Carbon Fiber Composite Rollers for High-speed/Wide Film Machines

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1. Introduction

Rollers with a roller shell made of cylindrical Carbon Fiber Reinforced Plastic (CFRP), called "Carbon Rollers," are well known for their high-level of performance that cannot be matched by steel and aluminum rollers. Initially, Carbon Rollers were primarily used for printing machines, including newspaper rotary printing machines, but recently they have been increasingly adopted for production lines for film, nonwoven fabric, and metal foils; winders and slitters; coaters and laminators; and paper making machines.

Recently, film machines and paper machines of 10 m in width have come into use, meaning the rollers installed in such machines have also become longer. The film produced in film machines is extremely delicate, and the rollers inside the machine are required to stably transport and process the film at speeds ranging from zero to a maximum of 1,000 m/min. The rollers inside paper machines must transport paper of 10 m in width at up to 2,000 m/min (120 km/hr). The conditions for high-speed, high-precision rotation of such long rollers are necessarily severe, so adopting Carbon Rollers is desirable to meet such conditions. Simply using Carbon Rollers, however, is not the answer. To achieve high-speed, stable operations, Carbon Rollers manufactured via technology that accurately reproduces the appropriate design are essential.

Mitsubishi Plastics, Inc. (MPI) manufacturers "DIALEAD" (standard modulus of elasticity=640 GPa), an ultra-high modulus pitch based carbon fiber that is ideal for use in Carbon Rollers. Using this material's strengths, MPI has been manufacturing and distributing Carbon Rollers since 1990 under the catch phrase "Integrated Production, from Carbon Fiber to Rollers." In this article, we begin by explaining the roller design concept for our high-speed, wide film machines, after which we introduce data verifying ultra-high-speed, stable operations at 2,000 m/min. for a 9,200 mm length chrome plated roller with an extremely small outer diameter of only 350 mm. Finally, we will close by reviewing the benefits of Carbon Rollers.

2. What Is a Carbon Roller?

Carbon Rollers are unique in that they use CFRP as the roller shell material. Table 1 compares the physical characteristics of several materials. Carbon Rollers have unparalleled characteristics, including being light weight (2/3 the density of aluminum) and highly stiff (modulus of elasticity exceeds that of steel). These characteristics are apparent in the light weight of the roller, reduced moment of inertia, reduced deflection, miniaturization (compact design), improved rotational precision, increased critical revolutions (increased stable operation region), and reduced run-out. For details, see References 1-5.

3. High-speed/Wide Film Machine Roller Design

3.1 Determining Roller Shell Inner/Outer Diameter and Modulus of Elasticity for Satisfying Stable Rotation Requirements up to Maximum Operational Speed

When designing rollers, we basically use a deflection model for a beam supported on both ends. Equation 1 is the fundamental equation for determining the deflection of a beam supported on both ends. Using the example of a hollow pipe as the roller, Equation 2 calculates the moment of inertia of area (I). In addition, Equation 3 calculates the natural frequency. Finally, Equation 4 calculates the critical speed (the point at which the natural frequency of the roller and revolutions resonate so that run-out clearly increases during revolution:

Table 1 Material Property Comparison

	Density [g/cm^3]	Modulus [GPa]	Deflection Ratio [—]
Steel	7.9	206	1.00
Aluminum	2.7	69	1.02
Carbon (CFRP)	1.6	100	0.42
	1.7	240	0.18
	1.7	320	0.14

Deflection ratio: dead load deflection of steel=1, relative ratio
Modulus of carbon (CFRP) can be set arbitrarily

1st order resonance). In general, resonance also occurs at half the 1st order resonance speed, so the roller design speed is typically based on half the resonance speed.

From Equation 1, we see that the deflection increases in proportion to the fourth power of the roller length, and from Equations 3 and 4, the natural frequency and critical speed decrease in proportion to the square of the length. In order to reduce deflection while increasing the natural frequency and critical speed, we must take the following measures.

Figure 1 Metal Clad CFRP Roller (Appearance and Features)

(i.) decrease w (distributed load): Specifically, use low-density material that reduces deflection from the roller dead weight. (The load applied by web tension, etc., is a constant operational condition independent of roller type.)

