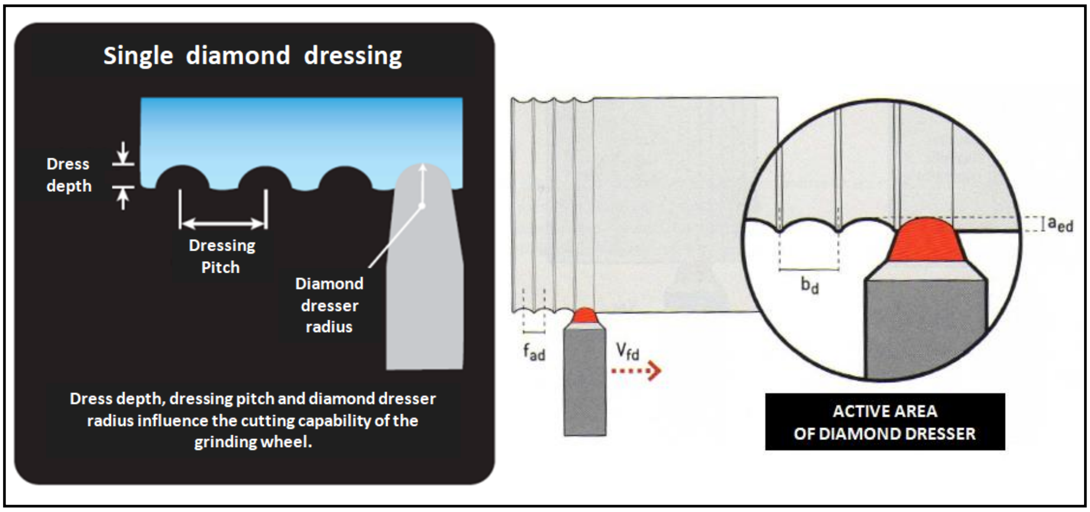


Fig. 39 Dressing parameters and active area of single diamond dresser

Typical values for Dressing Overlap factor are listed in Tab. 13.

Grinding Operation	U_d
Rough grinding	2 - 4
Semi-finish grinding	4 - 8
Finish grinding	8 - 16

Tab. 13 Dressing Overlap factor reference values

After a dressing, the grinding wheel is renewed with sharp grains and it cuts efficiently. The dressing is also needed to set-up the grinding wheel before grinding to avoid unbalance of the wheel and to optimize its cutting ability. This operation may also include the grinding wheel profiling to a desired shape. The dressing has the purpose of creating on the grinding wheel a specific topography in the active surface in order to obtain the desired cutting edge.
A quick dressing with high traverse feed could create on the grinding wheel a more wrinkled surface (Fig. 40). The dressing is often underestimated, it should be performed accurately. A renewed wheel well-dressed can also facilitate the coolant flow on the grinding wheel. The wear of the diamond needs to be checked because it leads to a dull wheel dressing which could result in a non-cutting grinding wheel even immediately after few cuttings. Therefore, the dressing diamond should be replaced frequently to keep its dressing capacity unchanged.

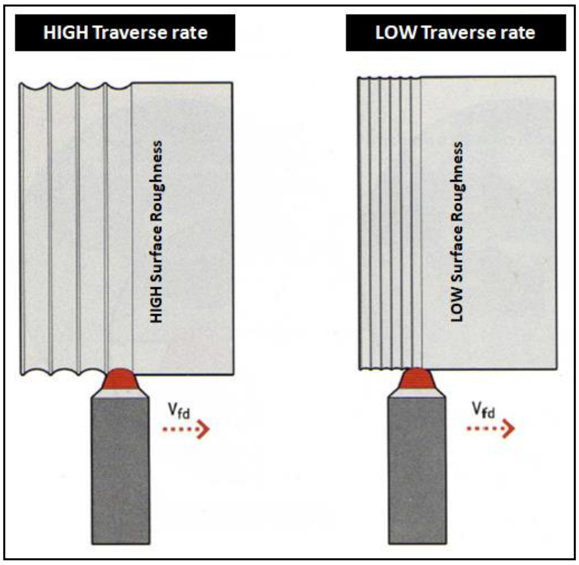


Fig. 40 Influence of dressing traverse feed on surface roughness

A dressing with diamond roll (Fig. 41) consists of a metal rollers tools in which diamond grains are embedded. They are mostly used to dress profiled wheel.
The use of diamond rolls is more complex because there are more parameters to consider. The diamond rolls can work at several speeds ratio with respect to the grinding wheel and can rotate concordant or discordant direction with respect to wheel rotation (conventionally this condition is referred to the contact area and not to the direction of rotation).
The dressing roll speed ratio is given by:

$$q_d = \frac{v_{rd}}{v_c}$$

where v_{rd} is the roll peripheral speed and v_c is the peripheral speed of the wheel.

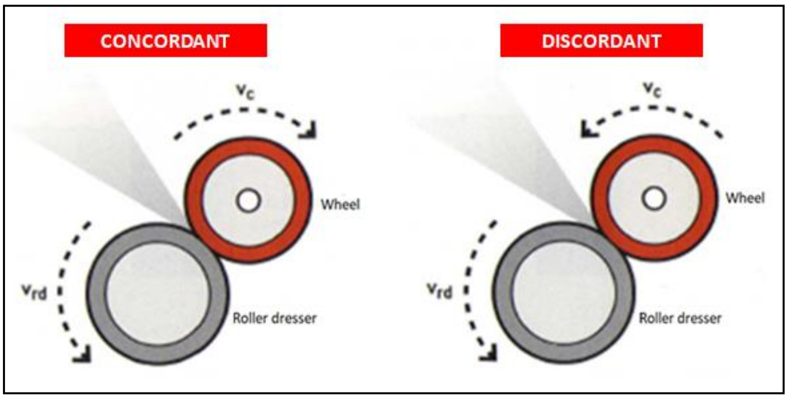


Fig. 41 Concordant or discordant dressing direction in the cutting area

Fig. 42 shows the relation of the wheel sharpness and the relative dressing forces as a function of the speed ratio settings.

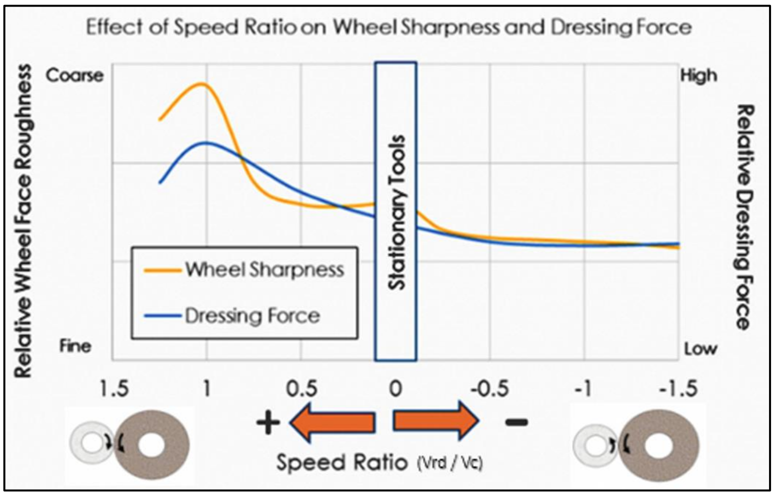


Fig. 42 Dressing speed ratio correlations

You can see that the wheel face roughness gradually increases when moving from the negative speed ratio to the positive speed ratio (right to left). This means that a grinding wheel dressed at positive speed ratio (concordant movement) will be sharper and more open than a wheel dressed at negative speed ratio (discordant movement).
As a result a sharper wheel will grind at lower power and force and, therefore, with high productivity and less risk of burn, but with a coarser surface finish on the workpiece. On the contrary, a dull wheel will typically grind at higher power and forces, with more risk of material damage (burn) but with a finer result in workpiece surface finish.
Typically the recommended dressing speed ratio (q_d) range for conventional abrasive vitrified wheels is from + 0.2 to + 0.8.
The wear of the grinding wheel is influenced by the process conditions but also by the composition of the workpiece steel. The grinding of high-alloy steels with their high hardness and hard carbide content leads to the rapid grinding wheel wear and higher power absorption. For example, grinding high-alloy steels rise to power absorption about equal to those of grinding low-alloy steels with a worn wheel.
Wheel self-balancing conditions are critical for grinding wheel, the unbalance occurs when the forces acting on the abrasive grains reach a critical point and the wear of the grinding wheel becomes extremely fast and discontinuous. At this point the grinding wheel "collapses" (Fig. 43) losing its roundness and causing vibrations, resulting in bad surface quality workpiece and risk of burns. The grinding becomes unstable and it must be interrupted. To prevent that it occurs, the wheel must be early dressed.

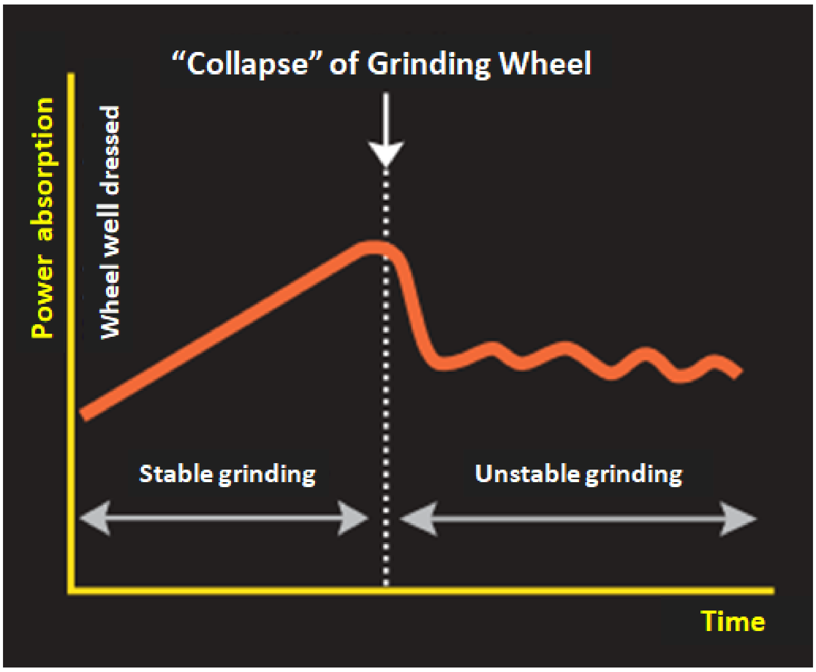


Fig. 43 Power absorption as a function of time, wheel collapse

1.6. Grinding abuses

Typically, grinding is used for finish machining of hardened steel components. However, attention needs to be focused on preventing 'grinding burns', this phenomenon happens when the workpiece temperature becomes high enough to change the material microstructure.

Grinding is particularly applied in precision aerospace components such as gas turbine engine gears made by nickel-chromium-molybdenum, a case hardening steel, with hardness of 58-62 HRC. These gears belong to power or accessory gearboxes, driven by the turbine engine through a gear train, and transmit the power to the propeller (turboprop engine, geared turbofan or helicopters application) or to the major engine accessories, such as fuel and oil pumps. Any gear failure could be therefore catastrophic. Accordingly, the quality acceptance is very high, and each gear is subjected to non-destructive testing after the final grinding operation to reveal any grinding abuse in the form of softening and/or hardening.

In some cases Nital penetrant inspection reveals white areas associated with the dark-etching areas, that are indications of grind hardening due to changes in the microstructure caused by over-tempering. Gears showing evidence of grinding abuse are rejected, and because of high rejection rate the present study has the objective to reduce non-conformance costs resultant from the gear high cost, sometimes up to thousand euros each. Non-optimized grinding can lead to thermal damage of a ground part generically called "Grinding burn".

Grinding is a process where a lot of frictional energy is concentrated in the cutting region, resulting in a local rise of temperature in the surface confined to the surface layers of the part being ground.

Depending on the increase in temperature and consequent damage in the microstructure, thermal damages are classified in four categories (Fig. 44):

- type 1: Oxidation burn
- type 2: Thermal softening
- type 3: Residual tensile stress
- type 4: Re-hardening burn

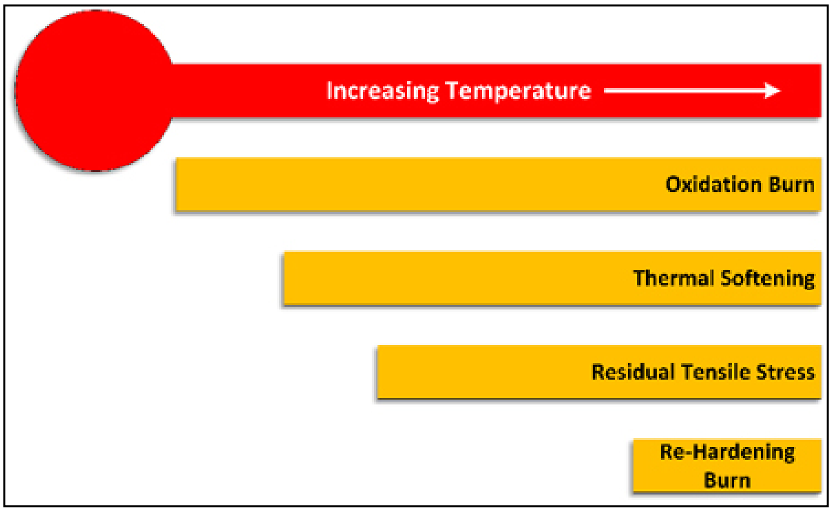


Fig. 44 Different types of thermal damage and temperatures

The oxidation burn (Fig. 45) is first of all a discoloration of the workpiece, typically blue on the part surface, this is due to an oxide that changes colors as the part is heated. The discoloration color indicates the temperature reached on the part. Oxidation burn is observed on the ground surface and in adjacent areas and it indicates high temperature generated in grinding.

It can also occur on a non-ground zone close to the cutting area where temperatures are high by thermal conduction. Sometimes oxidation is a purely "cosmetic" phenomenon and occurs without real metallurgical damage to the workpiece, in fact it is usually more frequent at high temperatures, but it does not indicate the presence or not of other thermal damage.

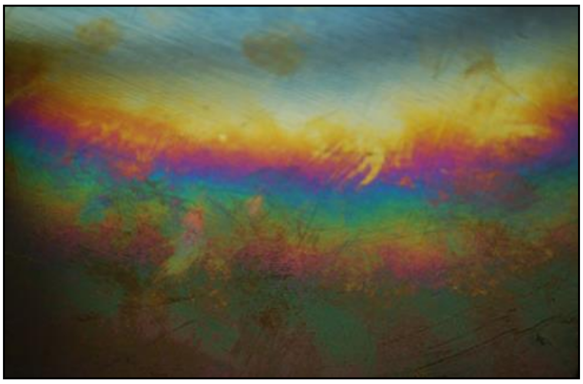


Fig. 45 Typical oxidation discoloration

The thermal re-hardening occurs when the grinding temperature exceeds the tempering temperature, producing a mixture of non-tempered and tempered martensite in the surface layer resulting in a reduction in the hardness of the surface.

The surface exhibits a high hardness due to the untempered martensite.

An over-tempered zone occurs just below the surface, where the hardness is lower than the basic hardness of the workpiece. Very high stresses arise in the material, sometimes leading to formation of cracks (Fig. 46).

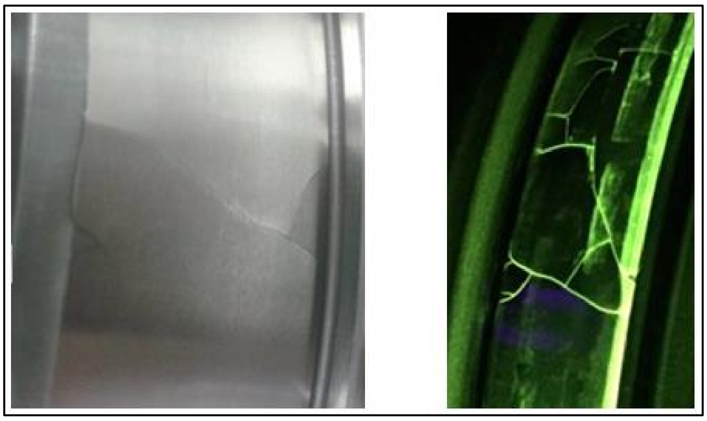


Fig. 46 Cracks on a bearing raceway

Fig. 47 is a diagram showing how the re-hardening impacts the hardness of a ground surface related to its depth. On the left the red area represents the stock material affected by re-hardening, its thickness could be around 0,1 mm with an increased hardness. Then in the middle in yellow is the surface layer with a depth between 0,1 and 0,4 mm in which tempering happens, resulting in thermal softening (reduced hardness). On the right the green area represents the material stock unaffected by thermal softening (undamaged material). If re-hardening phase does not occur, the inefficient grinding process leads to thermal softening and the red area of the diagram is not significant.

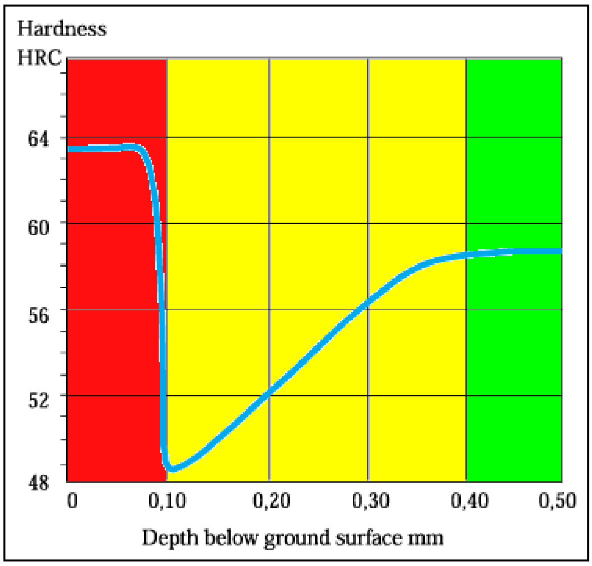


Fig. 47 Hardness as a function of depth in thermal damage

In grinding the plastic deformation of the workpiece surface material, as consequence to the action of the abrasive grains, leaves the surface in a state of residual compressive stress. Similarly to the known "shot peening", this mechanical effect can improve the mechanical properties of the workpiece, in particular the fatigue strength.
The tensile residual stress is due to thermal stress exceeding the yield stress when the part is locally heated, the surface layer expands, but it is constrained by the lower undisturbed material. Compressive residual stress occurs at the surface when the part cools, the surface layer contracts due to thermal contraction, resulting in an opposite stress. This expansion and compression phenomenon can result in locally high residual stresses that can exceed the ultimate tensile strength. This is known as re-hardening burn or cracking (Fig. 48) even if burning can occur without cracks. In moderate cases, the tensile residual stress has the only effect of negatively affecting the workpiece life, reducing the fatigue life of an in-service part.
However, if the process is "pushed" beyond limits to obtain higher productivity, grinding produces high tensile residual stress.

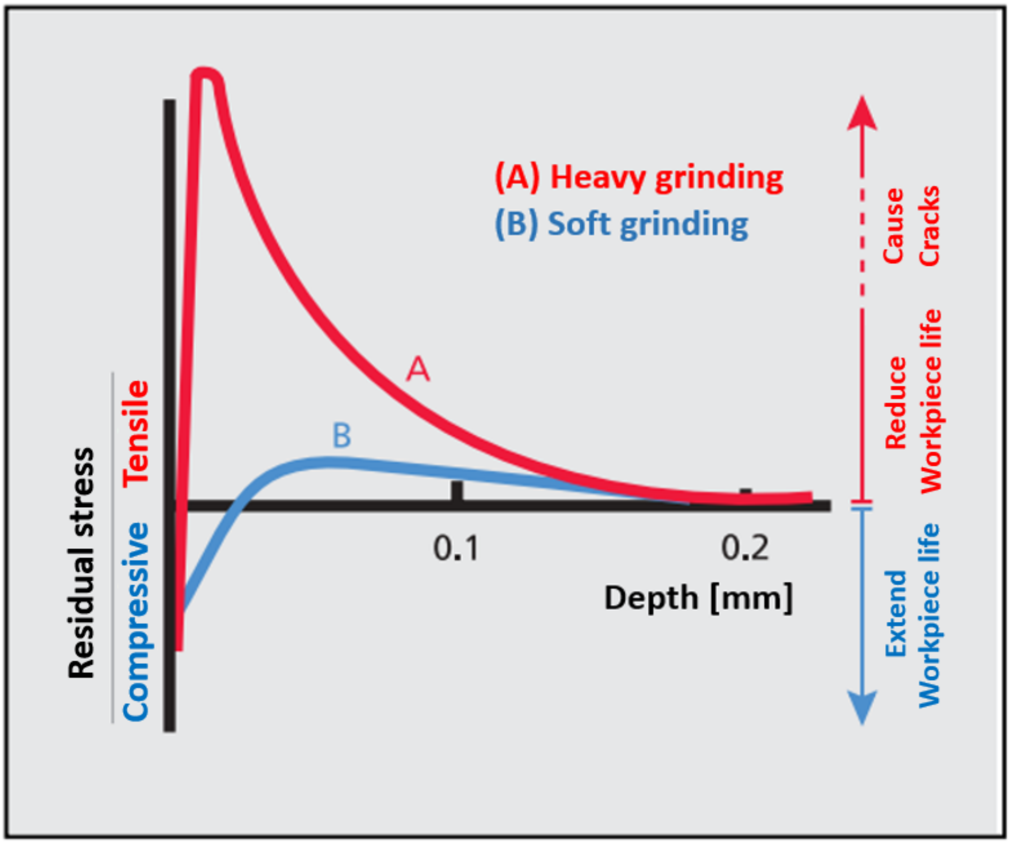


Fig. 48 Residual stress according to the depth under the workpiece surface

1.7. Grinding coolant

The grinding process generates a lot of heating in the cutting area, this means a high percentage of heat initially enters into the workpiece before coolant relieves it. Unless the coolant is applied correctly grinding can lead to undesirable re-hardening burn, thermal softening and tensile residual stresses damaging the workpiece. The containment of the temperature in the cutting area with the grinding wheel is really challenging. It can be achieved by reducing originated heat with appropriate grinding parameters including accurate wheel choice and by reducing temperature by an efficient cooling. Even in the best cooling conditions, pursuing high productivity always increase the risk of thermal damage.

Sometimes the burning problems are simply correlated to grinding speeds and feeds, but poor cooling leads surely to a workpiece damage.

The heat transferred to the workpiece during grinding should be minimized as much as possible, in Fig. 49 you can see the difference between an efficient cooling and a poor cooling system.

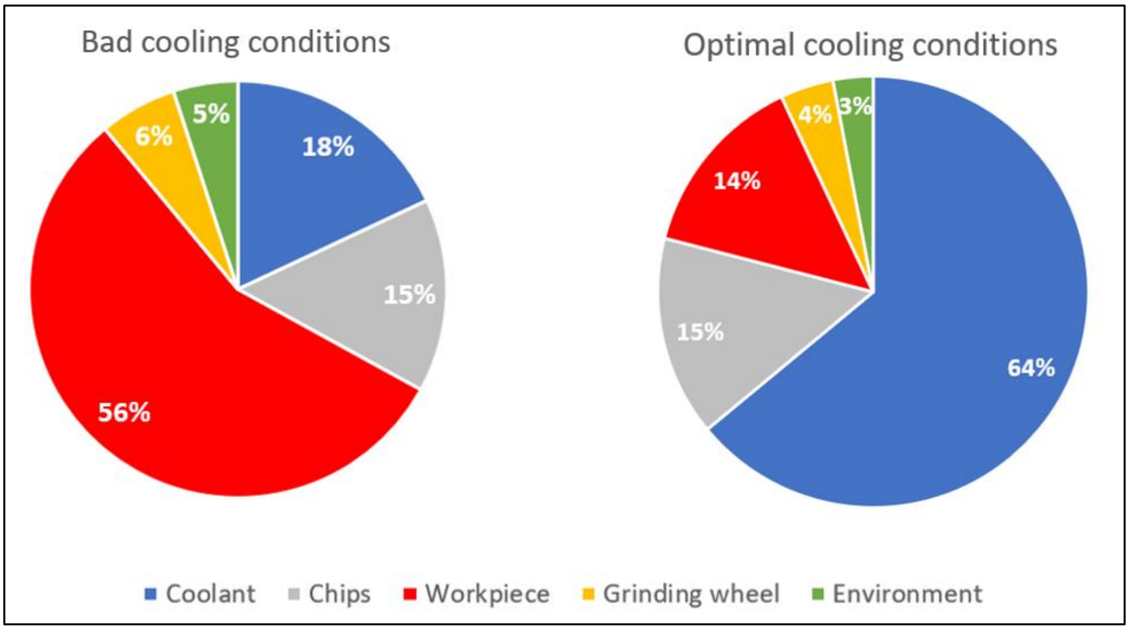


Fig. 49 Heat dispersion during grinding

Fluid is very important in the grinding process because its lubricant action reduces the heat generated by friction and at the same time it removes heat from the cutting area acting as a coolant and also improving hot chips evacuation.

In general, water-based emulsions ensure good cooling but limited lubrication while cutting oils ensure excellent lubrication but limited cooling. Emulsions are often preferred for this reason. The efficiency of the cooling is not just a matter of bathing the cutting area with fluid, but its application has to be engineered properly using the correct type and number of coolant nozzles and their proper orientation (Fig. 50).

Fig. 50 Typical coolant application

Good cooling methods deliver coolant fluid exactly to the point of cut, in the correct volume, and at the proper velocity. Because grinding wheel reaches high peripheral speeds, wheel produces a boundary layer of air surrounding its cutting surface. This air barrier can deflect coolant from the grinding zone unless the pressure is enough for the coolant to allow the fluid to wet the wheel and the workpiece penetrating this barrier. Examining the arc of cutting contact you could observe that if the portion of the circumference of the grinding wheel in contact with the workpiece is longer, the cooling is more critical.
The "hot-spot" in Fig. 51 is the portion of the wheel-to-workpiece cutting area where the temperature reaches the maximum value. The efficiency of the cooling depends on the capability of the coolant to penetrate into this hot-spot area.

