High Thermo-Conductive Fuser Roller with Carbon Filler for Printers

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Since 1993, Sumitomo Electric Industries, Ltd. has been manufacturing polyimide fuser rollers, important parts for laser beam printers (LBPs). In recent years, we have developed a high thermo-conductive fuser roller applicable to high-speed printing systems. It uses a composite material that combines carbon nanofiber with high thermal conductivity and tough polyimide resin. Carbon nanofiber is an excellent thermal conductor, but is subject to regulation due to the high risk of residuals when taken into the body. As an alternative to carbon nanofiber, we have developed a new fuser roller using graphite filler, which is also a carbon-based filler.

Keywords: laser beam printer, polyimide, thermal conductivity, graphite, fuser roller

1. Introduction

Saving energy consumption to decrease negative environmental impact is an important factor for electronic equipment, and office automation equipment is no exception. In laser beam printers (hereinafter, LBPs) using electrophotography, about 70% of power is consumed by the fuser that bonds the toner onto the paper by thermocompression. From the energy-saving perspective, it is important to reduce power consumption in standby mode in which most of the power consumption by the fuser occurs.

Inside a common fuser roller (Fig. 1 (a)), a halogen heater radiates heat for the metal roller, 1 to 3 mm in thickness, to reach 150°C to 180°C. Thermocompression bonding of the toner is accomplished when the paper on which the toner is present passes between the heated metal roller and the pressure roller.

Therefore, to reduce the time required between the beginning and the completion of printing by the fuser roller, it is necessary to keep the roller heated (standby mode) all the time, and accordingly, the amount of power consumption increases (see quick mode in Fig. 2).

Without preheating, the power consumption decreases; however, in return, the printing time will increase considerably (see energy-saving mode in Fig. 2).

A solution to the tradeoff between energy saving and quick starting of printing is the on-demand fuser. An on-demand fuser can transmit heat generated by a ceramic heater to the toner via a polyimide fuser roller just tens of micrometers in thickness with a small thermal capacity. Therefore, the on-demand fuser can quickly start printing with considerably reduced power consumption compared to the conventional fuser roller (Fig. 1 (b), Fig. 2).[1]

Sumitomo Electric Industries, Ltd. produces polyimide fuser rollers coating the surface of polyimide[1] rollers with fluoropolymer[2] to prevent the toner from adhering to the roller surface (hereinafter, fuser rollers). To be in line with the recent trend toward higher printing speeds, it is necessary to improve the thermal conductivity of the fuser roller while making sure that the fuser roller
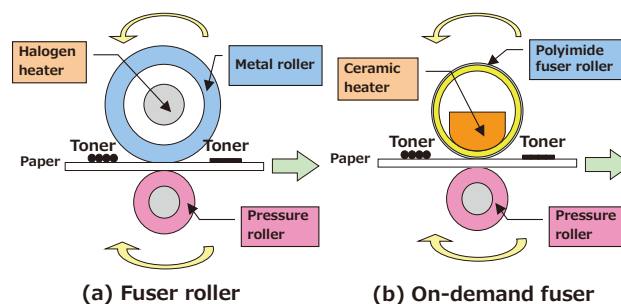

Fig. 1. Structural comparison between fuser roller and on-demand fuser
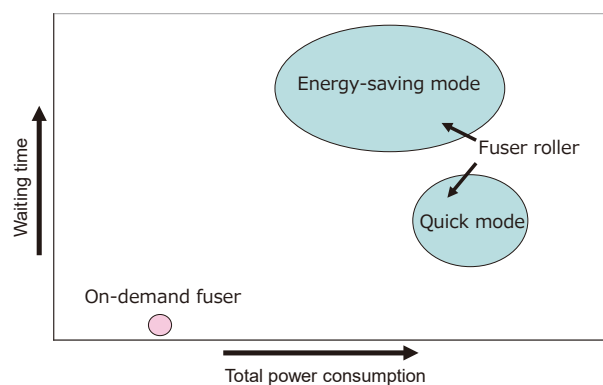

Fig. 2. Relationship between total power consumption and waiting time of LBPs

retains its strength as much as possible (as measured principally by MIT testing[3]). This report presents detailed information on the properties of the fuser roller made of a composite material comprising polyimide and carbon-based filler (graphite or carbon nanofiber (CNF)[4]).

