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Understanding the causes of grinding burn helps alleviate the problem.

Burn Awareness

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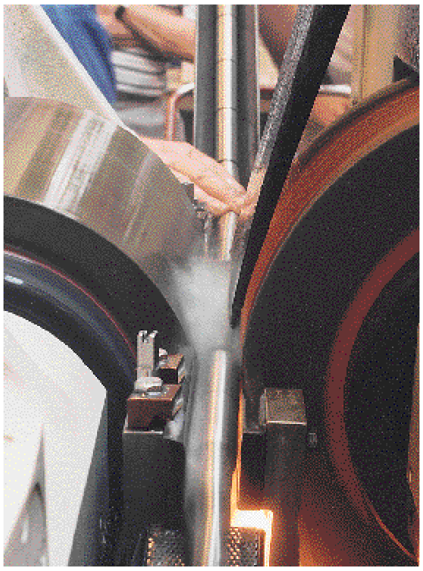
'Grinding burn" is a term loosely used to describe any type of thermal damage that occurs to the workpiece during grinding. Often, the grinding engineer simply looks for workpiece discoloration to determine whether or not there is a problem.

There are several different types of thermal damage. Some are strictly cosmetic, some inhibit grinding performance and some lead to immediate fracturing of the workpiece.

A workpiece's ability to tolerate the grinding temperature is dependent on its composition, heat treatment and form. Hardened tool steel, for example, can normally tolerate an arc-of-cut "hot spot" of 650° C without experiencing problems. But the same hot-spot temperature could cause an intricately shaped 52100-grade part to crack. Additionally, the amount of hard carbides in tool steel can determine whether a workpiece burns or not. A high percentage of carbides can blunt the wheel, making it grind too hot.

The changes that occur *during* grinding also must be taken into account. For example, the surface of a workpiece that has been gently ground (and, therefore, under low temperatures) will be left in a state of compressive residual stress. This is caused by the plastic deformation at the surface of the workpiece by the abrasive grits. Like shot peening, this can enhance the workpiece's mechanical properties, with the most notable improvement being to fatigue life.

However, as production rates increase, the arc-of-cut temperature tends to rise. This can cause parts to lose strength, suffer tensile stresses or even crack.



Part damage occurs because of the interaction between grinding energy and the workpiece's metallurgy. For real part-quality improvements to be made—while reducing scrap—it is essential for the grinding machine operator to understand the different types of damage, when they occur, which ones are dangerous and how to alleviate them.

Degrees of Burn

Table 1 lists the different types of thermal damage and gives a rough idea of the relative temperatures at which they occur.

Oxidation burn, caused by a thin surface layer of oxidized metal and coolant, causes discoloration of the workpiece. This discoloration is usually just cosmetic and frequently occurs without the part suffering any metallurgical damage. Oxidation burn can be seen on the ground surface and/or close to the grinding region, where temperatures are high due to conduction. Oxidation burn is a poor indicator of whether thermal damage has occurred because it's unpredictable.

Thermal softening occurs when the grinding temperature exceeds the tempering temperature of the workpiece material. Overtempering causes the workpiece surface to soften.

Residual tensile stress is caused by thermal expansion of the workpiece beyond its yield stress, which puts the material close to the surface under constant tension. This tension degrades the material's fatigue life and, in extreme cases, causes immediate cracking. The depth and severity of the cracking depends on the grinding temperature and the material.

Rehardening burn is caused by a metallurgical phase change in the material when the grinding temperature exceeds the austenizing temperature, creating a thin layer of hard, brittle, untempered martensite. To further exacerbate the problem, rehardening burn is also accompanied by secondary residual stress, because the newly formed material has a greater density than the original material.

Cracking Up

The development of residual tensile stress is complicated and influenced by many variables. The following is a simplified explanation of how this stress forms and why it's dangerous.

During grinding, a great deal of heat is generated. This heat penetrates the workpiece. As the temperature rises, the hot surface of the workpiece surface being ground wants to expand upward and outward (Figure 1). The upward thermal expansion is unrestricted. However, the surrounding material restricts the outward thermal expansion. When the hot surface tries to expand outward and is restricted, it is effectively in a state of compression. If the temperature is high enough, the compressive stress will exceed the yield stress of the material and it will permanently deform.

When the material cools after grinding, it tries to shrink to a size smaller than it was originally (due to the permanent compressive deformation). But material continuity restricts this shrinkage (it is being "pulled" by the surrounding material), which results in a surface material under tension.

Residual tensile stress can lessen the part's fatigue life during its intended use and, if severe enough, can cause it to crack immediately.

If cracking or microcracking are not present, residual stress can be alleviated by a post-grinding tempering operation. Residual stress cannot be seen by the naked eye, but detection is possible with X-ray diffraction, by taking Barkhausen noise measurements or acid dipping.

