Heating and Cooling of Circular Saws

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Introduction

Temperature differences between the rim and the eye of a circular saw have major effects on saw stiffness. Even small differences of say 10 C are significant, yet this can be created by only a small fraction of the power produced at the tooth tip or when the blades rubs against the wood. However, there are also mechanisms to take away large amounts of heat away from the blade.

This paper discusses where and how much heat is developed, how if flows through the saw, and how the heat leaves. The end result is a model that calculates the temperature distribution in the saw blade. Such information is needed to understand how to design and operate circular saws. Also, new materials such as stainless steel and cermet tips have different thermal properties that need to be investigated.

Effects of Temperature on Circular Saws

The problem of temperature changes in circular saws is that the rim usually gets hotter than the rest of the saw, causing a loss of stiffness and resulting in an increase in sawing deviation. If ΔT is the temperature difference between the rim and the eye, then the stiffness is affected as follows:

$$k = k_0 t^3 - k_1 t \Delta T$$

where t is the plate thickness. From this equation the relative change in stiffness due a temperature change is

$$\frac{k_1 t \Delta T}{k_0 t^3} = \left(\frac{k_1}{k_0}\right)\frac{\Delta T}{t^2}$$

which can be interpreted to mean that thinner saws are more sensitive to temperature differences than thinker saws. Given the industry trend to thinner saws, which have lower stiffness to begin with, the need to understand and control how heat moves through the saw is more critical. Furthermore, as will be shown below, thickness has a significant effect on hear slow.

Heat Flow Concepts

Heat has a source, it flows through materials, and is absorbed or dissipated. Since it takes time for heat to move, time is part of the discussion of heat flow in saws.

For a piece of material of mass, m, surface area, A, the change in temperature during a time period τ is

$$\Delta T = t\left(\frac{Q}{mC} - \frac{hA}{mC}\left(T - T_\infty\right)\right)$$

Q is the amount of heat from some source. Note that the larger the mass the larger the temperature rise. The value of C, the thermal capacity of the material, is larger for materials that can absorb more heat for a given temperature increase. The second term represents the loss of heat to the surrounding air or cooling water. T is the temperature of the material, and T_∞ is the temperature of the surrounding air. The convection coeeficient, h, accounts for how fast the air flows over the surface or the amount of water that adheres to and spins off the blade surface. Heat is taken away faster as the surface area increases and the difference between the temperature of the material and the surroundings increases.

Another aspect of heat flow is conduction through the material. Heat flows from one point to another when there is a difference in temperature between the two points. The amount of heat is proportional to the cross-sectional area that the heat must flow through and inversely proportional to the distance between the points. Mathematically, the change in temperature at Point 1 during a time period τ is

$$\Delta T = \frac{kat}{mC\Delta x}\left(T_2 - T_1\right)$$

Model of Heat Flow in a Circular Saw

The drawing below shows how the heat flow model partitions the plate into rings, each with its own mass, and surface area. Note that this model assumes all the heat flow to be radial. For the rotation speeds of operating saws, the temperature around the saw can be assumed to be uniform [Hauptmann and Ramsey]