2. Background of the Development

The fuser roller while rotating is compressed and deformed by the ceramic heater; accordingly, it must be durable against the induced stress. In addition, because it is heated by the ceramic heater throughout toner fusion, the fuser roller is required to have long-term heat resistance at 200°C or more. To meet these requirements, highly durable and heat-resistant polyimide is used as the base polymer material of the fuser roller.

Table 1 shows the composition of the fuser roller manufactured by Sumitomo Electric, which is a high-thermo-conductive fuser roller developed in 2017 to enable a printing speed of 45 sheets per minute.

Table 1. Composition of Fuser Rollers Designed for Conventional LBPs

Name	Function	Thickness (μm)	Material
Top layer	Avoidance of toner adhesion to fuser roller	12	Fluoropolymer + Carbon
Primer layer	Bonding between top and base layers Discharge of static electricity to ground	4	Fluoropolymer + Bonding agent + Carbon
Base layer	Provision of strength Conducting heat to toner	60	Polyimide + CNF

It is necessary to quickly conduct the heat generated by the ceramic heater to the toner in order to increase the LBP printing speed. To that end, the thermal conductivity of the fuser roller should be improved. To meet this challenge, in 2006, Sumitomo Electric began to use carbon nanofiber (CNF).[2]

CNF itself has a very high thermal conductivity of 1,200 W/mK and is a highly durable material. Its disadvantage is that as a raw material, its cost is extremely high. In addition, CNF fits the definition of nanomaterials listed in the notification issued in 2009 by the Director-General of the Labour Standards Bureau of the Ministry of Health, Labour and Welfare. At present, the use of CNF is not regulated. However, nanomaterials can reach any point within the body due to their small size, are highly reactive due to their large specific surface area, and stay in the body for long periods. Moreover, nanomaterials with a high aspect ratio potentially pose risks similar to asbestos.[3] These concerns made us undertake the development of a high-thermo-conductive fuser roller made of an alternative material to CNF.

3. Studying the Use of Graphite Filler

3-1 Selection of thermally conductive filler

One concern in selecting an alternative to CNF filler is how to make the roller highly thermally conductive. As described above, CNF itself is 1,200 W/mK in thermal conductivity, which greatly outperforms other types of thermally conductive filler (Table 2).

Figure 3 plots the thermal conductivity in the direction of the film thickness of a polyimide composite with CNF. The thermal conductivity of a composite material of a

Table 2. Thermal Conductivity of Thermo-Conductive Filler

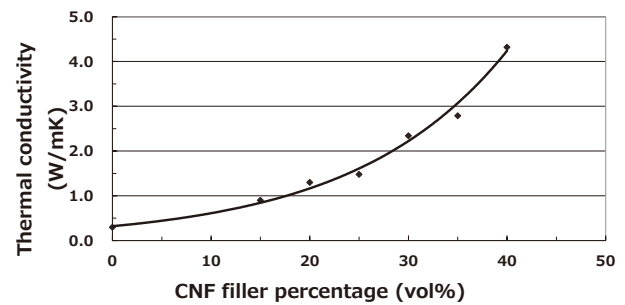| Filler type	Thermal conductivity (W/mK)
Silica	1 ~ 10
Alumina	20 ~ 40
Aluminum nitride	70 ~ 270
Graphite	100 ~ 200
Boron nitride	60 ~ 300
CNF	1,200

Fig. 3. Thermal conductivity in the direction of film thickness versus CNF filler percentage

polymer and thermo-conductive filler is determined by the thermal conductivity of the polymer, that of the discrete thermo-conductive filler, and the percentage of the thermo-conductive filler. In addition, the thermal conductivity of the composite also depends on the formation of thermally conductive paths by the thermo-conductive filler forming a three-dimensional network in the polymer, the matrix.

