

# STARTER BRUSHES

## Do Not Take Them Lightly



BY BOB THOMAS

Brushes are perhaps the most under appreciated and least understood component in any starter (see Figure 1). We expect them to wear out before any of the other parts do. Most rebuilders simply replace all brushes without closely inspecting the used ones being removed. Too many of us believe that a brush is just piece of carbon with wires attached.



Figure 1 – Starter brushes have been manufactured in many different shapes, sizes and compositions.

Consequently, brush purchasing is often based upon price alone, under the assumption that duplicating a brush formula is a simple task and that all brushes are created equal. Nothing could be further from the truth. In reality, a lot more goes into brush-making than mixing powdered carbon with other materials, molding it into a shape and attaching lead wires. The science behind brush manufacturing is well over a century old, it has never been simple and it is constantly changing.

Brushes that are used in heavy duty starters must carry a significant amount of amperage and transfer that current to a moving commutator with minimal brush loss and damage. If you can visualize the circuit of the typical series-wound DC starter, current flows into the motor at the field lead, passes through the field coils to the positive brushes, to the commutator, through the armature's coils, back to the negative brushes and then ground. This could be any starter, but let us say for example that it is a 12 volt 42MT with a peak output of 7,300 watts. Operating at 11 volts under load, this starter will consume over 650 amps, or 325 amps through each brush!

Total resistance in any heavy duty starter must be low so that current can be high. Power is measured in watts, determined by multiplying voltage times amperage. The field coils in the 42MT are solid copper, the armature's commutator and hairpins are copper, while the brushes are a mix of carbon, copper with other materials we will discuss shortly. Our 42MT starter's total resistance from field terminal to ground is a mere 2 milliohms, or two-thousandths of one ohm. From a dead start, much of that resistance is in the brushes themselves and their electrical connection to the commutator's bars.

The moment any starter engages the ring gear, maximum power is needed to get the engine turning. It is no different than

pushing a vehicle by hand from a dead stop. The hardest part is getting it to move a little. Once it begins to move, pushing gets easier. The same is true for starters. Initially, every starter is very close to a dead short. But after it gets the engine turning, the amperage draw will drop dramatically. You may wonder why that happens when the circuit above stays the same. The answer is that it does not stay the same. It changes the moment the armature moves and continues to change with armature speed.

As the armature turns, it begins to generate its own voltage, which is reverse of the applied voltage from the battery. This is often called back voltage or more properly, reverse electro-motive force. Reverse EMF generated within the armature acts as a resistance to current flow during cranking. In a free spin bench test, it also limits the maximum speed at which the armature can turn. There is always a direct correlation between cranking speed and amperage draw.

Any starter's performance depends heavily upon the brushes having the correct amount of resistance. Changing that resistance by even a small amount will affect the starter's cranking ability, current consumption, commutator wear and brush life. While brushes are the least costly of all starter components, they are the key part in providing durability and performance to a customer.

### MAKING BRUSHES

It is relatively easy for a brush manufacturer to measure the resistance of any competitor's brush and determine the amounts of carbon, copper and any other metals that might have been used in its making. But that is only a small part of what goes into a brush. The binders that hold the brush together and the temperature curves and timing in a complex heat treating processes change the atomic structure of the carbon and greatly affect both longevity and performance. Brush making is based on ceramic technologies and each manufacturer has developed their own techniques that are constantly evolving.

The main ingredient used to make brushes is **carbon**. It is the sixth most plentiful element in the universe and can be found in different mineral forms called allotropes. **Graphite** is the carbon allotrope used in brush making because it is a good conductor, excellent lubricant and relatively inexpensive. Another well-known allotrope of carbon is diamond, which just happens to be the exact opposite - a fantastic insulator, hard enough to cut granite and price prohibitively expensive. Both minerals are comprised entirely of pure carbon atoms but they have been naturally exposed to different pressures over thousands of years, causing variations in their crystalline structures. It is the structure of the carbon atoms that determines its allotrope and gives graphite its appearance and very unique properties.

All fossil fuels are carbon based and graphite occurs naturally as the highest grade of coal, just above anthracite. It is one of the oldest known minerals and has been used by man since antiquity. While it is still mined today in some parts of the world as a raw mineral, it can also be manufactured artificially as synthetic graphite. It is used in pencils, steel-making, batteries, brake linings, lubricants, resistors, microphones and brushes.