(ii.) increase E (modulus of elasticity): Specifically, use high modulus of elasticity materials.

(iii.) increase I (moment of inertia of area): Specifically, increase the outer diameter. Or increase wall thickness.

Because metals have a fixed density and modulus of elasticity, the only design parameter is I (moment of inertia of area). In other words, to decrease deflection and increase the critical revolutions, we must either increase the outer diameter or use thicker walls, which necessarily increases the moment of inertia. However, by using carbon, it is possible to design for all parameters: w, E, and I.

$$\text{Deflection [m]} = \frac{5wL^4}{384EI} \tag{1}$$

$$\text{Moment of Inertia of Area [m}^4\text{]} = \frac{\pi}{64}(d_o^4 - d_i^4) \tag{2}$$

$$\text{Natural Frequency (f) [Hz]} = \frac{\pi}{2}\sqrt{\frac{EI}{wL^4}} \tag{3}$$

$$\text{Critical Speed [m/min]} = 60 * f * d_o * \pi \tag{4}$$

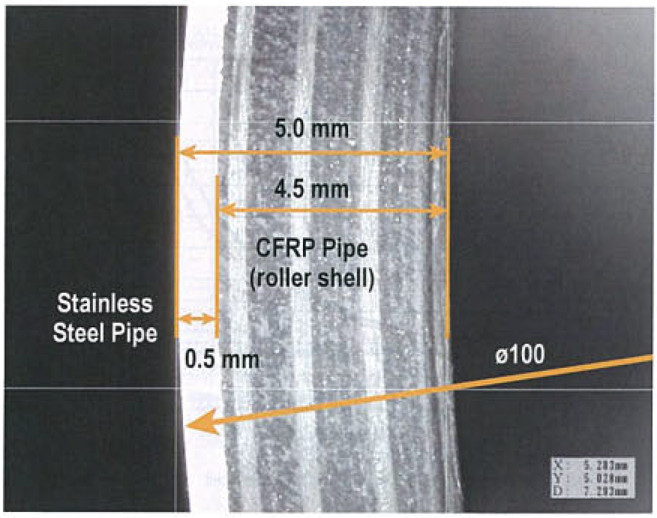
w: Distributed Load [N/m]
L: Beam Length [m]
E: Modulus of Elasticity (Young's modulus) [Pa]
I: Moment of Inertia of Area [m^4]
d_o: Pipe Outer Diameter [m]
d_i: Pipe Inner Diameter [m]

3.2 Roller Surface Design

The roller surface characteristics are important because the surface comes in direct contact with the web, such as a film. As such, the roller surface must be the same as that for conventional steel and aluminum rollers. Here, we will introduce the chrome plating technology used on carbon rollers.

The shell material for Carbon Rollers is CFRP, in other words, it is plastic. It is well-known that applying durable plating to plastic surfaces is difficult. As such, we use a method called "cladding" to metallize the Carbon Roller surface, after which the surface is chrome plated. We have been using this method to produce and distribute chrome plated Carbon Rollers for the past 20 years. Figure 1 is a photograph showing the chrome plated Carbon Roller structure and Figure 2 is a close-up photograph of the bonded surface of a ϕ100 mm carbon shell and metal surface layer.

Using the cladding method, the outer circumference of the carbon shell is press fit with a thin-walled metal pipe (stainless steel, steel, copper, etc.) to metallize the Carbon Roller surface. Because the roller surface is now a standard metal, the roller can be grooved or chrome plated, for example, in the same way as conventional metal rollers without a problem. As a result, the light weight and high stiffness of the carbon shell can be combined with highly corrosion resistant stainless steel and plated with highly abrasion resistant chrome to produce a roller that unites the strengths of three different materials.