While CNF filler itself is highly thermally conductive, our idea was that it should be possible for a composite material to achieve an equivalent thermal conductivity by selecting a thermo-conductive filler that can form thermally conductive paths in the direction of film thickness at a lower filler percentage than that of CNF even using a thermo-conductive filler material which itself has a poorer discrete thermal conductivity.

Our solution was to select a graphitic filler material about 10 μm in size that itself exhibits a high thermal conductivity and is more likely to form thermally conductive paths in the direction of film thickness than the CNF filler (100 nm in diameter × 5 μm), which is fibrous and tends to be oriented along the film surface. We then studied the formation of thermally conductive paths dependent on the filler shape.

3-2 Types of graphite filler

The selected types of graphitic filler are explained below.

(1) Flake graphite

Flake graphite is the most common graphitic filler variety of natural graphite. It has a flaky shape and a relatively high degree of graphitization (85–99.9% purity) (Photo 1 (a)).

(2) Synthetic graphite

In contrast to natural graphite, synthetic graphite is artificial graphite. It is manufactured using coke as the main raw material, adding pitch and tar to coke, heating,

kneading, forming, and burning, followed by graphitization at a high temperature of about 3,000°C. Its major application is for graphite electrodes; therefore, crushed and pulverized graphite electrodes are also termed synthetic graphite. Having undergone heat treatment, synthetic graphite has a higher degree of graphitization (99.9% purity) than common flake graphite. Synthetic graphite has a flaky shape (Photo 1 (b)).

(3) Spheroidal graphite

Spheroidal graphite is produced by mechanically processing flake graphite into sphere-like shapes. Common flake graphite is used to manufacture spheroidal graphite. Compared to flake graphite, spheroidal graphite has a high bulk density and a small specific surface area. Unlike flake graphite, spheroidal graphite is not oriented along the film surface because of its resemblance to spheres. Therefore, we assumed that these features would help form thermally conductive paths in the direction of the film thickness (Photo 1 (c)).

(4) Exfoliated graphite

Exfoliated graphite is produced using expanded graphite treated with sulfuric or other acids, by heat-expanding and turning the graphite into a sheet-like form (graphite sheets) followed by crushing. Exfoliation improves the electrical and thermal properties of the graphite because it becomes graphene-like graphite with fewer graphene lamination layers than the original graphite. At the same time, however, acidified surfaces may sometimes degrade the mechanical properties of polymers (Photo 1 (d)).

(a) Flake graphite   **(b) Synthetic graphite**

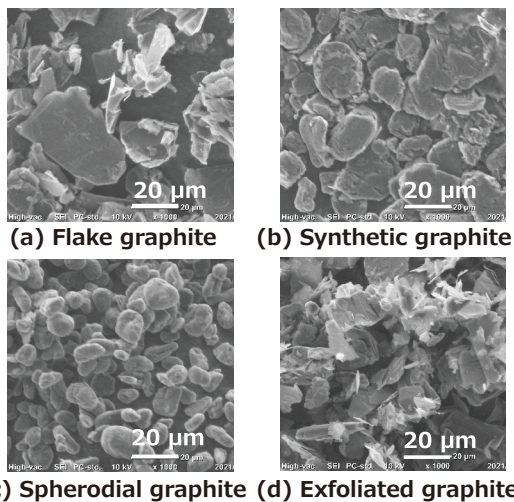**(c) Spherodial graphite**   **(d) Exfoliated graphite**

Photo 1. Shapes of graphite filler

3-3 Thermal conductivity measurement method

First, the filler best suited to the intended use was selected from the above-described types of graphitic filler.