Starter brush manufacturing begins with finely ground graphite. The grain size is tightly controlled and dependent upon

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the specific application. The powdered graphite is then mixed with a thermoplastic binder at elevated temperatures. Typically, these binders are composed of phenol (carbonic acid) resins. Petroleum cokes, pitch cokes or carbon black are also added. The cokes and carbon black are man-made by exposing raw carbon fuels to an incomplete combustion process by baking them at very high temperatures in the absence of oxygen.

In brush making, binder recipes are engineered in-house and as such are considered closely guarded secrets. These binders are virtually impossible to reverse engineer, making exact brush duplication by another manufacturer a true long shot. In the case of starter brushes, powdered copper is also added at this point. The size of grain of the copper is also tightly controlled and the exact amount is calculated to achieve a specific resistance.

Once these ingredients are thoroughly mixed they are formed into blocks that are called “green bodies” using injection or die molding. The pressures used in this molding process will vary, but may be as high as 60,000 PSI (pounds per square inch).

The green bodies are then baked, or heat treated in ovens at temperatures up to 2,000 degrees Fahrenheit under an artificial atmosphere that has been purged of oxygen. Hydrogen and nitrogen are used to displace outside air. The length of time and exact temperature curve of the baking process also varies by the end application. During the heat-treating, which is referred to as pyrolysis, the binders decompose. The result is a very hard substance called **hard carbon** or **carbon/graphite**. It can be used at this point in mechanical applications where a hard material with self lubricating properties is needed – such as sliding rings or bearings. But carbon/graphite is not suitable for use as brush material just yet.

The next step is called graphitization, which requires a second heat treatment at temperatures up to 5,500 degrees Fahrenheit. While this can be accomplished in ovens, it is often performed by passing current through the material itself. Sandwiched between two electrodes, the natural resistance of the hard carbon ensures even heating throughout the block. Current from the secondary side of a transformer enables precise control of both the time and temperature during this process, in which the graphite is re-crystallized into a higher degree of orientation. Here, orientation refers to the compactness of the crystalline structure at an atomic level.

The temperature curve of the second heat treatment is closely monitored and controlled to fine tune the final degree of orientation. That is when both the level of hardness and electrical properties of the finished product are created. In addition to the binder's composition, the temperature curve is the second big secret of each brush manufacturer. The result is a unique material that is nearly impossible for anyone to copy successfully.

Once re-crystallized, the graphitized carbon is now called **electrographite** – the stuff all brushes are made of. Electrographite is an excellent conductor with very low electrical resistance. It also has high thermal conductivity, excellent sliding properties and is naturally resistant to corrosion. While that sounds like a finished product we are not done yet. It must be cut into individual brush blanks and each blank is then machined or ground into the proper shape.

The material can be impregnated with synthetic resins to seal up pours that remain in the binder, making it impermeable to

liquids and gases. Metal impregnation can be used to increase hardness and strength. Coatings made of silicon carbide or treated carbon can also be used as a sealer to further inhibit corrosion.

Brush leads, called “shunts” by the manufacturers, are usually attached by tamping. The lead end may be tinned or attached to a copper rivet prior to tamping. The shunt is inserted into a hole that has been drilled into the brush. A thermo-setting resin is then injected and tamped around the shunt's wire. The resin may be cured by heating or chemical reaction. Today phenolic resins mixed with powdered copper are used most often to secure shunts, providing stability to the tamped connection. The size of the shunt's wire must be heavy enough to handle the current that the starter was designed to consume. It's resistance is part of the brushes total resistance.

### BRUSH WEAR

As was mentioned in the first paragraph, all brushes are expected to wear out eventually. They are tasked with providing an electrical connection sufficient to carry a high amount of amperage to a surface that is constantly moving. Brush wear is not just related to a brush's hardness. Their longevity is dependent upon many factors with hardness being only one of them. Lubricating qualities, the volume of the current being carried, the surface speed and condition of the commutator, the starter's ability to brake the armature after an engine start and spring tension all affect brush life.

Any discussion on brush wear must begin with the commutator's surface. If not for a thin oxide film, brushes would wear away like chalk on a board. This film is only a few angstroms thick. An angstrom is a metric unit that is equal to one ten-billionth of a meter, which is so thin it is hard to compare it with anything you can see without a microscope. It forms rather quickly on its own during operation when small particles of copper are transferred from the commutator to the brush. The copper powder is vaporized by heat on the face of the brush where it combines with air and moisture. Then it deposits itself back onto the commutator's surface as a metal oxide coating. Graphite from the brush is deposited along with it. Coincidentally, the film is also non-conducting. But no matter – it is thin enough for current to flow through it even at low voltages.