Close-up/Cross-section of Stainless Clad CFRP Pipe

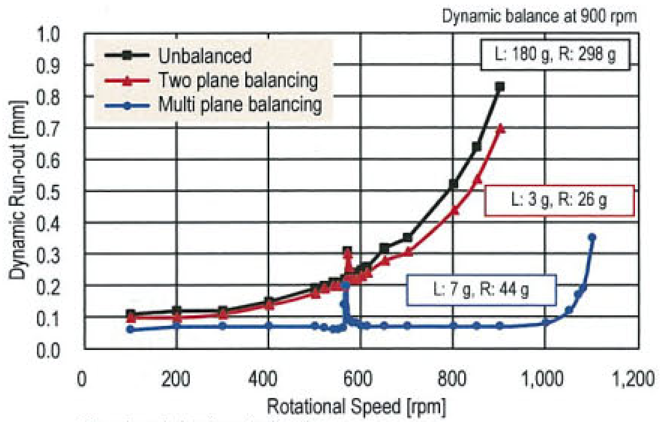
4. Dynamic Run-out Reduction Technology

4.1 Dynamic Balance for Preventing Dynamic Run-out at High-speed

Rollers for high speed, wide film machines naturally have a large roller length/roller diameter (L/D) ratio. Many of those involved in high L/D roller machine design and manufacture who have tried to reduce the dynamic balance to as close to zero as possible in order to prevent high-speed roller dynamic run-out have probably been unable to reduce such run-out. This leaves the question of why this phenomenon occurs. MPI assumes that the roller imbalance exists inside the roller. As such, ensuring dynamic balance at either end of the roller simply matches the values from the dynamic balance measurement device. Therefore, for high-speed rollers, we use four positions to correct the balance: two positions at either end of the roller and two positions inside the roller. In practice, we primarily correct for balance inside the rollers, and only correct at the ends as an additional measure. Taking this approach, by correcting close to the position where the imbalance actually occurs, it is possible to correct for true imbalance, not just apparent imbalance. We are thus able to prevent the occurrence of dynamic run-out during high-speed operation.

4.2 High-speed Operation Dynamic Run-out Reduction Comparison and Examples by Different Dynamic Balancing Methods

We measured the high-speed operation dynamic run-out of a ϕ260 x L8,600 mm roller under three conditions: before balance correction, after standard roller end balance correction (2 plane correction), and after our method using both end and internal balance (4 plane correction). Figure 3 shows the results. The first-order resonance revolutions of the roller is 1,130 rpm, so the small peak near 565 rpm on the graph is half the roller resonance revolutions.



Two plane: balancing at both ends
Multi plane: balacing at both ends and inside roller shell

Figure 3 Comparison of Balancing Methods for High L/D Rollers

First, in the uncorrected balance case, as the revolutions increase, centrifugal spinning imbalance inside the roller occurs and dynamic run-out increases. As the revolutions approach half the roller resonance revolutions, dynamic run-out exceeds 0.2 mm, the required specification for standard roller dynamic run-out, but dynamic run-out continues to increase even after exceeding half the resonance revolutions. Next, in the roller end balance correction case (2 plane correction), the dynamic balance for either end at 900 rpm is 3 g and 26 g, respectively, which is sufficient, but the dynamic run-out is only slightly improved compared with the uncorrected balance case. Naturally, as the revolutions approach half the resonance revolutions, dynamic run-out exceeds 0.2 mm, the run-out requirement for standard rollers. As such, with these kinds of rollers, the maximum revolutions is only 450 rpm, or 80% of half the resonance revolutions.

Finally, in the roller end and inside balance correction case (4 plane correction), the dynamic balance for either end at 900 rpm is 7 g and 44 g, respectively, which is a similar level to 2 plane correction, but we can see that the value of dynamic run-out is clearly improved. Although the dynamic run-out value at half the resonance revolutions (565 rpm) is 0.2 mm, when the revolutions is ±3 rpm of this point, the dynamic run-out drops to a safe level of under 0.1 mm. At 1,000 rpm, near the first-order resonance revolutions (1,130 rpm), dynamic run-out once again increases, and only when the revolutions exceed 1,080 rpm, does dynamic run-out exceed 0.2 mm, the required dynamic run-out for standard rollers. With this type of roller, the maximum revolutions is 80% of the first-order resonance revolutions, or 900 rpm, allowing for plenty of design freedom.

