

# Roles of Iron Metal Powders in Semi-Metallic Friction Materials

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## ABSTRACT

For more than 50 years, iron metal powders have been successfully applied in semi-metallic friction materials for OEM and aftermarket applications in North America. The advantages of using iron metal powders in brake formulations stems from its ability to enhance friction performance, to reduce brake/rotor wear, to make it easier to manufacture brake linings and to provide a cost-effective brake material. However, there are few publications exploring the roles of iron metal powders in friction materials due to manufacturing know-how reasons and/or lack knowledge in understanding powder characteristics of iron metal powders manufactured by different manufacturing methods and processes. On the other hand, more and more modified iron and alloyed iron powders have been developed in last 10 years. Many of them have unique chemical and physical properties and have been found wide applications in different industries including friction. However, the advantages of these modified iron-based powders have not been discussed in the past.

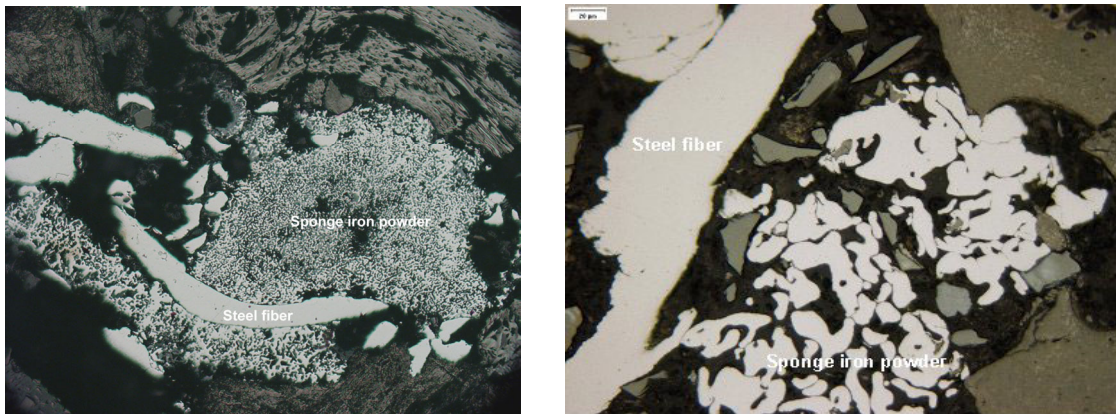
This paper investigates the roles of different types of iron metal powders manufactured today and discusses the effect of using various raw materials, production methods and processing technologies on the key characteristics of iron powder such as particle size, particle density, and particle morphology. In order to evaluate the effect of iron metal powders on friction noise and performance, dynamometer tests were performed based on a modified noise testing procedure. The testing results indicated that the difference in powder characteristics of iron metal powder could greatly affect the performance of brake materials, especially on coefficient of friction and braking noise.

## INTRODUCTION

Iron powders are known as environmental-friendly products that have been widely applied in many industries such as powder metallurgy, friction, welding, magnet, chemical and food industries since the early 1900s. In 2004, it was estimated that about 1000,000 metric tons of iron powder was manufactured worldwide, in which an about 80% is used for powder metallurgy (P/M) applications.

For friction applications, iron powders have being applied in various semi-metallic friction materials from resin-bonded light/heavy-duty disc and drum brake pads to sintered motorcycle brake pads, clutches, railroad and aircraft brake lining, etc. (see Figure 1). One of the earliest U.S. patents referred to the particular use of iron powder as a friction modifier. It is claimed that addition of such an ingredient to the friction material formula increases cold friction and reduce wear. Furthermore, the sponge iron powder is claimed to complement the noise attenuating components present to eliminate squeal obtained during a frictional engagement [1]. With combining characteristics analysis of iron powders with brake manufacturing practices, the benefits of adding iron powder in friction formulas can be considered as: 1) Modify brake performance; 2) Minimize brake noise; 3) Increase brake thermal conductivity; 4) Reduce rotor wear; 5) Make brake lighter; 6) Reduce production cost [2].

### Resin-bonded Brake Lining



### Sintered Brake Lining

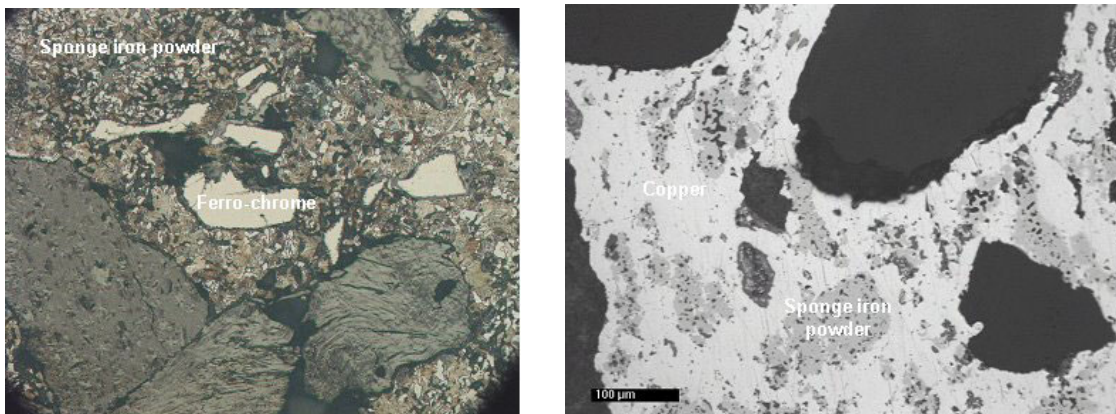


Figure 1 Applications of sponge iron powders in semi-metallic friction materials

Due to manufacturing know-how reasons and/or lack knowledge in understanding powder characteristics, there are few publications exploring the roles of iron metal powders in friction materials. On the other hand, many unique modified iron and alloyed iron powders have been developed and have been found wide applications in different industries including friction. However, the advantages of these modified iron-based powders have not been discussed yet in the past.