Sometimes called patina, this film creates a surface that is very low in friction and prolongs brush life (see Figure 2). The appearance of the film is controlled by the amount of graphite in it. A thick, dark and shiny patina contains an abundant deposit of graphite that is perfect for starting motors. It permits moderate brush wear and minimizes commutator wear.

But in spite of how smooth the brush and commutator may appear, only 10% of the brush face actually makes mechanical contact with the commutator at any given time. Current flow concentrates on the small points of contact and creates the streak marks often seen on a used commutator. Ideally, they are evenly distributed across the face of the bar. Evenly distributed streaking is normal. You may also find the trailing edge of each bar to be slightly darker (see Figure 3), as on this flat commutator. That is also normal, caused by **reactance voltage**.

An armature is made up of interconnected coils, attached between those coils by individual commutator bars. Commutation is the switching of current flow from one set of coils to the

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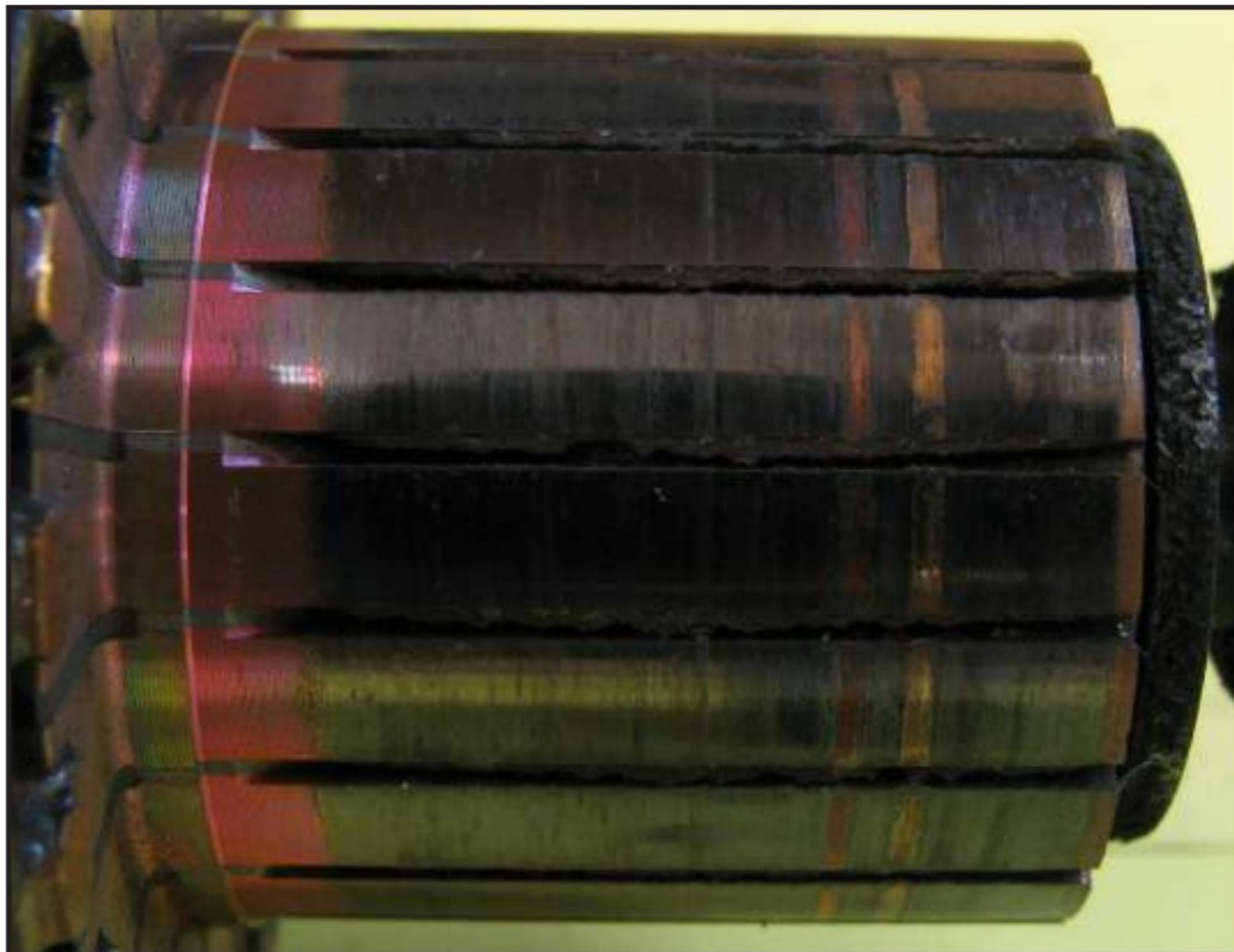