5. Small Diameter (ϕ350), Long (L9,200) Roller Design and 2,000 m/min Operation Verification

5.1 Roller Design Specifications

Table 2 shows the design specifications for the rollers. The required specifications satisfy the conditions of a roller length of 9,200 mm and an operational speed of 1,000 m/min. The roller surface is chrome plating for both the Carbon Roller and steel roller. The Carbon Roller uses the cladding technology explained earlier.

The Carbon Roller is designed so that 80% of the first-order resonance revolutions is 1,000 m/min, meaning the roller outer diameter is ϕ350 mm. For comparison, the table shows

Table 2 Design Specifications

Material			Steel		CFRP
Young's Modulus		[GPa]	206		240
Dimension	Face Length	[mm]	9,200		
	Overall Length	[mm]	9,760		
	Outer Diameter	[mm]	960	680	350
	Inner Diameter	[mm]	930	650	325
Weight	Total	[kg]	4,279	2,794	403
Deflection	Dead Load	[mm]	0.41	0.81	0.87
	Added Load	[mm]	0.02	0.05	0.42
	Total	[mm]	0.4	0.9	1.3
Moment of Inertia		[kg · m^2]	892	291	10
GD^2		[kg · m^2]	3,568	1,166	40
Critical Number of Revolutions		[rpm]	1,660	1,190	1,140
Critical Speed		[m/min]	5,000	2,530	1,250
1/2 Critical Speed		[m/min]	2,500	1,265	625
Design Speed		[m/min]	2,000	1,012	1,000
Demonstrated Speed		[m/min]	—	—	2,000

the design for a steel roller that operates at 1,000 m/min. and the design for a steel roller that can operate at 2,000 m/min., the speed at which we demonstrated the Carbon Roller, explained later. Because dynamic run-out is large at half the resonance revolutions for steel rollers, we designed each of the rollers to operate with 80% of half the resonance revolutions being greater than 1,000 m/min. and greater than 2,000 m/min., respectively.

Assuming an operational speed of 1,000 m/min., we compared the Carbon Roller and steel rollers. In contrast to the ϕ350 mm outer diameter of the carbon roller, we can see that the steel roller must have an outer diameter of ϕ680 mm to satisfy the operational speed requirements. As a result, the difference in weight (total weight including metal shaft) is significant. Compared with the steel roller, we can see that the Carbon Roller weight is 1/7 and the moment of inertia and GD^2 are 1/30. It is clear that when compared at 2,000 m/min., this ratio increases even further.

Figure 4 ϕ350 × L9,200 mm Roller Testing

5.2 Roller Performance Evaluation (high-speed revolution testing)

Figure 4 shows the measuring of dynamic run-out of a roller on a balancing machine. Figure 5 shows the relationship between roller operational speed and dynamic run-out. This dynamic run-out data is measured for each of the revolutions after being stabilized for a fixed time to prevent underestimates of dynamic run-out caused by changes in speed over time. This approach accurately measures the dynamic run-out value for the revolutions. As a result, we were able to verify the following items.

- Dynamic run-out at 550 rpm (605 m/min.), half the resonance revolutions, is 0.10 mm, which is sufficiently lower than the roller specification for dynamic run-out of 0.2 mm, and thus a safe level.
- Dynamic run-out at the required operational speed of 1,000 m/min. is 0.08 mm, showing an excellent stable revolution performance.
- After exceeding 1,000 m/min. to reach higher revolutions, as the revolutions approach the first-order resonance revolutions of 1,100 rpm (1,210 m/min.), dynamic run-out increases, but if the revolutions are maintained at 1,090 rpm (1,200 m/min.), 10 rpm below the first-order resonance revolutions, dynamic run-out stabilizes at 1.5 mm, but does not generate a strong vibration because run-out diffuses.
- We accelerated the roller rapidly to pass through the resonance point when the revolutions exceeded the first-order resonance revolutions of 1,100 rpm. At that point, a momentary vibration occurred.
- After exceeding the first-order resonance revolutions, we