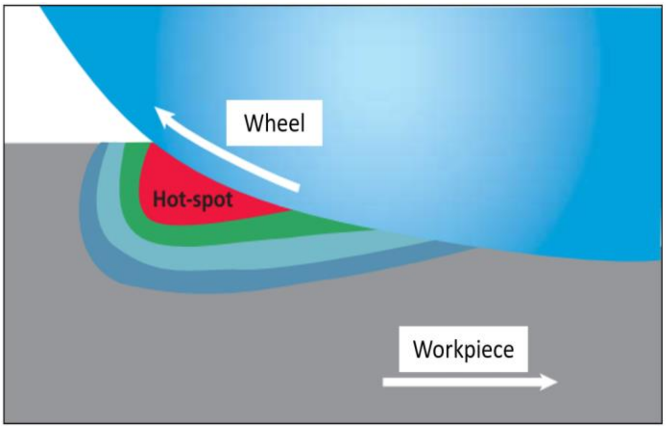


Fig. 51 Hot-spot in contact area between wheel and workpiece

This means that an appropriate shaped delivery nozzle is very important to direct efficiently the coolant at the proper speed. On the other hand, high speeds require high pressure (Fig. 52) and the nozzle shall be designed with an output section properly shaped with the aim to accelerate fluid at the desired speed, for instance a nozzle section too large causes a pressure drop in the system and a lower exit speed. An alternative technique is to force the liquid into the porosity of the grinding wheel so that the centrifugal force pushes the fluid toward the workpiece in the hot-spot zone. However, this option is achievable only with grinding wheel with high porosity binder and may require additional power in the system.

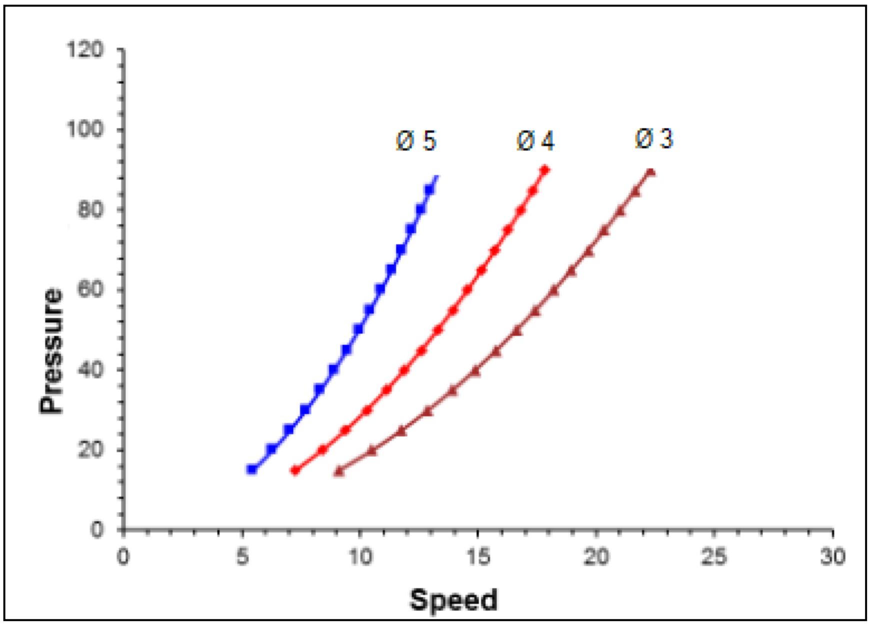


Fig. 52 Refrigerant pressure required

2. Grinding process control methods to detect abuses

Grinding abuses, such as burns as the extreme consequence, may occur during the grinding process of case hardened steel as widely explained.
Basically grinding burn is a thermal damage of a ground part caused by an incorrect grinding process, it happens if a local heat is too high to generate local tempered or even re-hardened zones.
Grinding thermal damages will shorten the fatigue life and can cause severe failures in critical components.
Different methods are applied to detect grinding burns on workpiece ground and should be integrated with in-process methods to prevent burns, monitoring the grinding process.
A Non-Destructive Testing (NDT) is preferred because it does not permanently alter the part to be inspected.
Commonly applied methods for grinding burns detection are:

1. Liquid Penetrant Inspection (LPI) also called Dye-Penetrant Inspection
2. Magnetic Particle Inspection (MPI)
3. Nital etching
4. Eddy-Current
5. Barkhausen noise
6. X-Ray Diffraction
7. Micro-Hardness Testing and analysis of microstructural sections

Since this thesis aims to explore widely the grinding process, just a short description of the above methods is provided.

2.1. Liquid Penetrant Inspection (LPI)

Liquid Penetrant Inspection is a Non-Destructive Testing method that is used to reveal surface cracks by a colored or fluorescent dye.
It is based on capillary action, the ability of a liquid to be drawn into a "clean" surface breaking flaw. After adequate penetration time, the excess of penetrant is removed, and a developer is applied. The developer with its draw action allows the indication to become visible to the inspector. Inspection is performed under ultraviolet or white light, depending upon the type of dye used. Due to the physical features of the eye, there is a threshold below which objects cannot be resolved. This threshold of visual acuity is around 0,09 mm for a person with 20/20 vision.
Liquid Penetrant Inspection can only detect severe grinding damages that lead to a rupture of the case hardened surface with evidence of micro cracks.

LPI comprises the following steps (Fig. 53):

1. Surface Preparation and Penetrant Application. Once the surface has been thoroughly cleaned and dried, the penetrant material is applied by spraying, brushing, or immersing the part in a penetrant bath.
2. Excess Penetrant Removal. After penetrant dwell, the excess penetrant must be removed from the surface of the sample, this step may involve cleaning with a solvent, direct rinsing with water, or first treating the part with an emulsifier and then rinsing with water.
3. Developer Application. A thin layer of developer is then applied to the sample to draw penetrant trapped in flaws back to the surface where it will be visible.
4. Inspection and cleaning. Inspection is then performed under appropriate lighting to detect indications from any flaws which may be present.

The final step in the process is to thoroughly clean the part surface to remove the developer from the parts that were found to be acceptable.

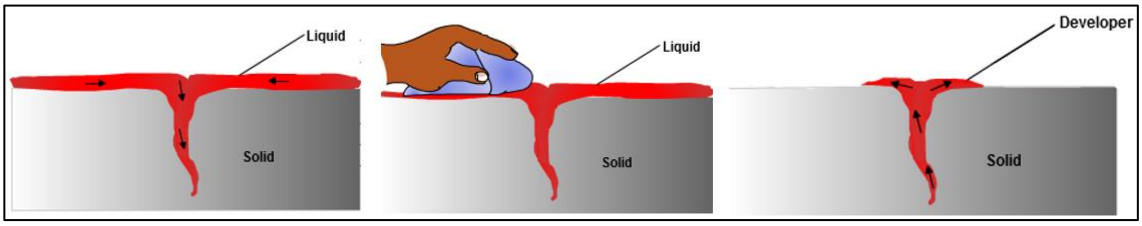


Fig. 53 Liquid Penetrant Inspection preparation steps

2.2. Magnetic Particle Inspection (MPI)

The magnetic particle control is a non-destructive test method particularly effective to detect surface discontinuities in ferromagnetic materials. The control with magnetic particles is able to detect surface cracks and therefore is suitable to inspect severe grinding abuse that lead to a rupture of the case hardened surface with evidence of micro-cracks.

This technique uses the principle, that during the magnetization of a ferromagnetic material, the magnetic lines of force pass through this medium magnetically conductive. If the lines of magnetic flux affecting an area with different magnetic permeability as a discontinuity close to the surface, a part of these lines of flux is deflected and flows out above the surface of the material giving rise to the indication that becomes detectable for the inspector.

Magnetic particle inspection can be performed using particles that are highly visible under white light conditions or particles that are highly visible under ultraviolet light conditions.

When fluorescent particles are used, special ultraviolet light must be used.

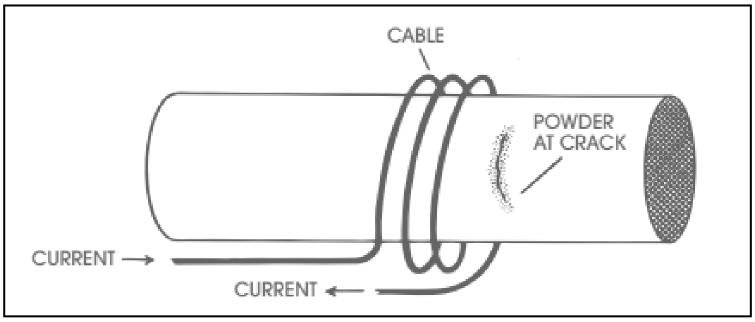


Fig. 54 Schematic Magnetic Particle Inspection

The magnetic particle inspection can be performed with the dry or wet powders. The powders have a magnetic permeability with a relatively low rate of residual magnetism, so that you keep attached to the material as long as the magnetic action is applied.

Fig. 55 MPI Testing equipment

2.3. Nital Etching

Nital Etching is a Temper Etch Inspection performed by chemically etching component surface with a solution of nitric acid in alcohol or water. The etched surface is examined visually to detect detrimental microstructural modifications (e.g. untempered martensite) that result from overheating during improper surface grinding.
There are several disadvantages using Nital etching.

Nital Etching is treated as a non-destructive testing procedure, but it inducts corrosion to the workpiece reducing its size approximately 0,003 mm, as a consequence any portion of the part that requires a tight tolerance which should not be exposed to Nital etching must be masked. A second disadvantage is the resulting appearance areas of discoloration as a result of Nital etching, these areas can be processed for removing the discoloration, but this action may cause stock removal or surface texture changes.
On the other hand, Nital etching is currently considered the industry standard for inspecting grinding burns.

Nital etching comprises the following steps:

1. Cleaning the workpiece and then dipping in 3% - 5% solution of nitric acid then rinsing with water and dipping in alcohol
2. Bleaching with hydrochloric acid in 4% - 6% alcohol or water
3. Rinsing again with water, neutralizing with an alkali solution
4. Rinsing a third time with water, dipping in alcohol; and applying an oil with rust preventative
5. Visually inspected for evidence of grinding burns under a light source of 2150 lux minimum

Grinding burns become evident with a dark gray, blue, or black appearance, light gray or light brown appearance could not be sign of burns.

Fig. 56 Nital Testing equipment

2.4. Eddy-Current Testing (ECT)

Eddy-Current Testing is one of many electromagnetic testing methods used in non-destructive testing (NDT) using electromagnetic induction to detect and characterize surface and sub-surface flaws.
Basically an ECT probe has a coil of conductive wire excited by an alternating electrical current. The alternating magnetic field produced by the coil around itself, when the coil approaches a conductive material, induces opposed currents in the checked material.
Variations in the electrical conductivity and magnetic permeability of the object to be tested cause a change in eddy current detecting the presence of defects.
Advantage of this type of testing are: no need for direct contact with the tested object, faster inspections with wide coverage, less operator - more automation, good detection and reliability.

Fig. 57 Eddy-Current Testing equipment

2.5. Barkhausen Noise

The nature of Barkhausen Noise was explained in 1919 by Prof. Heinrich Barkhausen. However, attention for its industrial applications begins in the 1980s.
Today, Barkhausen Noise Analysis (BNA) is applied as non-destructive method for materials characterization and heat treatment defect testing.
BNA is based on inductive measurement of a noise-like signal, generated when a magnetic field is applied to a ferromagnet.

In the absence of a magnetic field, magnetic domains are randomly oriented.
If the ferromagnet is subjected to a magnetic field, the magnetic domains tend to align themselves in the direction of the magnetic field.
When the magnetic field is applied, all the magnetic domains become parallel to the applied magnetic field by orienting themselves.
When applied magnetization becomes zero again, not all the magnetic domains are able to go back to their initial alignments. Pinning sites which are precipitates, grain boundaries, inclusions, dislocations and small volumes of second phase material, slow down the domain wall movement. The changes in the magnetization induce electrical pulses, which generate a noise-like signal called Barkhausen noise heard from the speaker used in the original experiment.
The intensity of the Barkhausen Noise signal depends on number of Barkhausen jumps which is directly related with the presence of impurities or material defects, therefore, the Barkhausen Noise can be used as a method of non-destructive evaluation of the degradation of mechanical properties in magnetic materials.

Fig. 58 Barkhausen Noise Testing equipment

2.6. X-Ray Diffraction

X-ray diffraction was explained the first time by English physicists Sir W.H. Bragg and his son Sir W.L. Bragg in 1913.
The Braggs were awarded the Nobel Prize in physics in 1915 for their work in determining the relationship between X-ray reflection with a certain angle of incidence and the atomic or molecular structures of a crystal of interest.
X-ray diffraction method allows us to calculate details about the crystal structure, the relation between the spacing of atomic planes and the angles of incidence at which these planes produce the most intense reflections of electromagnetic radiations, such as X rays and gamma rays.

X-ray diffraction (XRD) is a well-established and accurate method to investigate the residual stress levels on the surface layers of crystalline materials.
Non-destructive measurement of residual stresses in crystalline materials can be measured to a maximum depth of about 0,05 mm.
Layer removal such as etching is required for deeper measurements, making this method a form of destructive testing, in fact residual stresses are rarely completely described by a surface measurement alone, so to completely characterize the generated residual stress analysis, X-ray diffraction must be repeated at various depths.

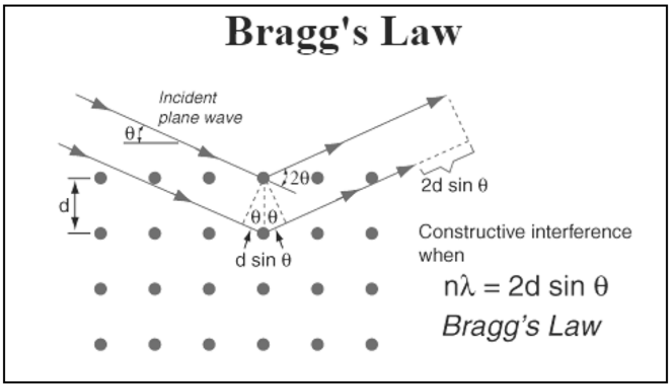


Fig. 59 X-Ray Diffraction law

The measurement of residual stresses allows engineers to understand fully the residual stress profile in the treated metallic components.
Thus, an accurate residual stress measurement is important in the design and quality control of mechanical or thermal treatment processes for metal components.

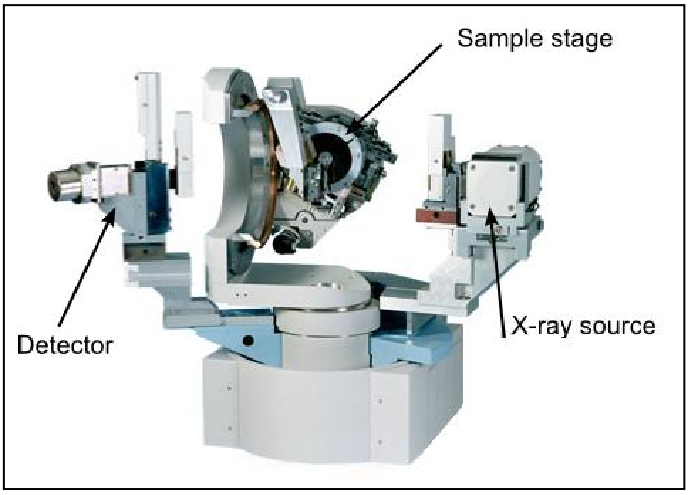


Fig. 60 X-Ray Diffraction Testing equipment

2.7. Micro-Hardness Testing and metallographic microstructure analysis

Superficial burning has always associated alteration of the microstructure of the ground material. From the accomplishment of micro-hardness measurements in case hardness steel subsurface, it has been observed the superficial burning induced by the grinding process is accompanied by a re-austenitization process of the material. Re-hardening of the material occurs, when the re-austenitization is associated with formation of untempered martensite. This can be found through the metallographic analysis, resulting in the increase of the surface micro-hardness.
Metallurgic evidences and measurements of micro-hardness suggest that the visible burn threshold is coincident with the onset of the austenitization.
In adjacent areas of the mentioned material, there usually exists a softening because temperatures below the austenitization have been reached.
The micro-hardness test is a destructive test, because is performed on samples that have been obtained from the workpiece and metallographically prepared.
These specimens are prepared using a mounting press to include the workpiece sample in a cylinder of phenolic, acrylic or polyester resin, the surface to be inspected will be accurately ground and polished. The micro-hardness test can measure surface to core hardness on carburized or case hardened parts (case depths), as well as surface conditions such as grinding burns, carburization or decarburization.
Micro Hardness Tester is a complex mix of Mechanics, Optics and Electronics machine.

Fig. 61 Micro-Hardness Testing equipment

3. Cylindrical grinding of case hardened steel surfaces

This study is focused on cylindrical grinding of case hardened steel surfaces of aeronautical gears with the aim to define optimal grinding strategy and the related set of safe process parameters to avoid risk of grinding abuses that could cause scraps.

3.1. The aeronautical gearbox and its gears

A gearbox is a transmission system based on gears train providing speed and torque conversion from a rotating power source to another device, usually reducing the higher engine speed to a lower speed, increasing the torque in this process.
In particular this happens in turbine propeller engine (turboprop), where the propeller turns much slower than the driving turbine shaft (e.g. 2000 RPM vs 30000 RPM, see Fig. 62).

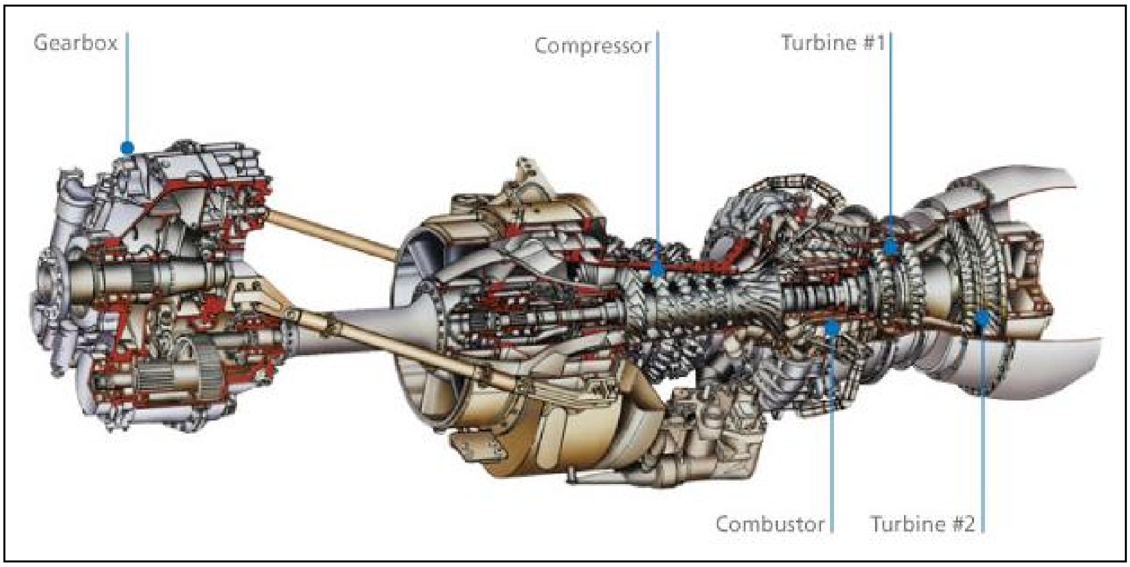


Fig. 62 Turboprop engine

An aeronautical gearbox could be classified, with respect its function:

- drive aircraft propeller or helicopter rotor (power transmission gearbox, Fig. 63)
- drive the accessories (accessory drive gearbox, Fig. 64)

A gearbox consists of a housing, usually divided in two or more parts that provide support for the gear drive assembly that transfers power from the engine to external propeller/rotor or to engine accessories. The main mechanical components of the drive gear assembly are gears, shafts, bearings and some other parts like seals, lubricant nozzles, keys, bolts, nuts, elastic rings and so on.

The housing has also the functions as an oil container and gives passageway for lubrication of the gear drive assembly.
The gears have a crucial role in transmission system therefore their quality is very important for the lifetime and consequently maintenance of the gearbox.
The design of transmission gears requires high knowledge and it is a balance between various requirements and restrictive constraints.
Although gearbox is not part of the engine's core, it is one of the most critical components of a gas turbine engine either it drives a propeller/rotor or many accessory devices.

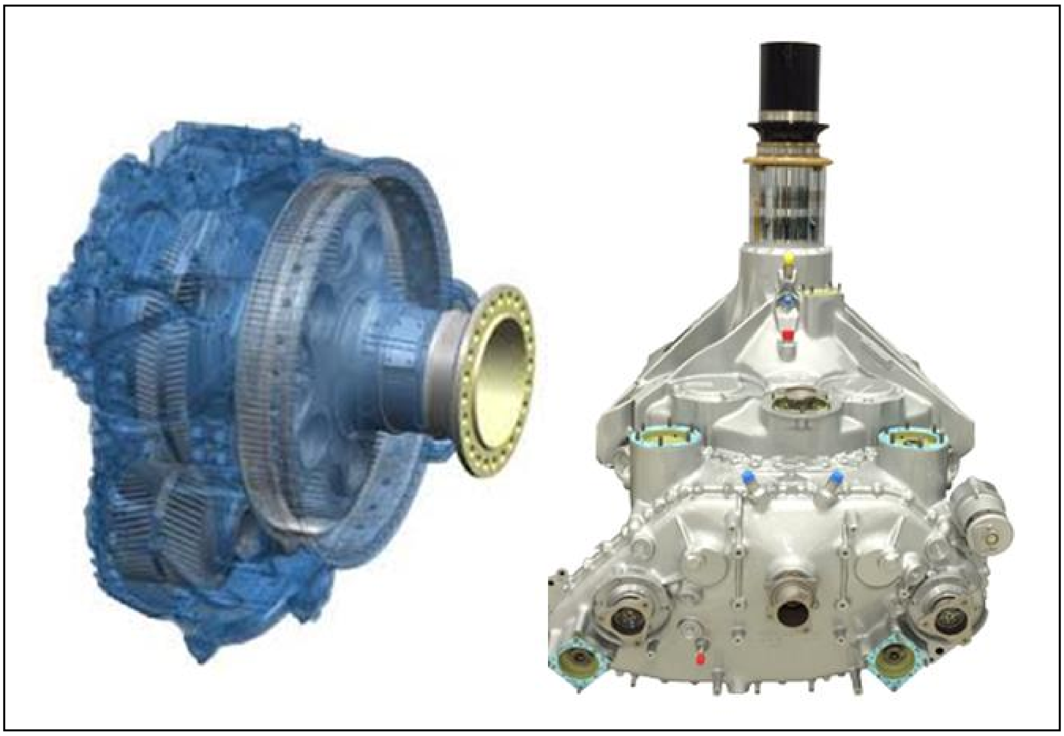


Fig. 63 Power transmission gearbox (aircraft and helicopter)

In helicopter gearboxes could be completely integrated merging the engine accessory gearbox, the main rotor gearbox (main rotor transmission) and the tail rotor gearbox.
In the helicopter this gearbox system is not redundant, and its failure will result, in most cases catastrophic, in fact it leads to a complete loss of control of the helicopter, rarely a nice safe auto rotation action avoids an ending in a crash.
In aircraft turboprop power transmission gearbox failure is a serious accident especially in mono rotor where an In-Flight Shutdown (IFSD) could lead to a loss of the aircraft.
The accessory gearbox (Fig. 64) plays a vital role in the total operation of the turbine engine, all the accessories have a symbiotic relationship between themselves and the engine and the gearbox are figuratively the center of this relationship.

A serious accessory gearbox failure leads to IFSD and consequently an emergency landing. Any failure shall be investigated according to airworthiness regulation and as a worst consequence the entire fleet could be ground.

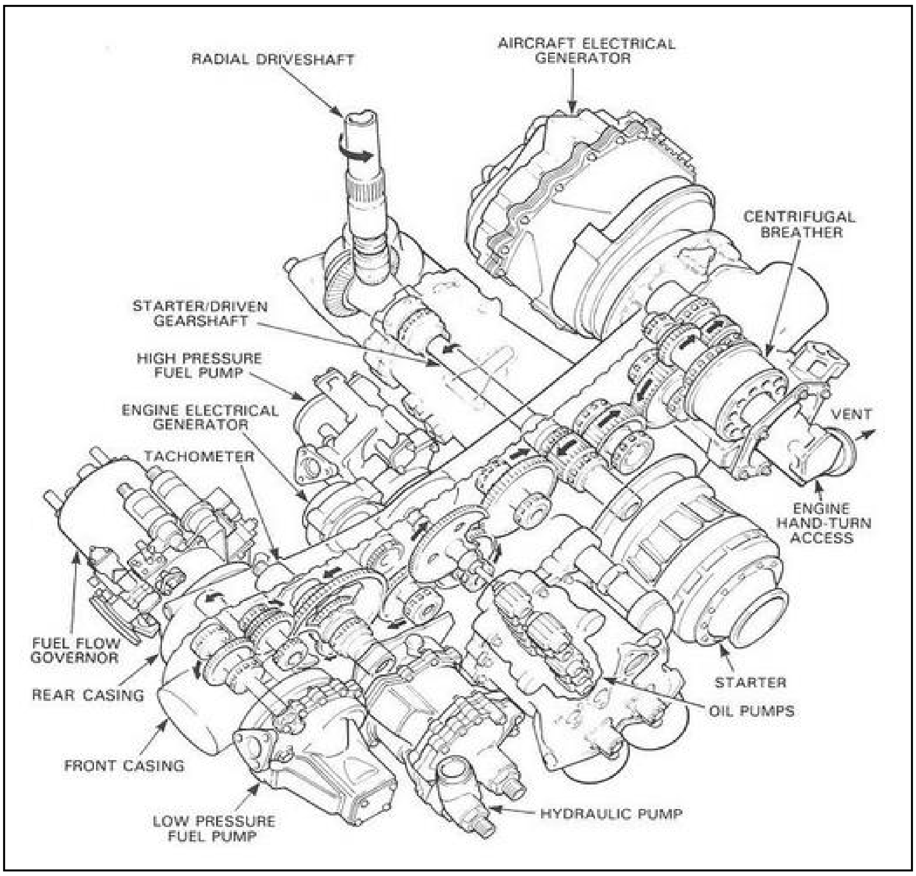


Fig. 64 Accessory drive gearbox exploded view

3.2. Gearshafts with integral bearing races

Typical gearbox gears are straddle mounted gearshafts. The terms “straddle design” means that the gear is provided with a shaft that extends from both sides of the toothed face to support the bearings. Unlike many other design, gearshafts with integral bearing races are assembled with bearings that not have any inner ring race because the inner race is machined directly into the shaft. Due to this design the gearshaft with integral bearing races are very compact with the advantage to reduce dimension and weight of the entire gearbox system.
Drawback of this solution are high costs because of the carburized and case hardened integral bearing race that requires high precision grinding.