Figure 2 – Good brush film should be dark, shiny and uniform. The two lines on the right indicate areas where current flow was absent.



Figure 3 – The darkened areas along the trailing edge of the bars on this flat commutator were caused by reactance voltage. It is normal.



Figure 4 – This 42MT commutator shows damage by reactance voltage in addition to excessive arcing from over cranking.

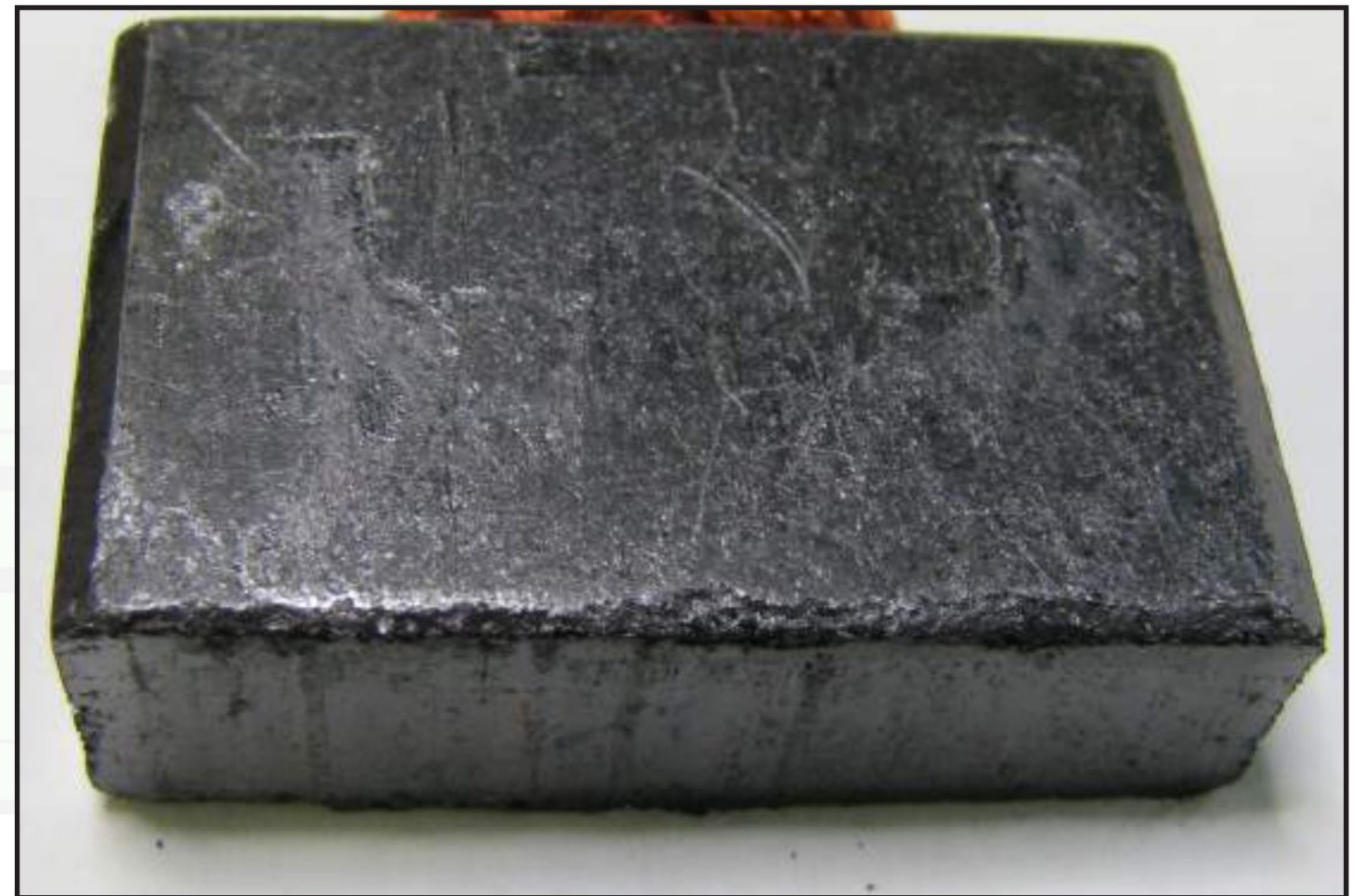


Figure 5 – The 42MT brush from the same starter clearly shows a loss of material all along the trailing edge.

next. As each bar separates from a brush the current flow is moved on to the following bar. But when electric current is flowing through any coil, it cannot be stopped instantly. Reactance voltage causes current to flow for a brief time after the circuit is broken. This can be witnessed physically as sparks when any switch is opened. The magnitude of reactance voltage is a directly proportional to the amount of amperage that is flowing when the circuit is broken. Therefore, heavy duty starters drawing hundreds amps will exhibit these signs much more prominently (see Figure 4). The trailing side of the brush will usually show signs where carbon was transferred away to the commutator by reactance voltage (see Figure 5).

### SPRING TENSION

To understand just how important the springs are, consider that total brush resistance is actually the sum of the resistance of the physical brush and the resistance caused by the contact between the face of the brush and the commutator, referred to as **contact resistance**. All electrical connections, no matter how clean and tight they are, have some resistance that contributes to the total resistance of a circuit. In the case of brushes, that connection is less than ideal.

The contact resistance of a brush is affected primarily by the brush's composition, the size of the brush face (contact area) and the spring pressure being applied to the brush. Obviously, the greater that pressure, the lower the contact resistance. However, brush wear is also affected by that pressure. Greater pressure wears the brush faster. Engineering a perfect brush spring pressure for any starter is a delicate balance the between brush wear and contact resistance.

Higher contact resistance from a weaker spring not only reduces the starter's power by restricting current, but it also generates significant heat and causes excessive arcing. In over-cranking scenarios, weak springs can damage both the brushes and the commutator within a short period of time. On the other hand, a stronger spring will improve conductivity, lower resistance and increase amperage flow. The trade off for that is an increase in brush wear and a reduction in service life. There is little doubt that a weak spring can do a lot of damage. Staying with original spring pressure is always prudent, but unfortunately, few

