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COMPOSITIONAL STUDIES OF CARBON-BASED ELECTRICAL BRUSHES USING THERMAL ANALYSIS*

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ABSTRACT

Electrical brushes are used in direct current motors to conduct current to the rotating armature. Classically, brushes are developed for certain applications with the composition, i.e. carbon and/or graphite, metals, and additives, remaining proprietary with the vendor. Analysis of some motor failures has indicated that the failure has resulted from brush-related problems. To date, the only tools available for brush analysis have been resistivity, density, and strength measurements. Together, these do not adequately describe the brush problem. This paper will present a method for brush evaluation using thermal analysis.

INTRODUCTION

Electrical brushes are used in motor applications to carry electrical current to the rotating armature. These brushes may be composed of carbon, graphite, metals (such as copper and lead), polymeric binders and additives for life and noise control. For higher voltage applications, pure carbon or graphite brushes are used while low voltage applications require metal and carbon or graphite brushes. Metal is added to reduce the voltage drop across the brush in the low voltage applications.

Brushes are produced by first blending the correct composition, compacting to the desired shape, then sintering to produce sound mechanical and electrical properties, Fig. 1.

Analysis of brushes has been accomplished using resistivity and density measurements coupled with hardness checks. These measurements only determine if the approximate amount of metal has been added and the correct compacting force and sintering temperature used. They do not indicate if the correct materials or quantities were used to produce the brush. This paper will present a method for compositional evaluation of a brush using thermal analysis. Both material type and quantity can be determined using this method.

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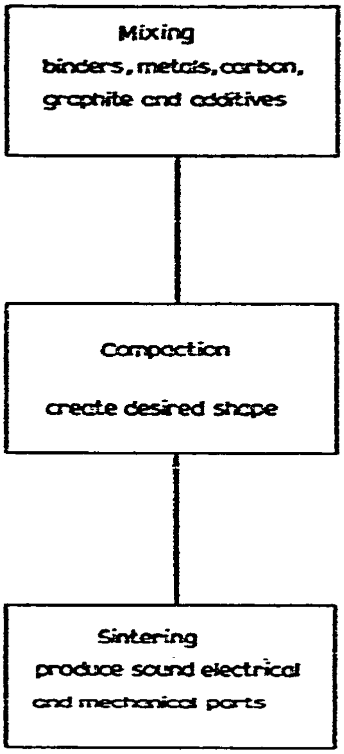

Fig. 1. Flow chart for electrical brush production.

EXPERIMENTAL

Composition of the brush samples was determined using wet chemistry, thermogravimetry and calorimetry. X-Ray, infrared, and atomic absorption analysis were used to verify the thermal analysis results. The brush is first run in a DSC, in this case the Perkin Elmer DSC-2, to detect the presence of metals other than copper. In some cases, lead or tin are added. If these metals are present, they will show up as a melt peak. It is possible, by measuring the area under the melt peak and comparing it with a standard, to obtain the percentage of the added metal, usually within two percent.

The metals are then extracted from the brush under study using a warm solution of 1:1 HNO_3 and distilled water. This step is necessary since copper, upon heating above 200°C, begins to oxidize to form CuO, i.e.

$$Cu + \frac{1}{2} O_2 \xrightarrow{T>250^{\circ}C} CuO$$

This reaction is shown as a weight gain on the curve in Fig. 2.

Since this weight gain occurs in the temperature regions of interest, it would obscure the reactions under study if not removed. Metals content was determined by plating the dissolved metal on a platinum electrode, then calculating the weight