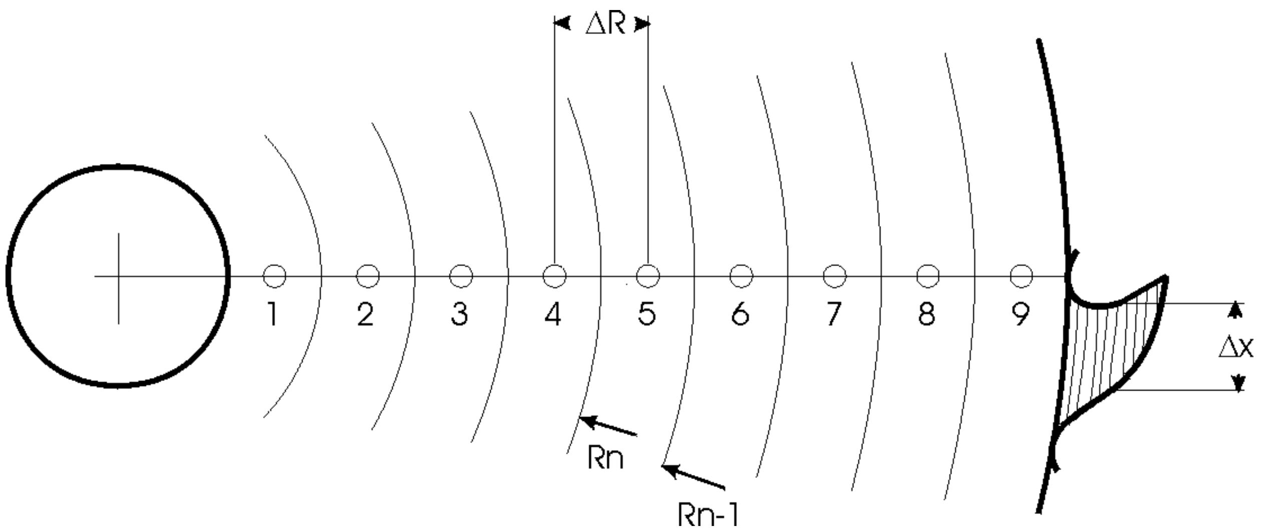

Figure 1. Lumped-mass model of heat flow through a circular saw.

Mass of node n	= m_n	= $\rho\pi t(R_{n+1}^2 - R_n^2)$
Surface area of node n	= A_n	= $2\pi(R_{n+1}^2 - R_n^2)$
Conduction area of node n	= a_n	= $2\pi t\, R_n$
Temperature of node n at time interval i	= $T_{i,n}$	
Time	= $i\tau$	

To calculate the temperature of each node, the following equation is solved:

$$T_{i+1,n} = T_{i,n} + \left(\frac{t}{m_m C}\right)\left[Q_{i,n} + \frac{ka_{n-1}}{\Delta R_{n-1}}\left(T_{i,n-1} - T_{i,n}\right) + \frac{ka_n}{\Delta R_n}\left(T_{i,n+1} - T_{i,n}\right) - hA_n\left(T_{i,n} - T_\infty\right)\right]$$

The same model can be extended to include the teeth by dividing the tooth into segments as shown above.

Heat Sources

In sawing the sources of heat are all caused by friction, such as friction:

- at the tooth tip (face, back and flanks)
- from sawdust spillage
- from rubbing with the wood surface
- from jammed slivers
- from tight guides.

An estimate of how much heat is generated at the tooth tip can be found from the Merchant model of cutting forces by calculating the heat from the chip sliding over the face of the tooth.

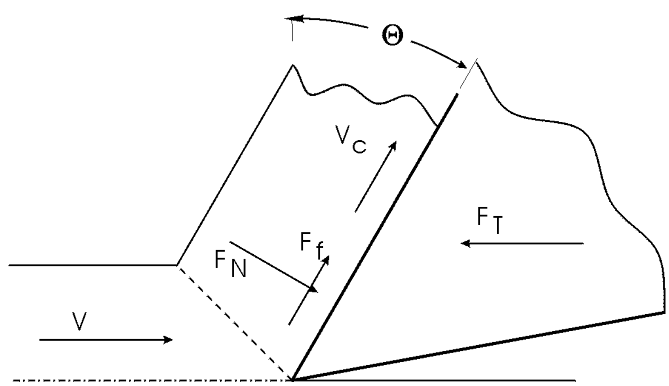

Figure 2. Cutting force model.

The friction force on the face of the tooth is:

$$F_f = mF_N = \frac{mF_T}{Cosq + mSinq}$$

The power lost to friction is

$$P_f = F_f V_c$$

and the power driving the saw is

$$P = F_T V$$

The fraction of power that ends up in heat is

$$\frac{P_f}{P} = \left(\frac{V_c}{V}\right)_c \left(\frac{m}{Cosq + mSinq}\right)$$

For a friction coefficient μ of 0.35, a hook angle θ of 30°, and assuming $V = V_c$, then the ratio is equal to 0.34, which is a significant about. The amount of heat that goes into the tooth rather than the sawdust is unknown at this time, but given that wood is a very poor conductor of heat compared to steel or tungsten carbide, a first approximation would be to assume all of the heat from the cutting action goes into the teeth.. In contrast, in metal cutting about 20% of the heat goes into the tool, 65% into the chip, and 15% into the workpiece [ ].