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stater manufacturer's publish those specifications. If you change springs, keep them all the same and err on the side of higher tension if you are unsure of original spring pressure.

### ELECTRICAL LOADS

Electrical loads affect brush wear too, but not in the way you might think. Brushes actually wear faster under light loads or no load at all, as in the case of a starter spinning down after engine start-up. This happens because **current flow reduces brush wear**.

While that may seem hard to believe, there is a reason it happens. As current flows between the brush and commutator, both surfaces are rapidly heated. The heat and current together cause plasma to form across the face of the brush. During cranking this plasma carries current and limits brush wear. When the current is cut off after engine start, the plasma dissipates immediately. Wear from abrasion between the brush and commutator increases greatly in the absence of current flow. Under normal operation, most brush and commutator wear actually takes place during the slow down period of a starter after dis-engagement. For that reason, braking is always important and should never be overlooked.

### RESISTIVITY VS VOLTAGE

While most of the starters that you encounter are probably for use in 12 volt systems, you undoubtedly run into some 6 and 24 volt units. Occasionally you may even come across a 32 or 48 volt starter. Generally, a lower voltage starter requires a lower resistance brush while higher voltage starters must have higher resistance brushes. If you compare brushes for the same series but different voltage ratings, you can usually tell them apart visually (see Figures 6 and 7). The amount of copper present in the brush versus carbon and the size of the shunts (lead wires) are the easiest way to differentiate them. Using the same brush as the original manufacturer is almost always the best choice.

However, experienced rebuilders sometimes substitute a brush of **higher resistance** for a specific reason. Keep in mind that Ohm's Law always applies. When resistance is increased and voltage remains the same, amperage must come down. So the end result of such a substitution is a reduction in current and a subsequent loss of power because voltage times amperage equates to power. You may wonder why an experienced rebuilder might do this, especially after this article began by emphasizing the importance of brush resistance.