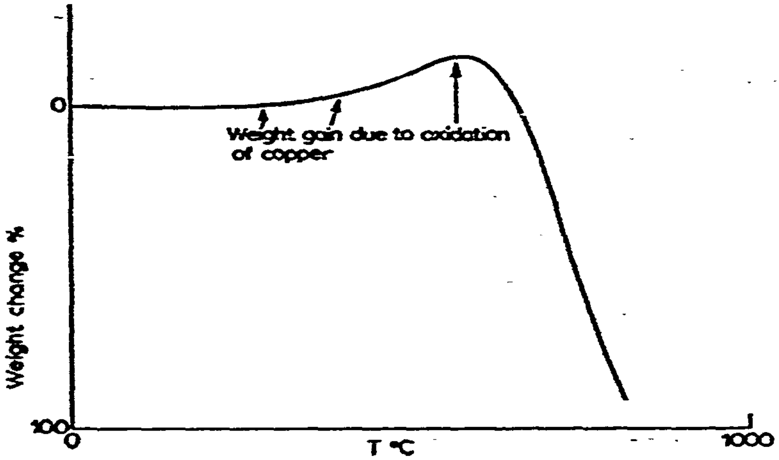

Fig. 2. Weight gain due to oxidation of copper.

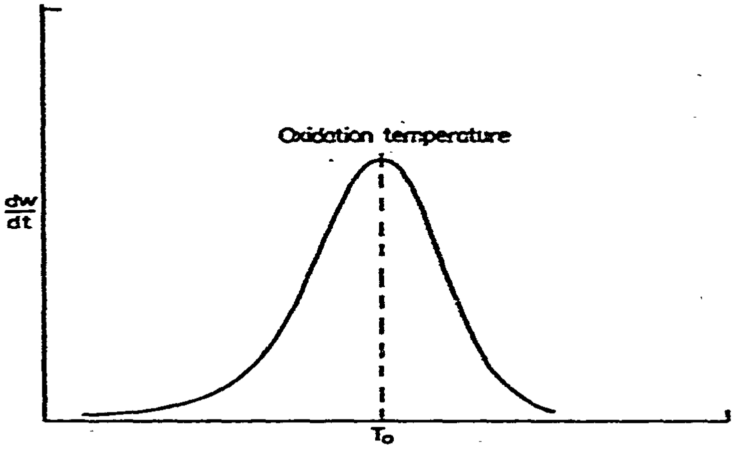

Fig. 3. Definition of peak oxidation temperature.

fraction. The remaining insolubles (carbon, graphite, etc.) were then washed with distilled water and dried at 100 °C.

Thermogravimetric analysis of the insolubles was performed using the Perkin Elmer TGS-1. Operating conditions were: 5.0 mg sample, 20 °C min^{-1} heating rate and 20 cc min^{-1} air flow. Oxidation temperatures are taken at the peak of the derivative curve, Fig. 3.

RESULTS AND DISCUSSION

Figure 4 shows a typical curve of the insoluble portion of a brush. As can be seen from the curve, a number of thermal events occur as the temperature of the material is raised. The low temperature events may be organic in origin while the higher temperature events are due to the oxidation of the carbon or graphite. In this

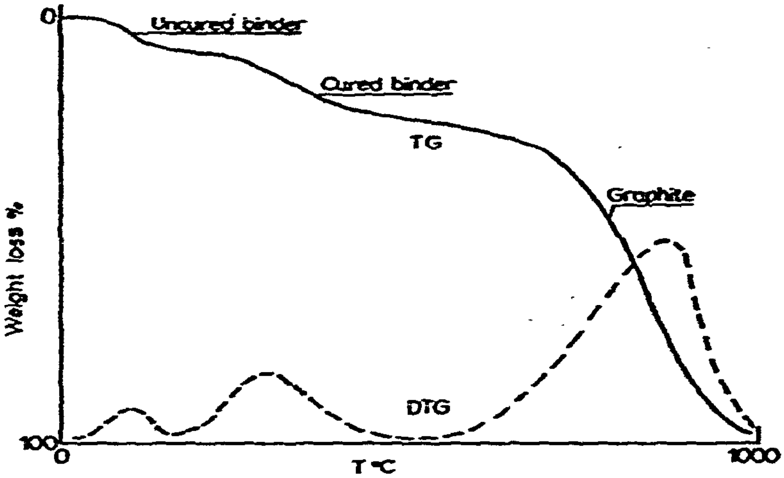

Fig. 4. Typical TG/DTG curve for a brush sample.