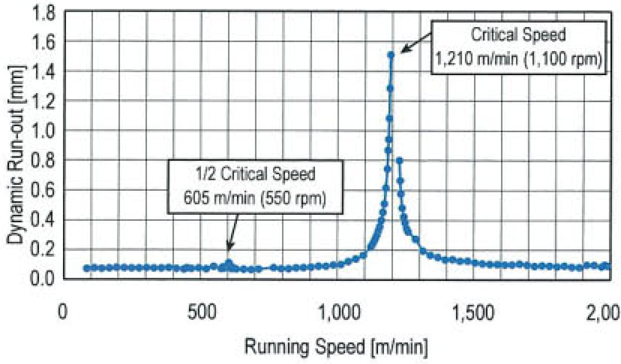


Figure 5 Dynamic Run-out of ϕ350 × L9,200 mm Roller

reduced the speed to near the first-order resonance revolutions, but at 1,120 rpm (1,230 m/min.), 20 rpm faster than the resonance revolutions, dynamic run-out only increased to 0.8 mm even when kept at this revolutions, and stable revolution was continued at this dynamic run-out.

- The only range in which first-order resonance occurs as a result of the resonance of the natural frequency of the roller itself and the roller revolutions confirmed by the tests, is 30 rpm (roughly 30 m/min.), so by passing through this range in a short time, we confirmed it is possible to use the roller above first-order resonance.
- If we assume that the roller specification for dynamic run-out is below 0.2 mm, the operational speed range in which run-out exceeds this is 1,120-1,320 m/min., so speeds above or below this have a dynamic run-out of under 0.2 mm, and in practice we verified stable revolution with a dynamic run-out of under 0.1 mm.
- The wide film field currently has a maximum operational level of 1,000 m/min. when using the fastest slitters, but in the paper-making industry, machines for 9 m wide paper are also set to operate at 2,000 m/min. Therefore, we increased revolutions in pursuit of 2,000 m/min. operation; at this speed dynamic run-out is 0.08 mm, allowing for very stable continued revolution.

6. Quantification of Carbon Roller Merits that Realize Light Weight, High Stiffness, Small Diameter, Long Length, and Stable High-speed Revolution

When driving a roller, using the gravitational system of units to express the equation calculating the motor capacity to rotate each roller, we get the following equation when the transmission efficiency is 1 (see box below).

Using this equation to compare the ϕ350 x L9,200 Carbon Roller and ϕ680 x L9,200 steel roller from Table 2, we can see the specific merits of the carbon roller. The most significant influence is from the value of GD^2, which is clear from the equation.

The total power consumption of the roller drive is calculated from the total of power consumption/storage during acceleration and deceleration, and power consumption during steady operations. Considering steady operations at a constant speed, because the weight of the Carbon Roller in this comparison is 1/7 that of the steel roller, the mechanical loss stemming from weight is reduced to 1/7. In addition, because the roller is lighter, the shaft can be made thinner and bearing size can be reduced, so we can expect an associated reduction in mechanical loss. Machine manufacturers have taken different approaches to reduce machine power consumption, but it is clear that adopting Carbon Rollers is one effective means of significantly reducing energy consumption.

Calculation 1: Calculation of the required motor capacity to accelerate the roller to constant speed over a fixed time.

Motor required to increase roller speed to 1,000 m/min. in 60 seconds:

Steel: 12 kW → Carbon: 2 kW, motor cost decrease

Calculation 2: Calculation of the necessary time to accelerate the roller to a constant speed when the motor capacity is constant.

