Advanced Ferrous Materials

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1. Introduction

Man has been long associated with iron. Evidence shows that iron was used in Egypt and Mesopotamia in 3000 to 4000 B.C. The Old Testament, probably written in about 400 B.C., contains references to iron. Ferrous metals have been indispensable materials for the life of people and will assume ever increasing importance in the future.

I will start my presentation with the history of ferrous metals, touch on the uses of ferrous metals as conventional structural and functional materials, and introduce new ferrous metals as advanced materials.

2. History of Ferrous Metals

Traces are found of iron used by man in Egypt and Mesopotamia in about 3000 to 4000 B.C.

Japan entered the "Iron Age" with the introduction of ironware from mainland China into Kyushu in approximately 300 B.C. The Manyoshu, a collection of verse from the earliest times to the year 760, contains poems on iron and testifies to the antiquity of man's relation with iron.

In the seventeenth century, the "tatara (furnace)" ironmaking process was developed, mainly in the Izumo region west of present Osaka, and reached its climax with the invention of "tenbin" and "fuigo (bellows)", as chronicled in Table 1.

In the middle of the nineteenth century, modern blast furnaces were built in Kamaishi, north of Tokyo, and marked the beginning of the steel industry in Japan. Since then, the Japanese steel industry has made phenomenal progress and now leads the world in ironmaking and steelmaking technology.

Table 1 History of ferrous metals

3000 to 4000 B.C.:
Iron was used in Egypt and Mesopotamia.

400 B.C.:
Use of iron was referred to in the Books of Isaiah and Micah in the Old Testament, as indicated by "they shall beat their swords into plowshares, and their spears into pruning hooks, ...".

300 B.C.:
Ironware was introduced from the mainland of China into Kyushu, Japan.

100 B.C.:
Ironmaking technology emerged in Japan. This can be inferred from a mythical story that the Ameno Murakumono Tsurugi (Rain-making Sword) was found in the dead body of the Yamata no Orochi (Eight-Headed and Eight-Tailed Dragon) slain by the Susanowo no Mikoto (Storm God).

607 A.D.:
Iron nails were used to build the Horyuji, a Buddhist monastery.

759 A.D.:
The Manyoshu was compiled. Of many poems mentioning iron, an example may be cited:
"Muratamano Kuruni kugisashi Katametoshi Imoga kokorowa Ayokunamekamo"

(Would my wife's lonely mind vacillate
In my absence that I locked as securely
As I locked the door hinges thrusting nails
Into the ever freakish pivot sockets?)

14th century
Many charcoal-fueled blast furnaces were built and used in Europe.

1543:
Muskets were brought by the Portuguese to Tanegashima, a small island off the shore of southern Kyushu.

1580:
Oda Nobunaga built an ironclad ship.

1681:
With the invention of "tenbin" and "fuigo (bellows)," the "tatara" ironmaking process reached its climax in the Izumo region.

1735:
A. Darby, Jr. of England established the coke-fired blast furnace process.

1850:
Japan's first reverberatory furnaces were built in Saga, a province in Kyushu.

1853:
A reverberatory furnace was built in Nirayama, Izu, south of present Tokyo.

1855:
H. Bessemer of England invented the pneumatic steelmaking process.

1856:
Work was started on the construction of a blast furnace in Kamaishi, Japan.

1864:
P. Martin of England invented the open-hearth steelmaking process.

1878:
S.G. Thomas of England invented the Thomas converter.

3. Ferrous Metals as Structural Materials (for Towers and Buildings)

3.1 Uses of ferrous metals as structural materials are too numerous to mention. The Eiffel Tower that was built at the site of the World Exposition in Paris in 1889, just 100 years ago, is a famous steel structure.

The 300-meter tall tower was constructed with 7,300 tons of Bessemer steel produced in France. The Tokyo Tower, erected 70 years later, stands at 333 meters and used 4,000 tons of steel, graphically attesting to the improvements that had been made in the strength and toughness of steel in the intervening years.

The Hong Kong Head Office of the Bank of China, scheduled for completion in December of this year, will be 315 meters (70 stories) high and consume 15,700 tons of steel.

The data for the these structures is given in Table 2.