In order to explain the roles of iron metal powder in semi-metallic friction materials, this paper first classified iron metal powders and specialty iron products utilized for friction applications. Then, analysis was given how to identify the difference in powder characteristics of iron powders made today based on their manufacturing methods and processing technologies. Finally, braking noise evaluations on different type of iron powders were performed with a typical semi-metallic brake pad based on a modified dynamometer noise test.

## CLASSIFICATION OF IRON METAL POWDERS

Iron powders are generally manufactured using either mechanical or chemical methods. Water-atomization of molten iron or alloy is a primary mechanical manufacturing method today, while chemical reduction of iron oxides is the least expensive, large-scale chemical manufacturing method compared to other chemical methods. However, the atomization and reduction methods create iron powders with completely different particle morphology. As demonstrated in Figure 2, the atomized iron powder particles are solid and have irregular particle shapes so that it is widely used for making P/M components. The reduced iron powder

particles are irregularly porous shaped, and therefore are referred as sponge iron powder. It is the porous morphology of the sponge iron powder which is responsible for its wide use in friction materials.

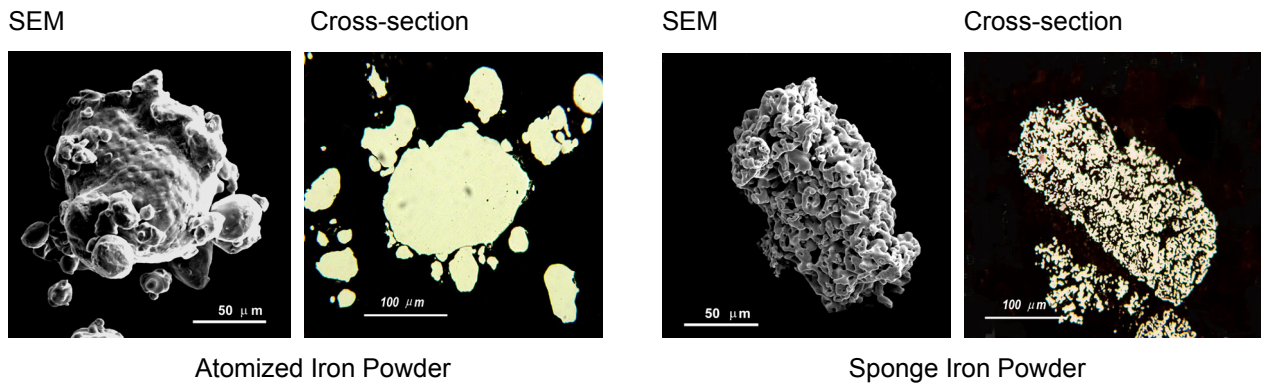


Figure 2 Photographs of atomized and sponge iron powders

There are two major chemical reduction methods used in the production of friction grade iron powders, one uses carbon monoxide and the other uses hydrogen as the reducing agent. The raw material used in the reduction methods is iron oxides either high-grade iron ore or selected mill-scale.

Reduction of iron oxide by carbon is the oldest method of producing iron powder and was developed in Höganäs, Sweden in the early 1900's, thus it is also called as the Höganäs process. Reduction of iron oxide by hydrogen is a well-known method used in laboratory studies. A large-scale reduction process, called as Pyron process, was developed in 1940 in Niagara Falls, NY. It provides an alternative method for the production of commercial iron powders from iron oxides [3].

The hydrogen-reduced iron powder has a sponge-like microstructure with very fine porosity. It has been used as premium friction grade powders since the 1950s when semi-metallic friction materials were first developed in North America. Figure 3 demonstrates particle morphologies of iron metal powders produced with water-atomization, carbon and hydrogen reduction.

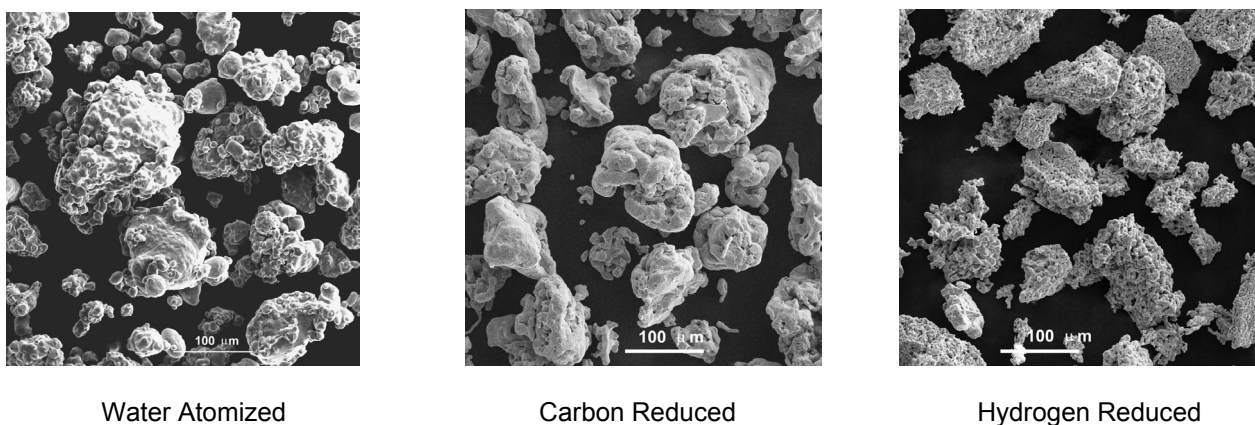


Figure 3 SEM of iron powders made from atomization, carbon and hydrogen reduction processes

