Grinding Burn

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Synonyms

Thermal damage in grinding

Definition

Grinding burn subsumes all unwanted changes in the surface and subsurface region of the workpiece due to heat release out of the grinding process.

This comprises microstructural changes, high residual tensile stresses, and cracks (Karpuschewski et al. 2011). It has to be avoided by an appropriate choice of the process parameters, grinding tool, and coolant strategies. Process monitoring is necessary in order to avoid malfunctions of components due to the thermal damage.

Grinding burn is in literature (e.g., Littmann 1953; Malkin 1974) used to characterize the visible surface damage. Most damage due to the grinding process is by the nature of the manufacturing process of thermal origin and can consist, besides oxidation of the surface, also of metallurgical phase transformations, softening of the surface layer with possible rehardening, changes in residual tensile stresses, cracks, and resulting in a reduced fatigue strength (Malkin and Guo 2007). Because the same mechanisms are responsible for the annealing colors as for the subsurface damage, more modern literature (e.g., Höhn et al. 2011; Karpuschewski et al. 2011; Thiemann et al. 2013; Rowe 2014; Denkena et al. 2014) subsumes under “grinding burn” all effects visible or invisible on the surface and independent of the depth of influence. This definition is used throughout this entry. It is independent of materials and includes unwanted heat induced structural changes from grinding also for non-iron alloys, ceramics, and even for biomaterials.

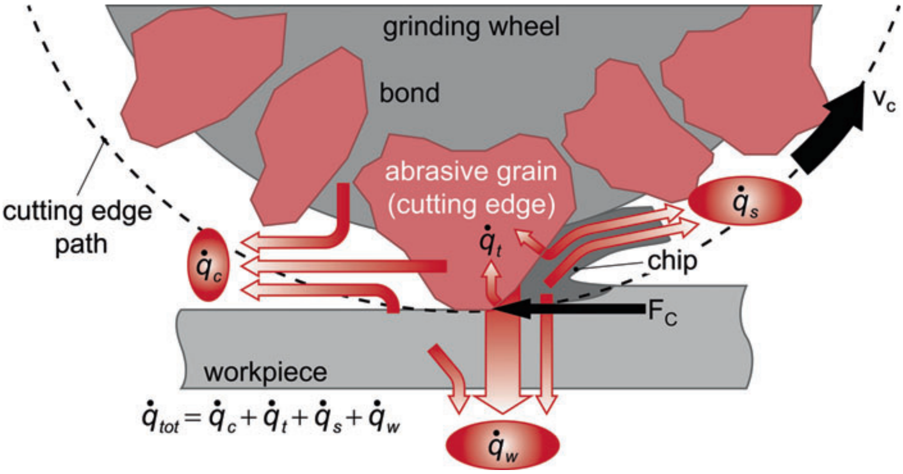
Theory and Application

Origin and Mechanism

In cutting processes, nearly all mechanical power, which is introduced into the process zone, is converted into heat. This is split up in heat spreading into the tool, into the workpiece, heat which is extracted by chips and debris, and heat which is extracted by cooling for instance by metalworking fluids and surrounding media as shown in Fig. 1.

In cutting processes with geometrically defined cutting edges as milling and turning, the heat input is less than in grinding, and the chips can remove a

The International Academy for Production Engineering et al. (eds.), *CIRP Encyclopedia of Production Engineering*, https://doi.org/10.1007/978-3-642-35950-7_16786-1