Table 2 Date for the two towers and one building

	Eiffel Tower Paris	Tokyo Tower Tokyo	Hong Kong Head Office Bank of China
Year constructed	1889 Built at site of International Exhibition in Paris (Centennial this year)	1958 (Completed in November 1958)	Scheduled for completion in December 1989
Height	Approx. 315 meters	333 meters	315 meters (70 stories)
Steel consumption	7,300 tons	4,000 tons	15,700 tons
Other	Designer: Alexandre Eiffel Type of steel: Bessemer steel	Designer: Kazunaka Naito	Engineering firm: Robertson, Fowler & Associates, USA

3.2 Bridges

The strength of galvanized steel wires for bridge cables has virtually remained at around 160 kgf/mm^2 for the past half century, as shown in Fig. 1. The Akashi Kaikyo Bridge now under construction is a long suspension bridge with a center span of 1,990 m, 1.4 times as long as that of the Humber Bridge, the world's longest suspension bridge to date. Cable wires of higher strength were essential for the structural stability and economy of the Akashi Kaikyo Bridge and the feasibility of the construction project depended on the development of such steel wires.

Wires with a strength of 180 kgf/mm^2, 20 kgf/mm^2 higher than that of conventional steel wires, were successfully produced from eutectoid steel containing 1% silicon, which is effective in strengthening the wire steel in the heat treatment stage before drawing and then softening the wire steel in the galvanizing stage after drawing. The high-strength galvanized steel wires have helped to allow the bridge roadway to be suspended with a single cable on either side, reduce the height of the towers, decrease the size of the substructure, and have contributed to the realization of the Akashi Kaikyo Bridge project (Fig. 2).

The Messina Bridge with a center span of as much as 3,300 m is being planned in Italy. The development of steel wires with a higher strength of 200 kgf/mm^2 is demanded for this bridge.

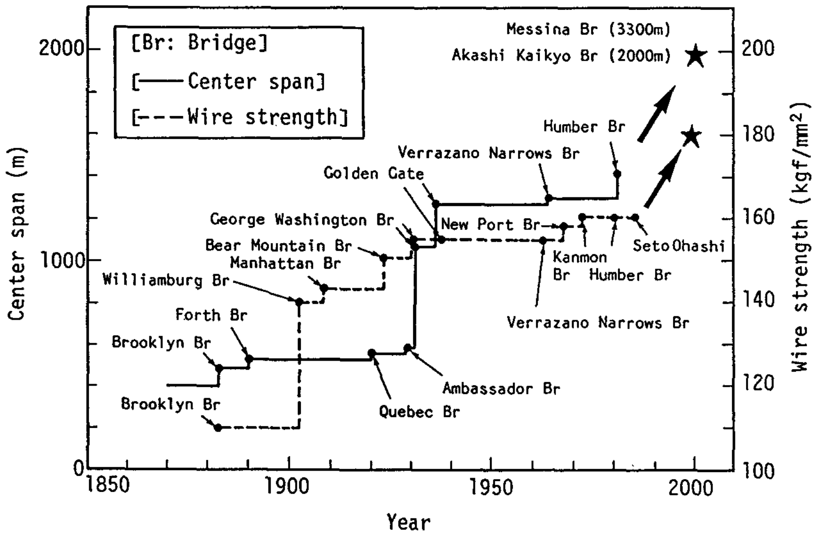


Fig. 1 Changes in center span and wire strength of Akashi Kaikyo Bridge and other suspension bridges.

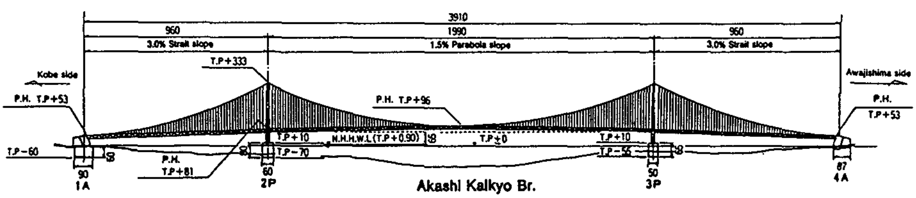


Fig. 2 Side elevation of Akashi Kaikyo Bridge (Source: Honshu-Shikoku Bridge Authority).

