After the Lubricants Fail: Wear

This page addresses the issue of why clocks eventually fail. The essay about cleaning and polishing brass, in this website, describes the chemical properties of brass and steel and how oxidation takes place. The essays about lubrication describe the physical properties of lubricants and how they work. The essays about bushings describe how repairs should be performed. Together, these essays present a more complete explanation of issues related to clock repair and preventive maintenance.

Lubricants reduce friction in the bushings by adhering to the metal surfaces to form a film that separates the metals, and protect the metals against corrosion with the protective film. Lubricants fail for many reasons, the most common of which is evaporation in the case of clocks. Each clock bushing has only about a quarter to half a drop of oil. If the oil evaporates, nothing is left. Oil can also deteriorate because of the presence of bacteria, resulting in corrosive acids being formed (the oil becomes "gummy"). If the correct lubricants were used, very little wear would take place in the bushings. Most of the wear takes place after the lubricants have failed. Understanding how and why wear occurs in clock bushings provides insight into how best to repair the clock bushings and how to ensure maximum durability after the repair.

When a clock is repaired, all the pivots are polished to make their surfaces smooth and also to remove any layer of iron oxide on the surface. While the surfaces of the brass plates should not be polished, as described in the essay about cleaning and polishing brass, the surfaces inside the bushing holes must be cleaned and the oxide layer removed. A clean brass hole has a bright yellow colour on the inner surface when examined with a loupe. The presence of an oxide layer in the hole can be seen because the colour becomes brown or black.

To understand why the brass plates should not be polished, consider how stainless steel remains stainless:

"Stainless steel is an alloy of iron (Fe) and carbon (C). The carbon content is not greater than 2wt%. Stainless steel also contains chromium (Cr) which gives it corrosion resistance due to an oxide of chromium that forms on the alloy surface. The chromium content should be greater than 12wt% in order to give adequate protection."

The zinc in brass similarly forms a layer of zinc oxide on the surface of the brass, protecting the metal underneath the surface. The protective layer of zinc oxide should not be removed, unless another form of protection, such as lacquer, were applied.

To determine why wear takes place, consider the physical properties of the metals and the oxides in the bushings, rather than their chemical properties. The first physical property to consider is hardness. Many of the hardness values in the table at the bottom of this page are only approximate, but they are useful to determine several things:

1. Metal alloys are usually harder than the individual metals. Brass is harder than copper and zinc. Steel is harder than iron.
2. Metal oxides are usually harder than the metals. The best example is aluminium oxide, which is

extremely hard. From the absolute hardness column in the table, however, you can see that the diamond is four times harder than aluminium oxide.

3. Copper oxide, zinc oxide and iron are of similar hardness. This means that these oxides, since they have crystalline structures, could scratch the surface of a soft iron pivot. High-carbon steel pivots, however, are considerably harder than these oxides. You would expect that steel pivots would be unlikely to be scratched by these oxides. However, even an oxide with less hardness, such as zinc oxide, could cause wear:

> "Zinc oxide is abrasive and zinc in the copper matrix promotes galling when mated with steel."

The most important point to remember here is that the main cause of wear in a clock bushing is the presence of metal oxides. If the formation of oxides could be prevented, the bushings and pivots would last much longer.

4. A steel pivot, unprotected by lubricant, could form a layer of iron oxide if exposed to oxygen and humidity in the air. The iron oxide could become embedded in the surface of the brass bushing, scratching the steel pivot. When the surface of the pivot is scratched, iron is removed, which is more likely to become oxidized with oxygen from the air than the pivot itself, because the iron that is removed is in powdered form and has a much greater surface area than the iron in the pivot. Iron oxide is much harder than iron. Wear takes place at an accelerated rate. The oxide layer inside the bushing should be removed to make sure that no iron oxide is embedded in the surface.

To explain why iron oxide is important here, consider an extreme example: aluminium oxide, Al_2O_3, the second hardest mineral on earth, second only to the diamond, is much harder and more abrasive than iron oxide, Fe_2O_3. Many of the least expensive clocks have plates made of aluminium instead of brass. This means that the bushing surfaces are of aluminium and the pivots are of steel. Clocks with aluminium plates do not last long because of the formation of aluminium oxide. The combination of steel and aluminium has the added disadvantage of an electrochemical reaction between the dissimilar metals in the presence of an electrolyte (such as humidity, water), accelerating the formation of aluminium oxide and the subsequent deterioration of the bushing and the pivot. To prevent the electrochemical reaction, the lubricant in the bushing must separate the metals and protect the bushing from humidity and other contamination.

Another physical property to consider is structure. Hard crystalline structures have fractures with sharp points and edges. The hardest minerals, such as diamonds, aluminium oxide, and silicon carbide, with their sharp points and edges, are often used as abrasives. Aluminium oxide is often used to make sandpaper and emery paper. Consider what would happen if you introduced a few grains of sand into a clock bushing. Its presence in a clock bushing quickly results in failure. Sand is silicon dioxide, SiO_2, another hard, crystalline mineral.