This design is adopted mainly in turboprop reduction gearboxes or helicopter main gearboxes or military accessory gearboxes.
Fig. 65 shows on the left a bearing with its race mounted on the gearshaft, while on the right side the bearings do not have any inner race and the rolls are directly mounted on the gearshaft (integral bearing race).

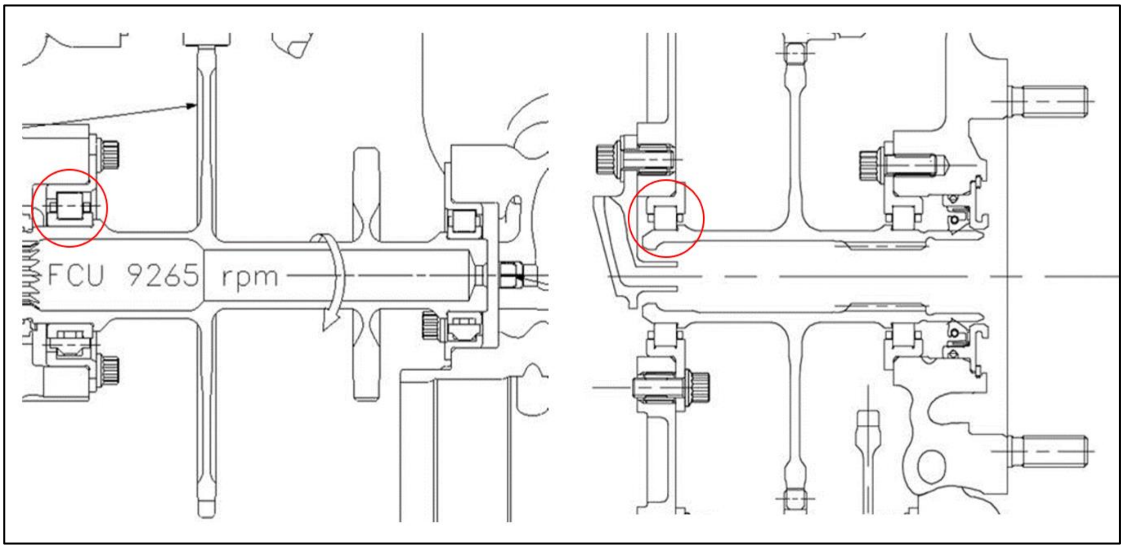


Fig. 65 Bearing race mounted on gearshaft vs integral bearing race gearshaft

In Fig. 66 an example of a gearshaft subject to the cylindrical grinding process.

Fig. 66 Gearshaft with ground diameter

3.3. Cylindrical grinding process of gears with integral bearing races

Gearshaft with integral bearing races includes a shaft with a housing to accommodate bearing rolls.

Machining of this integral bearing race that includes an abutment shoulder, requires peripheral grinding done by a tilted wheel, because the vertical sidewall must be tangentially ground to avoid scratches on it (Fig. 67).

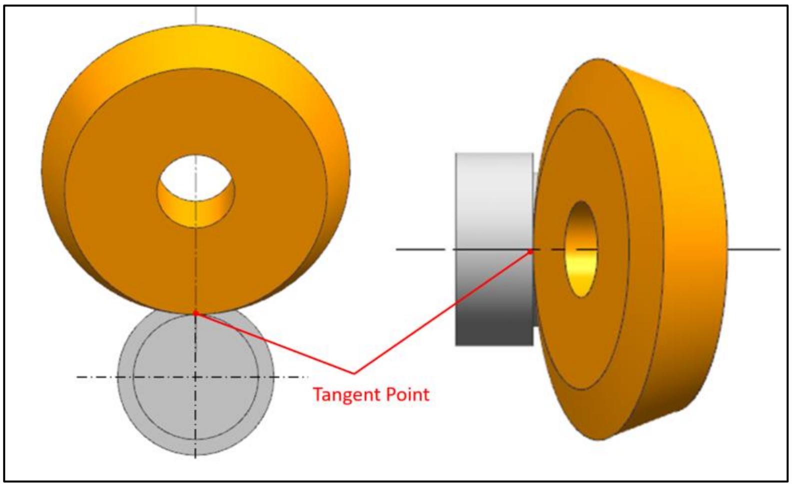


Fig. 67 Grinding Wheel tilting

Schematic cylindrical plunge grinding operation is shown in Fig. 68.

It can be observed the angle β, tilt of the grinding wheel axis with respect to the axis of the workpiece, the plunge angle α represents the feed in axial and radial direction, usually 45 degrees.

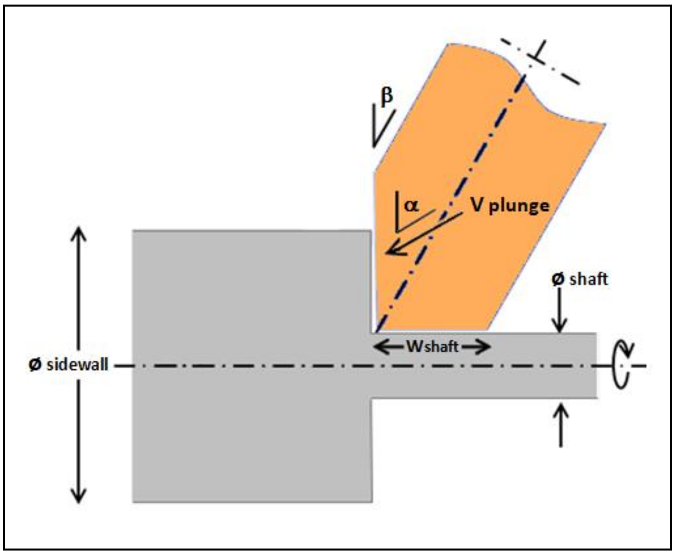


Fig. 68 Cylindrical plunge grinding

3.4. Traditional and CNC grinders

In aeronautical companies there are basically two types of machine for cylindrical plunge grinding:

- Traditional machines
- CNC machines

In the category of traditional grinders you can see a Fortuna machine in Fig. 69, while for the modern CNC category a Studer machine is in Fig. 70.

Fig. 69 Traditional grinding machine

The Fortuna technical machine requires big effort from operator, in terms of manual skill, knowledge and attention. While Studer S41 works with a CNC programme that reduce the actions needed by the operator. In particular the LCD display gives helps to the operator with feedback from the grinding by an in-process continuous check.
A curious feature of Fortuna grinder is the analogic button to control feed by a set of manual impulse.
Fig. 70 shows a typical CNC grinder.
The Studer S41 is a CNC universal cylindrical grinding machine of the latest generation. It boasts many technical features, such as the revolutionary Studer-Guide system with high-precision axis movements with linear motors, extremely fast direct drive spindle, an even a larger variant of grinding wheel type.
CNC programme includes all grinding parameters and all other actions repeated automatically by the grinder. Use of CNC grinder, if well set-up, ensures a more stable and repeatable process beneficial to product quality and productivity comparing to traditional grinders.

Fig. 70 S41 Studer

S41 Studer Technical data are:

- Centre height 225 / 275 mm
- Distance between centres 1000 / 1600 mm
- Max. workpiece weight between centres 250 kg
- Speed of X- and Z-axis 0,001 – 20000 mm/min
- Turret wheel-head with direct drive and 0.00005° resolution, up to four wheels
- C axis for the work head for form and thread grinding
- Full enclosure with two sliding doors
- Granite mineral-casting S103 machine base
- Reduced setup and resetting times with Studer Quick-Set
- Standardized interfaces for peripheral devices
- Studer-Guide system with linear drive
- Studer-GRIND software for writing grinding and dressing programs directly on board
- Very simple operation and programming (StuderWIN)

4. Database

4.1. Gearshaft P/Ns selection and process parameters

A careful selection of aeronautical gears P/Ns has been done, in order to gather data referred exclusively to grinding operations of case hardened steel surfaces, since this process is the most critical to workpiece burns. Therefore, the database includes exclusively the P/Ns with integral steel hardened bearing races.

Following this way nine gearshaft P/Ns have been identified as critical for this study. These gears belong to a same class material, carburized and case hardening steels (58-62 HRC), thus these items have been aggregated in a spreadsheet to be analyzed.

These gears have a high unit cost, some of them up to thousand euros. Therefore, you can easily understand the importance to define a process standard for cylindrical grinding, in order to better control this process and reduce the risk of grinding abuse due to a non-well controlled grinding, that can lead to undesired scraps and consequently economic loss.

Aim of this study is to establish the best grinding input parameters in terms of resulting quality and productivity. A precise input parameter definition is fundamental in programming of CNC grinders, but also traditional grinding process could benefit from this study identifying the critical to quality factors in grinding process.

Therefore, a definition of cylindrical grinding process standard for case hardened steel surfaces of aeronautical gears will help to better exploit the potentiality of innovative CNC machines including the in-process control of power monitoring.

Hence, the need to create firstly a robust and well-structured spreadsheet, to include all the peculiar items of the process in order to identify the grinding process as is.

The spreadsheet is split into five different blocks:

1. P/Ns to be machined and the related grinding operations
2. Grinding wheel characteristics
3. Dressing parameters
4. Machining input parameters
5. Control parameters

The following figures describe an example of semi-finish grinding operation, some cells are intentionally obscured according to Company not disclosure compliance rules.

Block1 of the spreadsheet (Fig. 71) includes on the left PN code, version code and grinder ID (machine plate). These 3 rows are relevant to 3 steps of an external semi-finish grinding operation of a gearshaft in Pyrowear53.

With reference to surface finish you can distinguish the grinding process in three distinct machining operations:

1. rough grinding
2. semi-finish grinding
3. finish grinding

The number of steps depends mostly on the type of grinder machine.
Traditional grinders because of the poor analogic control usually operate slower in a single step, while CNC grinders operate in two or more steps, the third step is usually needed to improve surface finishing required on integral bearing race, the surface finish requirement is achieved at the end step.
The first step is critical in terms of wheel-to-part approaching strategy starting the machining operation, while the end step is critical to obtain surface finish required (Ra requirement). The stock material is referred to the material removed (radial) in each machining step. The contact length is referred to the feature to be machined.

PN & OPERATION															
PN	Version Review	Grinder ID	Operation Number	Feature to be machined	Workpiece Material	Yield stress	Roughing Semi-finishing Finishing	External Internal	Machining Step	Radial/Axial	ø Initial	ø Final	Stock material removed	Contact lenght	Ra Workpiece Requirement
						MPa					mm	mm	mm	mm	µm
			610	Raceway	Pyrowear53		Semi-finishing	External	1	Radial	271,500	271,185	0,1575	36,5	
			610	Raceway	Pyrowear53		Semi-finishing	External	2	Radial	271,185	271,095	0,0450	36,5	
			610	Raceway	Pyrowear53		Semi-finishing	External	3	Radial	271,095	271,050	0,0225	36,5	0,4

Fig. 71 P/Ns and grinding operation data

Fig. 72 is an extract of the grinding wheel data, used in this grinding operation.
It tracks the wheel manufacturer, the Mesh number and its correlated average grit size, the shape classification, the abrasive abbreviated code, the binder type, grade and structure number. Moreover, the Ra range is the recommended achievable surface finish on the workpiece, depending on dressing parameters applied to the wheel.
The diameter and width are the geometrical data of the wheel, where the minimum diameter prescription indicates when the wheel shall be substituted with a new one of same characteristics. The minimum wheel width depends on the length of the cutting, that is the length of the feature to be machined.

GRINDING WHEEL DATA													
Manufacturer	Mesh Number	Grit Size	Shape	Abrasive	Wheel speed range	Grade	Structure	Binder	Ra Achievable	ø New Wheel	ø min	Wheel Width	Wheel Code
		µm			m/s				µm	mm	mm	mm	
KREBS	80	190	N	A	40-50	I	14	Ceramic	0,3 - 0,7	500	430	80	
KREBS	80	190	N	A	40-50	I	14	Ceramic	0,3 - 0,7	500	430	80	
KREBS	80	190	N	A	40-50	I	14	Ceramic	0,3 - 0,7	500	430	80	

Fig. 72 Grinding wheel data

Fig. 73 shows the dressing parameters block.
Dressing parameters impact on the grinding wheel behavior.
In this block are specified the peripheral wheel speed during dressing operation, the dressing depth and the traverse rate.
Note that dressing depth and traverse rate are referred to X axis and Z axis depending on feature to be worked. Dressing on X axis is referred to external wheel diameter consumed to grind the workpiece diameter. Dressing on Z axis is referred to the wheel flank if the grinding wheel has to machine an abutment shoulder.
The dressing operation shall be repeated one or more times (number of passes) depending on the wheel until it results with abrasive grains well sharp.
Moreover, the suitable diamond is tracked in relation to the prescribed wheel.

DRESSING PARAMETERS									
Peripheral Wheel Speed	Wheel RPM	Dressing Depth X axis	Dressing Depth Z axis	Traverse Time X axis	Traverse Time Z axis	Traverse rate X axis	Traverse rate Z axis	Diamond PN	Number of passes
m/s	RPM	mm	mm	s	s	mm/min	mm/min		
40	1527.89	0,015	0,0055	52.75	25.81	91	186		2
40	1527.89	0,015	0,055	52.75	25.81	91	186		2
40	1527.89	0	0	0	0	0	0		0

Fig. 73 Dressing parameters data

Fig. 74 is the block relevant to the machining input parameters as current process.
There are the peripheral speed of the workpiece and the rotation speed of the grinding wheel, the feed rate and the depth of cut. The feed-cutting angle, as shown in Fig. 68, not to be confused with the spindle angle.
Furthermore, it’s tracked the coolant flow (liters/min). In this example was prescribed the maximum coolant capacity of the grinder (100%) corresponding to 80 liters/min.

MACHINING PARAMETERS								
Workpiece RPM	Wheel RPM	Peripheral Workpiece Speed	Peripheral Wheel Speed	Depth of cut	Feed rate	Feed cutting angle (α)	Coolant flow rate	Cooling system utilization rate
rev/min	rev/min	m/s	m/s	mm/rev	mm/min	degree	l/min	%
23.26	1718.87	0,33	45	0,0028	0,065	45	80	100
23.26	1718.87	0,33	45	0,0017	0,039	45	80	100
23.26	1718.87	0,33	45	0,0011	0,026	45	80	100

Fig. 74 Machining parameters data

The last block (Fig. 75) includes control parameters.
These are calculated in order to check if the prescribed input parameters are consistent with the grinding best practice.

Control parameters are divided in two categories:

- Machining Control parameters (Speed Ratio, Aggressiveness and Grit Penetration Depth)
- Dressing Control parameters (Whack Ratio and Dressing Overlap Ratio)

CONTROL PARAMETERS				
Speed Ratio (q)	Aggressiveness	Grit Penetration Depth	Whack Ratio	Dressing Overlap Ratio
		μm	%	
136.36	24.58	1,181	7.89	8.39
136.36	19.16	1,042	7.89	8.39
136.36	15.41	0,935	0.00	0.00

Fig. 75 Control parameters data

A process parameters check could be done with Excel spreadsheet.
As an example, Fig. 76 and Fig. 77 show the results of an input check, in case of process control parameter cells highlighted in green, the check shows good results and process inputs are validated.

MACHINING PARAMETERS					
Workpiece RPM	Wheel RPM	Peripheral Workpiece Speed	Peripheral Wheel Speed	Depth of cut	Feed rate
rev/min	rev/min	m/s	m/s	mm/rev	mm/min
24.67	1833.46	0,35	48	0,0013	0,032
24.67	1833.46	0,35	48	0,0006	0,016
24.67	1833.46	0,35	48	0,0003	0,008

DRESSING PARAMETERS					
Peripheral Wheel Speed	Wheel RPM	Dressing Depth X axis	Traverse Time	Traverse rate X axis	Number of passes
m/s	RPM	mm	s	mm/min	
45	1718.87	0,015	57.83	83	1
45	1718.87	0	0	0	0
45	1718.87	0	0	0	0

CONTROL PARAMETERS				
Speed Ratio (q)	Aggressiveness	Grit Penetration Depth	Whack Ratio	Dressing Overlap Ratio
		μm	%	
137.14	19.79	0,865	11.84	10.35
137.14	13.99	0,727	0.00	0.00
137.14	9.89	0,612	0.00	0.00

Fig. 76 Process input verification using spreadsheet created (pass)

While, in Fig. 77 some control parameter cells are highlighted in red, therefore input parameters need to be reviewed.

MACHINING PARAMETERS					
Workpiece RPM	Wheel RPM	Peripheral Workpiece Speed	Peripheral Wheel Speed	Depth of cut	Feed rate
rev/min	rev/min	m/s	m/s	mm/rev	mm/min
79.64	795.78	0,58	25	0,0011	0,088
79.64	795.78	0,58	25	0,0006	0,048

DRESSING PARAMETERS					
Peripheral Wheel Speed	Wheel RPM	Dressing Depth X Axis	Traverse Time	Traverse rate X Axis	Number of passes
m/s	RPM	mm	s	mm/min	
25	795.78	0,03	40	60	1
25	795.78	0	0	0	0

CONTROL PARAMETERS				
Speed Ratio (q)	Aggressiveness	Grit Penetration Depth	Whack Ratio	Dressing Overlap Ratio
		µm	%	
43	72.60	2,34	11.84	6.63
43	53.62	2,01	0.00	0.00

Fig. 77 Process input verification (fail)

4.2. Gather process parameters

Process parameters have been gathered to capture the current process.
This was useful to me to understand in detail the grinding process and with the help of my Company's tutor the spreadsheet has been designed to give a quick look of cylindrical grinding process as is, in order to define a process standard.
In parallel to the thesis, I started writing a process specification for the Company about this argument.
To gather process parameters, I was joined to the Company's manufacturing team, whether thru the manufacturing management system or directly to the technical experts, like technologists, shop supervisors and machine operators.
At the beginning it was a hard job, I mean it was not really easy become familiar with the system and become friendly with the people in the shop.
I found most of the process parameters written in the process operation sheets stored in the Company's Product Data Management (PDM) and in parallel, with the precious support of the supply chain team, I was able to observe directly in the shop the grinding operations relevant to the identified part numbers asking to the operators and CNC programmers for any doubt about my comprehension of the process. Furthermore, for questions relevant to grinding wheel I met the tools procurement team and I really appreciated their suggestions.

4.3. Gather laboratory validation

Aeronautical significant process must be validated in compliance with the requirements defined by the design responsible. Validation is intended to ensure a product that meets the design requirements.

Usually technology validation includes geometrical and surface finish controls, material destructive controls (metallography cut-up, residual stress evaluation) and technical documentation (process operating data sheets). Technology validation is regulated by standard procedures that require retention of evidences in the Technological Substantiation package.

Typical evidences to support the validation of the grinding process are the residual stress measurements.

For all items these values are tracked in the spreadsheet from the laboratory validation records.

The residual stress is measured radially and axially (Fig. 78) on the case hardened steel of gearshafts having integral bearing races with X-ray diffraction method.

Fig. 78 Radial and axial measurement of residual stress

In Fig. 79 you can see the residual stress block.

A stress value below zero means compressive stress, that is the proper condition.

LABORATORY REPORTS	
Residual Stress Circumferential direction	Residual Stress Axial direction
MPa	MPa
-50	-410

Fig. 79 Laboratory Reports data (surface residual stress)

5. Analysis of cylindrical grinding process

In this chapter a careful analysis of grinding process has been carried out.
At first it analyses the database created and structured as described in the previous chapter, the second part is referred to machining and dressing strategy to be adopted and the last section has main focus on power and specific energy correlations with machining input parameters.
In particular the first step of the analysis is relevant to current grinding parameters of components examined in production during my experience in the Company.
No references to specific part number codes are reported according to Company compliance.
In the second part of this chapter machining and dressing strategy have been defined with the goal to have grinders that work effectively and safely to workpiece integrity.
In other words, a well-defined machining and dressing strategy should lead to high productivity and in the meantime to avoid grinding abuses.
That's the reason why a machining approaching strategy must not be underestimated.
The third part of this chapter has the purpose to present a grinding power model with a deep study of the grinding process and its correlation to burns with the effort to devise an in-process control method to prevent grinding burns.

5.1. Analysis of current process

In this section a complete analysis of correlations has been done to have a very deep understand of the current grinding process, hence the possibility to proceed with the modeling and optimization of the process and to define an experimental plan respectively debated in chapters 6 and 7.
This section has been split in two subsections:

- Current process input parameters
- Process control parameters

The current process input parameters and the process control parameters have been aggregated within Excel and Minitab spreadsheets to obtain an objective overall view of the current process.

5.1.1. Current process input parameters

Current process input parameters have been plotted in some graphs.
In our Company rough grinding is more similar to semi-finish grinding than literature rough grinding because of their parameters, thus they are classified in a unique range called rough/semi-finish grinding. Finish grinding has different parameters, therefore grinding operations are basically classified in two classes of range parameters.

A machining operation is the elapsed time during which the grinding wheel removes a certain material overstock, obtaining final phase part diameter ± tolerances as required by operation sheet according to product drawing.
Grinding operations performed in multiple machining steps are planned to remove the material overstock in different percentages. Great percentage of material overstock has to be removed in machining step1, and just a little remaining percentage is removed in next machining steps (classified as “other machining steps”, used to get better surface finish).
Fig. 80 is the 3D plot of depth of cut values (a_e on Z axis), with respect workpiece diameter and workpiece peripheral speed, respectively for rough/semi-finishing and finishing operations.

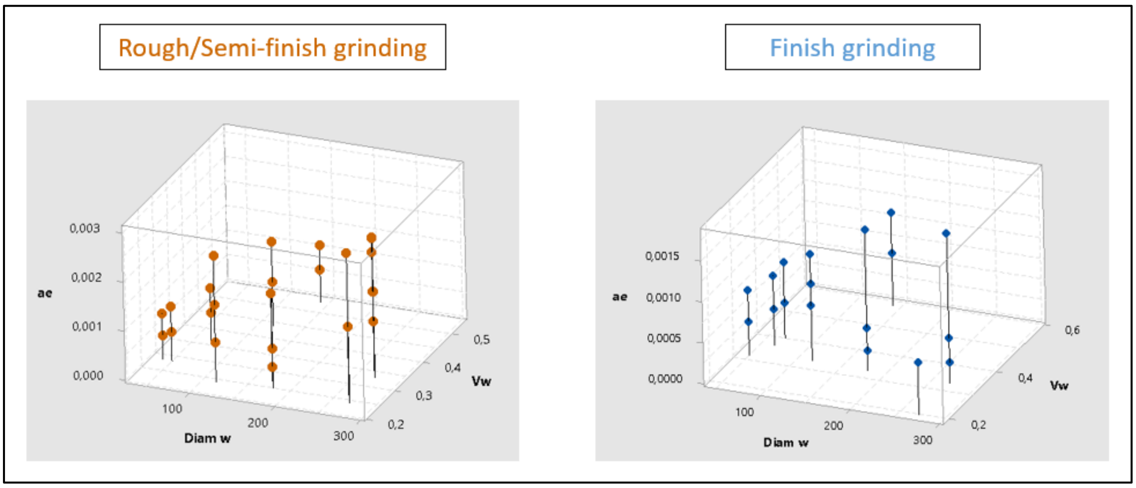


Fig. 80 3D plot of depth of cut (mm/rev)

Moreover, an interpolation of these data thru a 3D surface plot (Fig. 81) has been used to give an easier interpretation of the Z values that is more or less flat.

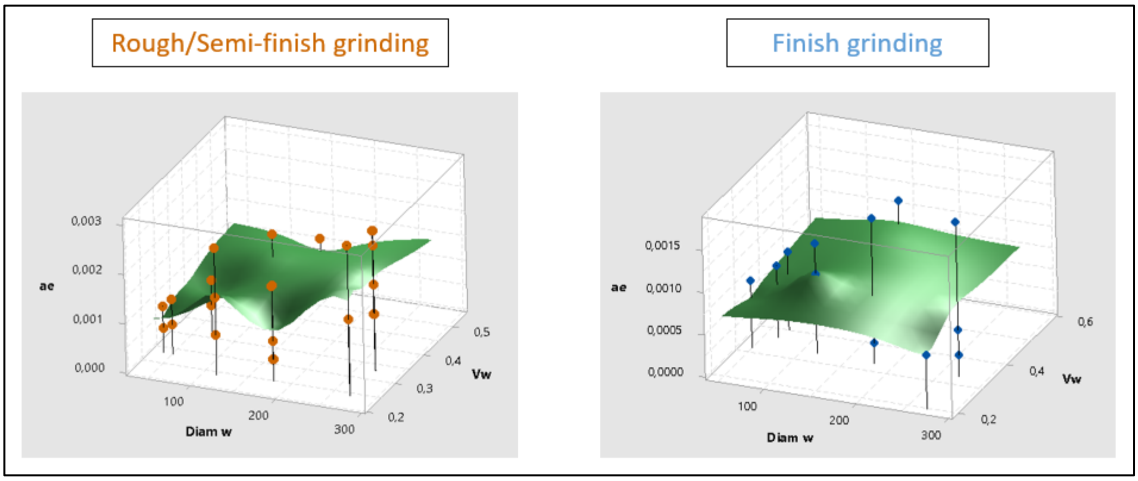


Fig. 81 3D surface plot of depth of cut (mm/rev)

Results confirm that feed rate is different with respect different diameter workpieces, but the depth of cut is more or less constant considering also machining steps.
The current safety range for depth of cut to be applied on rough/semi-finish grinding is shown in Fig. 82.