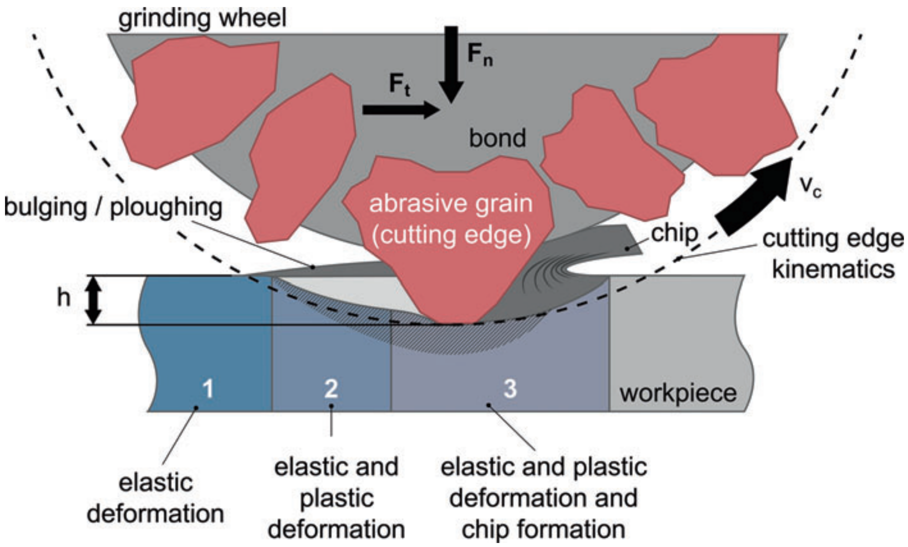
Grinding Burn, Fig. 1 Power balance of the grinding process. (Modified from Klocke (2009). Reproduced with kind permission of IWF, ETH Zürich). $\dot{q}_{tot}$ = total heat generation, $\dot{q}_c$ = heat flux into the coolant (or metalworking fluid), $\dot{q}_t$ = heat flux into the grinding wheel, $\dot{q}_s$ = heat flux into removed material, $\dot{q}_w$ = heat flux into the workpiece, F_c = cutting force, v_c = cutting speed

high share of the thermal energy from the process zone. Therefore, in many cases dry cutting is possible. However, in conventional grinding the introduction of heat into the workpiece with typically about 55% of the chip formation energy and all sliding and plowing energies according to Malkin and Anderson (1974) are conducted as heat into the workpiece and can induce grinding burn when poor process parameters or inadequate coolant delivery are applied. Poor cooling conditions can also arise due to film boiling of the coolant, when the thermal burn-out threshold temperature is surpassed on the workpiece surface (Guo and Malkin 1994). Malkin and Guo (2007) later specified the energy portion of the grinding energy dissipated by the workpiece by typically 60–85% depending on the grinding process and coolant conditions, where at shallow cut grinding the energy portion can be as low as 5%. A glance at the geometry of the cutting edges on the grinding wheel and the number of them engaged in the cutting process will help to describe the mechanics of the grinding process. Cutting edges in grinding operate with high wedge angles because of their high stability, which is required for the removal of very hard materials. This in turn results in highly negative rake angles, which introduce large plastic deformations and plowing in the workpiece surface as shown in Fig. 2. Also the penetration of the stout cutting edges into the material and the high number of them results into high normal forces. Taking the sublinear dependency of the cutting forces on the chip thickness as described by the Kienzle equation

$$F_t = F_c = k_{1.1} b h^{1-m} \tag{1}$$

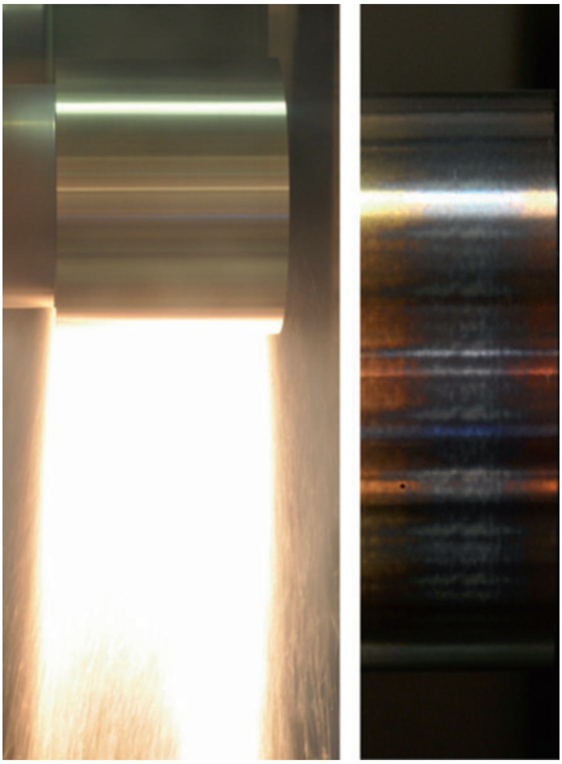
where F_c is the cutting force, b is the width of cut, h is the uncut chip thickness, and $k_{c1.1}$ and m are material parameters, into account, this effect is increased as a higher density of cutting edges reduces the effective chip thickness. Below a certain penetration depth only deformation and friction but no cutting occurs. These mechanisms, the high process forces and the high relative velocity between the grinding wheel and the workpiece, generate a massive dissipation of mechanical power and conduction of heat into the workpiece.