The heat from the rubbing due to a jammed sliver in the guide, assuming a contact force of say, 50N (about 10lb), a friction coefficient of 0.3, and a blade surface speed of 40m/s, is

$$P = (2)(0.3)(50N)(40m/s)$$
$$= 1.2\ KW$$

Heat Sinks

The air flowing around a spinning circular saw can carry away a large amount of heat. The model includes a formula for the convection coefficient, h, developed by Kreith [ ] that accounts for laminar (smooth) and turbulent air flow depending upon the rotation speed and the size of the saw. See Figure 3. Typical values of the convection coefficient are:

Near eye $h = 5\ W/m^2C$
Near rim $h = 85\ W/m^2C$

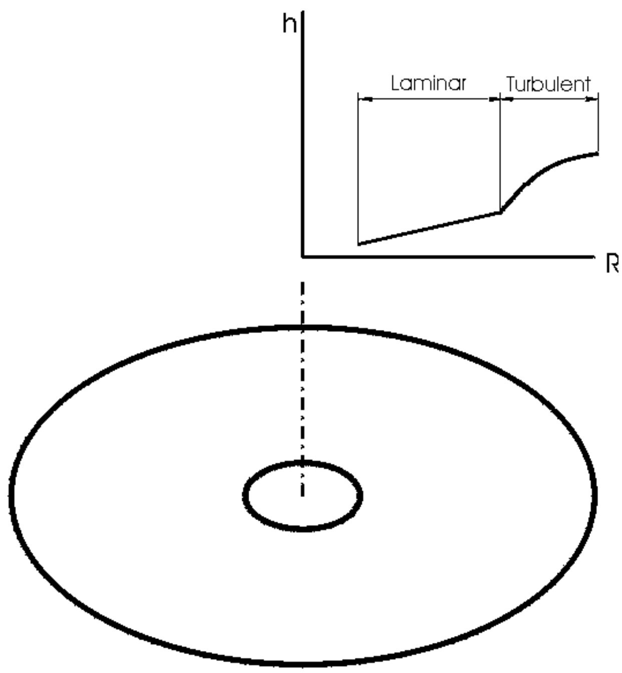

Figure 3. Convection coefficient for laminar and turbulent air flow around a spinning disk.

When water is used for cooling, especially with guides, the value of the convection coefficient could be 5 to 10 times that of air cooling. (These numbers are based on a comparison to experimental data from other industries using water cooling.)

Thermal Properties of Materials

The thermal properties of the materials involved in sawing are given in the table below.

Material	Density ρ Kg/m^3	Heat Capacity C KJ/kgC	ρC KJ/m^3C	Thermal Conductivity k W/mC	Diffusivity $\alpha = k/\rho C$ $m^2/s \times 10^9$
Wood	420	2.5	1050	0.10	95
Steel	7800	0.42	3280	36	11000
Stainless Steel	7880	0.46	3625	25	6900
Inconel	8500	0.42	3570	16	4480
Air	1.18	1.0	1.18	0.026	22000
Water	993	4.2	4170	0.62	149
Tungsten Carbide	14700	0.24	3528	63	17850
Cermet	6400	-	-	15	-

These properties, especially the diffusivity, determine how fast heat flow through a material. The lower the diffusivity value, the slower the temperature will change, or more precisely, the