Acceleration time required to increase roller speed to 1,000 m/min. using a 3 kW motor:

Steel: 4 min. (240 sec.) → Carbon: 30 sec., productivity increase

$$\text{Required motor power } P\,[\text{kW}] = \frac{T\,[\text{kg}\cdot\text{m}] \times N\,[\text{rpm}]}{974}$$

$$\text{Torque during accleration } T\,[\text{kg}\cdot\text{m}] = \frac{GD^2\,[\text{kg}\cdot\text{m}^2] \times \Delta N\,[\text{rpm}]}{375 \times \Delta t\,[\text{sec}]}$$

$$GD^2\,[\text{kg}\cdot\text{m}^2] = \text{roll shell } GD^2 + \text{shaft/boss } GD^2$$

$$\text{each } GD^2 = \frac{1}{2} \times \text{weight}\,[\text{kg}] \times (\text{outer diameter}^2 + \text{inner diameter}^2)\,[\text{m}^2]$$

N: revolutions (=operational speed [m/min] ÷ (roller outer diameter × π)) [rpm]

Δt: acceleration from stopped state ($N=0$) to N revolutions [sec]

ΔN: increase in revolutions during t [sec] (when accelerating from a stopped state $= N$) [rpm]

Let us look at this from another perspective. According to an equation for calculating the air layer entrained between the film flowing over the roller and the roller as proposed by Hashimoto, et. al.,[6] the thickness of the air layer generated in this space becomes thicker in proportion to roller radius. If the thickness of the air layer increases, the film rises off the roller surface and moves freely, so the friction force between the two becomes unstable. As a result, stable film transport becomes difficult. Typical solutions include cutting grooves into the roller surface and roughening the surface to allow the entrained air to escape, but because these approaches can cause damage to or cause physical property variation in some films, these approaches are sometimes avoided. If the roller diameter is reduced by switching to a Carbon Roller, it is possible to reduce air entrainment, so grooves and roughness can be eliminated or reduced, which is desirable for high-speed, stable transport of film.

7. Closing

Recently, there have been increased expectations for power conservation. We feel that light weight, high stiffness Carbon Rollers can fully meet these expectations. Although rollers are just one component, we hope that our high-quality Carbon Rollers contribute to the expansion of the international film industry.

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CARBOLEADER™

High performance carbon fiber composite roller

CARBOLEADER™ serves to improve the performance of film, nonwoven fabric, and metal foil production machines; coaters/laminators; and printing machines, etc.

4 key technologies support CARBOLEADER™'s high quality, high performance, and high reliability

- **Integrated production, from carbon fiber material to Carbon Roller production**
  Leave everything from roller design to manufacturer and quality assurance to us.
  We produce all DIALEAD™ pitch-based carbon fiber and high thermal stability resin in-house.
- **Light weight/low inertia and high stiffness**
  Our standard rollers have a specific gravity of 1.7 (2/3 that of aluminum) and a Young's modulus of 240 GPa (higher than steel).
- **Same surface as conventional metal rollers (rubber, plating, ceramic spraying, etc.)**
  We can offer high durability surface plating using our cladding technology (surface metallization).
- **High rotational precision**
  Our rollers have high rotational precision over a wide revolution region because of our ideal roller design and proprietary balancing technology.

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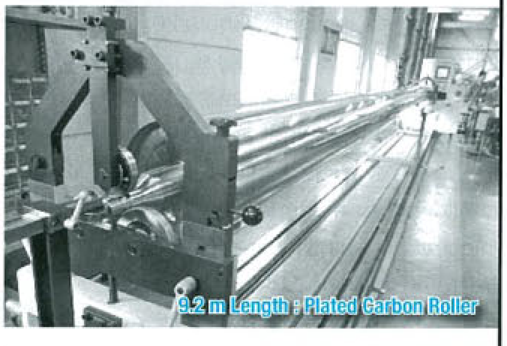
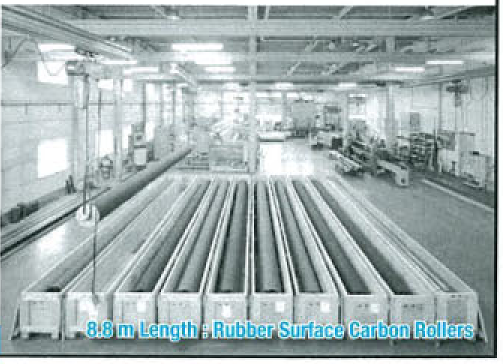


9.2 m Length : Plated Carbon Roller



8.8 m Length : Rubber Surface Carbon Rollers