The impact of the heat on the workpiece is depending on the intensity and the material itself including its prior heat treatment. Malkin (1974) recognized the connection of visible temper colors and structural changes of the workpiece subsurface. Generally, when a critical heat flux is exceeded, residual tensile stresses are rising in the subsurface layer of the workpiece depending on



Grinding Burn, Fig. 2 Chip formation in grinding from elastic to plastic deformation. (Modified from Klocke (2009). Reproduced with kind permission of IWF, ETH Zürich). h = uncut chip thickness, F_t = tangential force on the grinding wheel, F_n = normal force on the grinding wheel, v_c = cutting speed

Grinding Burn, Fig. 3 Dry cylindrical grinding and the resulting grinding burn with chatter marks. (Reproduced with kind permission of IWF, ETH Zürich)



the material changes in the micro structure. For hardened steel the martensitic structure becomes annealed and hardness is reduced. When the intensities are even higher, rehardened zones, so-called white layers at the surface above a tempered substructure as demonstrated by Karpuschewski et al. (2011) are formed in steels with martensitic structure. The high thermal stresses can lead to micro cracks in the surface due to fast heating in the grinding zone followed by quenching from the bulk material. The existence of a white layer can increase this effect. Other materials as, for example, Inconel 738 tend to fusion of areas with reduced melting temperature and hot crack development. Thermal damage can lead to high wear of the hardened surface layer and fast fatigue failure of the whole structure.

Detection

Grinding is the finishing step in a process chain and forms the final surface, thus the geometrical accuracy and geometrical surface quality, which mostly is functional and requires the state of hardening achieved before the grinding process. To meet the requirements of reliability and life time it is of greatest interest to identify deteriorations of the surface due to grinding burn right after the process and before delivery. In Fig. 3, an example of severe oxidizing burn and chatter marks as a result of dry grinding is shown. In this case, burn is easily recognized by dark blue stripes. As grinding process is usually divided in roughing, finishing, and spark out processes, the thermal damage is likely to develop in the first part of machining and the visible signs could be removed in the spark out period of grinding, while surface damage (modified hardness, cracks) still remains (Rowe 2014) and require one of the following methods to detect them.

The study of grinding burn demands surface integrity evaluation of the workpiece. Various methods exist for the measurement of microstructural changes and residual stresses in sublayers, where some of them are destructive. For the monitoring of grinding burn two main procedures have been established in industry so far, Barkhausen noise analysis and NITAL test. Recently, eddy current testing has evolved as a suitable method to detect not only cracks but grinding burn as well. None of them is really suitable for in-process measurements and none of them is able to predict the occurrence of grinding burn, which means that a closed loop control cannot be established. Therefore, procedures to predict the occurrence of grinding burn play a major role. The mentioned nondestructive methods are described shortly in the following.