3.3 Ultrafine Steel Wires

Steel wires for tire cord fabric have the highest strength of over 300 kgf/mm^2 among the ferrous metals in current use. They have a predominant position as tire reinforcement over competing fibers, such as aramid, glass and carbon fibers, in terms of tire performance, economy, and quality stability.

Research and development have made rapid progress in higher steel cord strength in recent years. Steel cord wires, measuring 150 to 300 μm in diameter and featuring a strength of 340 kgf/mm^2, are on the market. This level of strength is accomplished by the progress of the steelmaking technology that can eliminate inclusions and harmful elements that cause the breakage of ultrafine wires in the drawing and twisting stages. Much effort is also expended now in developing new steel grades and fabrication techniques to produce steel cord wires with a strength of 400 kgf/mm^2.

The construction of a steel-belted radial tire is illustrated in Fig. 3.

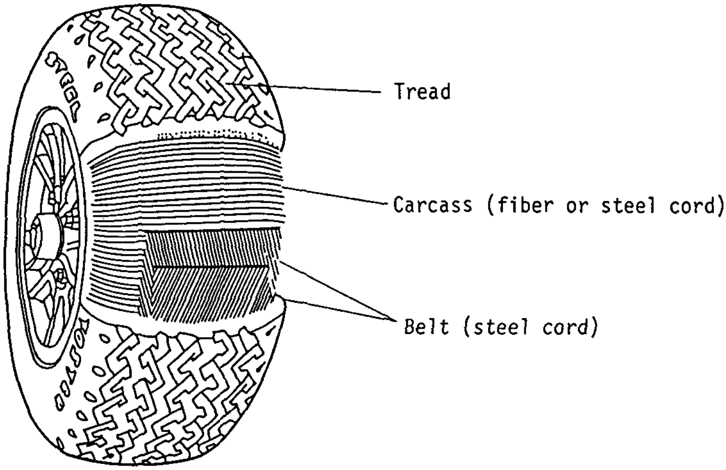


Fig. 3 Construction of a steel-belted radial tire and typical use of steel cord.

Table 3 Properties of ultrafine fibers

Item of comparison	Steel fiber	Kevlar fiber	Glass fiber	Carbon fiber
Diameter (μm)	15-300	12	15	7
Tensile strength (kgf/mm^2)	340-450	300	220	360
Young's modulus (kgf/mm^2)	21,000	13,000	7,000	60,000
Density (g/cm^2)	7.8	1.5	2.5	1.8
Price (1) (¥/kg)	500-5,000	10,000-30,000	1,000-1,500	10,000-20,000
Price (2) (¥/kg)	19-186	112-336	36-55	30

4. Ferrous Metals as Functional Materials

4.1 Silicon Steel

Silicon steel is a representative example of steel used as a functional material.

Silicon-bearing steel has excellent magnetic properties and is employed as electrical steel in many electric appliances.

A new process was developed whereby the irradiation of the silicon steel surface with a laser beam refines the magnetic domains in the steel and sharply reduces the eddy-current loss that accounts for most of the core loss in silicon steel. The (C) process provides a core loss reduction of about 10% as compared with the best grade of grain-oriented silicon steel, as shown in Fig. 4.

Another domain-refining process that imparts heat resistance to silicon steel has also been developed (D).