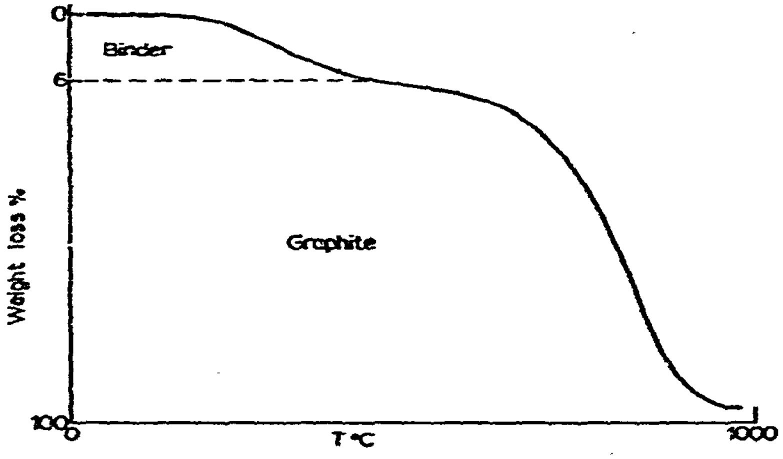

Fig. 5. Binder determination.

case, there are two high temperature weight losses. These events will be discussed in the order in which they appear on the curve.

Binders

Organic binders, such as phenolic, are used to produce a sound compacted part, and to produce the amorphous carbon content of the brush during the sintering step. Since binder content and type will have an effect on the potential brush noise from a motor, it should be closely controlled.

A curve run on a brush using a binder, Fig. 5, shows a weight loss occurring between 250 and 400 °C that corresponds to the degradation of the binder. This weight loss was verified as a binder using infrared analysis. A simple calculation will give the percent binder present, in this case, 6%.

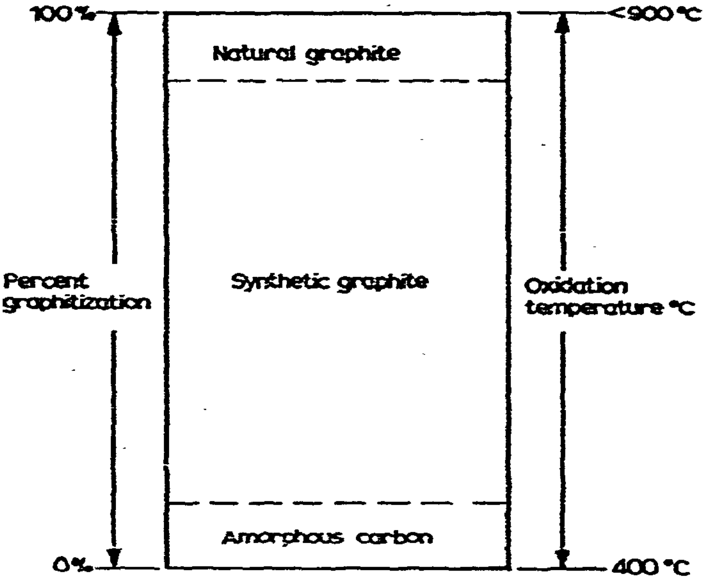

Fig. 6. Degree of graphitization.

Carbon

Carbon can be found in a number of crystalline forms; graphite, amorphous carbon, and structures exhibiting properties between these two end-points are of interest for motor brush application, see Fig. 6. The major difference for the divergencies found is the variations in the spatial arrangement of the carbon atoms. In graphite, the carbon atoms lie at the corners of regular hexagons and all atomic layers or planes are parallel to each other. In amorphous carbon, the hexagonal atomic arrangement is somewhat definite in one plane, but its arrangement in other planes is random. Upon graphitizing amorphous carbon, the planes or platelets are fairly definite in two dimensions, but random in the third. Due to the differences in structure, material properties vary, and it was theorized that different responses could be expected from thermogravimetry. Variable thermogravimetric responses were observed for various forms of carbon and graphite evaluated. Basically, graphite should have a higher oxidation temperature than amorphous carbon. The higher oxidation temperature is explained by the higher activation energy needed to initiate oxidation of the tighter and more highly ordered structure with T increasing as the degree of graphitization increases.

$$C + O_2 \xrightarrow{T} CO_2$$

Figure 7 shows thermogravimetric curves for both amorphous carbon and natural graphite. A comparison of the oxidation temperatures shows that the graphite oxidizes at a higher temperature. A further test of differences between carbons and graphites was conducted by measuring the responses of different samples obtained from various sources around the world. The samples used are tabulated in Table 1.