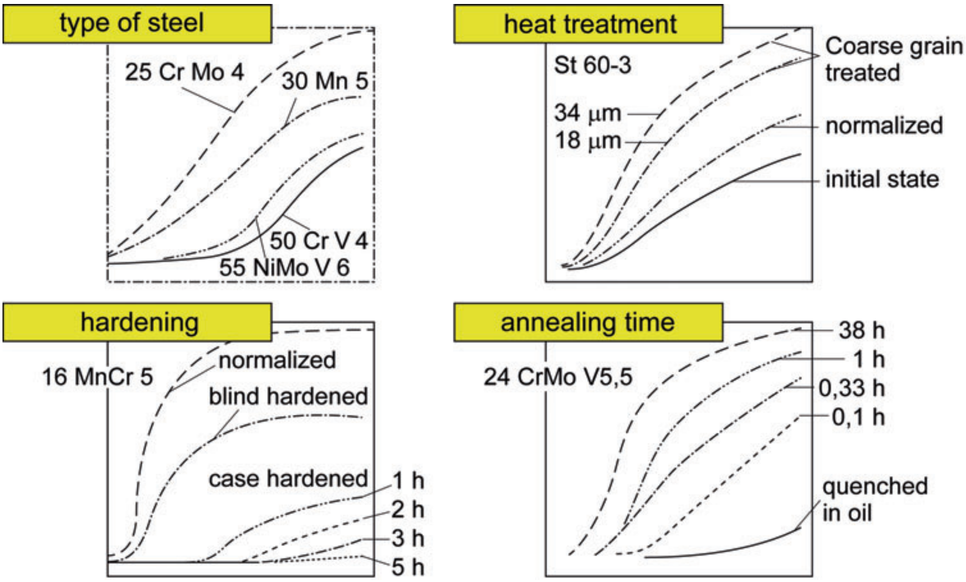
Barkhausen Noise Analysis

A very common nondestructive measurement method for grinding burn testing is the Barkhausen noise analysis, which is suitable for all ferromagnetic materials. The main principle is based on the analysis of a voltage signal that can be measured from the specimen by applying a time-varying magnetic field into the workpiece surface. The signal is induced by the motion of domain walls, as the magnetic field does move and rotate them (Santa-aho et al. 2014). The amplitude of the signal increases with rising residual stresses, where an upper limit has to be defined in a complex calibration process. Difficulties arise with variable thickness of the influenced layer, different compositions of the material as well as differences in heat treatment as described by Karpuschewski (1995), Karpuschewski et al. (2011), and Rowe (2014). Influences on the Barkhausen noise are shown in Fig. 4.

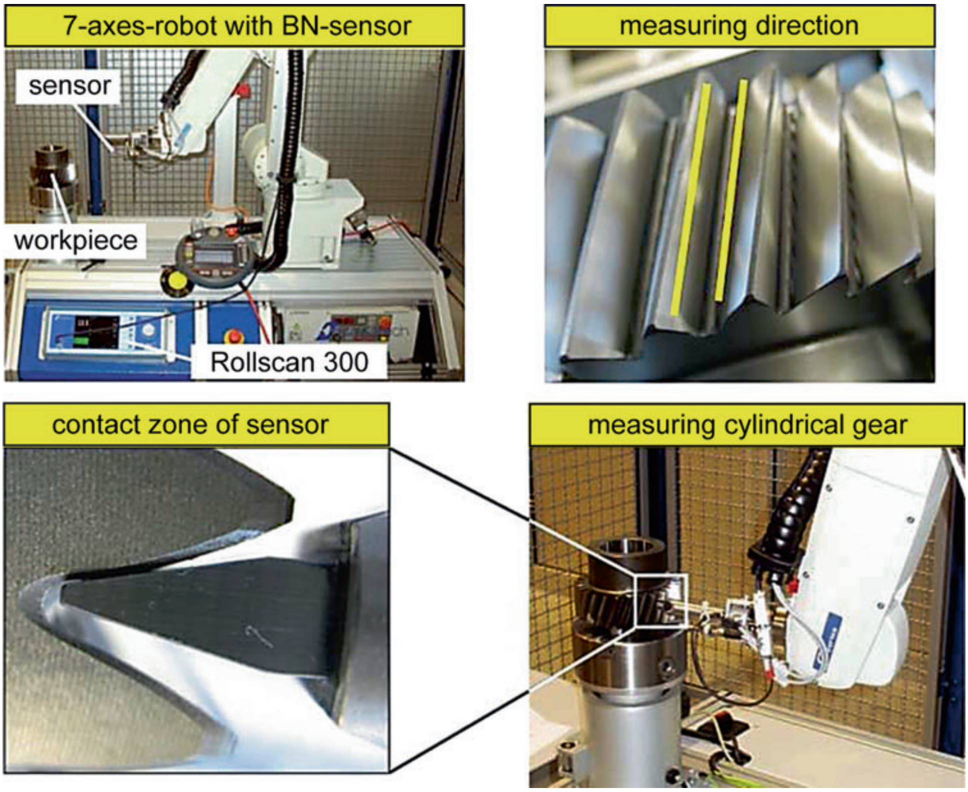
Barkhausen noise analysis evolved to an eminent method for grinding burn detection, which can be used in an automated station with specific adapted sensors for sample tests especially in parts with a tendency for thermal damage and high requested reliability. Figure 5 gives an example for the testing of gears with a robot guiding the sensor.