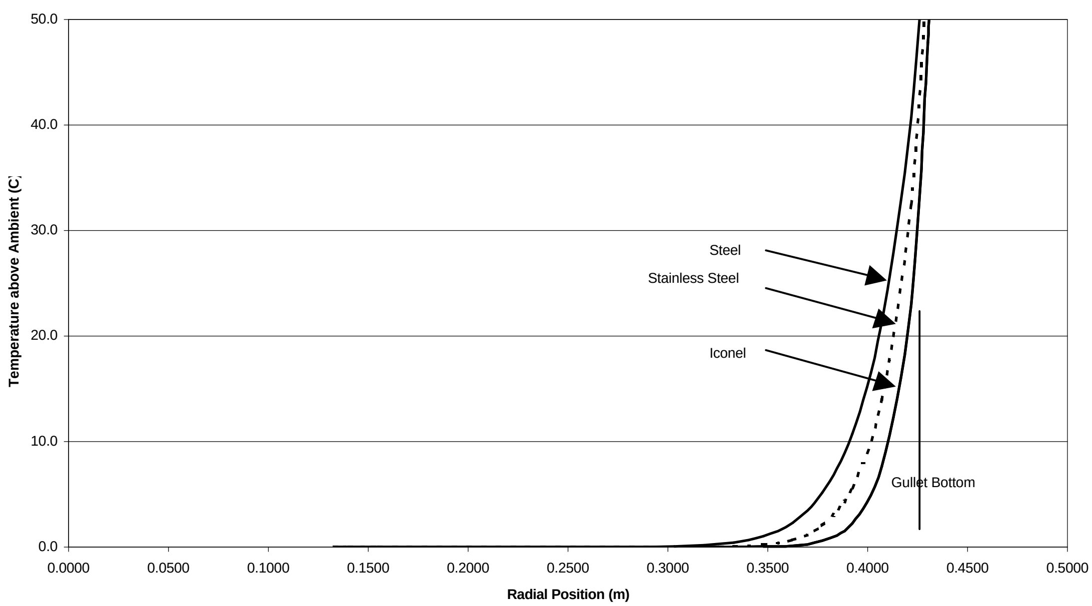

Figure 4. Effect of material properties on temperature. 2KW at tooth tip for 100 seconds.

slower the heat will spread to the surrounding material. As an example, heat will flow through a steel saw 60% faster than through a stainless steel saw. See Figure 4.

If most of the heat enters the saw though the tooth tips a low diffusivity is beneficial because the heat will stay in the teeth, resulting in less heating of the rim of the saw. Furthermore, because the tooth temperatures will be higher, more heat will be carried off by convection around the teeth.

The other important thermal property is the heat capacity, ρC. The larger the heat capacity, the small the temperature rise for a given amount of heat input. Figure 5 shows the temperature distribution for steel, stainless steel and Inconel saws for a heat input in the body of the saw, possibly due to a sliver.

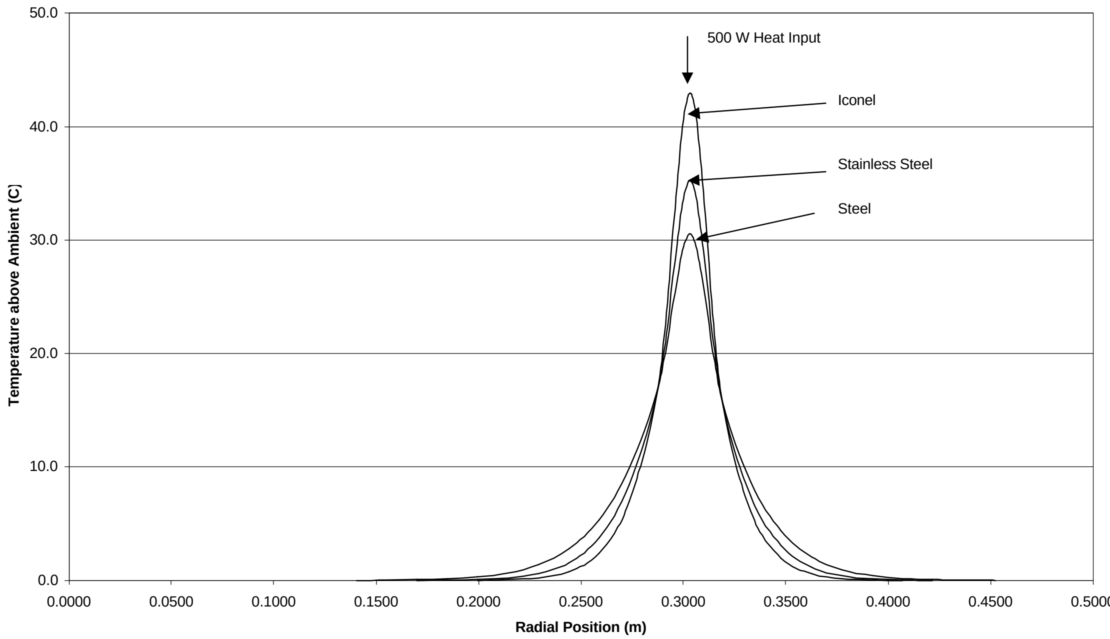

Figure 5. Effect on material properties on temperatures due to a sliver.

The value of ρC also affects the rate that the saw heats or cools. For example, see Figure 6, where the rim of the saw is heated for 10 seconds and then allowed to cool.