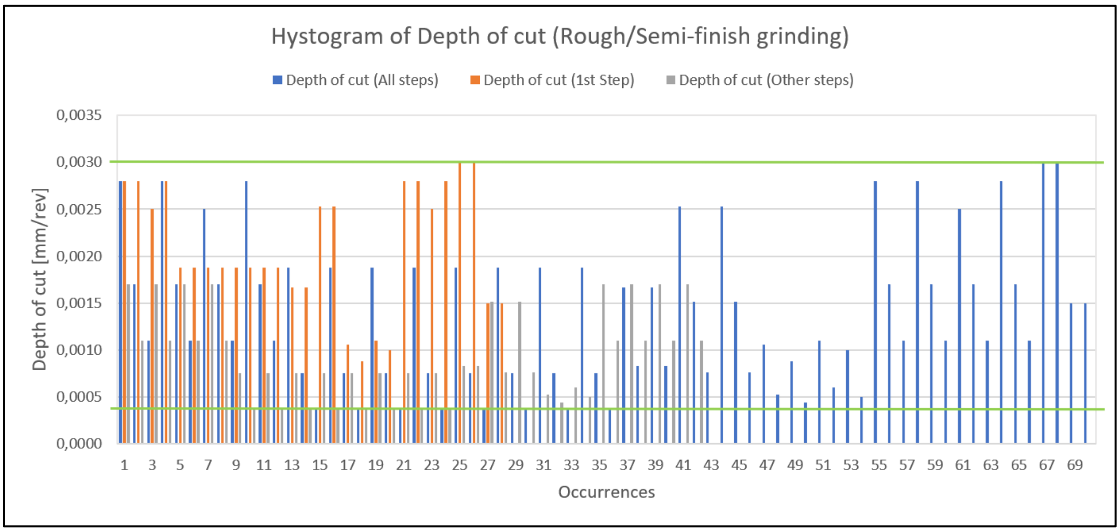


Fig. 82 Rough/semi-finish grinding depth of cut

Moreover, boxplots have been created to clearly highlight depth of cut range.
In Fig. 83 the blue boxplot represents the entire depth of cut range.
The orange boxplot is referred to depth of cut used to perform machining step1. Grey boxplot shows depth of cut values used in other machining steps (subsequent to machining step1).

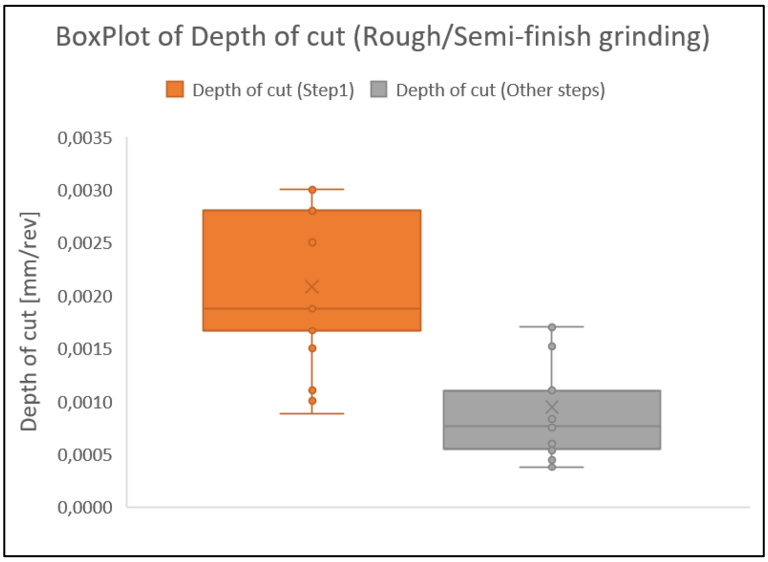


Fig. 83 Rough/semi-finish grinding boxplot of depth of cut

Similarly, the current safety range for depth of cut to be applied on finish grinding is shown in Fig. 84 and Fig. 85.

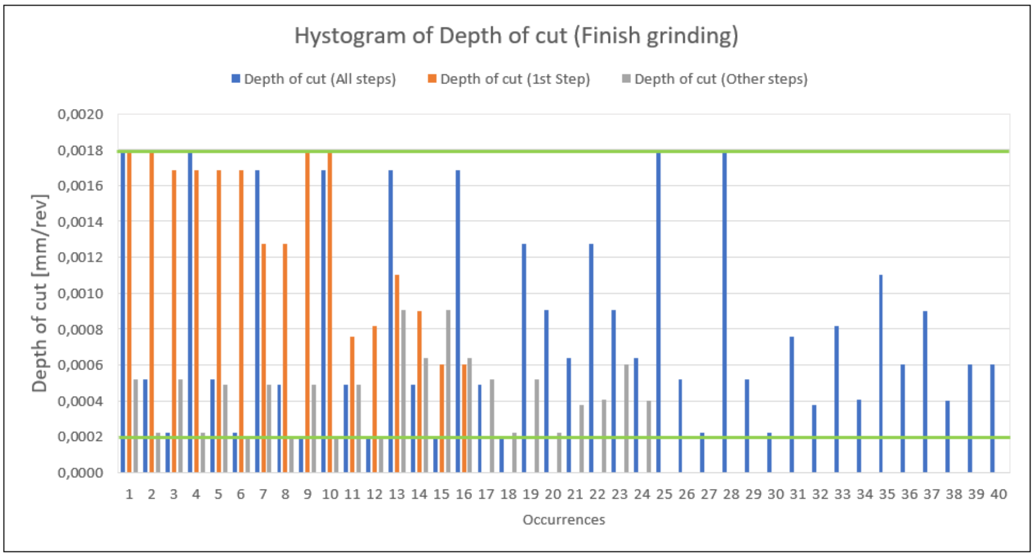


Fig. 84 Finish grinding depth of cut

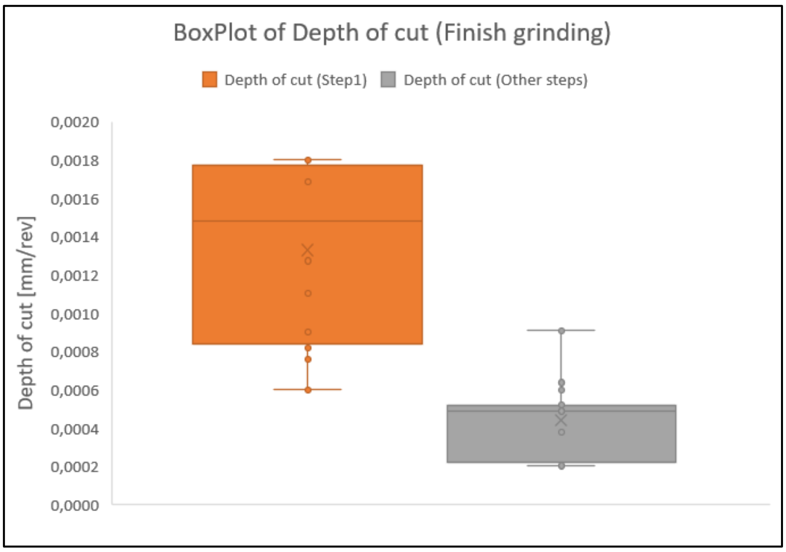


Fig. 85 Finish grinding boxplot of depth of cut

Recommended values for depth of cut are listed in Tab. 14 provided that control parameters limits are not exceeded.

Machining Phase	Depth of cut [mm/rev]
Roughing and Semi-finishing	0,0004 – 0,0030
Finishing	0,0002 – 0,0018

Tab. 14 Depth of cut recommended values

The first machining step is the most critical, because of its high feed rate values that increase risk of grinding abuses on which the study is focused.
Therefore, let's think to grinding operation as a single machining step of a traditional grinder, and the target is to avoid grinding abuses potentially caused by too high input parameters (high Qw' indicator).
Fig. 86 is the 3D plot representation of current feed rate.
Usually, small diameter workpieces turn faster and are machined with higher feed rate than larger diameters in order to maintain peripheral workpiece speed and depth of cut within defined limits.

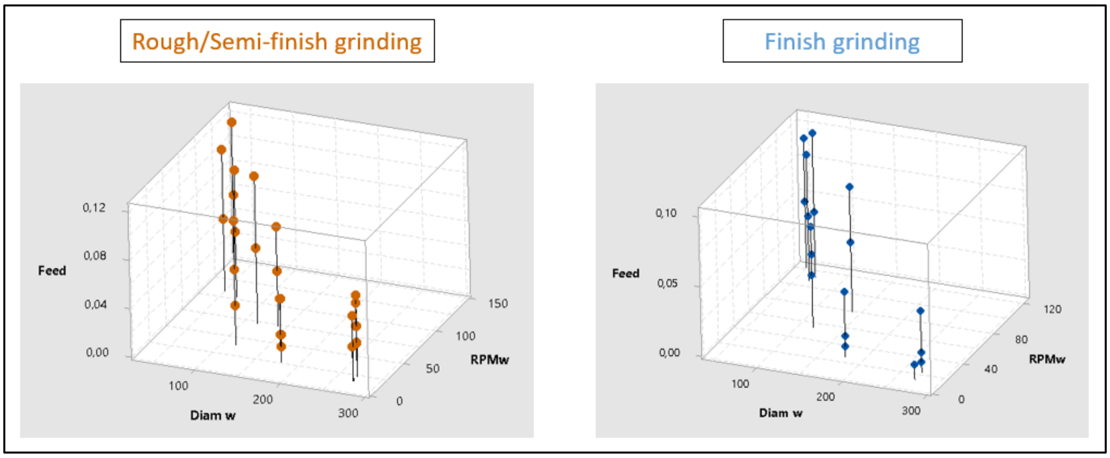


Fig. 86 3D plot of feed rate

For instance, if you consider two components with diameter respectively of 50 mm and 200 mm and you want to prescribe the feed rate for finish grinding, this will be in inverse proportion with respect the diameters. The following example explains this concept.
With a grinding wheel speed:

$$v_c = 48 \text{ m/s}$$

You will have a peripheral workpiece speed of both parts consistent to the legacy.

$$v_{w\,1,2} = 0{,}48 \text{ m/s}$$

In this way, the q value of 100 is within speed ratio range defined in paragraph 1.1.
Therefore, they turn respectively at:

$$\text{RPM}_w = \frac{v_w \times 1000 \times 60}{\pi \times diam\ workpiece}$$

$$\text{RPM}_{\text{Part1 } (\varnothing 1 = 50 \text{ mm})} = 183.35 \text{ RPM}$$
$$\text{RPM}_{\text{Part2 } (\varnothing 2 = 200 \text{ mm})} = 45.84 \text{ RPM}$$

Remembering that feed is calculated multiplying the workpiece RPM by depth of cut:

$$\text{Depth of cut } (a_e) = \frac{Feed\ rate}{RPMw}$$

In this way if you prescribe same feed rate of 0,07 mm/min on two components that turn four times one to each other depth of cut will be:

$$a_{e1} = \frac{0.07}{183.35} = 0{,}000382\ \frac{mm}{rev} = 0{,}382\ \frac{\mu m}{rev}$$

$$a_{e2} = \frac{0.07}{45.84} = 0{,}001527\ \frac{mm}{rev} = 1{,}527\ \frac{\mu m}{rev}$$

The wheel penetrates both components with same feed rate, but with different depth of cut that means larger chips that could be outside the limits.
Looking at the Specific Material Removal Rate Qw', components having different diameters shall have different RPM.

$$Qw' \left[\frac{\text{mm}^2}{sec}\right] = a_e \times v_w = a_e \times \frac{RPM_w \times \pi \times \text{Ø}_\text{W}}{60} = \frac{\boldsymbol{\pi} \times \text{Ø}_\text{W} \times Feed\ rate}{60}$$

This could be explained also thinking at machining operation time, bigger workpieces take more time to be ground with respect smaller parts.
In conclusion the feed rate shall be consistent to the depth of cut limit values.

5.1.2. Analysis using process control parameters

Process control parameters are useful to forecast process behavior as a consequence on input parameters.
The first machining control parameter is the speed ratio, defined as:

$$q = \frac{v_c}{v_w}$$

Fig. 87 shows current speed ratio for rough/semi-finish grinding operations.
It is referred to conventional medium-porosity grinding wheels with structure 5 to 9 and conventional high-porosity grinding wheels with structure 14.
High-porosity wheels turn up to 50 m/s while the others turn up to 35 m/s.
This major wheel speed leads to increase workpiece speed to have speed ratio within limits, maintaining same depth of cut, you can increase the feed rate getting higher productivity. This would be the right approach in using of high-porosity wheels, otherwise their potentiality is not entirely exploited. As you can see 88% of speed ratio is outside the speed ratio limits, and the high-porosity wheels are above the speed ratio upper limit that means the grinding is under-performing.

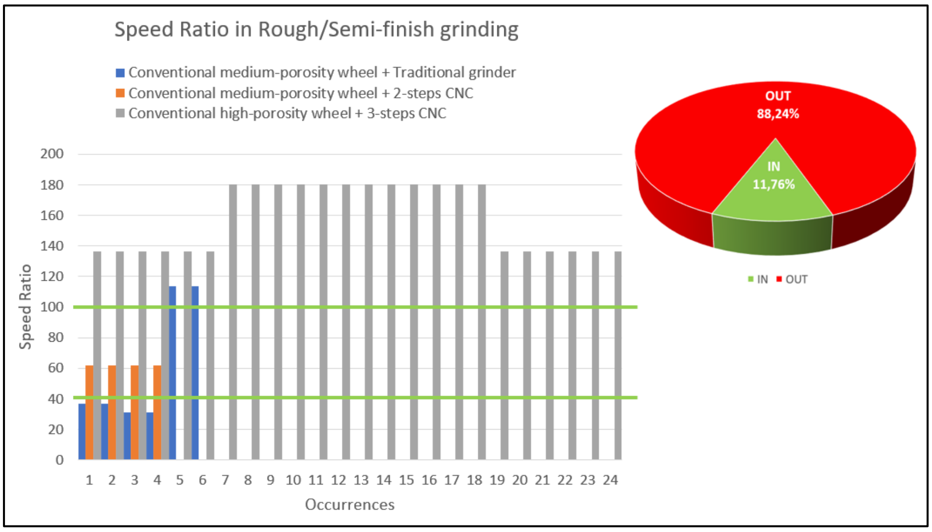


Fig. 87 Rough/Semi-finish grinding speed ratio

Fig. 88 shows current speed ratio for finish grinding operations and where the conventional medium-porosity wheels are used the workpiece speed is higher than expected.

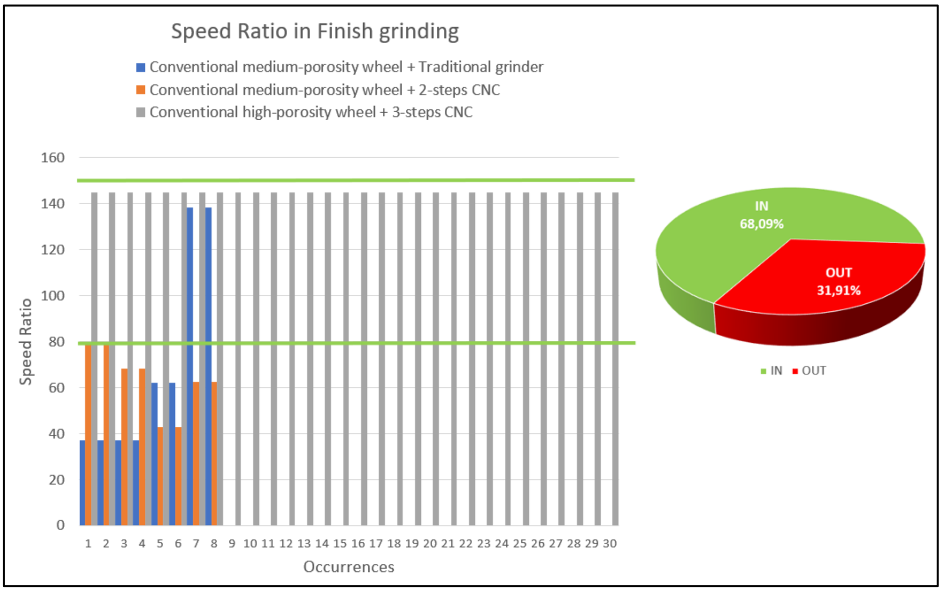


Fig. 88 Finish grinding speed ratio

Recommended peripheral workpiece speed shall be calculated using the speed ratio defined in Tab. 15.

Machining Phase	Speed Ratio
Rough and Semi-finish grinding	40 – 100
Finish grinding	80 – 150

Tab. 15 Recommended speed ratio values

A well-controlled process has the goal to avoid grinding abuses, in order to have the maximum acceptance rate of ground gearshafts.
Aggressiveness and Grit Penetration Depth are used to verify the effect of different combinations of input parameters.
Aggressiveness or Grain Impact Number is a measure of “aggressiveness” of the process. It determines the shear load imposed on each crystal.
The Aggressiveness shall be calculated using the following formula:

$$\text{Aggressiveness} = 52.3 \times \frac{\sqrt{Feed\ rate\ \left(\frac{mm}{min}\right) \times Part\ RPM\ \times Part\ \emptyset\ \ (mm)}}{Wheel\ Speed\ (\frac{m}{sec})} \times \sqrt{\frac{Wheel\ \emptyset\ (mm) + Part\ \emptyset(mm)}{Wheel\ \emptyset(\ mm)}}$$

The term $\sqrt{\frac{Wheel\ \emptyset\ (mm)+Part\ \emptyset(mm)}{Wheel\ \emptyset(\ mm)}}$ is a correction factor that considers dimensions of the grinding wheel and of the part to be machined.
For reference only for small pieces this factor could be almost equal to 1, while for large pieces it could be $\sqrt{2}$. This means that if you try to grind a workpiece using a grinding wheel with a diameter smaller than the workpiece diameter the aggressiveness increases. Fig. 89 is a plot of the aggressiveness variation as function of the feed rate (three curves) and of the peripheral workpiece speed.
It’s interesting to highlight that the aggressiveness rises up if workpiece speed increases. If workpiece turns really fast and generates aggressiveness higher than upper limit, the consequence are frictions and risk of workpiece burns, also with a usual feed rate curve (depth of cut within limits). On the other hand, if productivity needs to be improved with high feed rate, aggressiveness could result too high and it could lead to grinding abuses (depth of cut value above of safety limit).

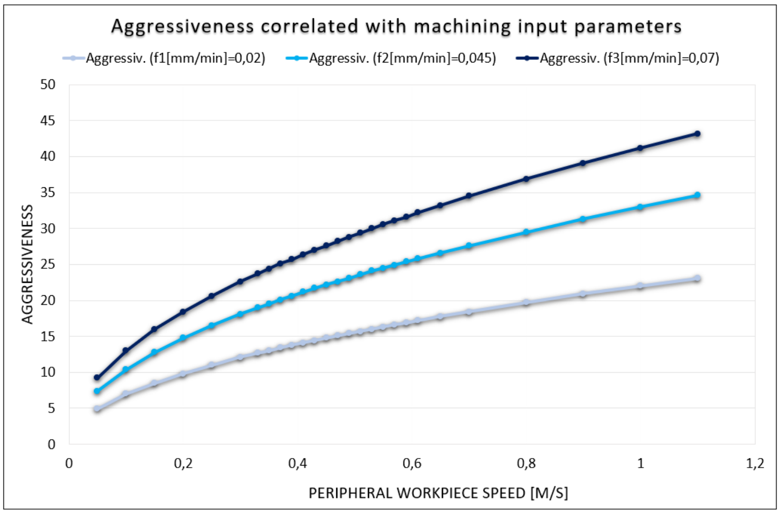


Fig. 89 Aggressiveness correlations

Tab. 16 summarizes correlations between aggressiveness and machining input parameters.

	↑ (RPMw * Part Ø)	↑ Feed rate	↑ Wheel Speed
Aggressiveness	↑	↑	↓

Tab. 16 Relation between Aggressiveness and input parameters

Fig. 90 shows current rough/semi-finish grinding input parameters analyzed with aggressiveness control parameter. As you can see in the pie chart, 50 % of machined features are out of limits defined in Tab 17.

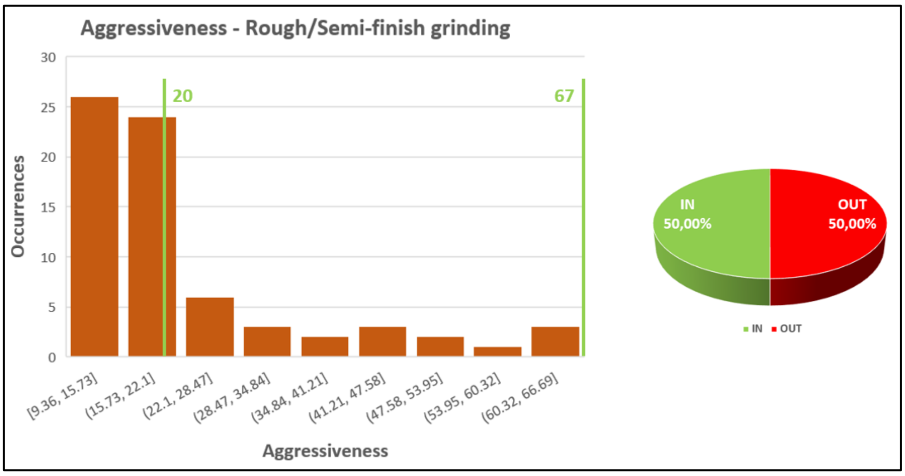


Fig. 90 Rough/Semi-finish grinding Aggressiveness check

Fig. 91 shows current finishing input parameters analyzed with aggressiveness control parameter. As you can see in the pie chart, 26.83 % of machined features are out of limits defined in Tab. 17.

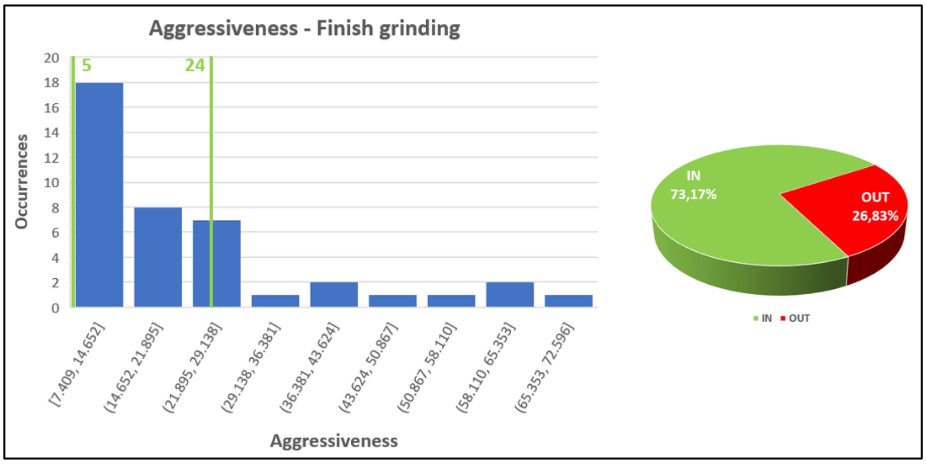


Fig. 91 Finish grinding Aggressiveness check

Comparing data available in Fig. 90 and Fig. 91, in rough grinding input parameters are basically too low "aggressive" (high percentage of values in histogram below the minimum aggressiveness safety limit). In finish grinding it's the opposite, some parts have too aggressive grinding parameters. The percentage of out of limits is higher in rough/semi-finish grinding than in finish grinding.
Tab. 17 includes required safety range of Aggressiveness.

Machining Phase	**Aggressiveness**
Rough/Semi-finish grinding	20 – 67
Finish grinding	5 – 24

Tab. 17 Aggressiveness required range

.

Chip Thickness or Grit Penetration Depth [µm] determines how deep each abrasive grain cuts into the workpiece surface to be ground.
It can be calculated as follows:

$$Grit\ Penetration\ Depth = 1000 \times \sqrt{\frac{6}{10} \times \frac{1}{2} \times \frac{15.2}{Mesh\ Number} \times \frac{52.3}{1000000} \times \frac{\sqrt{Feed\ rate \times RPMw \times \emptyset w}}{v_c} \times \sqrt{\frac{\emptyset w + \emptyset wheel}{\emptyset wheel}}}$$

Where 6 is a constant in Chip Thickness calculation, 10 is the ratio of chip width to chip height, and ½ because 15.2/Mesh number is the average grit size diameter, therefore divided by 2 is the average grit size radius.

Remember that Aggressiveness is

$$Aggressiveness = 52.3 \times \frac{\sqrt{Feed\ rate\ (\frac{mm}{min}) \times Part\ RPM\ \times Part\ \emptyset\ (mm)}}{Wheel\ Speed\ (\frac{m}{sec})} \times \sqrt{\frac{Wheel\ \emptyset\ (mm) + Part\ \emptyset (mm)}{Wheel\ \emptyset (\ mm)}}$$

Hence, Grit Penetration Depth could be written as:

$$Grit\ Penetration\ Depth = 1000\ \times \sqrt{\frac{6 \text{ x Aggressiveness}}{1315789 \text{ x } Mesh\ Number}}$$

Tab. 18 includes recommended safety range of Chip Thickness.

Machining Phase	**Chip Thickness [µm]**
Rough/Semi-finish grinding	1 – 2,3
Finish grinding	0,5 – 1

Tab. 18 Grit Penetration Depth required range

Fig. 92 shows current rough/semi-finish grinding input parameters analyzed with Chip Thickness control parameter. As you can see in the pie chart, 48.57 % of machined features are out of limits defined in Tab. 18.
This confirms that Rough/Semi-finishing grinding is under-performing.