NITAL Test

NITAL-etching (nitric acid and alcohol) is another well-established test for grinding burn. It makes use of the fact that different material contents at the surface react chemically different under nitric acid. In general, thermal damaged parts show darker discoloration. The whole process requires different chemicals, typically besides nitric acid



Grinding Burn, Fig. 4 Barkhausen noise (BN) analysis and influence on the signal (Karpuschewski 1995). (Reproduced with kind permission of B. Karpuschewski)



Grinding Burn, Fig. 5 Handling of Barkhausen noise (BN) sensor with robot (Karpuschewski et al. 2011). (Reproduced with kind permission of B. Karpuschewski) also hydrochloridic acid, methanol, and sodium carbonate solution, which requires careful handling. As the specimens need to be dunked completely in pure concentrations under defined timings, large parts are usually for economic and ecological reasons not suitable as huge dip tanks are required. Also damage in deeper layers cannot be identified, if the spark-out process creates a faultless surface. The results are very subjective and depend on the interpretation of the tester as stated by Karpuschewski et al. (2011).

Eddy Current Testing

Generally, this technique is known for the detection of cracks in electrically conducting materials. Eddy currents generated by alternating current in an exploring coil are induced in the surface in which surface defects and the inductivity of the subsurface area affect the impedance of the coil that can be detected by a measurement device. Cracks are a result of an extreme thermal surface damage, but recently eddy current testing can be used to detect structural and hardness changes in the material and thus grinding burn. However, changes of residual stresses, which develop earlier, cannot be detected, thus the absence of signals from the eddy current testing does not necessarily imply the absence of thermal damage. If a signal is detected, serious thermal damage has occurred. The sensors can be adapted to the measuring problem, e.g., for gear or profile grinding, but the measurement speed is low.

Additional Remarks

All these methods have in common that they can be highly dependent on the operator and the material conditions and do not consider all kinds of changes in the material attributed to grinding burn. Intensive training and experience are essential for reliable testing results. Karpuschewski et al. (2011) therefore recommends a combination of different measurement methods like, e.g., Barkhausen noise and hardness measurement with eddy current testing. Furthermore, there are more methods not specific to grinding burn, like dye penetrant inspections, which can be used for detection of cracks in surfaces. As described before, grinding burn often involves high normal forces and thus chattering can occur as well, which can be detected, for example, by noise and force variations during the grinding process and visual testing of the workpiece for chatter marks. Acoustic emission (AE) detection as well as measurement of spindle power can be used for process monitoring and therefore to recognize changes in the process which can eventually lead to surface damage and grinding burn (Webster et al. 1994; Yang et al. 2014).

Mitigation

Grinding burn is defining an upper limit for the desired grinding operation as it does heavily depend on the process parameters like cutting speed, feed rate, and coolant supply as well as the used tool and dressing conditions. Damage due to grinding burn destroys the whole value creation accumulated so far. In a worst case, parts are failing in operation if grinding burn is not detected. Therefore, it is of greatest interest to avoid grinding burn by presetting the process parameters. Heinzel et al. (2014) discusses a method to determine the grinding limits based on the specific introduced grinding power P_c'' and contact time Δt of grinding wheel and workpiece based on Malkin's burning limit (Malkin and Guo 2007).

The following parameters and techniques have a huge impact on the development of grinding burn and are for example proposed by Rowe (2014).

1. Structuring and sharpening of grinding wheels to produce sharper cutting surface and thus reduce normal forces
2. Wheels with better self-sharpening effect and sharp super abrasives
3. Suitable cooling by terms of delivery and choice of medium
4. Usually higher feed velocities
5. Machine learning
6. Model-based prediction and correct selection of process parameters
7. Reduction of removal rate

While some points can be seen as an optimization of the grinding process itself, the reduction of the removal rate, shorter dressing cycles, and additional coolant delivery does have a direct impact on the achievable cost effectiveness of the whole grinding process.

Exploitation

Brinksmeier followed the idea of making use of the mechanisms provoking grinding burn and invented grind hardening where the process of heat introduction is used in a defined manner for generating a temperature time profile, which results in the intended material state after grinding. The so-called grind-hardening intents to induce martensitic phase transformations as used by other surface strengthening processes (Brinksmeier and Brockhoff 1996; Alonso et al. 2015). This technique was also investigated in cylindrical components using cyclic heating for the generation of hardened layers (Liu et al. 2015).