The atomization, carbon and hydrogen reduction processes provide a wide selection of available friction grade iron powders. Table 1 listed representative products currently being used in friction formulations globally and they represent almost all grades of iron powders used for friction applications. Basically, these friction grade iron powders can be classified into two major groups and seven different types based on their manufacturing method, particle size and apparent density.

Table 1 Classification of friction grade iron powders

Powder Type	Definition	AD*, g/cm <sup>3</sup>	Representative Products	Manufacturing Process
A. Coarse Powder (80% > 105 μm)	1) Low AD	1.0~1.5	R-12	Hydrogen- reduction
	2) Med AD	1.5~2.0	M80/20-19	Carbon- reduction
	3) High AD	2.0~2.5	MH40.24	Carbon- reduction
B. Fine Powder (80% < 105 μm)	1) Low AD	1.0~1.5	R-80	Hydrogen- reduction
	2) Med AD	1.5~2.0	LD-80	Hydrogen- reduction
			MH65.17	Carbon- reduction
	3) High AD	2.0~2.5	P-100	Hydrogen- reduction
			M100	Carbon- reduction
4) Very high AD	>3.0	AHC100.29	Water- atomization	

\* AD - Apparent density, i.e. bulk density

On the other hand, many modified and alloyed iron powders have been developed for P/M applications in order to improve the product performance and meet special requirements. Some of them have being found to be good ingredients for friction applications (see Figure 4). For example,

1) Iron Powder diffusion-bonded with 10% and 25% copper

Copper diffusion-bonded with iron powder provides both benefits of copper and iron powder into friction formulations. Copper is well known to improve friction performance and brake/rotor wear by increasing thermal conductivity and coating the rotor.

2) Iron powder coated with 1% sulfur

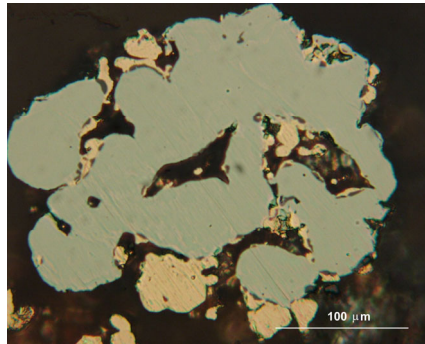
Sulfur is a good lubricant to improve friction performance and rotor wear.

3) Iron oxide with 65~70%Fe (magnetite and hematite)

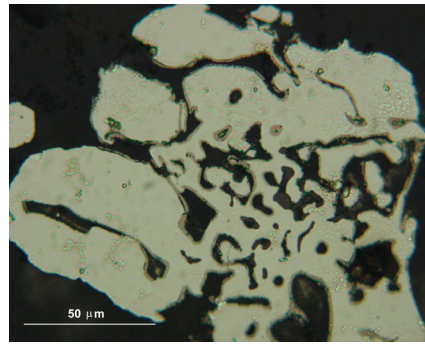
Iron oxide is a mild abrasive and is found useful for enhancing brake wear resistance and elevating cold friction.

4) High-alloyed steel powders

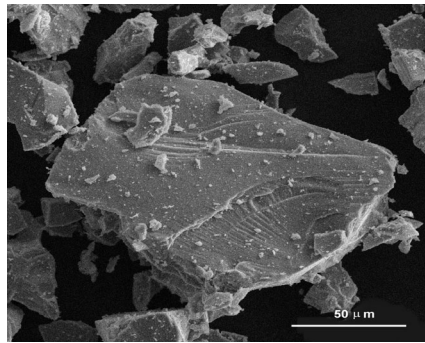
High-alloyed steel powders are providing formulation engineers further wide selections to design high performance friction materials.



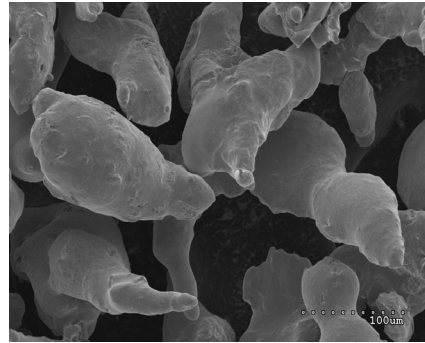
25% Copper Diffusion-bonded Iron Powder



1% Sulfur Coated Iron Powder



Magnetite Iron Oxide



High Alloyed Steel Powder (Fe-20%Cr-12%Ni)

Figure 4 Photographs of specialty iron powder products

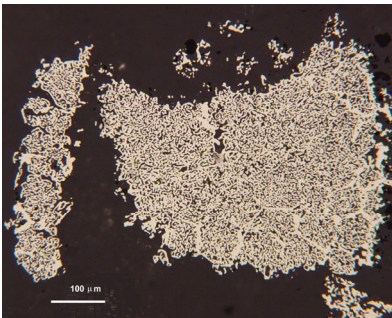
In addition, powder-bonding technologies provide great advantages in improving mixing operations to prevent material segregation. Iron powders can be bonded with other fine ingredients that are difficult to be mixed into formulations. This technology has been successfully applied in P/M industry and should have the same benefits to friction industry.