Calculating residual stresses is complicated. However, for the practical engineer, Tiberg's Rule provides a robust method for avoiding tensile residual stress. It provides a good approximation of the temperatures where residual stress begins, based on readily available workpiece material properties. The rule

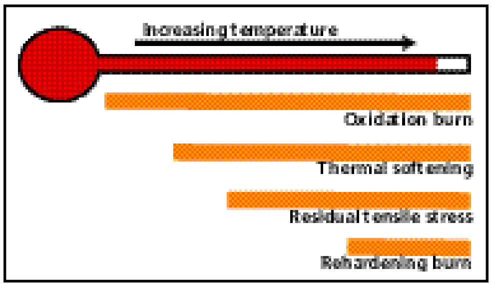


Table 1: Different types of thermal damage and the relative temperatures at which they occur.

is written as:

$$\sigma_{yt} > E \cdot \alpha \cdot \Delta_T$$

where E is Young's modulus, α is the coefficient of thermal expansion, Δ_T is the temperature rise and σ_{yt} is the yield stress at the temperature that is reached.

Creating Chips

During grinding, three primary interactions occur between the wheel and workpiece: cutting, rubbing and plowing (Figure 2). All generate heat.

The cutting interaction creates chips, which form at the sides of the grits. Rubbing involves the sliding of the abrasive against the part. No material is removed, but heat is generated due to friction. With plowing, material is pushed to the sides and front of the grit. Although plowing facilitates chip formation, the action removes no material.

All three interactions occur to varying degrees during grinding. A sharper wheel cuts more material while a duller wheel tends to plow and rub more.

Wheel dulling is an outgrowth of attritious wearing of the grain tips. And when grinding with a dull wheel, the excessive plowing and rubbing generate more heat, increasing the likelihood of thermal damage.

Steel is a commonly ground material. It is composed of two primary constituents: the matrix and the carbides. Tungsten, molybdenum and vanadium all combine with carbon to form hard carbides in the matrix. These large, refractory carbides tend to blunt the abrasive grains or grits, which results in excessive rubbing, less-efficient grinding, higher power consumption, higher temperatures, excessive wheel wear and a loss of wheel form. Tungsten carbide, molybdenum carbide and, particularly, vanadium carbide have hardness values near conventional abrasives (Table 2).

Typically, the higher the alloying content the higher the percentage of hard carbides. And, generally, the relative amounts of vanadium, tungsten, molybdenum and carbon in a material determine the rate at which the grinding wheel blunts.

Alleviating Thermal Damage

Thermal damage can occur anytime that grinding temperatures are high. The highest-temperature region, the hot spot, is directly in front of the wheel.

Alleviating thermal damage involves decreasing the amount of heat generated and/or lowering the heat entering the workpiece by making the cooling system more efficient. The following factors influence whether thermal damage occurs or not.

Abrasive Type and Wheel Type. Choosing the correct type of wheel and abrasive often pose the greatest challenges. A common mistake is to choose a wheel that is harder than necessary—one that won't release its dull grits.

Thermal damage can be greatly reduced by using a mixture containing a

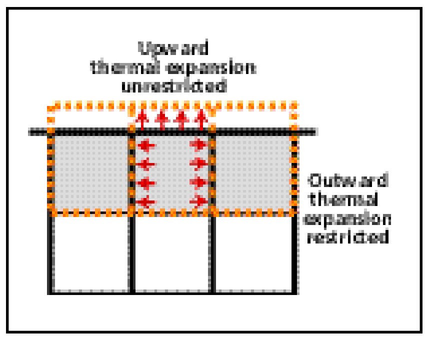


Figure 1: Residual tensile stress occurs if a ground material tries to shrink to a size smaller than it was originally.

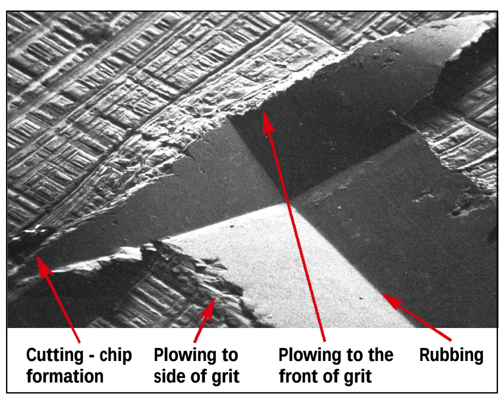


Figure 2: Three wheel/workpiece interactions occur during grinding: cutting, plowing and rubbing.

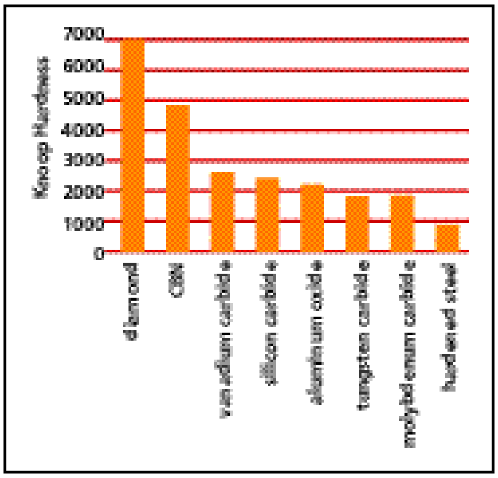


Table 2: Knoop Hardness values of various abrasives and workpiece materials.