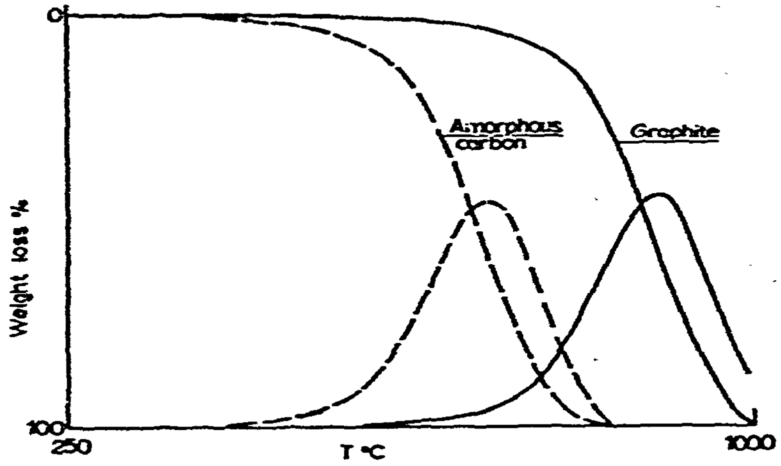

Fig. 7. TG/DTG comparison between amorphous carbon and graphite.

TABLE 1

OXIDATION TEMPERATURES OF DIFFERENT CARBON AND GRAPHITE SAMPLES

Sample	*Oxidation temperature (°C)*
Chinese	950
German	890
Ceylon (3 mines)	860–870
Madagascar	850
Artificial	850
Lampblack	640

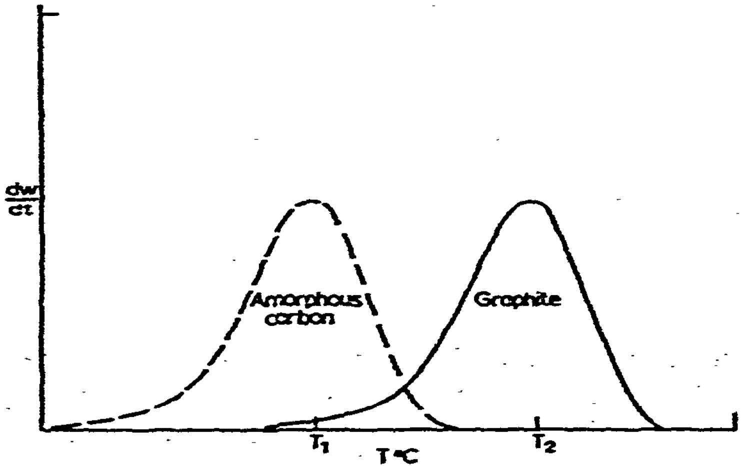

Fig. 8. DTG comparison between amorphous carbon and graphite.