(1) Filler dispersion methods

The physical properties of a composite material depend considerably on the dispersibility of the thermo-conductive filler used. Known methods of improving the dispersibility of graphitic filler include surface chem-

ical treatment methods, such as oxidation, plasma treatment, and surface polymer coating, as well as physical approaches of mixing and dispersion enhancement, such as adding a dispersing agent (e.g. surface active agent), ultrasonic dispersion, and roll milling (Table 3).[4] However, oxidation and plasma treatment involving batch processing is not readily applied to industrial uses that handle a large amount of filler. Polymer surface coating or the addition of a dispersing agent fails in improving the mechanical strength through improved dispersibility because of the decomposition of the residues at the polyimide baking temperature (higher than 300°C). What is even worse, they cause polyimide to decrease in strength. Furthermore, polyamic acid solution (hereinafter, polyimide varnish), the precursor of polyimide, is not suitable for improving dispersibility by ultrasonic means due to its high viscosity. We, therefore, concluded that the use of a physical shearing force for dispersion would be optimal for improving the dispersibility of graphitic filler and selected a dispersion process using three-roll milling.[*5]

Table 3. Filler Dispersion Methods

Type of technique		Example
Surface treatment	Chemical surface treatment/modification	Oxidation, plasma treatment, ozone/ultraviolet (UV) treatment
	Surface polymer coating	Polyvinyl alcohol, Polyvinylpyrrolidone
Addition of dispersing agent	Addition of solvent	Acetone, toluene, methanol, ethanol
	Addition of surfactant	Nonionic surfactant, cationic surfactant, anionic surfactant
Dispersion/mixture enhancement technique	Ultrasonic mixing/dispersion	High-shear mixing/dispersion
	Dispersion device incorporating ultrasonic irradiation	Roll mill, high-speed mixer

(2) Thermal conductivity measurement method

For the measurement of thermal conductivity, we used a thermal diffusivity measurement device based on a cyclic heating method. The device measured the thermal diffusivity α. The thermal conductivity λ in the direction of the thickness of the fuser roller was determined by Eq. (1), in which ρ is the density and C_p is the specific heat.

$$\lambda = \rho \cdot C_p \cdot \alpha \quad \text{...} \quad (1)$$

(3) Thermal conductivity measurement results

For the present development, the target thermal conductivity for the fuser roller was set at 1.0 W/mK. To meet this specification, the filler percentage of the previously mentioned CNF was set to 16 vol%. Considering the difference in discrete thermal conductivity of filler, each type of graphitic filler was dispersed in polyimide varnish using a three-roll mill to the filler percentage of 20 vol%. These types of graphite-filler polyimide varnish were applied and baked to form fuser rollers. Their thermal conductivity were evaluated, as shown in Fig. 4.

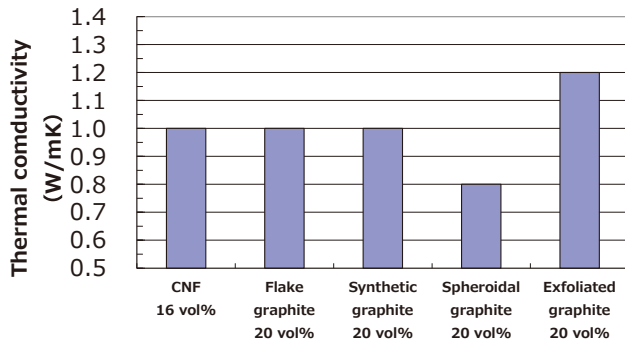The flake graphite measured 1.0 W/mK at the filler percentage of 20 vol%, achieving the target thermal

Fig. 4. Thermal conductivity of fuser rollers incorporating graphite filler

According to these results, we selected the exfoliated graphite, the highest in thermal conductivity at the filler percentage of 20 vol%, and measured the thermal conductivity of fuser rollers at varied filler percentages.
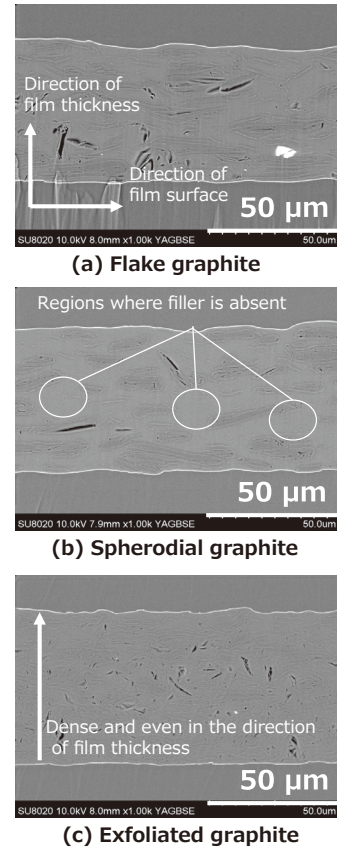