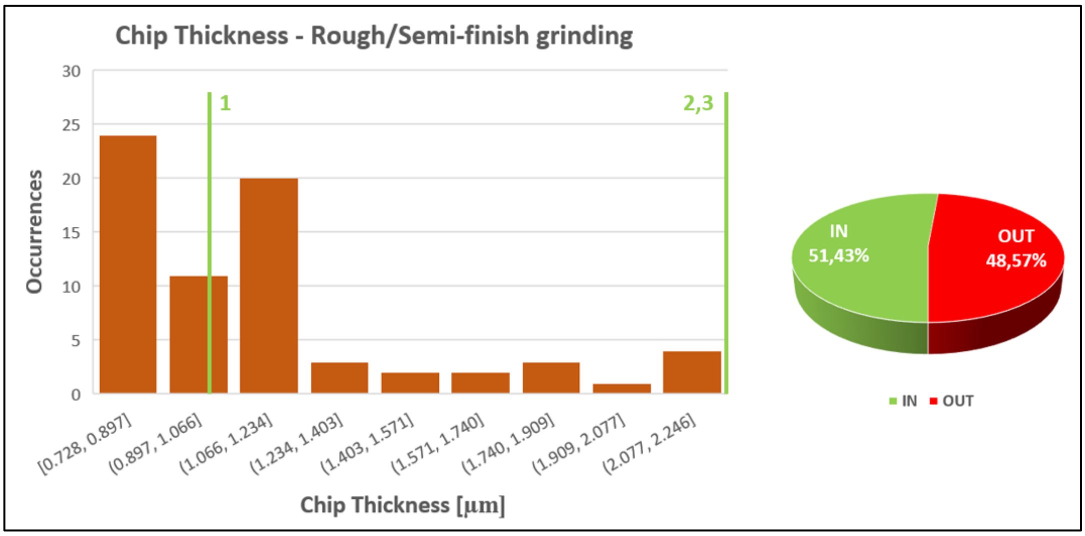


Fig. 92 Rough/Semi-finish grinding Chip Thickness check

Fig. 93 shows current finish grinding input parameters analyzed with Chip Thickness control parameter.
As you can see in the pie chart, 24.39 % of machined features are out of limits defined in Tab. 18.

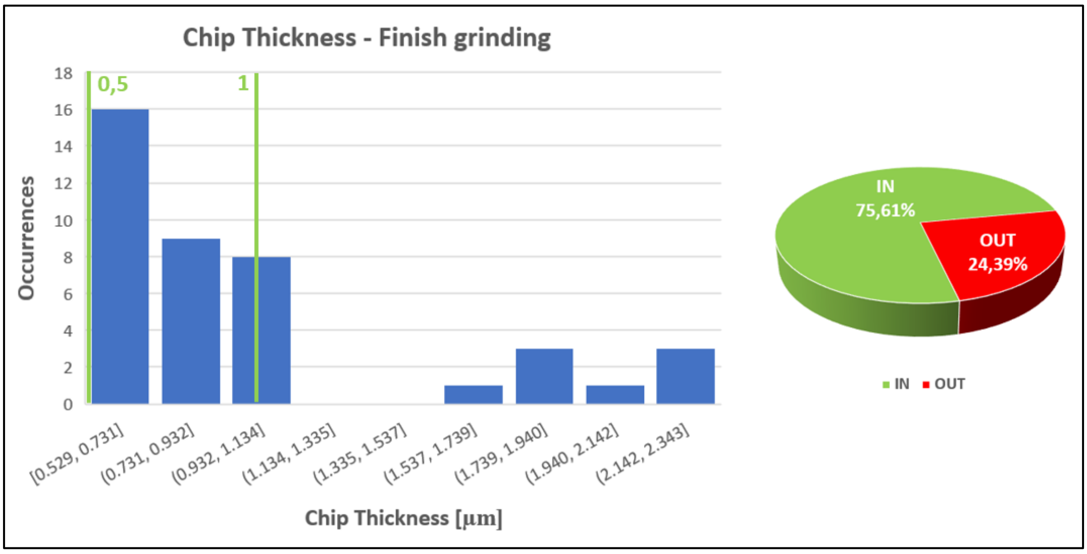


Fig. 93 Finish grinding Chip Thickness check

Fig. 94 shows correlation between Aggressiveness and Grit Penetration Depth control parameters, both Rough/Semi-finish and Finish grinding have the same tendency.

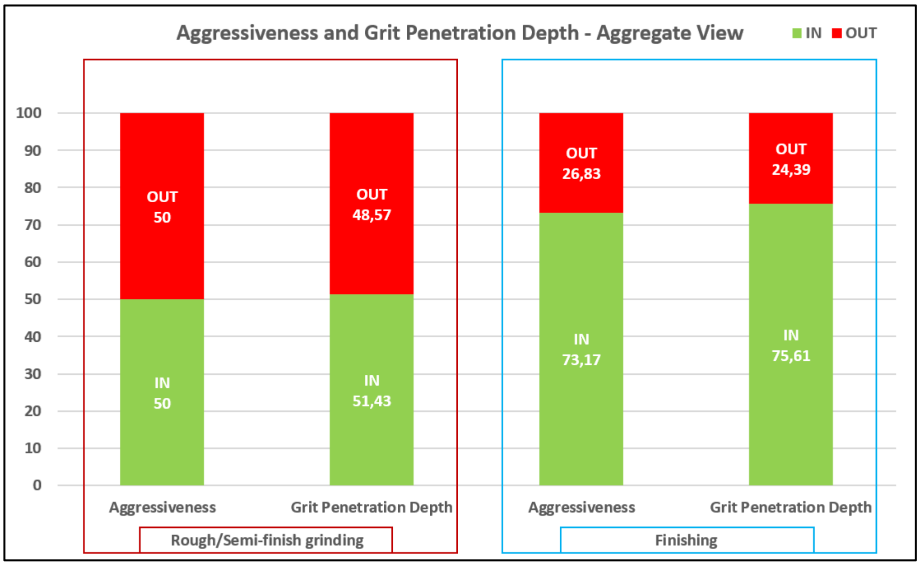


Fig. 94 Out of limit tendency

Fig. 95 shows the Mesh influence on Grit Penetration Depth for several workpiece speed. In this example a gearshaft with a diameter of 250 mm is ground using a feed rate of 0,04 mm/min, a peripheral grinding wheel speed of 48 m/s, different peripheral workpiece speed (let's assume to repeat the same machining operation, each time testing the effect of peripheral workpiece speed variation), with two scenarios: one with a 54 Mesh wheel and the other with a 120 Mesh wheel, even though typical finish grinding parameters have been used in both scenarios. Mesh 54 results outside safety limits.

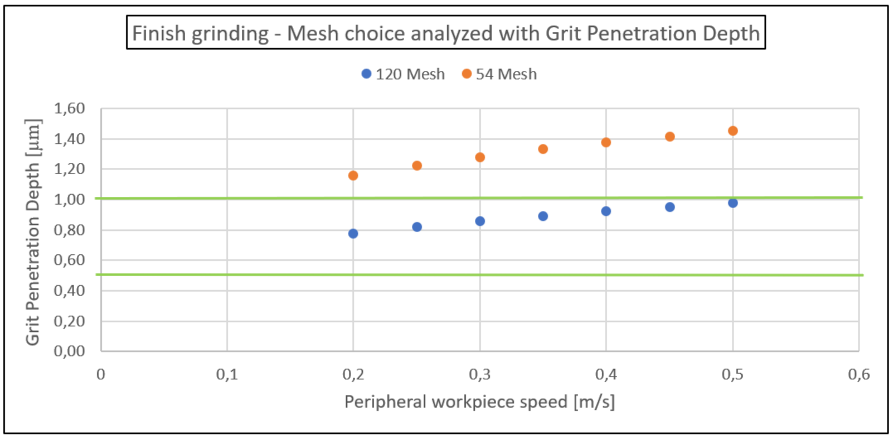


Fig. 95 Grit Penetration Depth correlation to workpiece speed and Mesh

Fig. 96 shows the Feed rate influence on Grit Penetration Depth for several workpiece speed using a 120 Mesh for finishing the same gearshaft diameter of example above.
In particular you can see the curve relevant to 0,1 mm/min feed rate that generates chip thickness too large outside upper limit, with only one occurrence below upper limits but with a q ratio not within recommended limits for finish grinding. On the other hand operating with a feed rate of 0,04 mm/min results safe with many different values of peripheral workpiece speed allowed but with reduced productivity. Then the optimal setting of feed rate and workpiece speed should be defined in order to maximize productivity with all control parameters within safety range.
A good compromise should be a feed rate of 0,06 mm/min with a maximum workpiece speed of 0,33 m/s (thus within q ratio = 48/0,33 = 145.45 < 150).
Hence, you got a Grit Penetration Depth as follows:

$$Grit\ Penetration\ Depth = 1000 \times \sqrt{\frac{6}{10} \times \frac{1}{2} \times \frac{15.2}{120} \times \frac{52.3}{1000000} \times \frac{\sqrt{0.06 \times 23.26\ RPM \times 250}}{48} \times \sqrt{\frac{250+500}{500}}} = 0{,}97\ \mu m$$

That is below maximum chip thickness for finish grinding operations ($0{,}97\mu m < 1\mu m$).

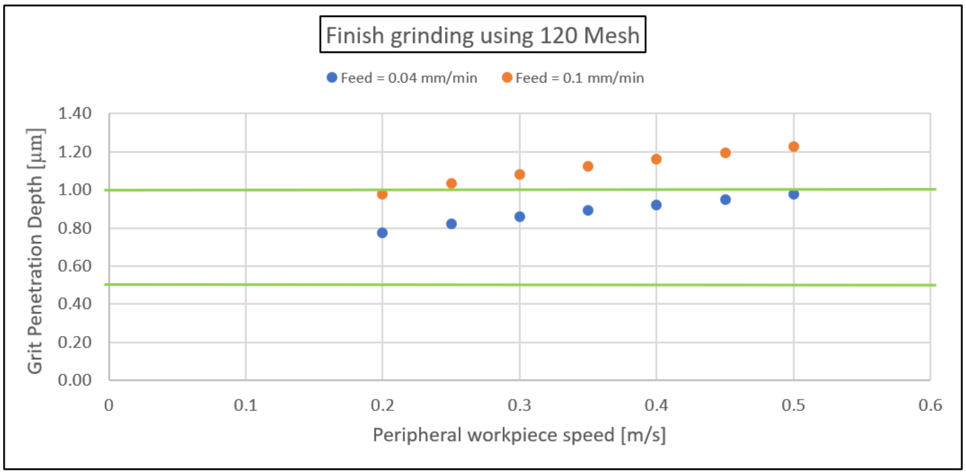


Fig. 96 Grit Penetration Depth correlation to workpiece speed and feed rate

Fig. 97 aggregates speed ratio, grit penetration depth and specific material removal rate of rough/semi-finish grinding occurrences.
Considering control parameters speed ratio and grit penetration depth limits, the best current parameter mix in terms of productivity (Qw’) is at occurrences 13 and 14.

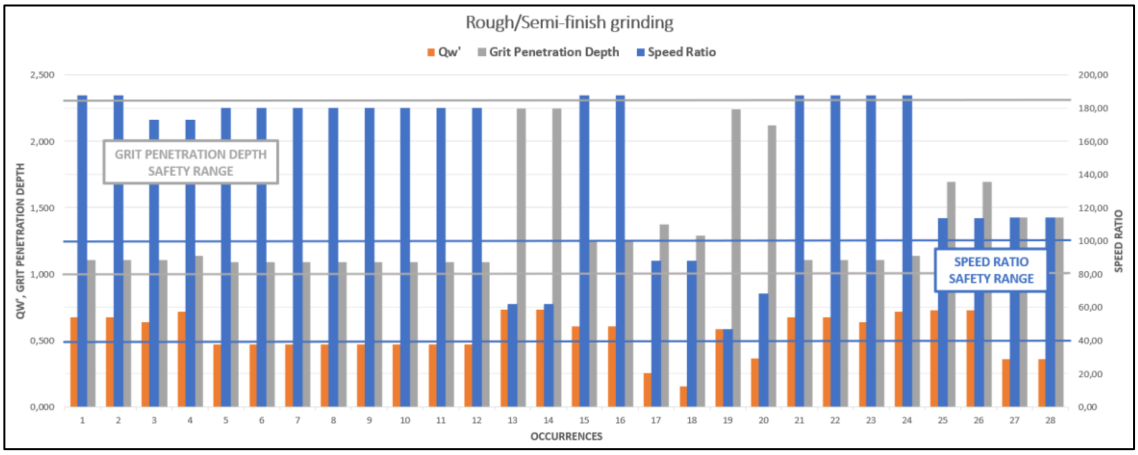


Fig. 97 Rough/Semi-finish grinding Qw' current occurrences

Fig. 98 is the same view of current finish grinding process.

Considering control parameters speed ratio and grit penetration depth limits, the best current parameter mix in terms of productivity (Qw') is at occurrences 1, 4, 29 and 32.

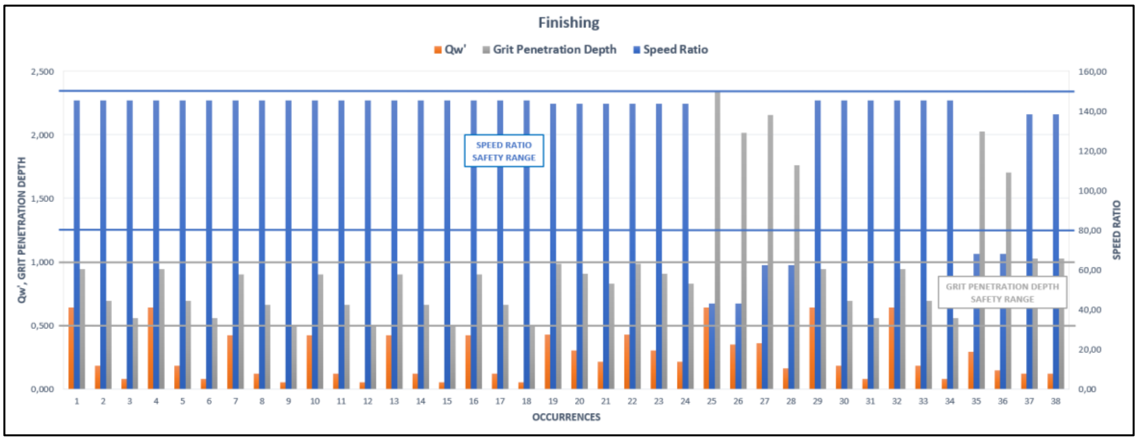


Fig. 98 Finish grinding Qw' current occurrences

Fig. 99 shows whack ratio, the control parameter relevant to grinding wheels dressing applied in current process. Remember, grinding wheels could be basically dressed in three manners: standard, dull and sharp dressing. Occurrences above upper limit means excessive wheel wear in dressing, while below lower limit shows too dull dressing, hence the grinding wheel appears with blunt grains.

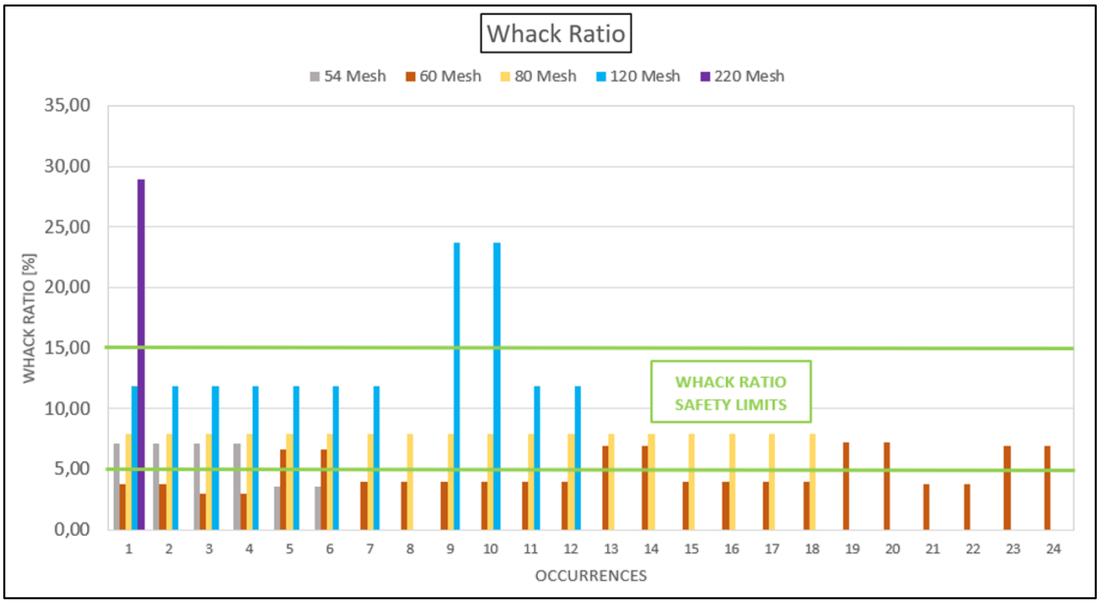


Fig. 99 Whack Ratio current occurrences

Fig. 100 aggregates whack ratio with respect grinding wheel mesh.
It is clearly shown that 80 Mesh currently used complies with defined standard.
54 Mesh and 60 Mesh are below whack ratio lower limit because of the use for finish grinding operations (non-proper for them), thus dressed as really dull. 120 Mesh, in occurrences 9 and 10, should be dressed with a lower dressing depth.
220 Mesh is only applied to machine one operation, and it is over-dressed depth.
Best practice is to apply dressing within whack ratio limits depending on grinding wheel Mesh number and eventually to repeat dressing, if needed.

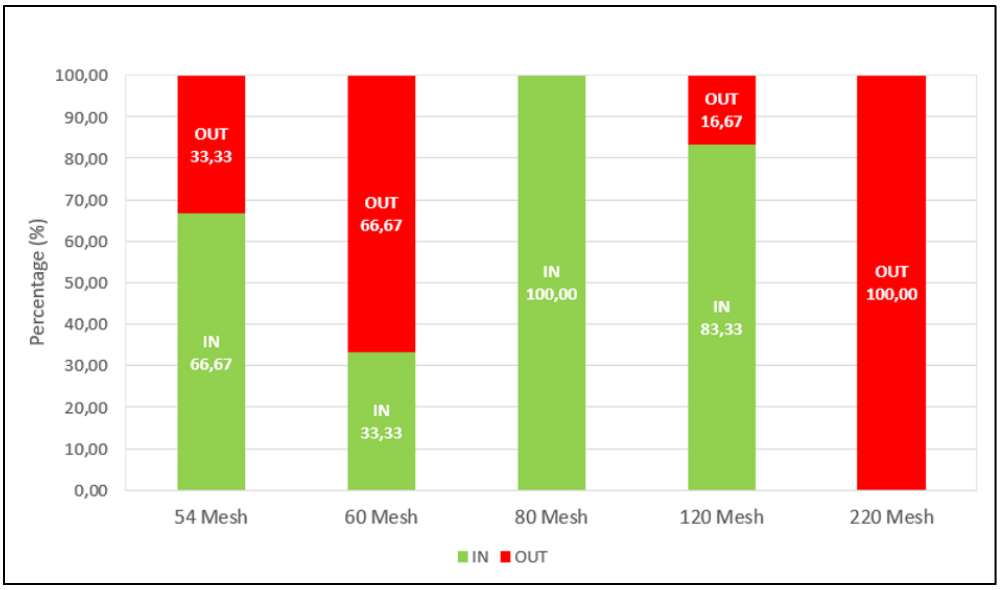


Fig. 100 Whack Ratio - Stacked Columns Chart

Fig. 101 shows Dressing Overlap Ratio applied to current dressing occurrences.
Occurrences clearly out of limits are 60 Mesh dressed to perform semi-finish and finish grinding operations (dressed too fast) and 80 Mesh dressed to perform rough grinding operations (dressed too slow).

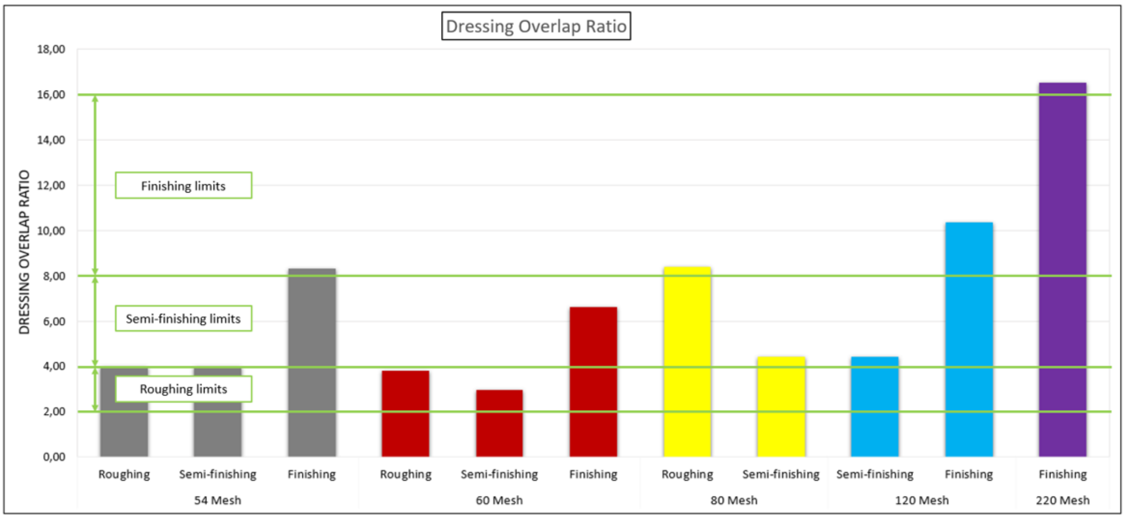


Fig. 101 Dressing Overlap Ratio check

5.2. Identify working strategy

5.2.1. Machining strategy

A critical aspect of machining strategy is the approach to the workpiece.
If it's underestimated could lead to scrapped parts.
Approach of the grinding wheel to the workpiece in 'machining mode' shall be based on the max dimension of the part, max position error, max roundness of the part and at least 0,05 mm of safety margin.
To approach the workpiece in traditional grinders the following procedure must be followed:

1. Place workpiece accurately on grinder
2. Define maximum runout of diameter to be machined
3. Rotate the workpiece so that the point corresponding to maximum runout is on grinding wheel direction
4. Approach the grinding wheel to the diameter to be machined, insert a piece of paper (0,1 mm) between the two elements and take them in contact
5. Define the zero-contact point between wheel and workpiece
6. Move the wheel away from the piece, start the wheel and workpiece rotation and open coolant nozzles

7. Bring the wheel to 0,01mm from the zero point with a feed of 0,01mm/rev and starting from the zero-point approach the part with a feed of 0,001 mm/rev.
8. After the first ‘wheel to part’ contact, use the grinding parameters defined in the operation sheet

The approaching procedure in CNC grinder is defined as follows:

1. The default diameter to start the approach to the part in ‘working mode’ is defined based on the max dimension of the part, max position error, max roundness of the part and at least 0,05 mm of safety margin.
2. The equipment shall measure the part (by probing or by contactless sensors) to define the actual max material diameter.
3. If actual max material diameter is equal or smaller than the default starting diameter, equipment can start machining from default diameter with the defined parameters.
   If actual max material diameter is greater than the default starting diameter, equipment shall stop giving a warning to the operator. Operator shall increase the default diameter, as required per instruction, and then start machining.

It’s recommended to leave 0,006 – 0,025 mm of stock material for finish grinding.

5.2.2. Dressing strategy

Dressing is very important to avoid risk of burns.
A dressing strategy should be as follows:

1. Before starting each grinding operation, grinding wheel needs to be dressed
2. Dressing to be performed with at least 2 passes (repetition) for each dressing
3. Visual inspection of the grinding wheel before each machining step, if cutting surface seems irregular or wrinkled or with any scratch or too smooth, grinding wheel needs to be dressed
4. Pay attention to cutting sound during dressing, it must be continuous. If irregular the dressing must be repeated
5. Automatic monitoring of dressing process by acoustic emission should be useful.
   Commercial AE sensor and device (Dittel-Marposs) are available

Fig. 102 shows relations between dressing and grinding wheel behaviour in terms of roughness resultant on workpiece taking into account the grinding wheel Mesh number. Mesh number has correlation with resultant roughness, low mesh number wheels are suitable for rough or semi-finish grinding, while high mesh number wheels are used for finish grinding, however grinding wheel behaviour depends also on dressing parameters. The curve in the middle represents the roughness capability of a wheel with a certain mesh dressed with average standard process. The upper and lower curves are the roughness limits achievable with a forced dressing to obtain a wheel dressed as sharp or dull. Occurrences below dull dressing limits are unsafe for risk of burns. Values above the sharp dressing limit mean over-dressing, that is waste of the wheel without benefit on its cutting behaviour.

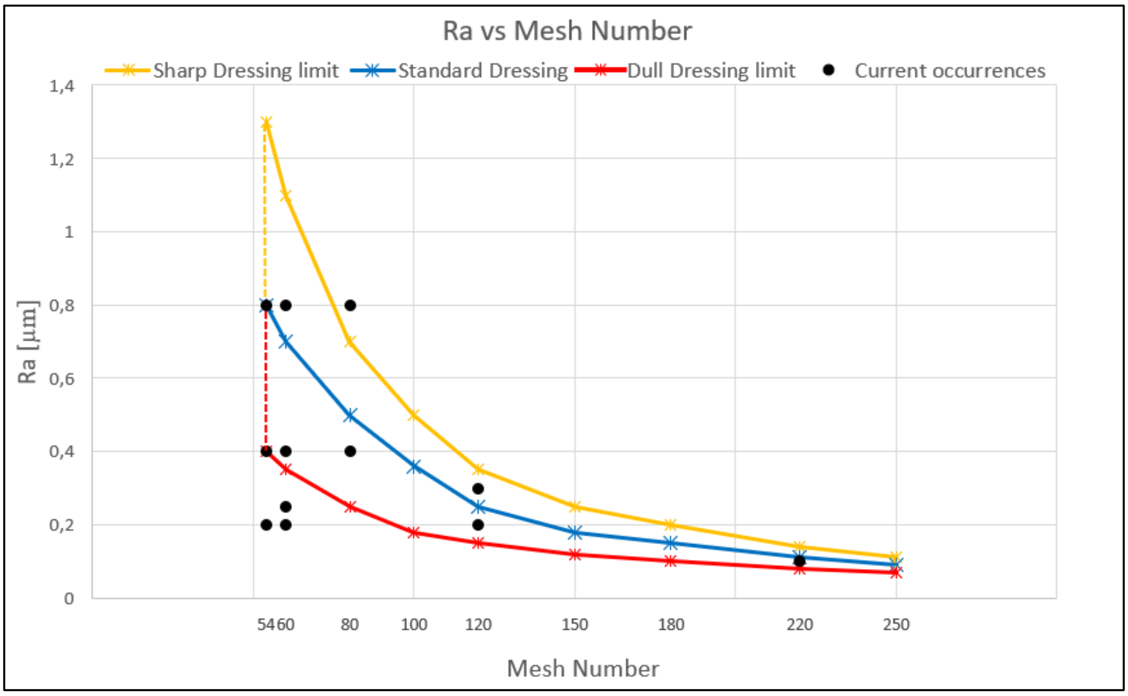


Fig. 102 Surface roughness correlation to Mesh number

5.3. Grinding power

As already explained, this thesis has the target to improve the grinding process control. Therefore, a supplementary control parameter is defined in this paragraph.
This parameter is the power consumed to rotate the grinding wheel spindle during cut.
Installing a dedicate SW directly on board of CNC grinder, it is possible to measure this power consumption. On this way an in-process inspection could be done, ensuring better process monitoring.