## CHARACTERISTICS OF IRON POWERS

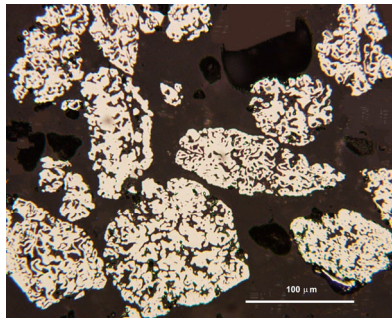
### PARTICLE MORPHOLOGY

As described previously, the particle morphology of iron powder varies depending on the manufacturing method and finishing operations. In general, atomized iron powder has much less porosity than sponge iron powder made by hydrogen/carbon reduction. Iron powder reduced by hydrogen has very fine porosity and iron powder reduced by carbon has relatively coarse porosity (see Figure 5). Furthermore, the porosity and irregularity can be reduced by adjusting grinding operations to increase density. The very irregular shape and internal porosity of sponge iron particles ensure that the particles lock into the material matrix firmly. This helps improve the wear properties of a friction material.

a) Hydrogen-reduced powders

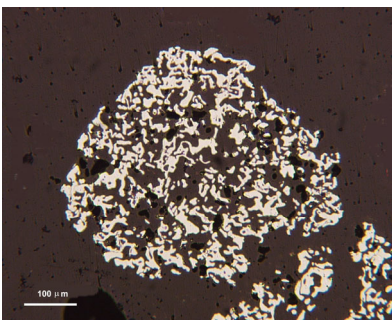


Low AD and coarse particle

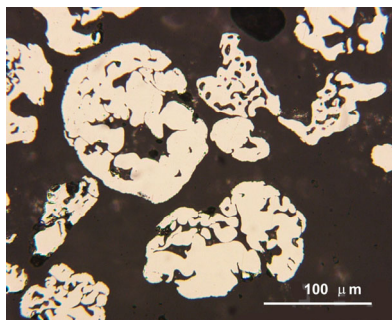


High AD and fine particle

b) Carbon-reduced powders



Low AD and coarse particle



High AD and fine particle

Figure 5 Cross-section photographs of iron powders made by hydrogen reduction and carbon reduction

### PARTICLE DENSITY

A density of powder is generally defined as the ratio of mass to volume. However, the density is not necessarily the same as that of the substance if there is internal porosity. Therefore, the true density (or solid density) is defined as the ratio of mass of the particle to its actual volume excluding all porosity. The particle density is defined as the particle mass divided by the particle volume, including the closed pores. The apparent density (or bulk density) is defined for powder and particle beds (a ratio of the mass to the volume of the bed in a vessel, including the voids between the particles). Obviously, the apparent density is lower than the particle density while the particle density is lower than the true density.

An effective method for measuring particle density is pycnometer method that uses a liquid as a media [4]. The liquid can be water or solvent but it must be a nonvolatile liquid, in which the particles are both wettable and insoluble. Table 2 shows the difference in particle density and apparent density between the atomized powder, hydrogen and carbon reduced powders. It can be seen that the hydrogen-reduced powder contains the greatest internal porosity while the atomized powder contains the least porosity.

Table 2 Particle density and apparent density of different iron powders

Iron Powder Process	Apparent Density g/cm <sup>3</sup>	Particle Density g/cm <sup>3</sup>	% of True Density*	Porosity %
H <sub>2</sub> -reduced	1.22 ~ 2.44	<b>6.48 ~ 6.74</b>	82.3 ~ 85.6	17.7 ~ 14.4
C-reduced	1.55 ~2.50	<b>7.22 ~7.57</b>	91.7 ~ 96.2	8.3 ~ 3.8
Atomized	3.18	<b>7.83</b>	99.5	0.5

\* True density: 7.87 g/cm<sup>3</sup> for pure iron

The particle density is the density that should be used to calculate the additions of powder in a friction formulation. The addition of ingredients in a formulation is established by volume, while the ingredients are usually in practice added by weight. Therefore, the particle density is an important factor needed to determine the amount of powder to be used. Iron, for example, has a true density of 7.87 g/cm<sup>3</sup>, while the typical particle density of the hydrogen-reduced iron powder sample measured by pycnometer is less than 6.80 g/cm<sup>3</sup> due to the effect of internal porosity.

Since formulations are developed based on volume, the lower particle density of iron powder would lead to developing materials utilizing less iron powder on a weight basis. The introduction of porosity into the friction matrix would also minimize the need for additional resin, thus reducing overall cost. The technical benefits would include a lighter friction material and minimization of noise.