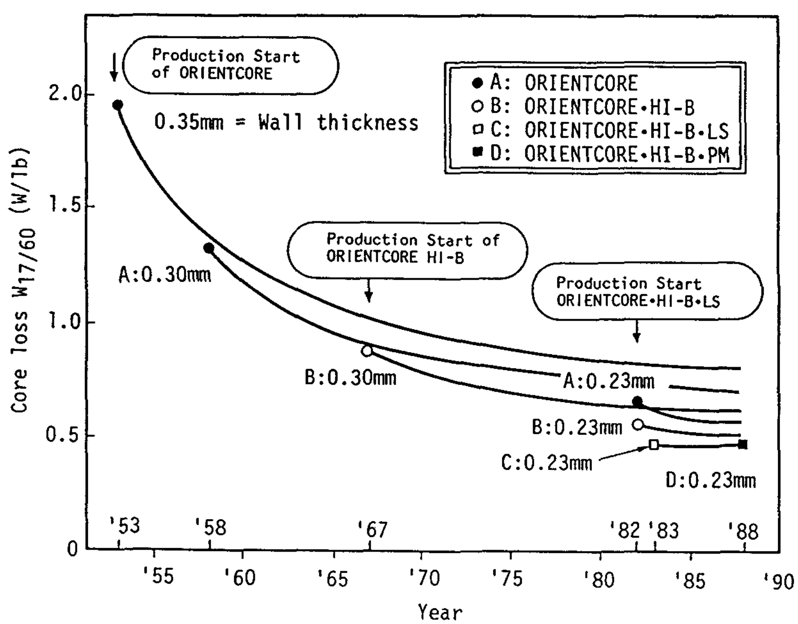


Fig. 4 Change in core loss of grain-oriented silicon steels in Japan.

5. Topics for Steel as an Advanced Material

5.1 Bake-Hardenable Steel Sheet

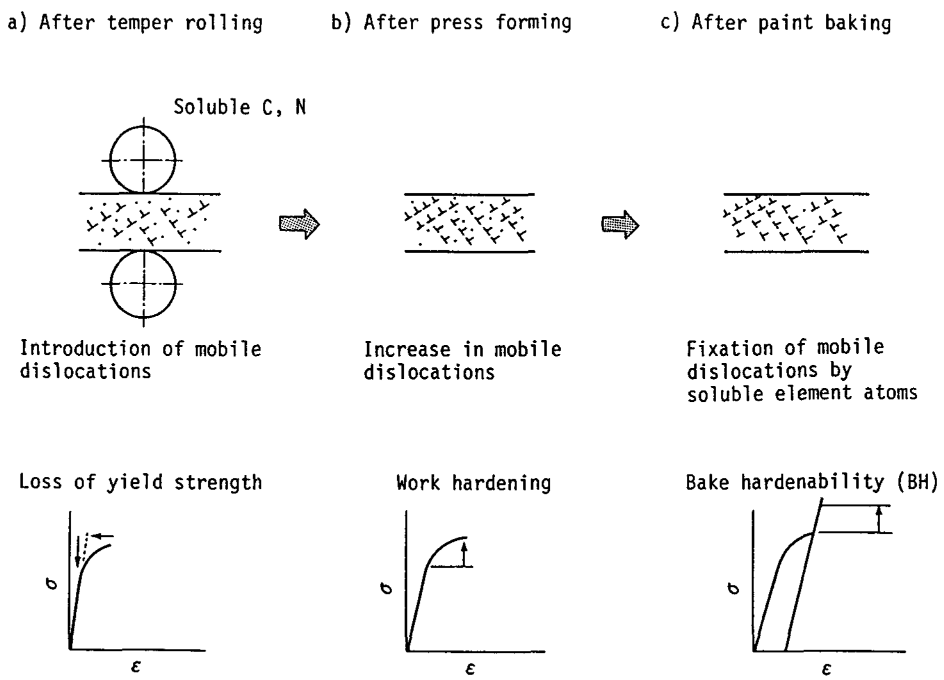
The first oil crisis of 1973 challenged the automobile industry to conserve materials and energy, and made it a most urgent issue to develop automobiles with greater fuel economy. Auto body weight reduction was devised as one measure for improving fuel economy and high-strength steel sheet was applied for this purpose.

One advantage of high-strength steel sheet is section thickness reduction (weight reduction). Production problems had to be solved to assure good press formability as well as high stretch stiffness, dent resistance, and impact strength.

After the solution of these problems, such bake-hardenable steel sheet was developed that has a tensile strength of approximately 40 kgf/mm^2 before press forming and provided a tensile strength of 60 kgf/mm^2 in the baking step after press forming. The basic concept of imparting bake hardenability is illustrated in Fig. 5.

The bake-hardenable steel sheet satisfied the demand of customers and has been extensively adopted since 1980.

High-strength steel sheet with a high retained austenite content and high-strength steel sheet of the copper solid solution type have been also developed.



According to Fig. 5

a) Temper rolling introduces slight mobile dislocations and decreases yield strength.

b) Press forming introduces more mobile dislocations and causes the work hardening phenomenon to appear.

c) Paint baking helps soluble atoms to fix the mobile dislocations and provide a higher yield strength. This is called bake hardenability (BH).