5.3.1. Power model and correlations

A power model to describes correlations between grinding power and machining parameters is provided below.

$$Power\,[W] = e_c \times Q_w' \times l_g$$

$$e_c = Specific\ Energy\ [J/mm3]$$
$$l_g = Contact\ length\ [mm]$$

Specific energy is not static, because the hardness and material properties of the gearshaft during grinding process change. This consideration is clearly evident for machining parameters close to burns limits. In fact, a gearshaft proximate to burns limits shows a high and fast variation of its thermal conductivity properties.
In particular, from literature specific energy model is:

$$e_c = \frac{70}{Grit\ Penetration\ Depth^{\,1{,}5}} + 20$$

20 is the asymptotic limit of the model, generally actual grinding operation conditions to machine real components don’t generate specific energy lower than 20.

Hence, the complete model of grinding power is:

$$Power = \left(\frac{70}{Grit\ Penetration\ Depth^{\,1{,}5}} + 20\right) \times Q_w' \times l_g$$

Grit Penetration Depth (Chip Thickness) is directly correlated to all input parameters, thus you know all the correlations between specific energy and input parameters.
Specific energy and power correlations versus input parameters are shown in Tab. 19.

	↑ Workpiece Speed	↑ Wheel Speed	↑ Depth of cut	↑ Workpiece diameter	↑ Wheel diameter	↑ Contact lenght	↑ Mesh number
Specific Energy	↓	↑	↓	↓	↑	=	↑
Power	↑	↑	↑	↑	↑	↑	↑

Tab. 19 Specific Energy and Power correlations

In Fig. 103 Aggressiveness and Power are correlated to workpiece speed in relation to three different Feed rates (using 120 Mesh grinding wheel). For each feed rate value aggressiveness has positive correlation to workpiece speed, while Power decreases because of depth of cut reduction.

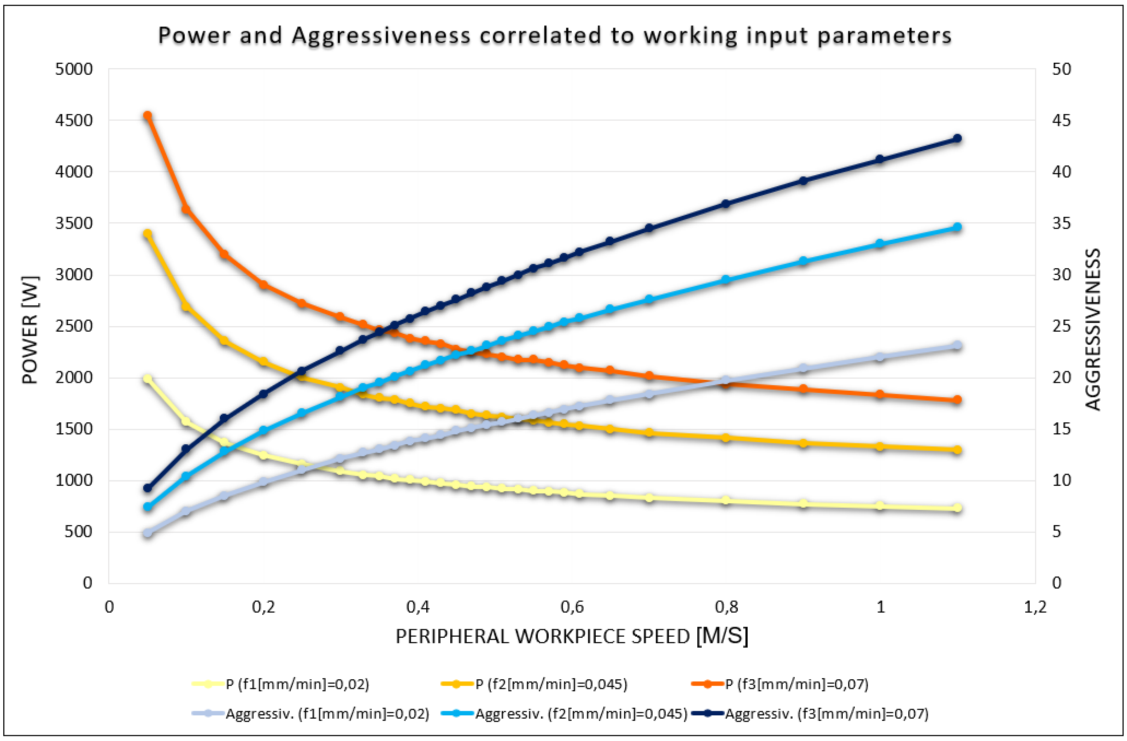


Fig. 103 Power and Aggressiveness correlations to workpiece speed and feed rate

A different representation of Power variation with respect feed rate and workpiece speed is in Fig. 104, as you can see increasing workpiece speed, Power decreases for a certain feed rate. Increasing feed rate, Power increases because of the material removal rate increase. 3D Plot has been generated using 120 Mesh grinding wheel.

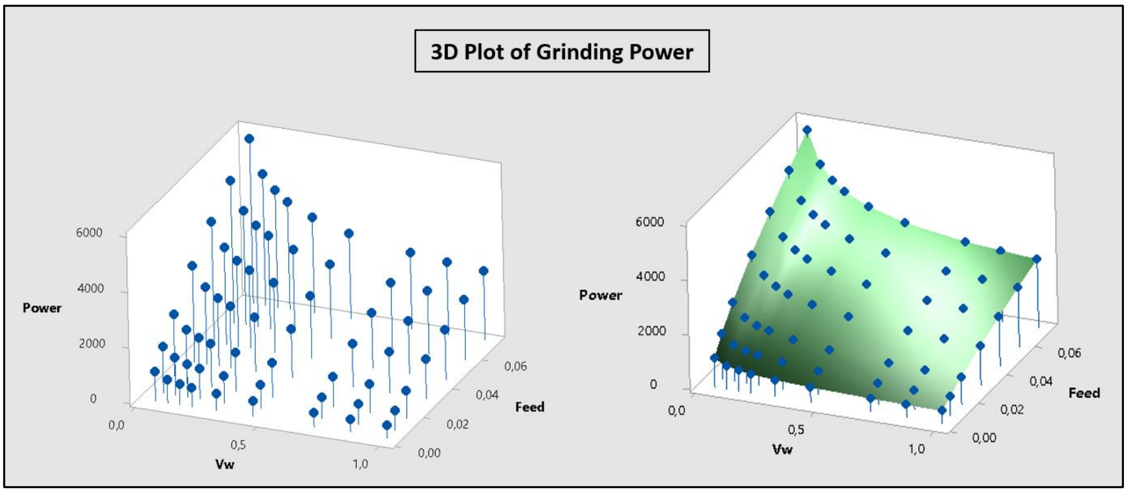


Fig. 104 3D plot of grinding power related to feed rate and workpiece speed

In Fig. 105 a comparison between power and specific energy is plotted.

Specific energy curves are dotted lines. You have to know that increasing feed rate curves from feed rate1 (0,02 mm/min) to feed rate3 (0,07 mm/min) power increases whereas specific energy decreases. This is due because increasing feed rate you cause higher depth of cut therefore power and surface temperature increase, since you are using more aggressive parameters. Whereas specific energy (J/mm^3) decreases because you generate faster cutting and less sliding and displacement (sliding and displacement phases, that come before cutting phase, are shortened). Gradient arrows have been plotted on primary and secondary axis to highlight different intensity and direction of power and specific energy with respect to feed rate variation. For the same feed rate curve, increasing workpiece speed, both power and specific energy decrease.

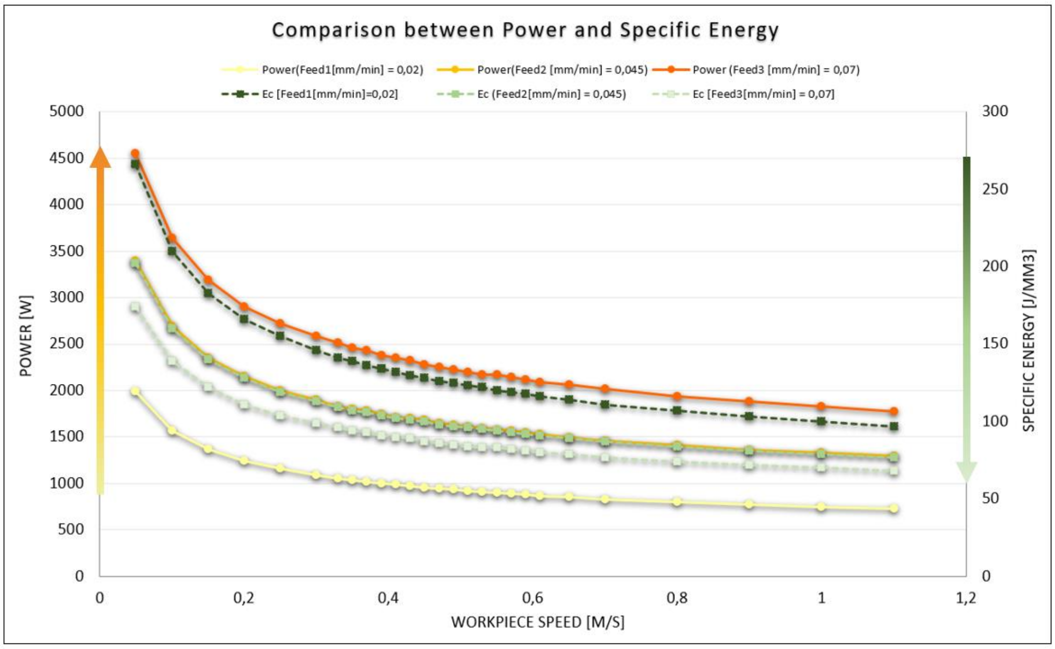


Fig. 105 Grinding power and Specific Energy comparison

Fig. 106 shows the influence of Mesh number on grinding power for same combination of machining parameters. In particular this is an example of machining of 250 mm diameter gearshaft with different grinding wheel mesh, with a feed rate of 0,04 mm/min, and varying workpiece speed to generate a power absorption curve.

As you can see, 54 Mesh number is a grinding wheel with an average grit size diameter bigger than a 120 Mesh, thus it generates higher chip thickness and consequently less specific energy and less power. To conclude, a grinding wheel mesh with coarser Mesh generates less power but have to be checked if can ensure desired surface roughness on workpiece. Whereas a finer Mesh (higher Mesh number) ensures better surface roughness but generates more power and heat, thus need to be checked the combination of machining parameters applied, in order to have a controlled chip thickness and not too much aggressive parameters, otherwise the risk is to have fast wear of grinding wheel thus the need to dress it more frequently to avoid burns.

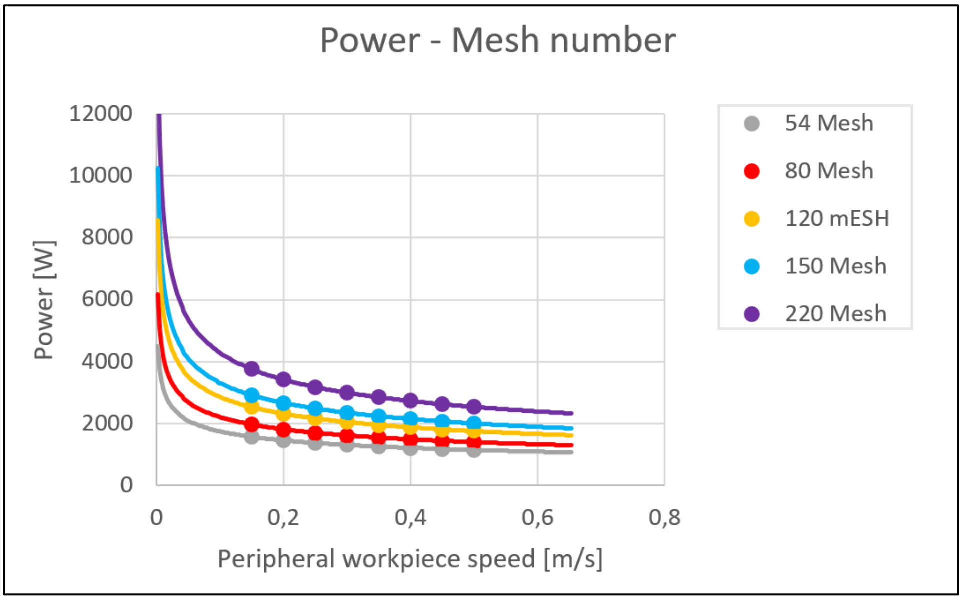


Fig. 106 Power correlation to Mesh number

6. Modeling of optimized cylindrical grinding process

This chapter contains a description of two different tools developed to supply help in defining optimized grinding process parameters.

The first one is a spreadsheet that is a guideline to validate all grinding input parameters.

The second one is a spreadsheet with the aim to give a smart feedback about choice between some different key parameters in order to optimize productivity within safe process limits.

6.1. Input parameters validation tool

This spreadsheet has been developed using VBA Excel Macro with the aim to give a guideline in defining and validate grinding input parameters.

A Yes/No logical approach has been used to validate step by step all input parameters using already explained formulas to calculate control parameters such as Aggressiveness, Chip Thickness, Whack Ratio, Dressing Overlap Ratio comparing them to legacy values as per Database and technical literature to get positive or negative validation feedback, see Fig. 107.

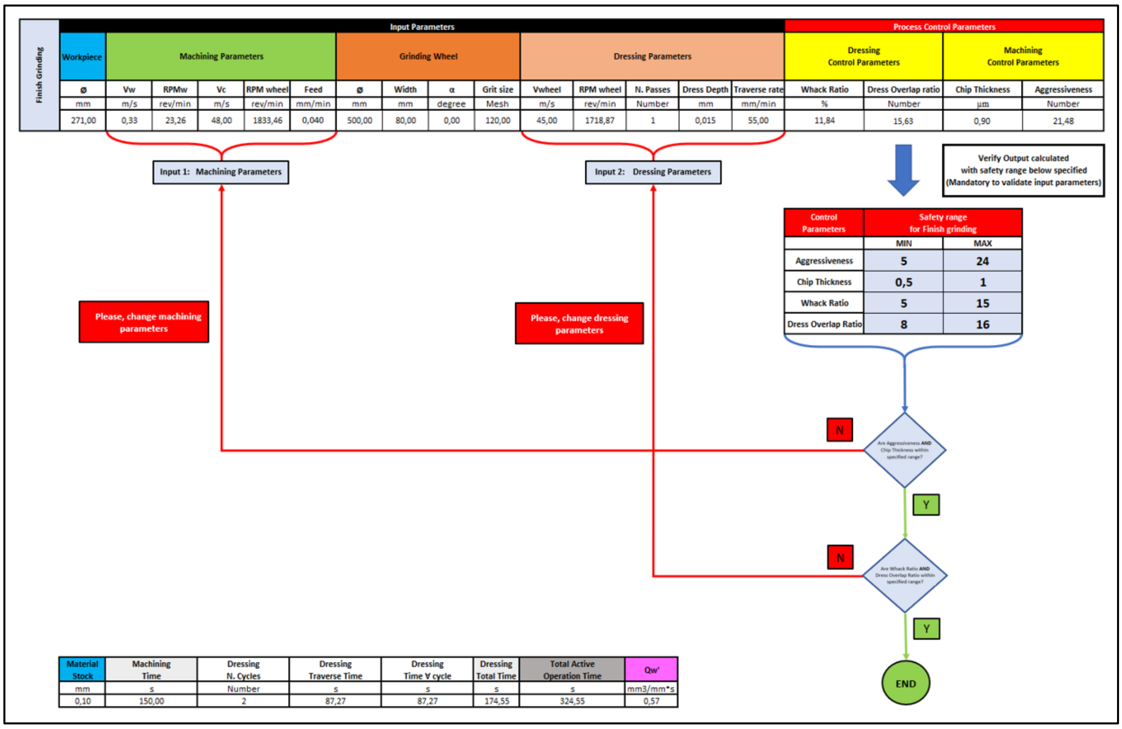


Fig. 107 Input parameters validation spreadsheet logic

In Fig. 108 there is a screenshot of the complete spreadsheet, the following figures are some excerpts to explain in detail how the validation tool works.

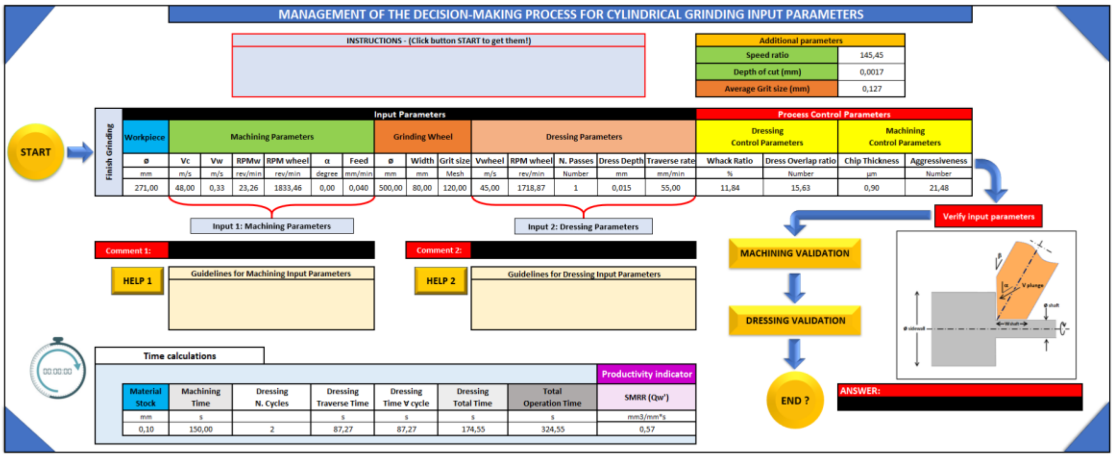


Fig. 108 Whole screenshot of tool interface

As shown in Fig. 109 when you push Button "Start" instructions for proper use of the grinding tool appear.

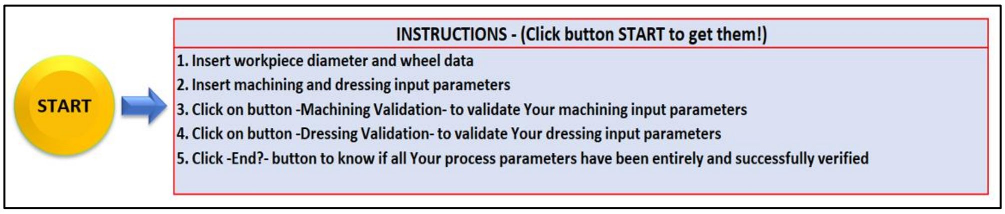
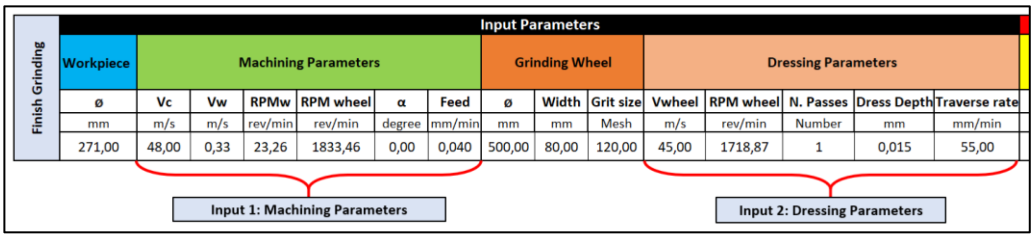


Fig. 109 Initial instructions

The entered input data as shown in Fig. 110 are machining and dressing data in addition to workpiece diameter and grinding wheel data.

In particular for machining data the editable fields are peripheral grinding wheel speed v_c, peripheral workpiece speed v_W and Feed and Feed cutting angle α, while workpiece RPM and wheel RPM are not editable because they are calculated and shown for reference.

Similarly for the dressing data editable fields are peripheral wheel speed, number of dressing passes, Dressing Depth and Traverse rate.



Input Parameters															
Workpiece	Machining Parameters						Grinding Wheel			Dressing Parameters					
ø	Vc	Vw	RPMw	RPM wheel	α	Feed	ø	Width	Grit size	Vwheel	RPM wheel	N. Passes	Dress Depth	Traverse rate
mm	m/s	m/s	rev/min	rev/min	degree	mm/min	mm	mm	Mesh	m/s	rev/min	Number	mm	mm/min
271,00	48,00	0,33	23,26	1833,46	0,00	0,040	500,00	80,00	120,00	45,00	1718,87	1	0,015	55,00

Fig. 110 Input parameters block

In Fig. 111, 112 and 113 are shown some return message from the tool if some inputs are missed or completely wrong (for instance peripheral workpiece speed).

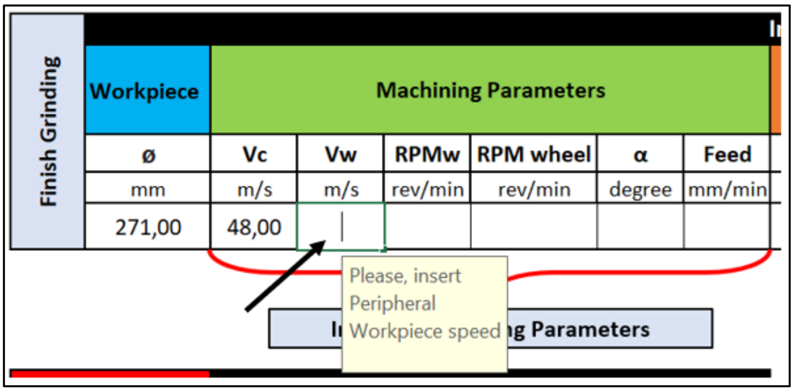


Fig. 111 Input parameters entering

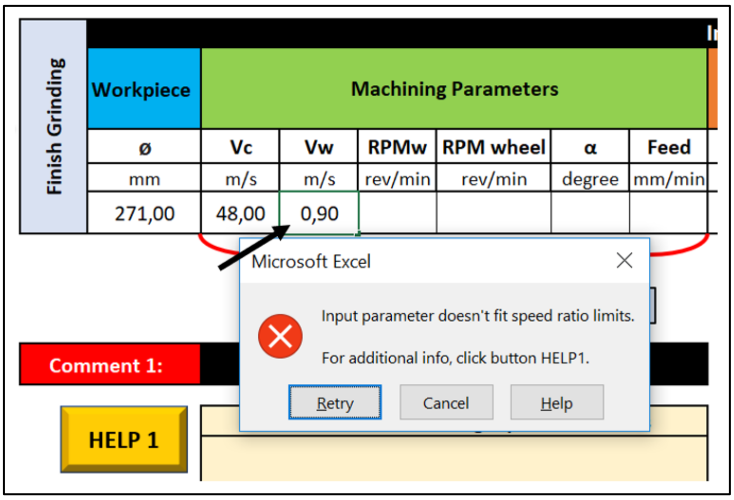


Fig. 112 Input parameter warning message 1

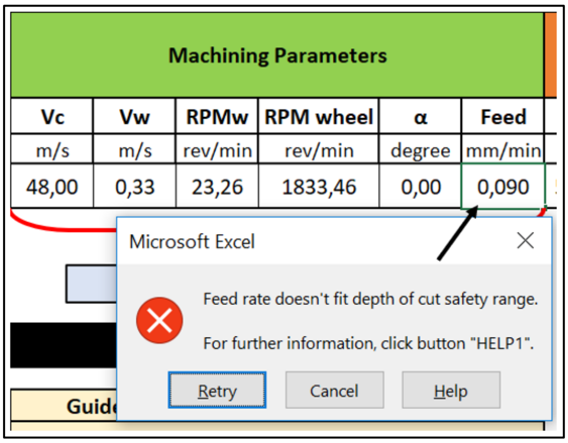


Fig. 113 Input parameter warning message 2

Help Buttons allow to get some useful guidelines to insert input parameters, see Fig. 114, 115.

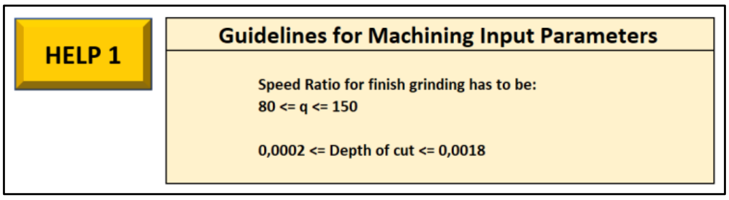


Fig. 114 Help Button message

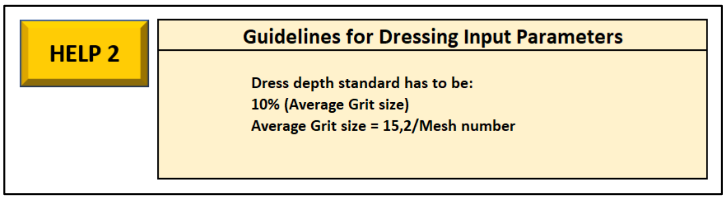


Fig. 115 Help Button message

Grinding wheel Mesh number can be selected among values available in the list-box as shown in Fig. 116.