An example can be seen in the 42MT commutator on the cover photo. Notice the marks on the bars that resemble pockmarks (see Figure 8). Those have been caused by severe arcing across the brush face. This particular armature was removed from a remanufactured starter that had the latest version of Delco brushes in it. The new brushes (see Figure 9) are packaged with new springs to insure proper tension. Note the wide braided shunts on the new brushes, compared to the older version 42MT brush on the right. The new brushes are designed for extremely low resistance. Weak springs did not cause this damage. This starter had been cranked for an extended period of time, as was evidenced by the reddish discoloration on the commutator and the brushes (see Figure 10).

Several production rebuilders that I have communicated with have confided that they routinely install 24 volt brushes in all of their 12 volt 42MT starters to limit that kind of arcing. The same policy extends to their 39MT starters. They use higher resistance



Figure 6 – These 40MT brushes are for different voltages - less copper and smaller wire for 32 volts - more copper and heavier wire for 12 volts.



Figure 7 – The early style 42MT brush on the left is 24 volts while the one on the right is 12 volts.



Figure 8 – This 42MT commutator shows evidence of extended over-cranking. The discoloration indicates extreme over heating. The burn marks are from arcing.

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brushes to protect their starters from over-cranking by the end operators.

The downside of a higher resistance brush is a reduction in power, but evidently it is not enough to matter in the vast majority of applications. This is not a blanket endorsement to install higher resistance brushes in all starters. But it can certainly be beneficial in cases where an application or customer is prone to over-cranking. Everyone that I spoke to about the practice told me that it has greatly reduced their warranties on 42MT and 39MT starters while none of their customers have noticed or complained of slower starting.

A second example involves using 12 volt brushes in 6 volt starters. In some cases, the 6 volt brush may be obsolete and no longer available. Or, you may simply not have the 6 volt brush in stock. Personally, I have made this substitution many times. The measured loss of amperage draw was barely detectable. However, some applications in which a starter's power rating is marginal for the engine's size and compression may make them poor candidates for this type of substitution.

Note that these examples are both going from a lower to a higher resistance brush and not the other way around. Substituting a lower resistance brush is more apt to cause a warranty, especially if it is ever over cranked. A lower resistance brush will increase the starter's amperage draw and power. But it will also cause it to heat up much faster and drastically reduce the length of time it can be operated without damaging itself.

### PERMANENT MAGNET STARTERS

Up to this point, the examples have all been series-wound starter motors. Once common across the spectrum, they are mostly used today on heavy duty applications. The vast majority of automotive, marine and small industrial engines today utilize permanent magnets in place of field coils. When you replace the field coils in a starter circuit with magnets it changes brush resistance requirements because the brushes have to make up for the lost resistance that was in the field coils.

Therefore all PM starters must have brushes of higher resistance, which means they contain less copper depending upon the application and power requirements. In addition, most PM starters today are planetary gear reduction, meaning the armature will be turning much faster than a direct drive starter – up to 5 times faster. The minimal amount of copper and higher resistance do not necessarily mandate a softer brush. The size of the brushes and their shunts can be used to increase resistance.

Generally, PMGR starters require a hard brush for longevity, a high level of lubrication to protect a fragile commutator, and high resistance. PMGR commutators are for the most part not designed to be serviced. The bars are too thin for that. When the brushes wear out, a persistent operator determined to get one more crank out of the starter can easily destroy the armature by overheating a bar that is making insufficient contact. If contact resistance is high enough, the bar can quickly heat to a point that it melts the phenolic material used to hold it in place. For that reason, brush composition in PMGR starters is especially important. When composition and hardness are not right, the brushes can easily wear out within the warranty period. When that happens, the armature is often destroyed too.

### BALANCE BRUSHES

Balance is not normally a big problem because most rebuilders routinely replace all brushes as a complete set. But it is worth mentioning that all brushes in a single starter should be identical. Different brush manufacturers should never be mixed because no two make exactly the same brush – even though they may appear to be the same. Unbalanced brushes will affect both performance and longevity. A set of brushes that is unbalanced can cause uneven wear or damage to the commutator. Brushes are a key part in providing your customer with a reliable starter. Do not make the mistake of under-estimating their importance.



Figure 9 – Notice the difference in the shunts between the latest version and the original on the right.



Figure 10 – Notice the reddish discoloration of the used brush on the right, caused by extended over-cranking.