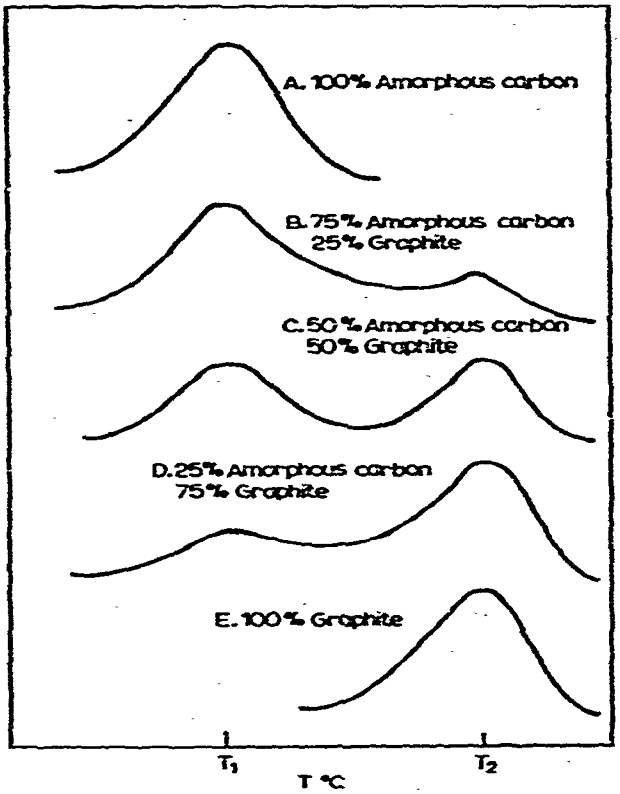

Fig. 9. DTG response from blends of amorphous carbon and graphite.

The Chinese graphite exhibited the highest oxidation temperature, 900°C, while the lampblack exhibited the lowest, 640°C. Both materials are common to brush manufacture and are used either singly or in combination.

Carbon/graphite mixtures

Since the peak oxidation temperatures for amorphous carbon and graphite are substantially different (Fig. 8) a mixture of the two should produce two oxidation peaks. Three samples of carbon and graphite were prepared to test this hypothesis by blending 25, 50, and 75 wt. % of carbon with the graphite. Figure 9 shows the resultant DTG curves. Curves A and E are the carbon and graphite while B through D are the blends. As can be seen from these curves, two oxidation temperatures are present with the temperature corresponding to each component. Actual percentages for each component can be determined by measuring the areas under the curve. Therefore, if the brush under test is supposedly composed of both carbon and graphite, it is possible to determine the type and amount.

Additives

A major additive to the brush composition is molybdenum disulfide, MoS_2, which is added to a brush to act as a filming agent between the brush and the com-

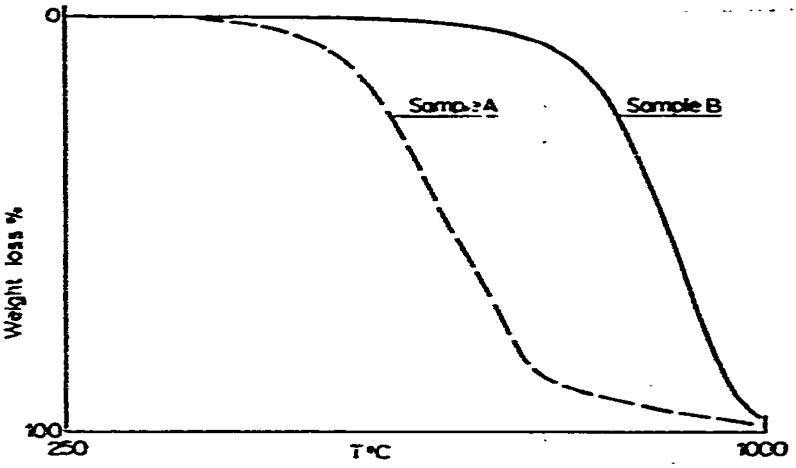

Fig. 10. TG response from two brushes using the same graphite. Sample A contains a filming agent.

mutator. A filming agent acts as a lubricant for the brush. If too little is added, the brush would wear down quickly due to friction, but if there is too much film, it becomes difficult to conduct current between the brush and the commutator resulting in lost performance or, at the extreme, inability of the motor to operate at all.

During our investigations involving graphite brushes, it was found that two samples using identical graphite produced different curves, Fig. 10. A possible cause of this difference would be if sample A were carbon and sample B, graphite. To evaluate this, both were subjected to X-ray diffraction analysis to determine if there were differences between the graphite used.

Differences in crystal structures have commonly been studied by X-ray diffraction techniques for the past 30 years. It was felt that this procedure could be used to identify the response found by thermogravimetry.

As was discussed earlier, the difference between amorphous carbon and graphite is structural orderliness. This can be determined using X-ray diffraction to ascertain the atomic spacing between planes of atoms from the Bragg relationship. The degree of graphitization is determined from the raw data by the following three techniques.