#### PARTICLE HARDNESS

Particle hardness of iron powders depends on the chemical composition, especially the carbon content and the amount of alloying. The diffusion of carbon in small amounts can cause significant increases in hardness. Therefore, the particle hardness can be adjusted by controlling the carbon content. In addition, the manufacturing process also influences the particle hardness of iron powder. Iron powder made by the water atomization of molten iron becomes hard due to the residual stresses. Hydrogen-annealing the iron powder releases the stresses and minimizes carbon and oxygen content so that the iron powder softens. Table 2 presents the microhardness values of various iron powders, including steel fibers and specialty iron products. The softer iron powders could prove to reduce rotor wear as well as improve noise versus harder iron powders and steel fiber.

Table 3 Microhardness of iron powders and specialty iron products

Products	Grade	Microhardness (Hv <sub>.25g</sub> )
Hydrogen-reduced		124
Carbon-reduced	Annealed	126
	unannealed	159
Water-atomized	Annealed	136
	unannealed	324
Steel fiber		269
High alloyed steel	Fe-20%Cr-12%Ni	310
Magnetite	Fe <sub>3</sub> O <sub>4</sub>	598
Hematite	Fe <sub>2</sub> O <sub>3</sub>	1186

## PARTICLE SIZE

The maximum particle size of sponge iron powders that are used in friction applications is generally less than 850 $\mu\text{m}$  (20 mesh). According to their particle size distribution, friction grade iron powders can be classified into two groups- coarse powders, 80% >105  $\mu\text{m}$  (140 mesh), and fine powders, 80% <105  $\mu\text{m}$ . Figure 6 shows the relationship between particle size and specific surface area of representative iron powders. In general, the finer the particle size is, the larger the specific surface area is. Iron powder with a sponge-like microstructure has different surface area values dependent on its manufacturing method. As mentioned before, the iron powder produced by hydrogen reduction contains extremely fine pores while iron powder produced using carbon reduction has far fewer but much larger pores. Therefore, the sponge powder made by hydrogen reduction has a higher surface area, even with a coarser particle size distribution. The iron powder with high surface area bonds well with the resin to increase the strength of the friction material and to improve wears. Higher surface area also provides a more consistent surface for better friction performance.

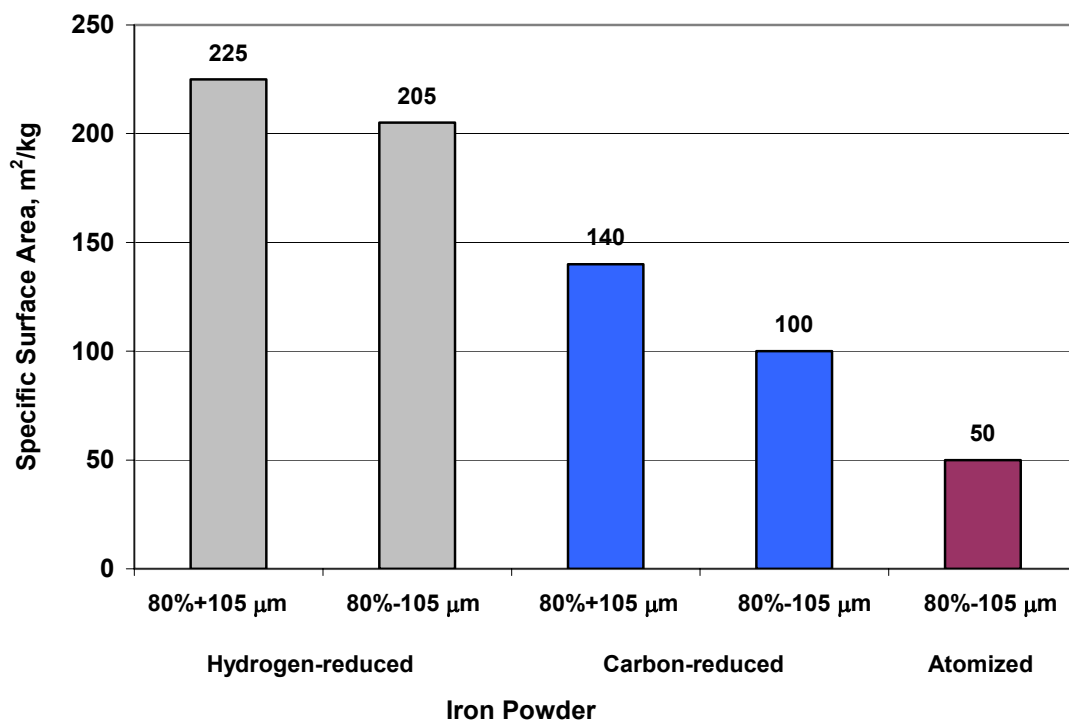


Figure 6 Specific surface area of iron powders made from atomization, hydrogen and carbon reduction

## GREEN STRENGTH

Green strength refers to the mechanical strength of a cold pressed powder compact. The strength results mainly from mechanical interlocking of irregularities on the particle surfaces, in addition to plastic deformation during pressing. Therefore, the particle shape is the most important factor contributing to green strength. Powder with lower apparent density (irregularity), and/or higher porosity and surface area (particle surface roughness) provides higher green strength. Figure 7 shows the green strength of different iron powders used in friction applications. In general, the compact using sponge iron powders have higher green strength than that using atomized iron powder because sponge iron powder has much more irregularities than atomized iron powder. In addition, green strength is affected by particle size. Coarse particles contribute to higher green strength than fine particles [2].

The irregularities of the iron particles help to lock iron powder securely in the resin matrix and thereby increase the strength of friction material. The iron powders with higher green strength would help maintain the strength provided by steel fibers. Thus, the higher the green strength of an iron powder, the more steel fiber that could be replaced. A strong mechanical interlock contributes significantly to strength and wear resistance at high temperature when the resin bonding deteriorates.