(a) Flake graphite

(b) Spherodial graphite

(c) Exfoliated graphite

Photo 2. Cross sections, obtained by SEM, of fuser rollers containing graphite filler

conductivity. The synthetic graphite also achieved the target thermal conductivity, reaching 1.0 W/mK. Nonetheless, it was inferred that the effect of the degree of graphitization was not considerably high because the thermal conductivity of the synthetic graphite was comparable to that of the common flake graphite.

Next, despite the intent to improve thermal conductivity in the direction of film thickness, the thermal conductivity of the spheroidal graphite was 0.8 W/mK, failing to achieve the target thermal conductivity, comparing poorly even to flake graphite. Photo 2 presents scanning electron micrographs of cross- sections of the fuser rollers. With the flake graphite, although individual pieces of the filler are oriented completely along the film surface, the graphitic filler with good wettability is dispersed evenly in the matrix—the polyimide—in the direction of the film thickness as well (Photo 2 (a)).

In contrast, with the spheroidal graphite with a small specific surface area, the filler is present in some regions and is absent in some other regions, being dispersed unevenly in the direction of the film thickness (Photo 2 (b)). Because of this, we assume that the spheroidal graphite was not so effective in forming thermally conductive paths and failed to meet the target thermal conductivity. Moreover, some non-spheroidal pieces of the filler are observed here and there. Therefore, one possible cause of the thermal conductivity of the spheroidal graphite being lower than the target thermal conductivity is that the filler was shredded under shear stress during dispersion by the three-roll mill.

Lastly, the exfoliated graphite exhibited a higher thermal conductivity than those of the other types of graphitic filler, achieving the target by reaching 1.2 W/mK in thermal conductivity. The exfoliated graphite with a large specific surface area was evenly dispersed, with good wettability, in the matrix and the polyimide, as in the case of the flake graphite (Photo 2 (c)). Furthermore, the exfoliated graphite, which makes thin and flexible pieces of filler, is less likely to be oriented along the film surface than the flake graphite; some pieces of the filler are oriented in the direction of the film thickness and the filler is present densely in the direction of the film thickness as well. Consequently, the thermal conductivity of the exfoliated graphite was higher than that of the flake graphite due to its formation of thermally conductive paths in the direction of the film thickness.

(4) Filler percentages and thermal conductivity of exfoliated graphite

Figure 5 plots the thermal conductivity of fuser rollers prepared with varied exfoliated graphitic filler percentages. The thermal conductivity of exfoliated graphite itself is lower than that of CNF. Nevertheless, up to the filler percentage of 15 vol% they are similar in thermal conduc-
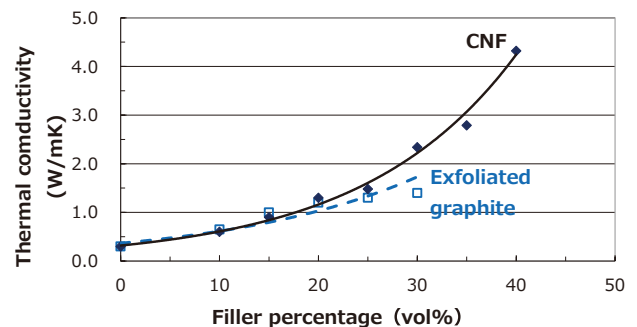

Fig. 5. Thermal conductivity of fuser roller versus filler percentage

High Thermo-Conductive Fuser Roller with Carbon Filler for Printers

tivity as a fuser roller. This is attributed to the fact that CNF, being fibrous, is less likely to be oriented in the direction of film thickness. Therefore, at low filler percentages, CNF does not form a thermally conductive path remaining at low thermal conductivity. In contrast, the exfoliated graphite forms thermally conductive paths even at low filler percentages below 15 vol%, contributing to high thermal conductivity in the direction of film thickness.