Aluminium oxide plays a major role in horology because virtually all jeweled clocks and watches have synthetic ruby jewels, made of aluminium oxide. Some high-grade timepieces also have diamond cap jewels. The surfaces of the ruby jewels are highly polished with diamond-impregnated polishing compound. When a ruby jewel becomes cracked, its sharp edges quickly damage the steel pivot. Thus the physical properties of the mineral are of paramount importance: as a highly polished surface, it has very low friction, but as a cracked surface or as a powder, it has very high friction and is extremely abrasive.

Bronze bushings are often used in electric motors because of the hardness and durability of the copper and tin alloy. These bushings are made of cast and heated (sintered) powdered bronze, which is porous. The porous nature of the bushing makes it possible to impregnate the bushing with a relatively large quantity of oil by submerging the bushing into hot oil. Bronze bushings for clocks, however, are not porous because they are made from bronze wire. The quantity of oil the clock bushing can retain is much smaller. When the lubricant fails, and especially if it evaporates, the bronze surface is exposed to air and a layer of tin oxide is formed. Tin oxide is even harder and more abrasive than iron oxide. This is why most clocks with bronze bushings that come in for repair have badly scored pivots. All bronze bushings in clocks should be replaced with brass bushings whenever possible.

Another question to consider is the durability of different clocks, why some pivots are more frequently scored than others. Many French clocks and other high-grade clocks have hard pivots made from high-carbon steel. When these clocks are repaired, they often have one or more badly scored pivots, and iron oxide is visible in the bushing. Comparing these clocks with American clocks of similar vintage (1850 - 1910), such as New Haven, Sessions, Seth Thomas, and Waterbury, a difference becomes clear. American clock pivots become rusted and scored less frequently. Bushings wear but the pivots are usually not badly damaged. The reason for this is simple. Unlike the expensive clocks, these American clocks were designed to be affordable, and their steel parts were made of mild steel dipped in molten zinc, called galvanized steel (the same material as the common nail). The zinc forms a thin layer of zinc oxide, protecting the metal underneath in the same way as it protects brass. The zinc becomes the sacrificial metal, protecting the iron. These American clocks were less expensive, more reliable, more durable, and easier to repair: this is obviously a winning combination.

I have simplified the explanations on this page by not mentioning the presence of other elements in the metals, either intentional (in the case of alloys) or unintentional (in the case of impurities). Aluminium clock plates are usually an aluminium alloy with added copper, manganese, or magnesium. Brass clock plates are made with copper (about 70%), zinc (about 30%), and lead (1%), but it may contain impurities, such as a small amount of iron. Lead is added to improve machinability (ease of cutting). Bronze is a copper (about 90%) and tin (about 10%) alloy, but it may also contain impurities, such as small amounts of lead, zinc, nickel, iron, sulphur, and aluminium. Involving the impurities would make the problem more complicated, but it should be mentioned that some impurities are present in every metal. Clocks made prior to the Industrial Revolution usually have higher levels of impurities in their metals because of older technologies used in the manufacturing processes. High levels of impurities often cause problems with quality control.

Knowing what causes wear suggests the importance of meticulously polishing the pivots and remove the oxide layer from the inner surface of every bushing. It also suggests what properties the lubricants should have, to separate the surfaces of the metals and to protect the surfaces of the metals from corrosion (caused by air and humidity). Since the best lubricants last about six years, every clock should be inspected carefully at least every five years and lubricated as needed.

	Mohs Hardness	Absolute Hardness
Talc: $Mg_3Si_4O_{10}(OH)_2$	1	1
Lead: Pb	1.5	
Gypsum: $CaSO_4.2H_2O$	2	3
Tin: Sn	1.5	
Zinc: Zn	2	
Copper: Cu	2.5	
Calcite: $CaCO_3$	3	9
Brass: copper and zinc alloy	3	
Aluminium: Al	3	
Bronze: copper and tin alloy	3.5	
Fluorite: CaF_2	4	21
Copper oxide: CuO	4	
Zinc oxide: ZnO	4	
Iron: Fe	4	
Apatite $Ca_5(F,Cl,OH)(PO_4)_3$	5	48
Lead oxide: PbO_2	5	
Typical knife blade (steel)	5.5	
Orthoclase: $KAlSi_3O_8$	6	72
Iron oxide: Fe_2O_3	6	
Good steel file (high-carbon steel)	6.5	

Tin oxide: SnO_2	6.5	
Quartz: SiO_2	7	100
Topaz: $Al_2SiO_4(F,OH)_2$	8	200
Sapphire, ruby: aluminium oxide Al_2O_3	9	400
Silicon carbide: SiC	9.5	
Diamond: C	10	1600

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