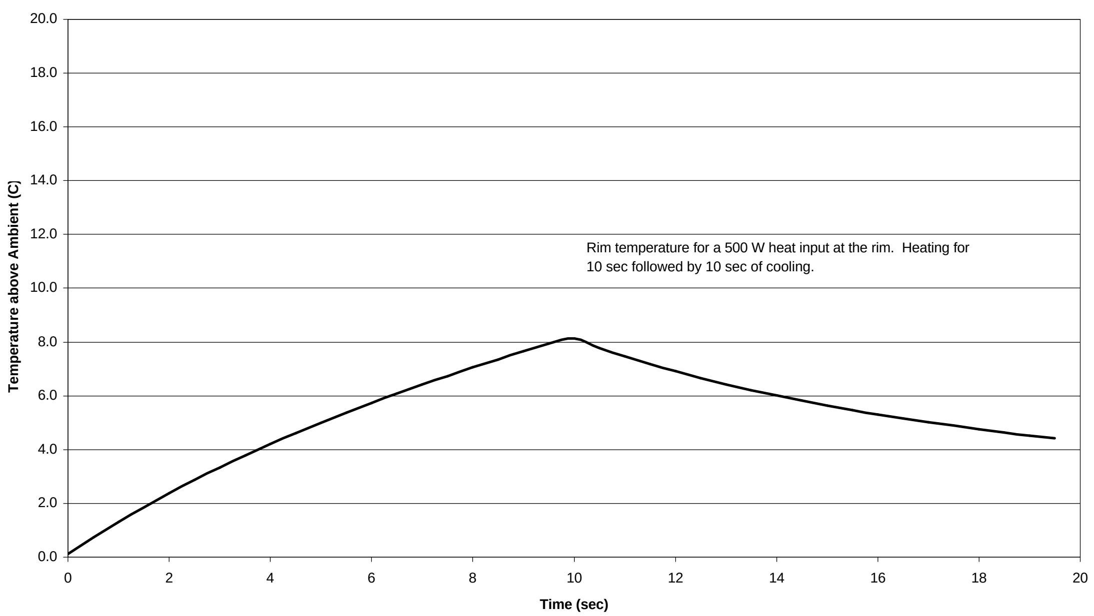

Figure 6. Heating and cooling of a steel saw.

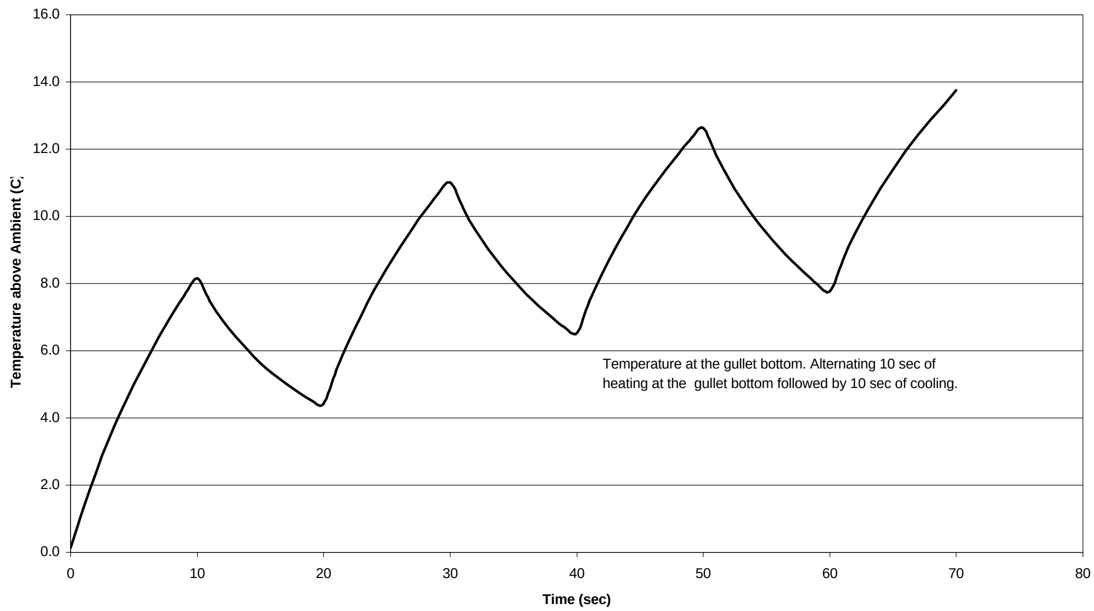

Figure 7. Temperature at the gullet bottom due to repeated heating and cooling cycles as would occur during production.