(*1*) Measuring the 20 diffraction angle and calculating the dÅ value. Natural graphite should have a dÅ value of 3.35 for the basal (002) plane of atoms, and this value of dÅ will increase as the degree of graphitization decreases.

(*2*) The degree of graphitization can be determined by the number of diffraction peaks observed. As the degree of graphitization increases, the intensity of minor crystal planes increases and the number of observable peaks increases.

(*3*) Measuring the broadening of the (002) basal diffraction peak, the height of the peak is measured as well as the width at 1/2 the height. It will be found that the ratio of the half width/height will increase as the degree of graphitization decreases.

Tables 2 and 3 list the X-ray data obtained on the two samples. As the degree of graphitization increases, the order of appearance of peaks should be as shown in Table 4. Analysis of the data indicated essentially the same high degree of graphitiza-

TABLE 2

X-RAY DIFFRACTION DATA OF SAMPLE A

Peak no.	*dÅ*	*Intensity*	*Identification*
1	9.026	Minor	
2	6.759	Minor	
3	6.109	Major	MoS_2
4	3.723	Major	Graphite
5	3.401	Largest, broad base	Graphite
6	3.069	Minor	MoS_2
7	2.730	Major	MoS_2
8	2.667	Medium	MoS_2
9	2.522	Medium	
10	2.270	Major	MoS_2
11	2.122	Major	Graphite
12	2.045	Major	Graphite/MoS_2
13	1.965	Minor	
14	1.827	Major	MoS_2
15	1.724	Minor	
16	1.698	Minor	
17	1.689	Medium	
18	1.678	Medium	Graphite
19	1.639	Minor	
20	1.577	Medium	MoS_2
21	1.535	Medium	MoS_2/graphite
22	1.477	Minor	
23	1.364	Minor	MoS_2
24	1.339	Minor	
25	1.297	Minor	
26	1.252	Minor	MoS_2
27	1.238	Medium	Graphite

TABLE 3

X-RAY DIFFRACTION DATA OF SAMPLE B

Peak no.	*dÅ*	*Intensity*	*Identification*
1	3.739	Major	Graphite
2	3.414	Largest, broad base	Graphite
3	2.823	Minor	
4	2.536	Minor	
5	2.368	Minor	
6	2.127	Major	Graphite
7	2.080	Major	
8	2.036	Major	Graphite
9	1.801	Minor	Graphite
10	1.707	Medium	
11	1.695	Major	
12	1.683	Major	Graphite
13	1.544	Minor	Graphite
14	1.233	Major	Graphite
15	1.157	Minor, broad case	Graphite
16	1.120	Minor	Graphite

TABLE 4

DEGREE OF GRAPHITIZATION

hkl *Plane*	*dÅ*
002	3.350
004	1.675
100	2.130
110	1.230
006	1.117
101	2.040
112	1.154
106	0.988
103	1.541

tion between samples with the exception of the presence of MoS_2 in sample A. From this data, it was estimated that there was 8–10% MoS_2 added to sample A. There were also a number of unidentified peaks listed in Table 2, which indicates a second impurity or additive. Due to the lack of standard data, we were unable to identify these peaks.

Since the only major difference between the two samples was the addition of MoS_2 to sample A, and sample A oxidized at a lower temperature, it was postulated that MoS_2 must act as a catalyst for carbon. To test this theory, a number of samples were prepared using natural graphite and different percentages of MoS_2. Figure 11 shows the responses obtained. As the quantity of MoS_2 added is increased, the rate of oxidation of the graphite increases resulting in a lowering of the peak oxidation temperature, Fig. 12. Also, as the amount of MoS_2 is increased, there is more residue remaining after the loss of the graphite. This residue is not thermally stable and