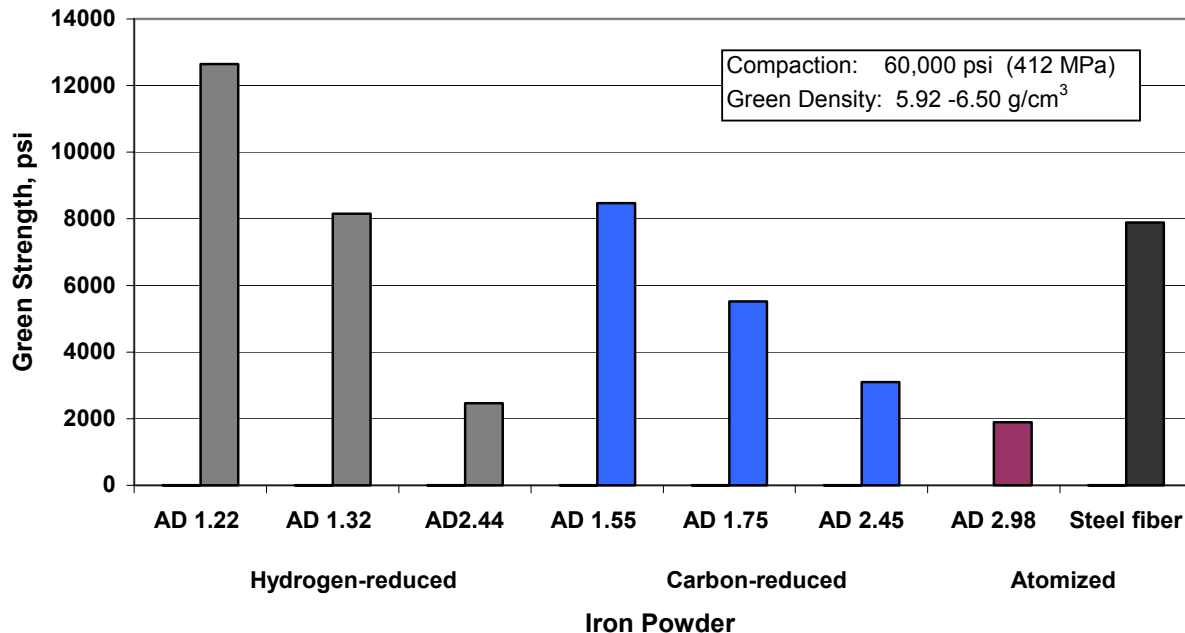


Figure 7 Green strength of different iron powders and steel fiber (AD: apparent density)

## BRAKING NOISE EVALUATIONS OF SEMI-METALLIC FRICTION MATERIAL

It is well known that braking is often accompanied with loud noise, particularly a high-pitched squealing. Although the geometry of brake pads and brake rotor can exert a major influence on the occurrence and nature of the brake noise, the composition of the friction material also exerts an important effect.

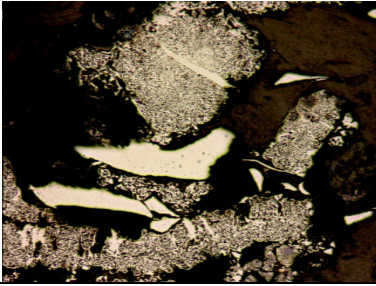
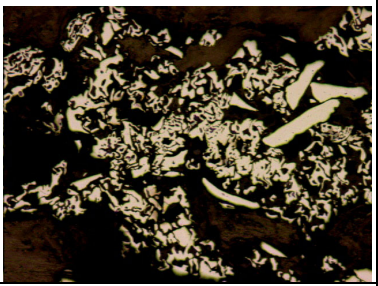
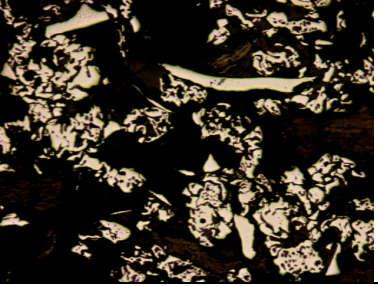
In North America, the most common type of brake friction materials on passenger cars and light or medium trucks are the so-called "semi-metallic" type. These usually have a high content (>40% by weight) of ferrous metal in the form of steel fiber with and without iron powder. The iron powder is considered to be a key ingredient in controlling brake noise.

During the development of a friction material, the tendency to generate brake noise is best evaluated by vehicle testing, which is a very time consuming and costly process since noise is not a functional property of the brake lining (unlike the coefficient of friction).

Dynamometer testing can simulate on-vehicle braking in a very controlled and reproducible manner. Recent developments in test methods for brake noise now allow useful comparisons to be made between different friction materials at a significantly lower cost than vehicle testing.

In this noise study, a typical OEM and premium aftermarket semi-metallic disc brake formula that contains 10% by weight steel fiber and 50% by weight iron powder was chosen. Three iron powders, one hydrogen-reduced powder and two carbon-reduced powders, were selected for comparison studies. Table 4 presented the brake pad sample microstructures, iron powder properties and molding physical properties.