Fig. 5 Basic concept of bake hardenability development.

5.2 Galvanized Steel Sheet for Automobiles

Highways are sprayed with large amounts of deicing rock salt in the cold regions of North America and North Europe. In this environment, automobiles are severely corroded and annually, increasing corrosion resistance has been required for coated steel sheet for automobiles.

Five and ten years of guarantee against surface corrosion and perforation, respectively, are the worldwide goals at present. These corrosion protection goals can be easily met by use of steel sheet coated with large amounts of zinc. Heavy zinc coatings, however, cause problems with press forming, welding, and painting.

Nippon Steel developed the new coated steel sheet "Excelite" jointly with an automaker. Excelite is a steel sheet electroplated with a zinc-iron alloy of higher corrosion resistance than pure zinc. It consists of an iron-rich upper layer and a zinc-rich lower layer as illustrated in Fig. 6. The two layers supplement each other in corrosion resistance and paintability as shown in Fig. 7. Thanks to its superior overall performance, Excelite is used in large quantities and is highly rated by customers.

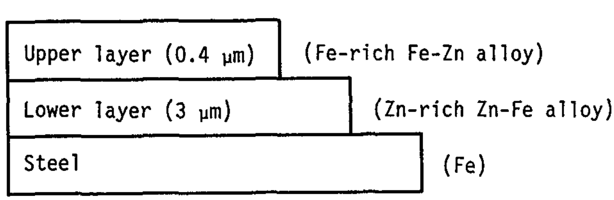


Fig. 6 Coating construction of Excelite.

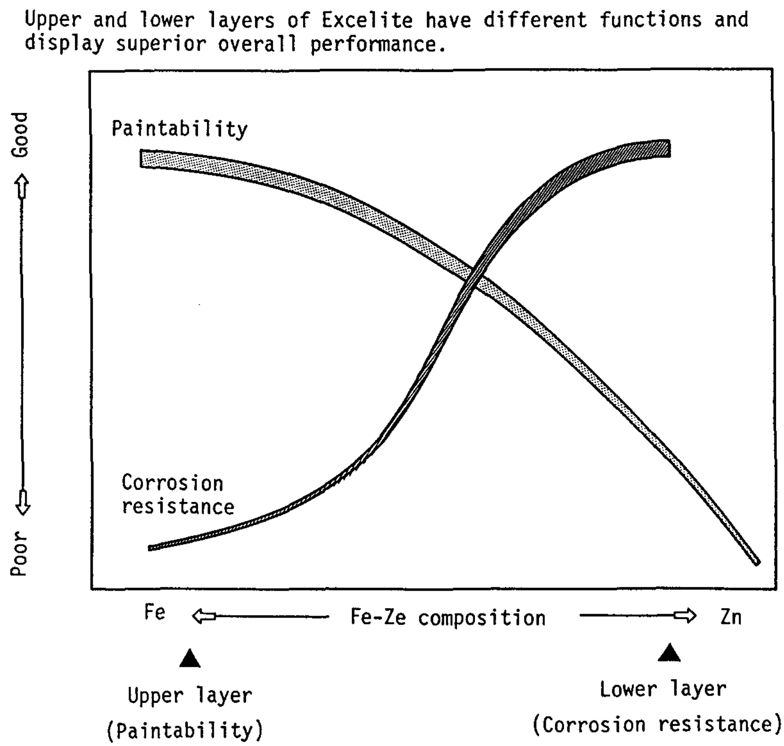


Fig. 7 Functions of Excelite surface layers.

5.3 Vibration-Damping Steel Sheet

Vibration-damping steel sheet is a plastic-steel composite of sandwish construction that has a viscoelastic resin layer of 40 to 80 m thickness enclosed between two steel sheets (Fig. 8). This material is characterized by a large vibration energy absorbing capability or an extremely large loss factor.

When the vibration-damping steel sheet is subjected to vibration, the resin layer undergoes shear deformation (slip deformation) and converts deformation energy into thermal energy. Vibration and noise are thereby abated.

The loss factors of different metals are shown in Fig. 9. Metallic materials generally have a low loss factor and are likely to vibrate and produce noise.