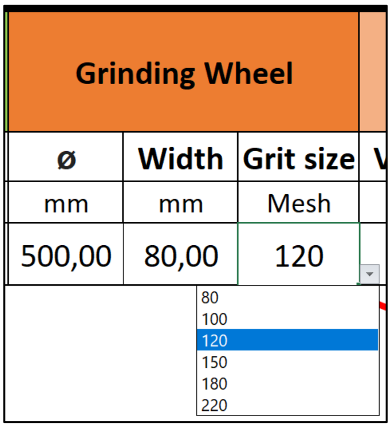


Fig. 116 Grinding wheel Mesh selection

Fig. 117 is relevant to Process Control Parameters block and validation buttons.
Process Control Parameters are calculated and are shown for reference only.
Machining Validation and Dressing Validation must be run in sequence to have feedback from the tool.

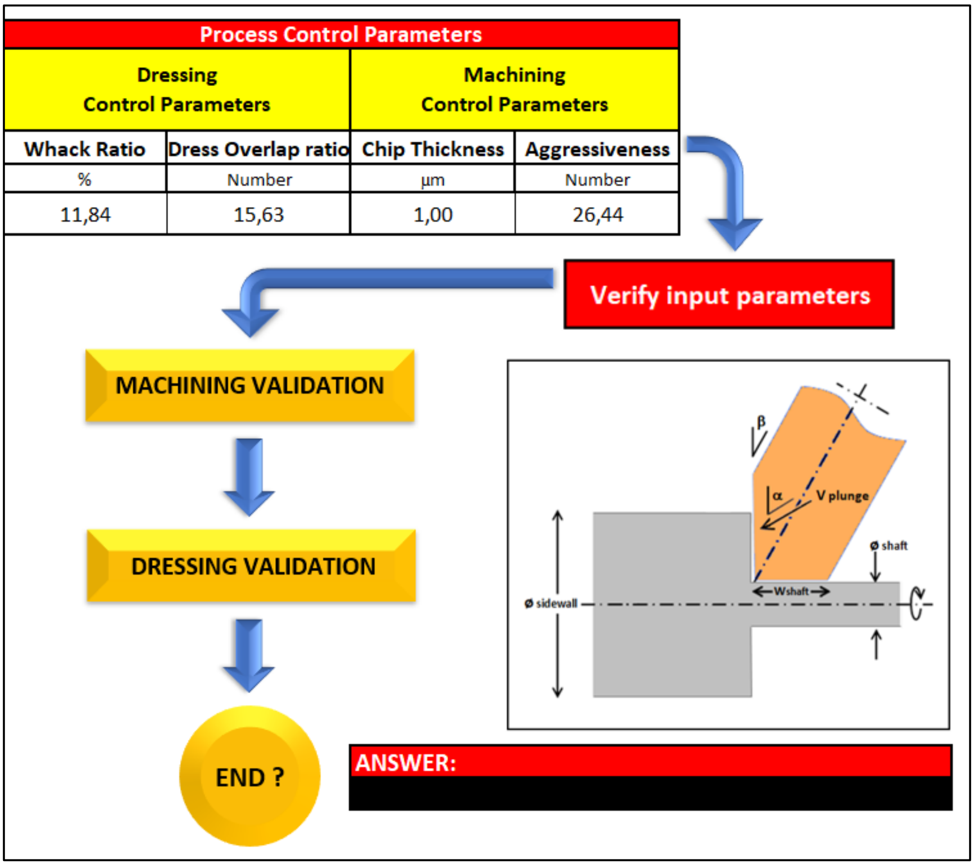


Fig. 117 Validation buttons

Examples of machining validation return message are shown in Fig. 118, 119 and 120. Validation has failed because of too high Aggressiveness, reducing Feed as first option, validation of input parameters is satisfied because of the reduced Aggressiveness, positive result could be also obtained changing peripheral workpiece speed.

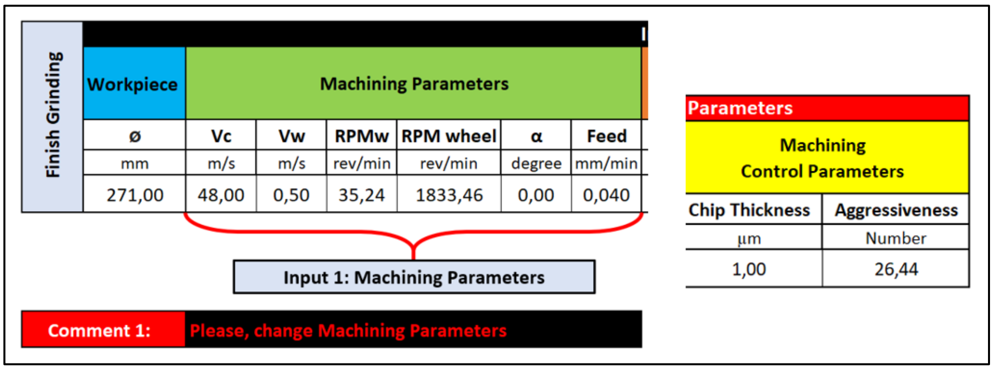


Fig. 118 Machining parameters feedback (fail)

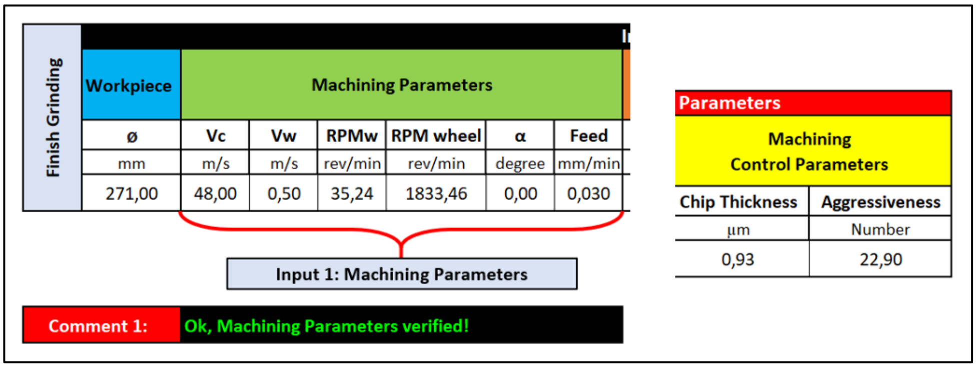


Fig. 119 Machining parameters feedback (pass)

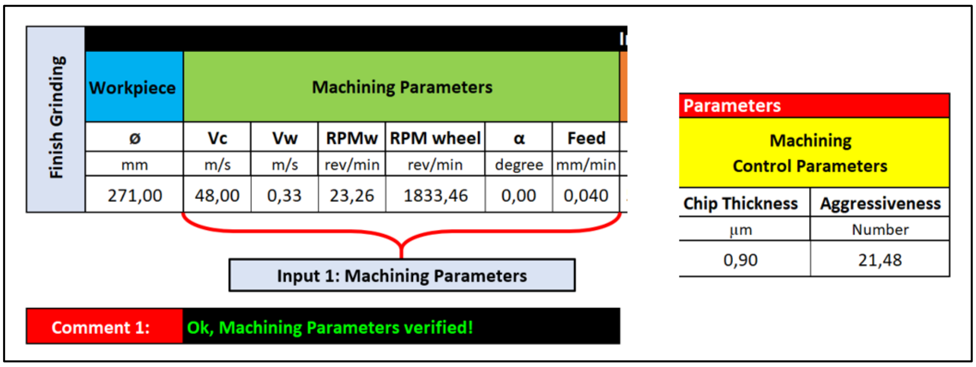


Fig. 120 Machining parameters feedback (pass)

Similarly if dressing validation fails, as shown in Fig. 121, dressing input parameters must be changed in order to receive a positive validation feedback from the tool.
In this example validation fails because of too high Whack Ratio, reducing dressing depth check of dressing parameters is positive because of the reduced Whack Ratio as shown in Fig. 122.

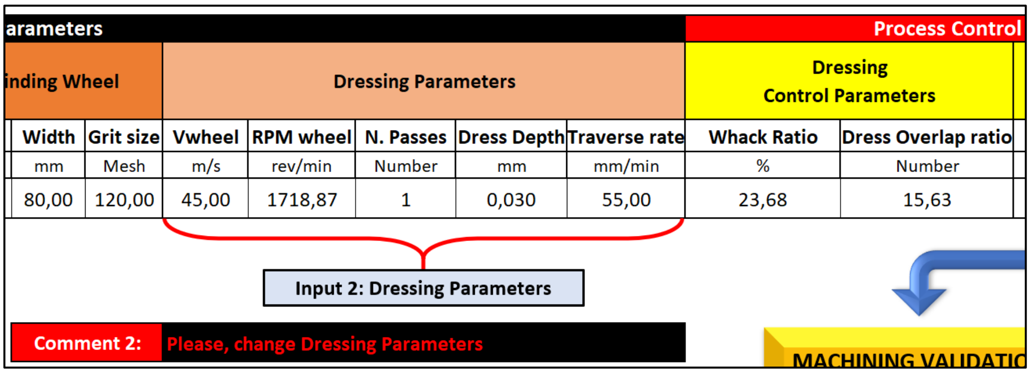


Fig. 121 Dressing validation (fail)

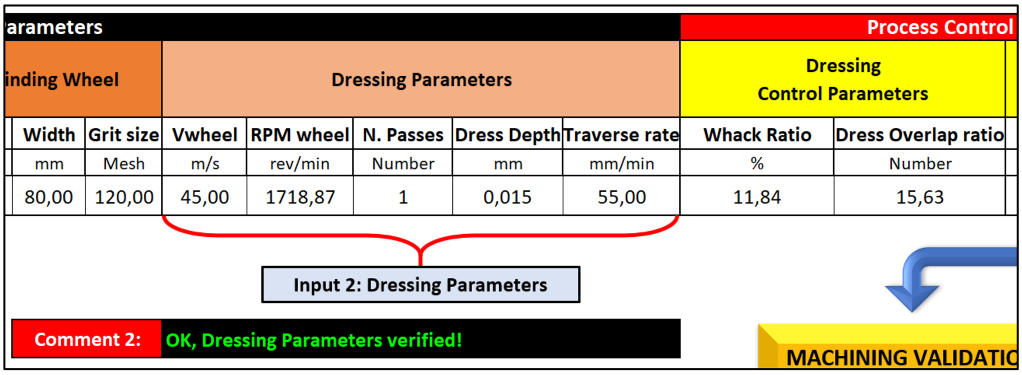


Fig. 122 Dressing validation (pass)

At the end of the validation flow, a supplementary button is useful to confirm that all required checks have been performed successfully, as shown in Fig. 123.

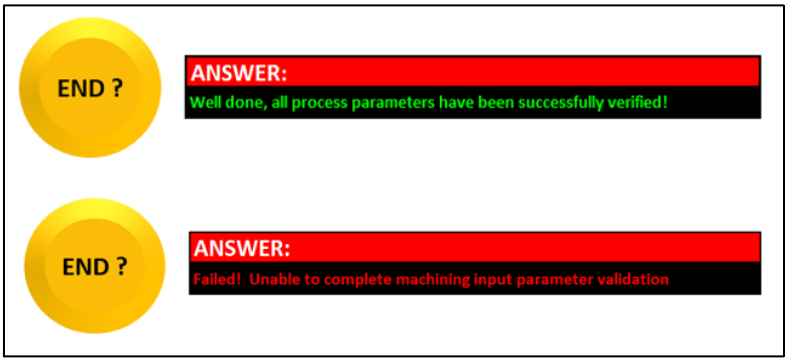


Fig. 123 End button

At the bottom of the spreadsheet there is an information block with the time calculations as shown in Fig. 124.
At the right end there is a very important productivity indicator, the Specific Material Removal Rate.

Time calculations

Material Stock	Machining Time	Dressing N. Cycles	Dressing Traverse Time	Dressing Time ∀ cycle	Dressing Total Time	Total Operation Time	Productivity indicator SMRR (Qw')
mm	s		s	s	s	s	mm3/mm*s
0,10	150,00	2	87,27	87,27	174,55	324,55	0,57

Fig. 124 Time calculations section

The use of this input parameters validation tool makes it easier the definition of grinding parameters and it avoids the risk to have high scrap rate in delivering new products.
As an example the historical data of scrap rate due to workpiece burns about one critical component are summarized in Tab. 20.
The 2016 shows a high scrap rate due to unreliable process.
Improvement with revised process parameters and new CNC grinders in the second half of 2017 shows strong reduction of grinding abuses.

	2016	2017	2018
Volume	112	127	82
Accepted	105	126	82
Scrap	7	1	0
Scrap Rate	6.25%	0.79%	0.00%

Tab. 20 Scrap Volume along three years

This component has a unit product cost of about 29000 €.
Raw material cost is 41% of it.
36% is the added value of material transformation up to grinding operation.
23% is the added value of material transformation after grinding process to the ending product-cycle operations.
The lost value for workpiece burns is 77% of unit product cost.
Fig. 125 is the allocation of product cost of that part and highlights the real percentage of value lost because of grinding burns.

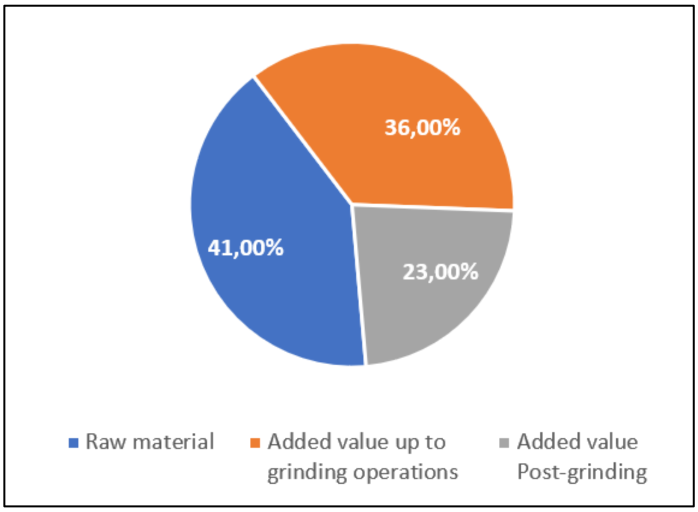


Fig. 125 Cost allocation

Hence, the economic loss on the worst of the last three years is:

$$Economic\ loss_{\ workpiece\ burns,\ \ 2016} = (1 - 0.23) \times \frac{Cost}{Part} \times N.Scrapped\ Parts =$$

$$= 0.77\ \times 29000\ \times 7 = 156310\ €$$

The target to minimize risk of grinding abuses, in particular in delivering new products, can be achieved by the definition of a standard set of process parameters as presented in this thesis.

6.2. Input parameters optimizer tool

This tool using an Excel Solver optimizes a set of input parameters with the aim to maximize productivity within safe limits.
Optimizer tool includes two different spreadsheets one for rough/semi-finish grinding and another for finish grinding. Here is reported the optimization model of machining input parameters for rough/semi-finish grinding, for finish grinding is similar but with different constraint values.

$$\mathbf{max}\ \ \frac{\mathrm{PI}() \times \text{Feed rate} \times \cos(\alpha * \mathrm{PI}()/180)\ \times\ \text{Øw}}{60}$$

Subject to following constraints:
(Depth of cut constraint)

$$0{,}0004 \leq \frac{\text{Feed rate} \times \cos(\alpha * \mathrm{PI}()/180)}{\frac{\mathrm{v_w} \times 60 \times 1000}{\mathrm{PI}() \times \text{Øw}}} \leq 0{,}0030$$

(Speed ratio constraint)

$$\frac{\mathrm{v_c}}{100} \leq \mathrm{v_w} \leq \frac{\mathrm{v_c}}{40}$$

(Aggressiveness constraint)

$$20\ \leq 52.3 \times \frac{\sqrt{\text{Feed rate}\ \left(\frac{\text{mm}}{\text{min}}\right) \times \cos(\alpha \times \mathrm{PI}()/180)\ \times\ \frac{\mathrm{v_w} \times 60 \times 1000}{\mathrm{PI}() \times \text{Øw}}\ \times\ \text{Part Ø}\ \ (\text{mm})}}{\text{Wheel Speed}\ \left(\frac{\text{m}}{\text{sec}}\right)} \times \sqrt{\frac{\text{Wheel Ø (mm)} + \text{Part Ø(mm)}}{\text{Wheel Ø(mm)}}} \leq 67$$

(Chip Thickness constraint)

$$1 \leq\ 1000 \times \sqrt{\frac{6}{10} \times \frac{1}{2} \times \frac{15.2}{\text{Mesh Number}} \times \frac{52.3}{1000000} \times \frac{\sqrt{\text{Feed rate} \times \cos(\alpha \times \mathrm{PI}()/180)\ \times\ \frac{\mathrm{v_w} \times 60 \times 1000}{\mathrm{PI}() \times \text{Øw}} \times \text{Øw}}}{\mathrm{v_c}} \times \sqrt{\frac{\text{Øw} +\ \text{Øwheel}}{\text{Øwheel}}}}\ \leq\ 2{,}3$$

Variables:
Øwheel, Øw, $\mathrm{v_c}, \mathrm{v_w}$, Feed rate $\in \mathbb{R}^+$, Mesh $\in \{36, 46, 54, 60, 80, 100\}$, $0 \leq \alpha \leq 90$

Excel Solver spreadsheet provides results as shown in Fig. 126, 127 and Fig. 128. Workpiece and wheel diameters, Mesh number, peripheral wheel and workpiece speed, feed rate and feed cutting angle (α) are in the input block. Peripheral workpiece speed and feed rate are optimized running the solver in order to find the maximum output and so to identify the best parameter setting that ensures maximum productivity within safe limits (depth of cut, speed ratio, aggressiveness and chip thickness).

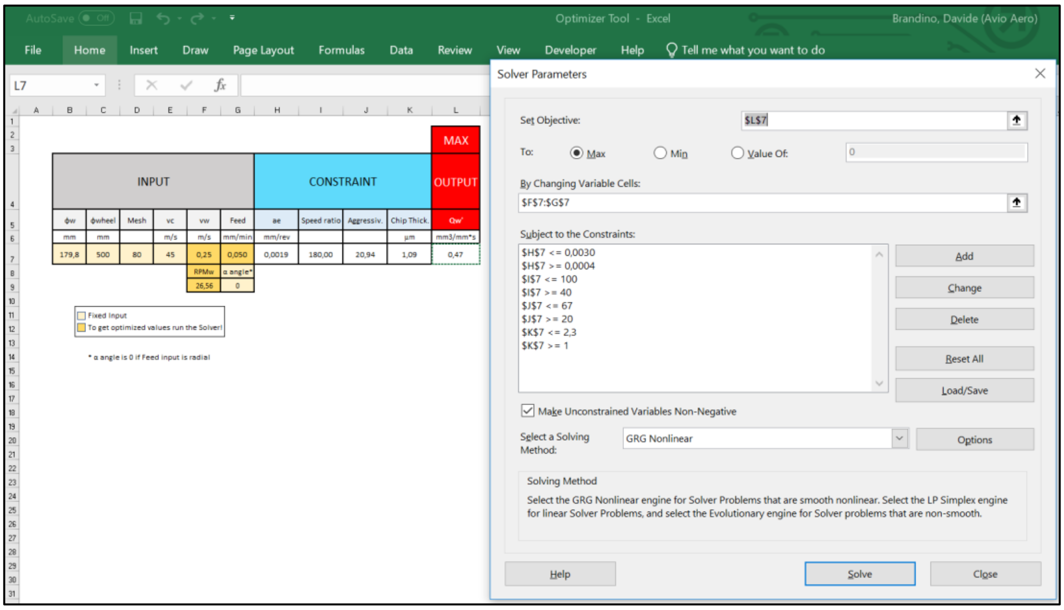


Fig. 126 Screenshot of optimizer interface

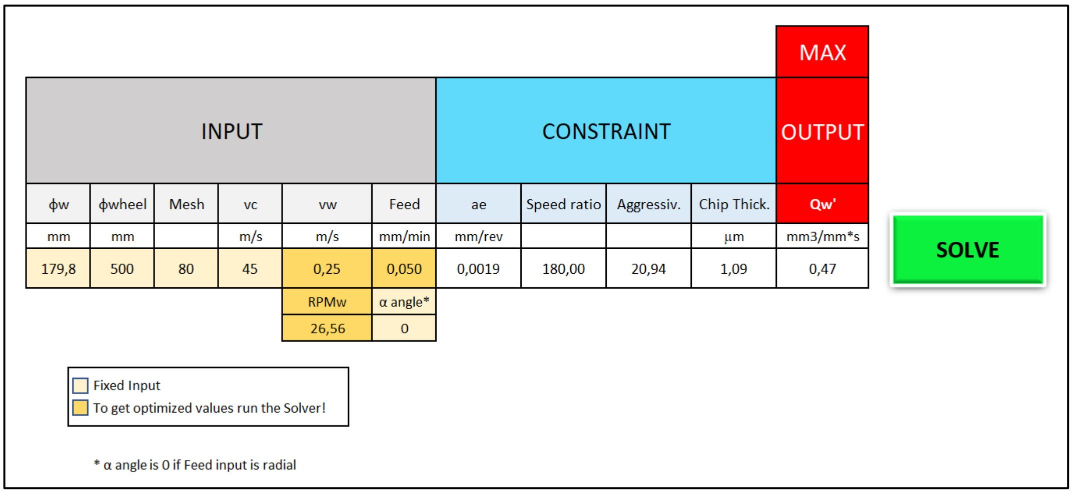


Fig. 127 The macro button “Solve”

To automate the Solver Parameters window the button “Solve” has been created, using VBA Record Macro.

In Fig. 128 the results of the optimization solver.

Comparing Fig. 126 to Fig. 128, the productivity indicator is increased by the solver about four times (1.90/0.47 = 4.04).

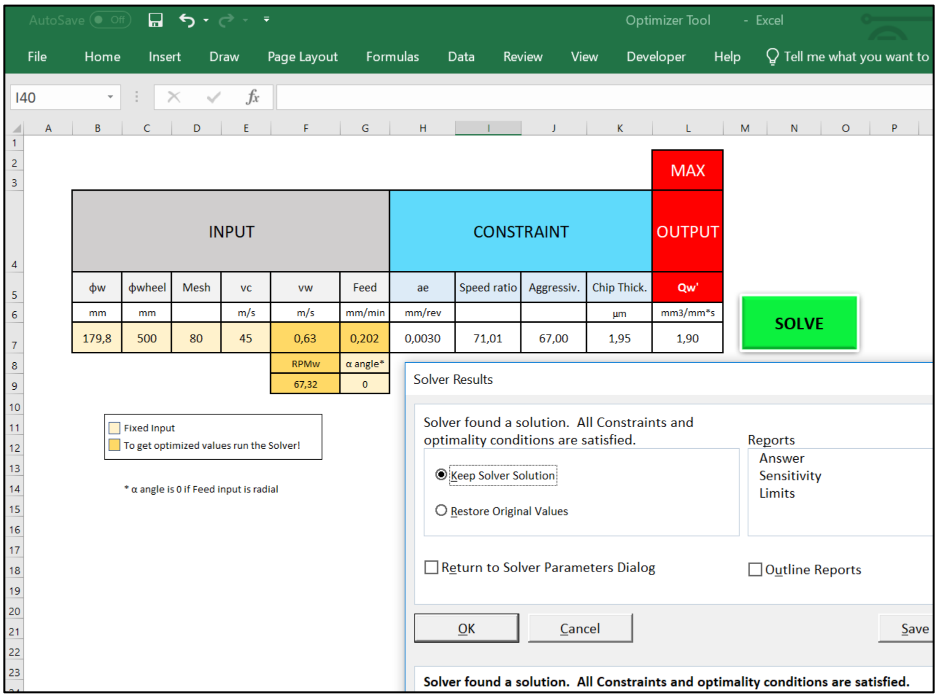


Fig. 128 Screenshot of optimization solver at the end of the optimization

An excerpt of current rough grinding operations is shown in Tab. 21, highlighted cells in red are referred to values exceeding limits.

INPUT								CONSTRAINT				TARGET
Feature N.	$Diameter_w$	$Diam_{wheel}$	Mesh	v_c	v_w	α	Feed	a_e	Speed Ratio	Aggressiv.	Chip Thickness	Current Qw'
	mm	mm		m/s	m/s		mm/min	mm/rev			µm	mm3/mm*s
1	271,8	500	80	45,00	0,24	45,00	0,048	0,0028	187,50	21,33	1,10	0,68
2	271,8	500	80	45,00	0,24	45,00	0,048	0,0028	187,50	21,33	1,10	0,68
3	179,8	500	80	45,00	0,25	45,00	0,050	0,0019	180,00	20,94	1,09	0,47
4	179,8	500	80	45,00	0,25	45,00	0,050	0,0019	180,00	20,94	1,09	0,47
5	179,8	500	80	45,00	0,25	45,00	0,050	0,0019	180,00	20,94	1,09	0,47
6	179,8	500	80	45,00	0,25	45,00	0,050	0,0019	180,00	20,94	1,09	0,47
7	116,9	600	60	27,17	0,44	45,00	0,120	0,0017	61,93	66,71	2,25	0,73
8	116,9	600	60	27,17	0,44	45,00	0,120	0,0017	61,93	66,71	2,25	0,73
9	271,8	500	80	45,00	0,24	45,00	0,048	0,0028	187,50	21,33	1,10	0,68
10	271,8	500	80	45,00	0,24	45,00	0,048	0,0028	187,50	21,33	1,10	0,68
11	271,8	750	54	27,49	0,24	45,00	0,051	0,0030	113,75	34,07	1,70	0,73
12	271,8	750	54	27,49	0,24	45,00	0,051	0,0030	113,75	34,07	1,70	0,73

Tab. 21 Excerpt of current rough grinding process

The same view with optimized rough grinding parameters (values in orange), obtained from optimized parameters tool, is in Tab. 22. You can notice all control parameters are within limits and in the target column the productivity indicator results increased at the maximum value within control parameters constraints.