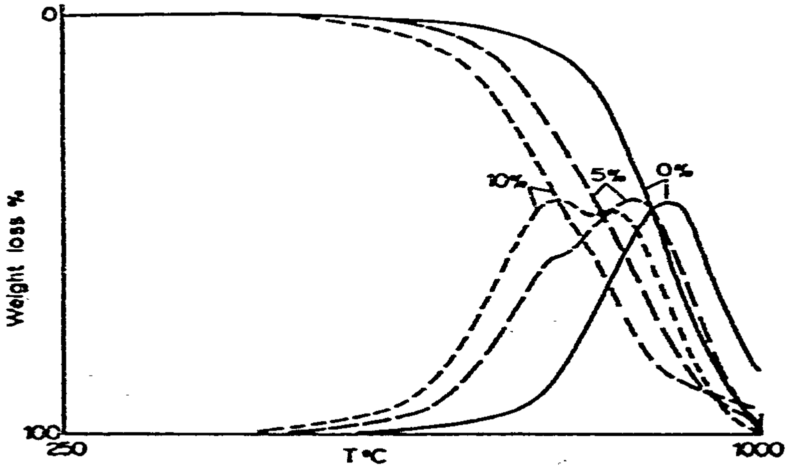

Fig. 11. Addition of MoS_2 to graphite.

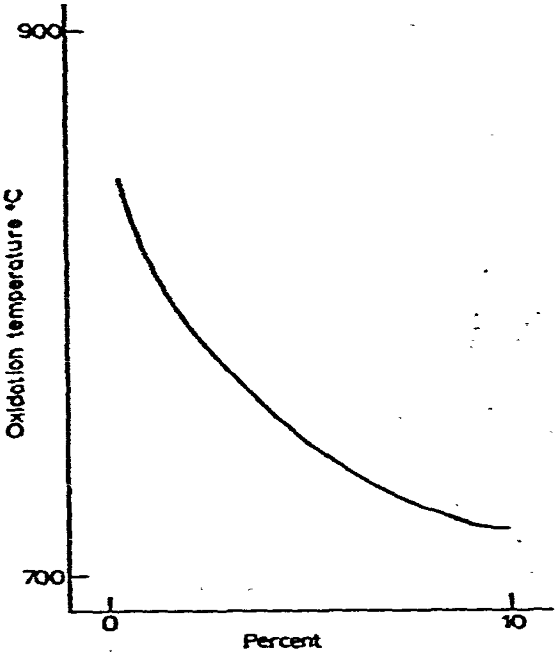

Fig. 12. Oxidation temperature vs. percent MoS_2.

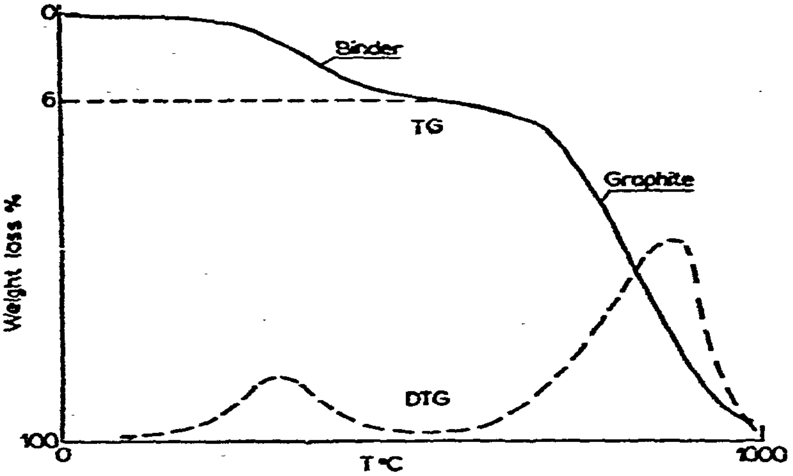

Fig. 13. TG/DTG response from a brush exhibiting acceptable noise characteristics.

constantly loses weight through 1200°C. Again, thermogravimetry has given an insight into the brush composition. If the brush being used should contain MoS_2, thermogravimetry will indicate it.

Brush Analysis

Figure 13 shows a brush containing 6% binder, as crosslinked phenolic, and 94% lightly graphitized graphite. The degree of graphitization was verified through the use of X-ray analysis. Once the components of a brush are established and identified, any change will show up on subsequent thermogravimetric curves.