In Figure 6 only one heating and cooling cycle is shown. In production, boards may be separated by only a few seconds, which may not be enough time for the blade to completely cool. The result is a gradual increase in blade temperature, eventually reaching a sustained amount, as shown in Figure 7.The implication is that more cooling is required as the board piece-count is increased, even if the feed speed remains the same.

Effect of Plate Thickness

Reducing the plate thickness has two effects on heat flow:

1. The thermal resistance to heat conduction is higher because the cross-sectional area for the heat to flow through is smaller.
2. The amount of mass available to absorb heat is smaller, resulting in higher temperatures.

In the case of heat conduction, the two effects exactly cancel each other resulting in the same temperature distribution for plates of different thicknesses.

The differences in plate temperature for different thicknesses occurs because the heat inputs do not decrease in proportion to decreases in plate thickness. For instance, heating at the tooth tip is proportional to the kerf, not the plate thickness; and the heat from a sliver is not affected by plate thickness. As a result, thin blades heat more because they have less mass to absorb the heat.

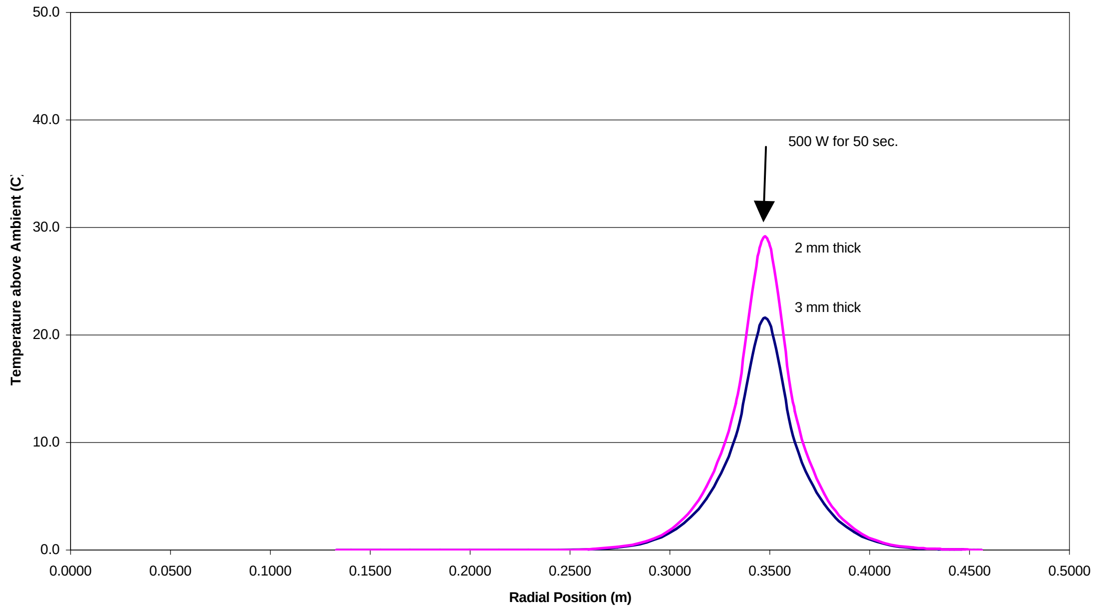

Figure 8. Effect of plate thickness on temperature.

Conclusions

1. The stiffness of thin saws is much more sensitive to a temperature rise at the rim. Furthermore, because thin saws have less mass to absorb heat, more more care is needed to avoid heat getting into the saw in the first place, and to providing adequate cooling.
2. Alternate plate materials such as stainless steel improve the thermal response of the saw because it can absorb more heat and the heat stays in the teeth rather than moving into the rim of the saw.
3. The amount of heat entering the saw through the tooth tips is on the order of 30% of the arbor power. On the other hand, the cooling effect of the air flowing around the rotating saw takes most of the heat away. Furthermore, water spray can absorb about five times as much heat as does air cooling.
4. Heating and cooling times for circular saws is measured in seconds, not micro-seconds or minutes. More heat and thinner saws result in faster heating. More external cooling and thinner saws result in faster cooling.

References

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