INPUT								CONSTRAINT				TARGET
Feature N.	$Diameter_w$	$Diam_{wheel}$	Mesh	v_c	v_w	α	Feed	a_e	Speed Ratio	Aggressiv.	Chip Thickness	New Qw'
	mm	mm		m/s	m/s		mm/min	mm/rev			µm	mm3/mm*s
1	271,8	500	80	45,00	0,73	45,00	0,154	0,0030	61,54	67,00	1,95	2,19
2	271,8	500	80	45,00	0,73	45,00	0,154	0,0030	61,54	67,00	1,95	2,19
3	179,8	500	80	45,00	0,63	45,00	0,202	0,0030	71,01	67,00	1,95	1,90
4	179,8	500	80	45,00	0,63	45,00	0,202	0,0030	71,01	67,00	1,95	1,90
5	179,8	500	80	45,00	0,63	45,00	0,202	0,0030	71,01	67,00	1,95	1,90
6	179,8	500	80	45,00	0,63	45,00	0,202	0,0030	71,01	67,00	1,95	1,90
7	116,9	600	60	27,17	0,33	45,00	0,161	0,0030	82,55	67,00	2,26	0,99
8	116,9	600	60	27,17	0,33	45,00	0,161	0,0030	82,55	67,00	2,26	0,99
9	271,8	500	80	45,00	0,73	45,00	0,154	0,0030	61,54	67,00	1,95	2,19
10	271,8	500	80	45,00	0,73	45,00	0,154	0,0030	61,54	67,00	1,95	2,19
11	271,8	750	54	27,49	0,44	45,00	0,094	0,0030	61,83	62,65	2,30	1,33
12	271,8	750	54	27,49	0,44	45,00	0,094	0,0030	61,83	62,65	2,30	1,33

Tab. 22 Excerpt of optimized rough grinding process

An excerpt of current semi-finish grinding operations is shown in Tab. 23, highlighted cells in red are referred to values exceeding limits.

INPUT								CONSTRAINT				TARGET
Feature N.	$Diameter_w$	$Diam_{wheel}$	Mesh	v_c	v_w	α	Feed	a_e	Speed Ratio	Aggressiv.	Chip Thickness	Actual Qw'
	mm	mm		m/s	m/s		mm/min	mm/rev			µm	mm3/mm*s
1	271,50	500	80	45,00	0,26	45,00	0,045	0,0025	173,08	21,41	1,10	0,64
2	271,50	500	80	45,00	0,26	45,00	0,045	0,0025	173,08	21,41	1,10	0,64
3	179,40	500	80	45,00	0,25	45,00	0,050	0,0019	180,00	20,96	1,09	0,47
4	179,40	500	80	45,00	0,25	45,00	0,050	0,0019	180,00	20,96	1,09	0,47
5	179,40	500	80	45,00	0,25	45,00	0,050	0,0019	180,00	20,96	1,09	0,47
6	179,40	500	80	45,00	0,25	45,00	0,050	0,0019	180,00	20,96	1,09	0,47
7	116,40	500	80	45,00	0,24	45,00	0,100	0,0025	187,50	27,68	1,26	0,61
8	116,40	500	80	45,00	0,24	45,00	0,100	0,0025	187,50	27,68	1,26	0,61
9	50,20	600	120	25,00	0,28	45,00	0,097	0,0011	88,19	50,00	1,38	0,25
10	39,63	600	120	25,00	0,28	0,00	0,096	0,0009	88,19	49,31	1,37	0,20
11	140,47	600	60	25,00	0,53	0,00	0,080	0,0011	46,85	66,47	2,25	0,59
12	68,48	600	60	25,00	0,37	0,00	0,103	0,0010	68,15	59,47	2,13	0,37
13	271,50	500	80	45,00	0,26	45,00	0,045	0,0025	175,86	21,41	1,10	0,64
14	271,50	500	80	45,00	0,26	45,00	0,045	0,0025	173,08	21,41	1,10	0,64
15	271,50	750	54	27,49	0,24	45,00	0,026	0,0015	113,94	24,09	1,43	0,36
16	271,50	750	54	27,49	0,24	45,00	0,026	0,0015	113,94	24,09	1,43	0,36

Tab. 23 Excerpt of current semi-finish grinding process

In Tab. 24 you can see the same table with adjusted input parameters and target column confirms the increased productivity.

INPUT								CONSTRAINT				TARGET
Feature N.	$Diameter_w$	$Diam_{wheel}$	Mesh	v_c	v_w	α	Feed	a_e	Speed Ratio	Aggressiv.	Chip Thickness	Actual Qw'
	mm	mm		m/s	m/s		mm/min	mm/rev			µm	mm3/mm*s
1	271,50	500,00	80,00	45,00	0,73	45,00	0,154	0,0030	61,56	67,00	1,95	2,19
2	271,50	500,00	80,00	45,00	0,73	45,00	0,154	0,0030	61,56	67,00	1,95	2,19
3	179,40	500,00	80,00	45,00	0,63	45,00	0,202	0,0030	71,06	67,00	1,95	1,90
4	179,40	500,00	80,00	45,00	0,63	45,00	0,202	0,0030	71,06	67,00	1,95	1,90
5	179,40	500,00	80,00	45,00	0,63	45,00	0,202	0,0030	71,06	67,00	1,95	1,90
6	179,40	500,00	80,00	45,00	0,63	45,00	0,202	0,0030	71,06	67,00	1,95	1,90
7	116,40	500,00	80,00	45,00	0,54	45,00	0,264	0,0030	84,03	67,00	1,95	1,61
8	116,40	500,00	80,00	45,00	0,54	45,00	0,264	0,0030	84,03	67,00	1,95	1,61
9	50,20	600,00	120,00	25,00	0,25	45,00	0,198	0,0021	100,00	67,00	1,60	0,52
10	39,63	600,00	120,00	25,00	0,25	0,00	0,202	0,0017	100,00	67,00	1,60	0,42
11	140,47	600,00	60,00	25,00	0,33	0,00	0,133	0,0030	76,54	67,00	2,26	0,98
12	68,48	600,00	60,00	25,00	0,25	0,00	0,193	0,0028	100,00	67,00	2,26	0,69
13	271,50	500,00	80,00	45,00	0,73	45,00	0,154	0,0030	61,56	67,00	1,95	2,19
14	271,50	500,00	80,00	45,00	0,73	45,00	0,154	0,0030	61,56	67,00	1,95	2,19
15	271,50	750,00	54,00	27,49	0,44	45,00	0,094	0,0030	61,85	62,65	2,30	1,33
16	271,50	750,00	54,00	27,49	0,44	45,00	0,094	0,0030	61,85	62,65	2,30	1,33

Tab. 24 Excerpt of optimized semi-finish grinding process

The benefits of adopting an optimization and objective approach includes:

- Reduced risk of scraps
- Increased productivity, so lowered costs
- Decreased delivery times

The resultant machining time reduction is about 70 % with respect the current (Tab. 25), as detailed in Tab. 26 and 27.

	Current Machining Time	New Machining Time
	min	min
Rough grinding	1937.73	700.98
Semi-finish grinding	2682.03	784.21
Total	4619.76	1485.19
Machining Time Reduction [%]	67.85 %	

Tab. 25 Machining Time calculation

Feature N.	Qw' new / Qw' current	Material Stock to be removed	Current Machining Time	New Machining Time	Expected Volume 2019	Cumulated Machining Time	New Cumulated Machining Time	Expected Machining Time Reduction (Percentage)
		mm	min	min	units	min	min	%
1	3,24	0,150	3,15	0,97	40,00	126,05	38,92	69,12%
2	3,24	0,150	3,15	0,97	40,00	126,05	38,92	69,12%
3	4,04	0,200	4,00	0,99	60,00	240,00	59,42	75,24%
4	4,04	0,200	4,00	0,99	60,00	240,00	59,42	75,24%
5	4,04	0,200	4,00	0,99	60,00	240,00	59,42	75,24%
6	4,04	0,200	4,00	0,99	60,00	240,00	59,42	75,24%
7	1,34	0,250	2,08	1,55	60,00	125,00	92,99	25,61%
8	1,34	0,250	2,08	1,55	60,00	125,00	92,99	25,61%
9	3,24	0,150	3,15	0,97	40,00	126,05	38,92	69,12%
10	3,24	0,150	3,15	0,97	40,00	126,05	38,92	69,12%
11	1,84	0,150	2,94	1,60	38,00	111,76	60,82	45,58%
12	1,84	0,150	2,94	1,60	38,00	111,76	60,82	45,58%
					Total	1937,73	700,98	63,82%

Tab. 26 Expected time reduction percentage for rough grinding

Feature N.	Qw' new / Qw' current	Material Stock to be removed	Current Machining Time	New Machining Time	Expected Volume 2019	Cumulated Machining Time	New Cumulated Machining Time	Expected Machining Time Reduction (Percentage)
		mm	min	min	units	min	min	%
1	3,43	0,225	5,00	1,46	40,00	200,00	58,34	70,83%
2	3,43	0,225	5,00	1,46	40,00	200,00	58,34	70,83%
3	4,04	0,180	3,60	0,89	60,00	216,00	53,40	75,28%
4	4,04	0,180	3,60	0,89	60,00	216,00	53,40	75,28%
5	4,04	0,180	3,60	0,89	60,00	216,00	53,40	75,28%
6	4,04	0,180	3,60	0,89	60,00	216,00	53,40	75,28%
7	2,64	0,180	1,80	0,68	60,00	108,00	40,97	62,06%
8	2,64	0,180	1,80	0,68	60,00	108,00	40,97	62,06%
9	2,04	0,100	1,03	0,50	16,00	16,49	8,07	51,07%
10	2,10	0,050	0,52	0,25	16,00	8,33	3,97	52,36%
11	1,66	0,200	2,50	1,50	24,00	59,98	36,03	39,93%
12	1,87	0,200	1,94	1,04	24,00	46,64	24,89	46,63%
13	3,43	0,225	5,00	1,46	40,00	200,00	58,34	70,83%
14	3,43	0,225	5,00	1,46	40,00	200,00	58,34	70,83%
15	3,68	0,225	8,82	2,40	38,00	335,29	91,16	72,81%
16	3,68	0,225	8,82	2,40	38,00	335,29	91,16	72,81%
					Total	2682,03	784,21	70,76%

Tab. 27 Expected time reduction percentage for semi-finish grinding

7. Design of Experiments, Grinding Test Plan

Expectation of this Thesis is the optimization of the grinding process with a robust process control to avoid damage on workpiece due to grinding abuses.
Abusive grinding can lead to thermal damage of a ground part depending on the increase in temperature and consequent damage in the workpiece microstructure.
Examining this issue we can identify two different situations.
The first one is when the grinding abuse is caused by a quite low workpiece speed with high feed rate, therefore high depth of cut. The second one happens when high friction is generated in grinding, that is when the workpiece speed is higher than recommended and the sum of workpiece and grinding wheel peripheral speeds become very high generating high speed rubbing that leads to very high temperature on workpiece cutting area even in presence of good cooling conditions.
The goal is to avoid exceeding these damage limits.
The limit due to friction is easier to control than the limits for high depth of cut.
It could be enough to check if input parameters relevant to grinding wheel and workpiece speeds are correct with respect the best practice or setting a block in CNC grinder program to prevent exceeding peripheral speeds limit.
Whereas finding process limit to avoid grinding abuses due to improper feed rate is very difficult, also because it depends on many other factors such as coolant efficiency and correct and punctual grinding wheel dressing.
Hence an effective process monitoring to avoid damage is of great interest in grinding process especially with so high cost ground parts, also because a well-controlled grinding process leads to lower scraps rate and to higher productivity thus to a lower production cost.
The implementation of an intelligent process with adaptative ability to avoid damage is the best goal as you can imagine, for instance with capability to correct input parameter or providing information to optimize the process parameters, detecting problems such as blunt grinding wheels (wheel to be dressed) or even blocking the grinding process for any detected anomaly.
A way to implement a smart grinding process is the power monitoring.
Having said that, the first step is to identify the maximum power limit safe to avoid grinding damage.
A Design of Experiments is needed to find these safety limits and verify how far the current process is from them.
The Company is planning a grinding test with a University or a technology development center, where all the equipments for the tests are available.
Another DOE expectation is to verify if there are significant correlations between tensile residual stress on workpiece and grinding power.

With these purposes, various process conditions will be tested gradually shifting parameters toward burn limits, since the optimal process conditions in order to obtain the highest productivity will be in correspondence of the upper power limit that should include a safety margin depending on confidence to process variations.
Grinding method to be used for this DOE is the plunge grinding.
Test shall be carried out on a cylindrical test sample. Test pieces are portions of steel pipes with dimension in mm of 150x75, where 150 is the diameter.
It shall be provided 40 test samples.
Sample will be prepared as shown in Fig. 129 with the following characteristics:

- Material Pyrowear 53
- Cylindrical test piece with external diameters, carburized and heat-treated

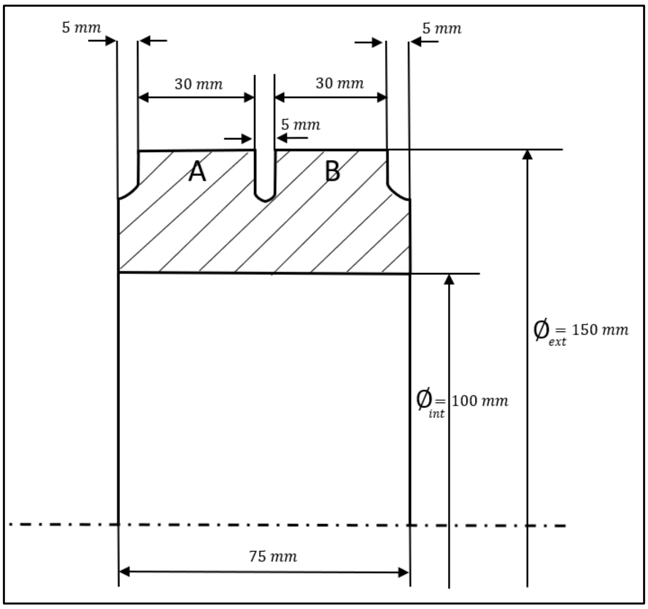


Fig. 129 Test sample section

DOE execution will be as follows:

- Workpiece preparation before starting grinding (if necessary light grinding to normalize test piece)
- Rough grinding A and B diameters with defined DOE parameters (32 workpieces)
- Finish grinding only diameter B with defined finishing parameters
- Check ground diameter A and B according to measurement plan
- Collect in-process data (power and acoustic monitoring)

The machining strategy, as summarized above and depicted in Fig. 130, is to grind diameter A and B first applying DOE parameters, to grind in a second step diameter B using fixed finishing parameters.

Grinding to be performed with good cooling conditions.
Grinding wheel will be Mesh 80, high-porosity type.
Grinding wheel shall be dressed before each machining test operation.
Dressing parameters will be:

- Dressing depth (0,02 mm)
- Traverse rate (0,0522 mm/rev to setup on CNC grinder, that maintains constant this value and peripheral wheel speed changing wheel RPM depending on its diameter reduction due to number of dressing cycles)
- Two passes each dressing cycle
- Peripheral wheel speed (40 m/s)

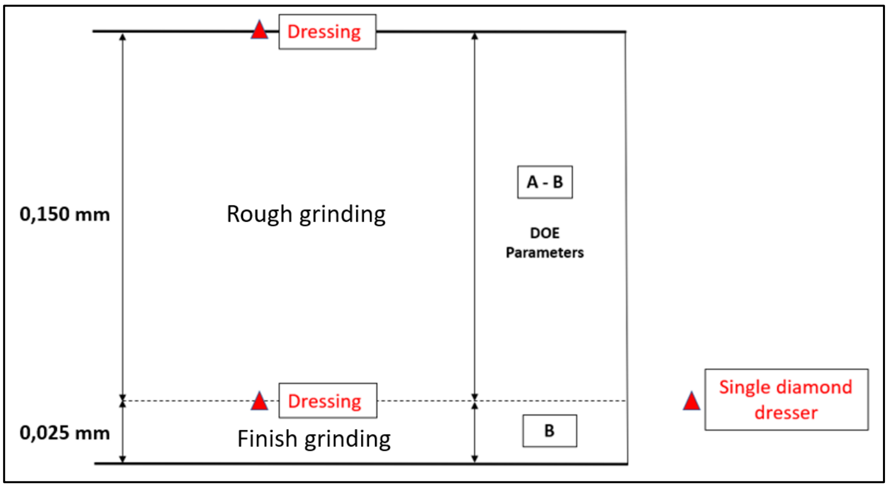


Fig. 130 Material stock removal and dressing strategy

Fixed parameters are:
- Peripheral cutting speed of high-porosity grinding wheel = 45 m/s
- Test sample diameters and axial length
- Material stock to be removed on each sample diameter
- Grinding wheel type
- Single diamond dresser, dressing parameters

Variable input parameters (factors), see Tab. 28, are:
- Feed rate: 4 levels
- Peripheral workpiece speed: 4 levels

Each combination has to be repeated on two samples (2 trials).

The number of DOE runs, see Tab. 29, is:

$$N.of\ runs = (N.of\ levels^{\ N.of\ parameters}) \times N.of\ trials = 4^2 \times 2 = 32\ runs$$

Remaining 8 test pieces (40 available – 32 runs) are available as spare pieces in case of false results.

Variable parameters – LEVELS (Lv)							
Feed rate [mm/min]				Peripheral workpiece speed (v_w) [m/s]			
Lv1	Lv2	Lv3	Lv4	Lv1	Lv2	Lv3	Lv4
0,08	0,12	0,16	0,20	0,15	0,30	0,60	1,20

Each Feed rate level shall be tested with all peripheral workpiece speed level (and fixed peripheral wheel speed)

Each setting: 2 trials

Tab. 28 Variable parameters levels and values

Run N.	Trial	Peripheral Vc	Peripheral Vw	Feed rate
		[m/s]	[m/s]	[mm/min]
1	*1st*	45	0,15	0,08
2	*2nd*	45	0,15	0,08
3	*1st*	45	0,30	0,08
4	*2nd*	45	0,30	0,08
5	*1st*	45	0,60	0,08
6	*2nd*	45	0,60	0,08
7	*1st*	45	1,20	0,08
8	*2nd*	45	1,20	0,08
9	*1st*	45	0,15	0,12
10	*2nd*	45	0,15	0,12
11	*1st*	45	0,30	0,12
12	*2nd*	45	0,30	0,12
13	*1st*	45	0,60	0,12
14	*2nd*	45	0,60	0,12
15	*1st*	45	1,20	0,12
16	*2nd*	45	1,20	0,12
17	*1st*	45	0,15	0,16
18	*2nd*	45	0,15	0,16
19	*1st*	45	0,30	0,16
20	*2nd*	45	0,30	0,16
21	*1st*	45	0,60	0,16
22	*2nd*	45	0,60	0,16
23	*1st*	45	1,20	0,16
24	*2nd*	45	1,20	0,16
25	*1st*	45	0,15	0,20
26	*2nd*	45	0,15	0,20
27	*1st*	45	0,30	0,20
28	*2nd*	45	0,30	0,20
29	*1st*	45	0,60	0,20
30	*2nd*	45	0,60	0,20
31	*1st*	45	1,20	0,20
32	*2nd*	45	1,20	0,20

Tab. 29 Runs input parameters for grinding

DOE input values comprise the current average values calculated with respect the test piece diameter of 150 mm. In particular the current workpiece peripheral speed is 0,30 m/s while the current feed rate is 0,08 mm/min.

In this way increasing the feed rate up to 0,20 mm/min, productivity will result two times and half than current. The peripheral workpiece speed is extended to obtain a significant range of values to be tested.

The last machining step, on B diameter only, is performed to evaluate results on finish parts in terms of shape and roughness requirements and material integrity.

Finish grinding fixed parameters to remove last 0,05 mm on diameter B are in Tab. 30.

Fixed finishing parameters		
Vc	Vw	Feed rate
m/s	m/s	mm/min
45	0,3	0,04

Tab. 30 Finish Grinding parameters on dia B

Fig. 131 to explain main topics of this DOE, the sixteen points represent the 32 runs.

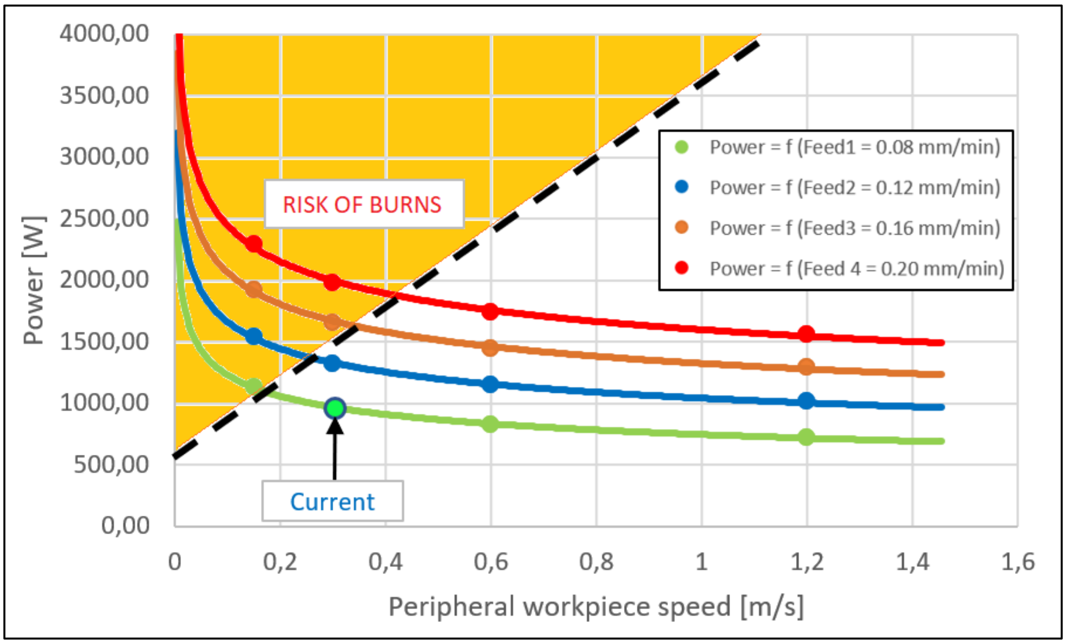


Fig. 131 Limit of burns to be assessed by DOE

On vertical axis are the values of Power estimated by calculation for each run of DOE, burn area should be above the dotted line, only pictorial on this diagram.

Output of DOE should be a similar diagram resulting from test, including monitored values of power obtained from power monitoring and burns limits if occur (test piece with burns).

Referring to burns occurrences you will have two possible scenarios.
Scenario1: Burns detected during test. Reduce DOE domain excluding remaining tests above the burning limit.
Scenario2: Burns non-detected in any test. Evaluate DOE domain extending runs with more challenging parameters on new test pieces.
In Tab. 31 are the Calculated Parameters referred to DOE runs, for reference only runs with risk of burns are highlighted, in particular those runs have depth of cut outside the recommended limits.

				Calculated Parameters		
Run N.	Trial	Peripheral Vw	Feed rate	Qw'	RPMw	ae
		[m/s]	[mm/mi	mm3/s*m	rev/mi	mm/re
1	1st	0,15	0,08	0,628	19,10	**0,00419**
3	1st	0,3	0,08	0,628	38,20	0,00209
5	1st	0,6	0,08	0,628	76,39	0,00105
7	1st	1,2	0,08	0,628	152,79	0,00052
9	1st	0,15	0,12	0,942	19,10	**0,00628**
11	1st	0,3	0,12	0,942	38,20	0,00314
13	1st	0,6	0,12	0,942	76,39	0,00157
15	1st	1,2	0,12	0,942	152,79	0,00079
17	1st	0,15	0,16	1,257	19,10	**0,00838**
19	1st	0,3	0,16	1,257	38,20	**0,00419**
21	1st	0,6	0,16	1,257	76,39	0,00209
23	1st	1,2	0,16	1,257	152,79	0,00105
25	1st	0,15	0,2	1,571	19,10	**0,01047**
27	1st	0,3	0,2	1,571	38,20	**0,00524**
29	1st	0,6	0,2	1,571	76,39	0,00262
31	1st	1,2	0,2	1,571	152,79	0,00131

Tab. 31 Runs with risk of burns

Measurement Plan includes:

- Measurements of test pieces after grinding
    - Dimensional inspection
    - Surface roughness
- Non-Destructive Tests (NDT)
    - NITAL
    - Barkhausen Noise
    - XRD surface residual stress
- Destructive Tests (DT)
    - Metallography
    - XRD residual stress profile
- In process data acquisition
    - Power monitoring
    - Acoustic monitoring

8. Conclusions

Grinding standard allows to identify stable set of parameters and therefore a more robust process mainly to avoid grinding abuses difficult to be detected that could cause failures during flight.
The cylindrical grinding process standard herein defined has as its goal to achieve an expected scrap rate for new components launch equal to zero, with reference to grinding abuses. Thus, it's pursued to avoid undesired previous scenarios were some scraps due to grinding burns have been occurred, leading to high economic losses.
To identify grinding burns limits, a Design of Experiments has been planned as described in chapter 7. This DOE would be also beneficial to find limits that could lead to higher productivity, and at the same time to test the potentiality of power and acoustic monitoring as new methods to prevent grinding abuses. The target is to have scrap rate due to workpiece burns equal to zero on components ground with CNC machines.
This target can be achieved by the definition of a standard set of process parameters that creates a surface consistent to accuracy, integrity and damage tolerance requirements and by a robust control of these parameters.
Therefore the standard herein defined integrated with the released spreadsheets is helpful in process definition of grinding input parameters with the purpose to reduce iterations for grinding technological validation for new part introduction "NPI".
Continuous improvement shall be pursued on process control methods to identify the optimal parameter settings and to further prevent grinding abuses. Process monitoring (e.g. grinding power monitoring) could be helpful for this purpose, thus the idea of its installation on CNC grinders.

Some bullet points of my skills growth during my experience in GE Avio S.r.l. are:

- Learning by experience
- Use of technical product and process management system
- Improved comprehension of mechanical drawing
- Effective communication, interfacing with a large variety of employees and managers in their roles
- Be part of a complex company environment, developed by functions in a global context

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