Table 4 Iron powder properties and brake molding properties

Brake pad	Sample A	Sample B	Sample C
Microstructure			
Iron powder			
Particle size %+105 $\mu$ m	85.7	71.4	16.4
Surface area m <sup>2</sup> /kg	225	140	130
Apparent density g/cm <sup>3</sup>	1.22	1.65	2.47
Particle density g/cm <sup>3</sup>	6.48	7.61	7.22
Brake moldings			
Mix bulk density g/cm <sup>3</sup>	1.28	1.40	1.52
Specific gravity	3.233	3.281	3.332

The noise testing used for this study was based on the procedure of SAE J2521 (Disc Brake Dynamometer Squeal Noise Matrix). It is a comprehensive test incorporating both drag (constant speed) brake applications as well as normal (deceleration-type) brake applications over a range of speeds, pressures and temperatures. In this test, a modified test sequence was chosen. After break-in and bedding, the standard test matrix was followed by a fade and recovery, and then another test matrix. During the fade section, the brake temperature rises to approximately 600°C. Out of the 979 brake applications in the test, 131 are deceleration-type applications and 848 are drag-type applications.

During each brake application of the dynamometer test, clamp pressure and generated brake torque were measured in order to determine the coefficient of friction of the friction material. When brake noise generated, a noise "spectrum" of the noise intensity (in dB) vs. the noise frequency (in kHz) was recorded with data acquisition software. The surface temperature of the brake rotor and pad were also recorded during each braking application.

Figure 8 presented graphical plots of peak sound pressure level in decibels vs. frequency of the noise peak collected from each. For the brake pad samples with carbon-reduced iron powder, there are a number of significant noises generated at 11.83 kHz. They are within narrow frequency bands as shown by vertical lines of dots on the charts. These frequencies are assumed to be resonant frequencies of the brake system. For the sample with hydrogen-reduced powder, there is no this kind of pattern and most of noise found in low frequency bands with relative low noise levels.

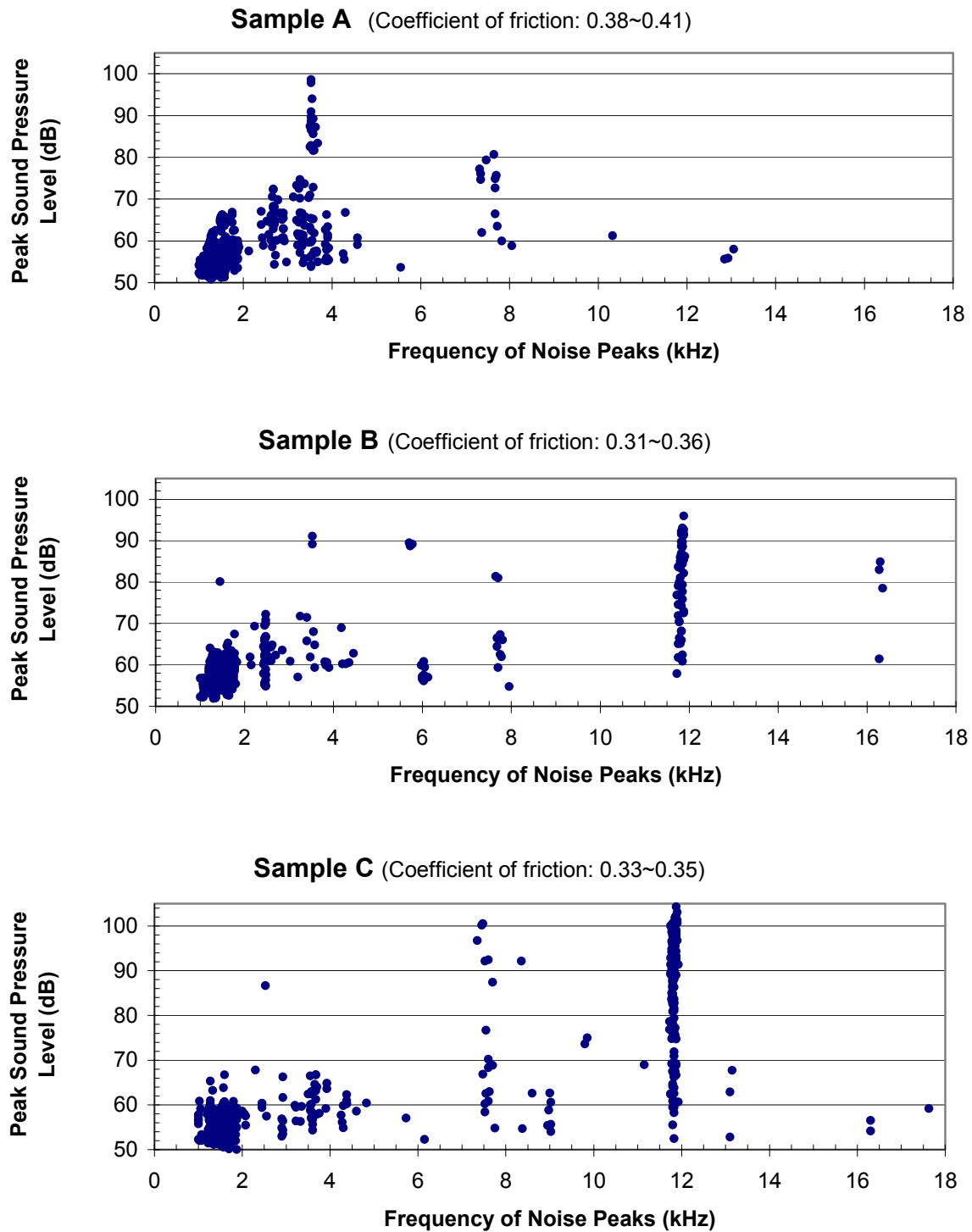


Figure 8 Spectra of noise peaks generated from brake pads  
Sample A): 50%wt coarse hydrogen-reduced powder with low AD  
Sample B): 50%wt coarse carbon-reduced powder with low AD  
Sample C): 50%wt fine carbon-reduced powder with high AD