In recent years, noise control has come to be considered as an important social issue, as well as a critical economical issue, because low noise enhances the commercial value of machines and structures.

Vibration-damping steel sheet is used in various industries, including automobiles, electric appliances, building materials, and industrial machinery, and is finding increasing use in many applications.

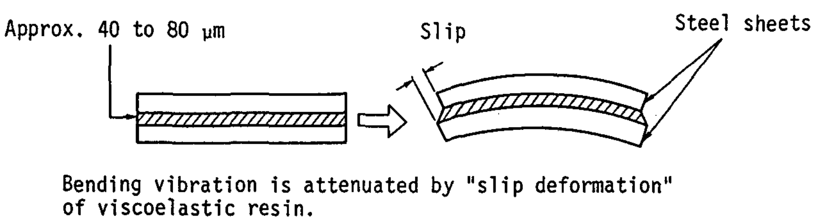


Fig. 8 Construction of vibration-damping steel sheet.

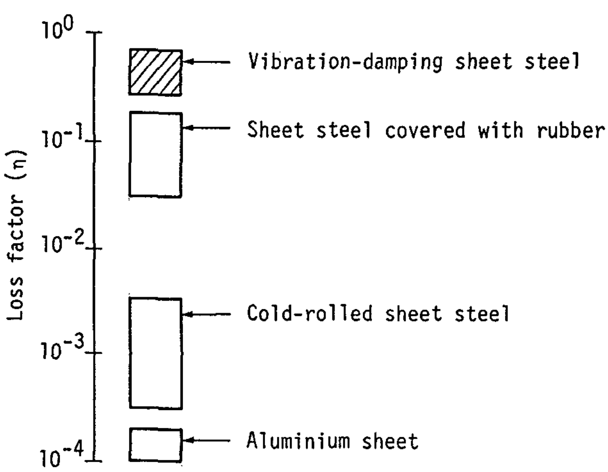


Fig. 9 Loss factor of various metallic materials at room temperature.

5.4 Metallic Supports for Catalytic Converters

Ceramic honeycombs have been used in catalytic converters for automotive emission control.

Attempts had long been made to use metal support of heat resistant stainless steel, but they did not succeed mainly because of insufficient heat resistance of the steel foil.

Recent progress of material engineering has made it possible to stainless steel foils of higher heat resistance, and some European automobile models reportedly have actually started using this type of catalytic converters.

The steel foil is made from 20Cr-5Al heat-resistant stainless microalloyed with rare-earth elements.

In the hot exhaust gas of the automobile, the aluminum in the foil is selectively oxidized to create an aluminum oxide film which improves oxidation resistance. Furthermore this aluminum oxide film contributes to the better adhesion between the γ-alumina washcoat pregnated with platinum catalyst and the metal support.

The wall thickness of ceramic honeycomb is 120 - 200 μm, while it is only 50 μm for a metal support which offers a higher open cross section, resulting in lower exhaust gas back-pressure. The metal support does not need a knitted mesh cushion of expensive heat resistant alloys, as is necessary for the ceramic honeycomb, and it can also be used at higher temperatures, enabling the engine output increase.

Thus the metal support is anxiously awaited by automakers as a promising part that meets the recent trend towards higher engine output.

6. Conclusions

The history of ferrous metals has now been reviewed. It is known that man has used tools made of ferrous metals since ancient times.

The blast furnace ironmaking process was invented in the fourteenth century and the pneumatic steelmaking process was invented by Henry Bessemer in the middle of the nineteenth century. The two processes helped to establish the modern ironmaking and steelmaking processes and usher in the "Industrial Age."

History tells us that ferrous metals have made immeasurable contributions to the advancement of modern civilization.

To meet rapid changes in the conditions surrounding the more recent steel industry, iron and steel engineers have been opening up a "New Age of Steel" as an advanced functional material by making the most of refining, material engineering, and other related technologies.

Ferrous metals are expected to provide high economy with high functionality when combined with other materials and to play a more important role as advanced materials to support future technological innovations.

Materials other than ferrous metals are presently being developed as advanced materials. With the recognition, however, that ferrous metals belong to the family of advanced materials, we intend to continue our effort to develop better ferrous metals.