"seeded-gel" abrasive. The microfracturing characteristic of this abrasive helps keep the wheel sharp, which prevents wheel blunting and part burning.

Dressing, Speeds and Feeds. It's important to understand how grinding wheel speeds, feeds and dressing relate to grinding burn. Thermal damage can be greatly reduced by using the correct operating parameters and dressing strategies.

For example, both the dressing depth and the dressing lead (the speed at which the diamond traverses the wheel) affect the sharpness of the wheel. However, the dressing lead usually plays a more important role than the dressing depth. Therefore, decreasing the dressing depth and increasing the dressing lead results in a sharper wheel while simultaneously extending wheel life. The wise grinder is aware of the relationship between the two.

In addition, the grinding temperature depends on the workpiece (table) speed. With proper coolant application, the temperature can be kept to a minimum at low table speeds, as is the case with creep-feed grinding. The temperature can be kept low at high table speeds, too, as in high-efficiency deep grinding. HEDG is possible because the workpiece moves through the grinding zone so quickly that the hot spot is ground away before the heat has time to enter the workpiece.

Between these two velocity extremes lies the "mountain of burn," which should be avoided at all costs. Table 3 depicts the relative partition ratios for velocity for a typical set of conditions. The fraction of heat that is partitioned to the coolant and to the workpiece depends on the workpiece velocity. The result is a peak in the middle where the temperatures are highest.

Having a rough idea of where one's application lies on the mountain of burn enables the wise grinder to determine the appropriate parameters. But, beware! The table speed at which burning occurs depends on many other grinding and workpiece parameters, such as metal-removal rate, type of coolant used, wheel diameter, and workpiece shape and material.

Heat Treatment. Improper or careless hardening and tempering of the workpiece can lead to undesirable metallurgical properties that could affect grinding. Ajudicious adherence to heat-treating specifications will result in the production of better parts.

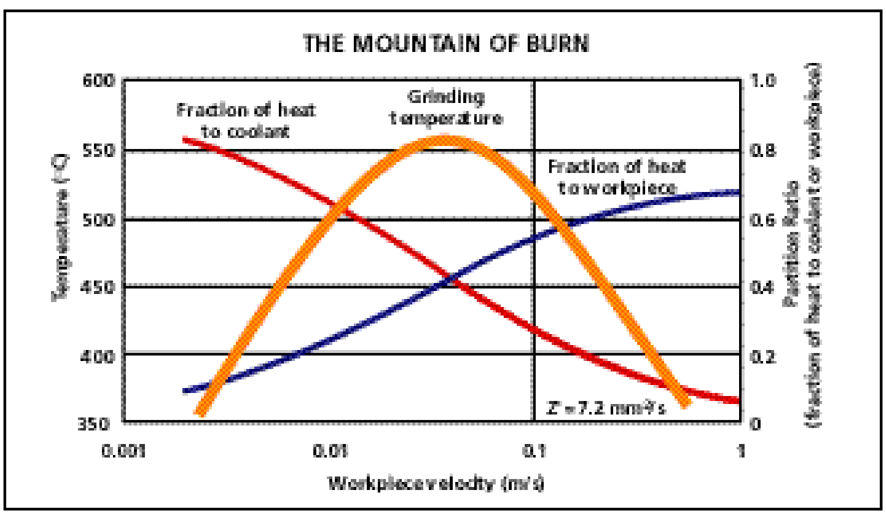


Table 3: Avoid temperatures that fall within the mountain of burn.

Coolant Application. Getting coolant through the air barrier surrounding the wheel and into the hot spot can be difficult. A common mistake is to assume that quantity is more important than quality and then simply flood the grinding zone with coolant delivered at a low pressure.

Abetter approach is to deliver coolant with small, well-positioned nozzles at a velocity that matches the wheel velocity. This allows the coolant to penetrate the area between grits and carry coolant into the hot spot.

Education. Understanding the fundamentals of grinding, such as coolant application, chip size, wheel wear and power relationships, will give the operator the tools to solve problems and optimize the process himself.

A flute-grinding operation that was changed demonstrates the impact of making simple modifications. The operation was being performed with resin-bonded wheels, which, because of their poor porosity, are a challenge to cool.

First, a proprietary change was made to the heat-treatment procedure. Second, a well-aimed coolant nozzle with a small orifice was added just behind the grinding zone. (Large orifices can cause large pressure drops in the coolant-delivery system, resulting in a coolant velocity that doesn't sufficiently cool the workpiece.) The coolant velocity in the flute-grinding operation matched the wheel velocity.

The outcome was that stress-related scrap—and stress among the staff—was virtually eliminated.

Similar results can be achieved wherever personnel have a thorough knowledge of grinding fundamentals.

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