Cross-References

- ▶ Dressing
- ▶ Grinding Wheel
- ▶ Plowing

References

Alonso U, Ortega N, Sanchez JA, Pombo I, Izquierdo B, Plaza S (2015) Hardness control of grind-hardening and finishing grinding by means of area-based specific energy. Int J Mach Tool Manu 88:24–33

Brinksmeier E, Brockhoff T (1996) Utilization of grinding heat as a new heat treatment process. Ann CIRP Manuf Technol 45(1):283–286

Denkena B, Köhler J, Schindler A, Woiwode S (2014) Continuous generating grinding – material engagement in gear tooth root machining. Mech Mach Theory 81:11–20

Guo C, Malkin S (1994) Analytical and experimental investigation of burnout in creep-feed grinding. Ann CIRP Manuf Technol 43(1):283–286

Heinzel C, Sölter J, Jermolajev S, Kolkwitz B, Brinksmeier E (2014) A versatile method to determine thermal limits in grinding. Procedia CIRP 13:131–136

Höhn B-R, Stahl K, Oster P, Tobie T, Schwienbacher S, Koller P (2011) Flank-load-carrying capacity of case hardened gears with grinding burn. In: Proceedings of the ASME 2011 international design and engineering conferences & computers and engineering in engineering conference IDET/CIE 2011, pp 1–8

Karpuschewski B (1995) Mikromagnetische Randzonenanalyse geschliffener einsatzgehärteter Bauteile [Micromagnetic sub surface analysis of ground case hardened parts]. PhD thesis, University Hannover, Fortschritt-Berichte VDI, Reihe 8, Mess-, Steuerungs- und Regelungstechnik Nr. 498 (in German)

Karpuschewski B, Bleicher O, Beutner M (2011) Surface integrity inspection on gears using Barkhausen noise analysis. In: 1st CIRP conference on surface integrity (CSI), Bremen, 30 Jan–1 Feb 2012. Procedia engineering, vol 19, pp 162–171

Klocke F (2009) Manufacturing processes 2 – grinding, honing, lapping. Springer, Berlin/Heidelberg

Littmann WE (1953) The influence of the grinding process on the structure of hardened steel. Doctoral thesis, Massachusetts Institute of Technology

Liu M, Nguyen T, Zhang LC, Wu Q, Sun DL (2015) Effect of grinding-induced cyclic heating on the hardened layer generation in the plunge grinding of a cylindrical component. Int J Mach Tool Manu 89:55–63

Malkin S (1974) Thermal aspects of grinding part 2 – surface temperatures and workpiece burn. ASME J Eng Ind 96(4):1184–1191

Malkin S, Anderson RB (1974) Thermal aspects of grinding part 1 – energy partition. ASME J Eng Ind 96(4):1177–1183

Malkin S, Guo C (2007) Thermal analysis of grinding. Ann CIRP Manuf Technol 56(2):760–782

Rowe WB (2014) Principles of modern grinding technology. William Andrew/Elsevier, Waltham/Oxford

Santa-aho S, Sorsa A, Hakanen M, Leiviskä K, Vippola M, Lepisto T (2014) Barkhausen noise-magnetizing voltage sweep measurement in evaluation of residual stress in hardened components. Meas Sci Technol 25(8):085602, 6 pp. https://doi.org/10.1088/0957-0233/25/8/085602

Thiemann P, Ströbel G, Goch G (2013) Mikromagnetische und photothermische Charakterisierung thermomechanischer Schädigungen [Micromagnetic and photothermal characterization of thermo-mechanical damages]. Tech Mess 80(6):206–212. https://doi.org/10.1524/teme.2013.0020 (in German)

Webster J, Marinescu I, Bennett R, Lindsay R (1994) Acoustic emission for process control and monitoring of surface integrity during grinding. Ann CIRP Manuf Technol 43(1):299–304

Yang Z, Wu H, Yu Z, Huang Y (2014) A non-destructive surface burn detection method for ferrous metals based on acoustic emission and ensemble empirical mode decomposition: from laser simulation to grinding process. Meas Sci Technol 25(3):035602, 9 pp