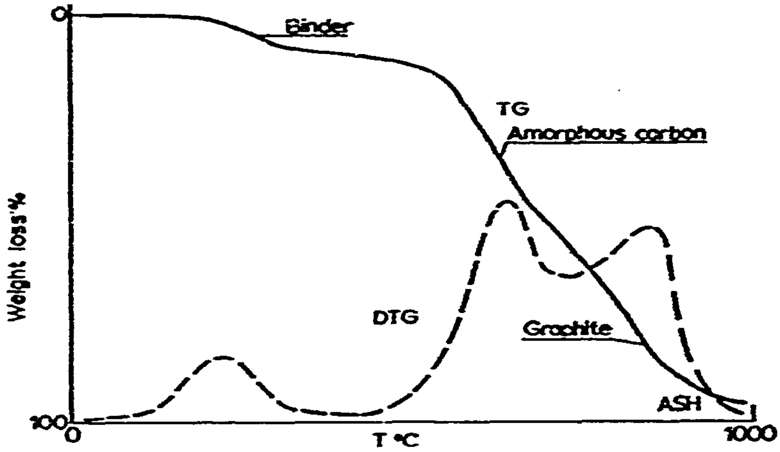

Fig. 14. TG/DTG response from a brush exhibiting excessive noise.

Motors produced using brushes similar in composition to that shown in Fig. 13 exhibited acceptable noise characteristics. During the course of testing, a group of motors using a new lot of brushes had completely unacceptable noise characteristics. Brushes from this lot were evaluated using the thermogravimetric technique, and the resulting curve is shown in Fig. 14. These brushes had two low temperature components, one occurring around 150 °C, and the other in the temperature range expected, 250–400 °C. Infrared analysis revealed that the low temperature component was organic binder that had not been cured, in this case, phenolic. A problem in the manufacture of this group of brushes caused this and was not detected using normal brush testing techniques.

Brush life is important in a closed motor where the brushes cannot be changed if they wear out. It has been thought to depend upon frictional forces, current density, atmospheric conditions, and brush temperature. Using thermogravimetry, it has been

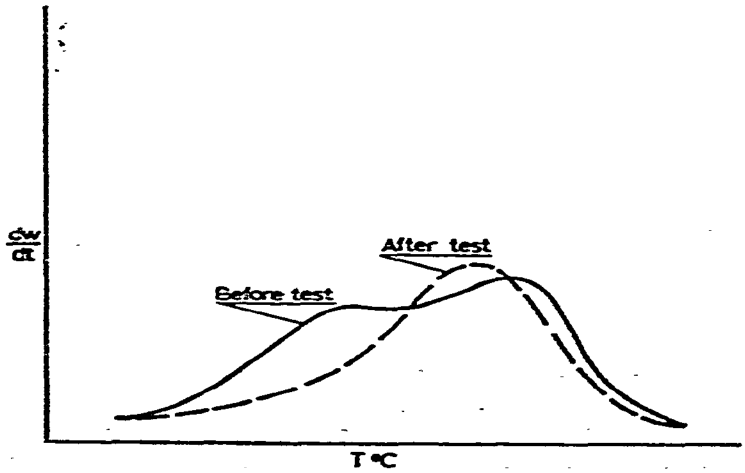

Fig. 15. DTG responses from a brush sample before and after life testing.

possible to detect compositional changes in a brush during its life, in this case greatly shortened life. Analysis of the brush remains after life testing revealed that the graphite portion of the brush had changed its characteristics, Fig. 15. Instead of the two component curve characteristics of the original brush, only one component is evident after life. This brush nominally contains 5% McS_2 and, referring to Fig. 11, the DTG curve should contain two peaks. It appears, then, that the MoS_2 is becoming depleted causing excessive frictional wear. The mechanism for this depletion is currently under study.

CONCLUSIONS

Brush composition can be determined using thermal analysis, particularly thermogravimetry. Precision on the determination of component percentages is within two percent and oxidation temperatures within 10°C.

By comparing with standards, it is possible to determine changes in composition.

Thermal analysis offers a quick, convenient method for inspecting brushes either during manufacture or by the user.

ACKNOWLEDGEMENT

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