4. Long-Term Durability of Graphite-Filler Fuser Rollers

The long-term durability of fuser rollers is evaluated using, as the indicator, the number of cycles at break obtained by MIT testing (folding endurance testing). The number of cycles at break in MIT testing tends to be lower with the increasing coefficient of elasticity of the fuser roller because the number is generally determined by the tensile fracture strength of the fuser roller and by the stress imparted on the fuser roller during bending. Consequently, while increasing the percentage of thermal conductive filler is effective in increasing the thermal conductivity, the tradeoff is a decrease in tensile strength and an increase in coefficient of elasticity, which results in an extremely low number of breaks in MIT testing. Figure 6 plots the number of cycles at break in MIT testing of fuser rollers at varied percentages of exfoliated graphitic filler. The exfoliated graphite, at the filler percentage of 15 vol%, proved able to fulfill the target of 10,000 for the number of cycles at break in MIT testing and also to achieve the target thermal conductivity of 1.0 W/mK.
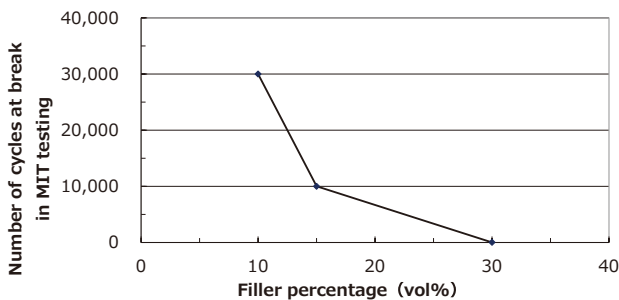

Fig. 6. Number of cycles at break in MIT testing versus filler percentage

5. Properties of the Newly Developed Product

Table 4 presents the properties and composition of the newly developed fuser roller. The newly developed product successfully incorporates an alternative to the nanomaterial, CNF, and considerably reduces the raw material cost while being equivalent to the current product in thermal conductivity and in the number of cycles at break in MIT testing. Moreover, tested on an actual machine, the newly developed product proved to be capable of handling fast printing at 45 sheets per minute.

Table 4. Composition and Properties of Newly Developed Product

Item			Newly developed product
Composition	Top layer	Material	Fluoropolymer + Carbon
		Thickness(μm)	12
	Primer layer	Material	Fluoropolymer + Bonding agent + Carbon
		Thickness(μm)	4
	Base layer	Material	Polyimide + Exfoliated graphite
		Thickness(μm)	60
Thermal conductivity (W/mK)			1.0
Number of cycles at break in MIT testing			10,000
Printing speed (sheets/min)			45

6. Conclusion

We had success in developing a high-thermo-conductive fuser roller, which leads to a considerable cost reduction and is suitable for fast printers (45 sheets/min) by using exfoliated graphite as an alternative to the nanomaterial, CNF, used in conventional fuser rollers. With the newly developed fuser roller provided as a sample to our user companies, we have begun to prepare for its mass production.

Future tasks include the development of novel fuser parts that will meet market demand for faster LBPs with higher durability.

Technical Terms

∗1 Polyimide: Polyimide is a generic term for polymers made of repeated units that have imide bonds. The thermal, mechanical, and chemical properties of polyimide are among the highest class of synthetic polymers.

∗2 Fluoropolymer: Fluoropolymer is a generic term for synthetic polymers obtained by the polymerization of olefins containing fluorine. Its features include superb resistance to heat and chemicals and a low coefficient of friction.

∗3 MIT testing: MIT testing refers to a fracture test performed using an MIT folding endurance tester.

∗4 Carbon nanofiber: Carbon nanofiber is a material in which graphene sheets (individual graphite layers) made of carbon are formed into a multilayer coaxial tube.

∗5 Three-roll mill: The three-roll mill is a dispersion device consisting of three rolls rotating at different speeds. The device accomplishes dispersion by leveraging the compression utilizing the pressure between the rolls and the shear imparted by the rolls rotating at different speeds.

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