Figure 9 summarized the difference in noise occurrence at the decibel levels of >65, >75, >85 and >95. We can easily rank the tested friction materials as: the sample A with adding hydrogen-reduced powder (coarse, low AD) is the least noisy, while the sample C with adding carbon-reduced powder (fine, high AD) is the most noisy at all decibel levels. Previous powder characteristics analysis explained why hydrogen-reduced powder could minimize the braking noise, i.e. the extremely high porosity and fine internal pores play the important roles.

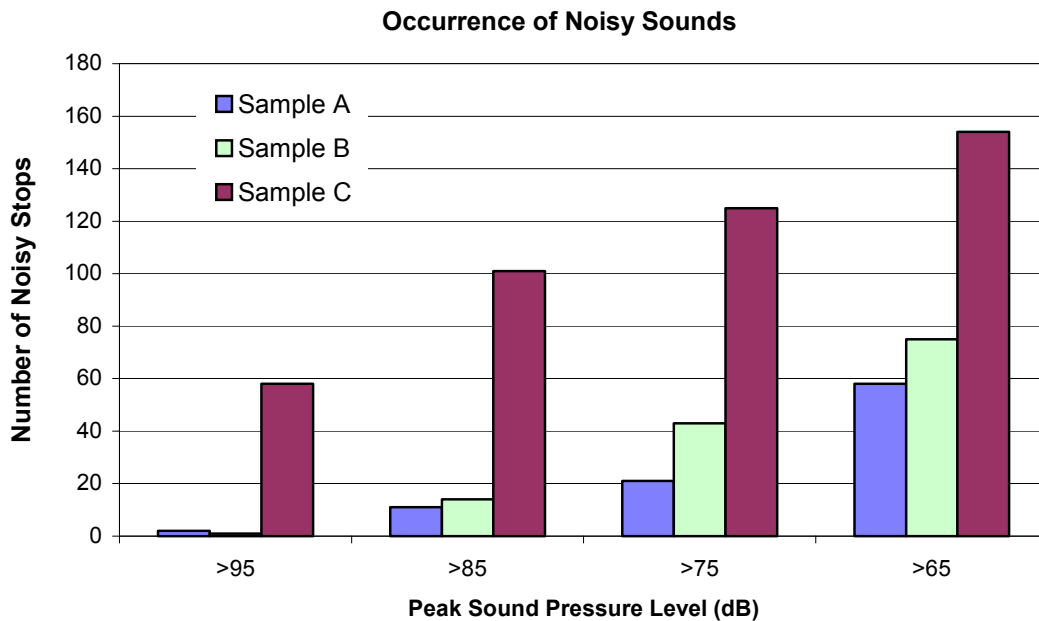


Figure 9 Occurrence of noise sounds at different peak sound pressure levels generated from brake pads

Sample A): 50%wt coarse hydrogen-reduced powder with low AD

Sample B): 50%wt coarse carbon-reduced powder with low AD

Sample C): 50%wt fine carbon-reduced powder with high AD

## SUMMARIES AND CONCLUSIONS

Iron powders are mainly manufactured by mechanical and chemical methods – atomization and hydrogen/carbon reduction.

The iron powders produced by chemical reduction have irregular porous particles, i.e. sponge-like microstructure. This kind of particle morphology not only helps the resin to lock iron powder securely into the resin matrix thereby increasing the strength of the material but also enhances the friction performance.

The density of friction grade iron powder is not necessarily the same as iron due to the presence of internal porosity. The particle density that includes the inside closed pores should be used to calculate the amount of the powder added in the friction formulation. A lower particle density would lead to developing materials utilizing less iron powder on a weight basis and introduce porosity into the friction matrix to produce a lighter friction material and minimize noise.

The particle hardness of iron powders depends on the carbon content and the amount of alloying and is also influenced by the manufacturing process. It could affect friction performance of brake materials and wear of pad and rotor.

Iron powder has different surface area values dependent on the method of manufacture. The powder made by hydrogen reduction has a high surface area, even with a coarser particle size distribution. The iron powder with high surface area bonds well with resin to increase the strength of friction material.

The green strength of iron powder results mainly from mechanical interlocking of irregularities on the particle surfaces. The irregularities of sponge iron powder can increase the strength of friction material and wear resistance at high temperature when the resin bonding deteriorates.

Therefore, the benefits of adding iron powder into friction formulations can be summarized as:

- 1) Modify the brake performance by adjusting the iron powder additions
- 2) Minimize the brake noise since the fine internal pores in iron powder absorb sound well
- 3) Increase thermal conductivity of brake pad as the iron powder usage increases
- 4) Reduce rotor wear because iron is much less abrasive ingredient than steel fiber
- 5) Make brake lighter by creating porosity into the formula matrix
- 6) Reduce production cost because iron powder is less expensive and the porosity introduced by iron powder also reduces the usage of resin

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