# MATERIALS

## 1 Introduction

Ever since automobiles were invented, materials have played a crucial role in the history of automotive development. Automobiles are increasingly expected to exhibit environmental friendliness through measures such as massive reductions in the amount of $CO_2$, as well as to conform with stricter regulations concerning collision safety and other issues. Solutions to these issues will require a further evolution of automobile materials. In addition to improving the material properties, it is necessary to reduce the amount of $CO_2$ emitted during manufacturing and reduce the environmental burden at the time of disposal, as well as to address the risk associated with scarce resources. This situation is leading to the vigorous pursuit of technological development in all areas of materials, including steel, light metals, and nonmetallic materials, from which automobiles are built. The following sections introduce the technological trends in automotive materials in 2017.

## 2 Ferrous Materials

### 2. 1. Steel Sheets

In Europe, the U.S., and Japan, there has been a definite transition away from steel sheet material toward multi-materialization, which includes low specific gravity materials such as aluminum and carbon fiber reinforced plastics (CFRP), for premium vehicles(1). However, for the mass production models that make up the majority of the automobile market, steel sheets, which offer excellent cost performance and represent a mature technology solution, have remained the main material of choice for most automobiles. In addition, the rapid shift toward electrification has been raising expectations for ferrous materials as magnetic materials even further.

#### 2. 1. 1. Parts for the Vehicle Frame

Technologies to greatly increase the strength of the material used for these parts are being developed to both reduce vehicle weight and enhance collision safety performance. The main technologies involved are cold-formed high-tensile strength steel sheets (high-tensile steel) and hot stamping. High-tensile steel in the 980 to 1,180 MPa class has been developed and used for the members that ensure the interior cabin space is protected because they do not deform easily in the event of a collision. In recent years, a 980 MPa class high-tensile steel featuring both ductility and localized bendability was developed, and efforts are being made to apply it to a greater number of locations, as illustrated by its use in collision energy absorbing members to which applying high-tensile steel was previously difficult.(2). In addition, the evolution in automotive materials has been paralleled by improvements in stamping technology, the development of new methods of spot welding(3), and advances in CAE and other predictive technologies(4). Furthermore, a NEDO project to develop innovative steel sheets that possess both a tensile strength of 1,500 MPa and an elongation of 20% is expected to result in even greater use of high-tensile steel in the future(5). At the same time, the increasing globalization of ultra-high-tensile strength steel production is providing a boost to the wider adoption of this material.

Hot stamping involves simultaneously performing molding and quenching within the die during the stamping process, providing not only improvements in the material, but also bringing about advances in the development of hot stamping molding techniques and methods to increase productivity, achieving a further strengthening the steel from 1,470 MPa to 1,800 MPa. Hot stamping is being combined with both tailor welded blanks (TWB), in which sheets of steel of different thicknesses and strengths are joined before forming, or with the tailor rolled blanks (TRB) method, which applies a continuous thickness transition in the rolling direction. Technologies that control the temperature during cooling in the die or rely on lasers to provide different levels of strength in different portions of the sheet are being developed in anticipation of their applicability to B-pillars[6].

Exceeding 1,000 MPa generally makes high-tensile steel liable to delayed fracture, leading to calls to establish a delayed fracture evaluation method to further expand the applicability of this material[7].

### 2. 1. 2. Outer Panels

Outer panel components must have high formability and excellent surface quality to realize beautiful and distinctive styling, leading to the widespread use of ultra-low carbon steel because it possesses this required high formability. Given their large surface areas, the thinner the outer panels can be made, the more their weight can be reduced, and therefore made from bake-hardened type high-strength steel, which increases yield strength through a paint baking process, to make the panels lighter while maintaining their formability and performance.

Steel materials with a strength in the 440 MPa class or higher are also increasingly used for roof panels and door outer panels, among others, due to demand for even further weight reduction.

Side outer panels are now also being employed to function as vehicle frame parts, so TWB technology is being used to realize steel materials in the 590 MPa class and 780 MPa class that can be adopted for some portions of these panels. This has allowed manufacturers to reduce the number of reinforcement parts required to secure the cabin space and also reduced the weight[8]. In addition, ultra-high-tensile steel in the 1,180 MPa class has begun to be used on mini-vehicles as well[9].

### 2. 1. 3. Chassis Parts

As critical safety parts that ensure proper vehicle functions, chassis parts must be highly reliable in terms of strength, durability, corrosion resistance, and other requirements. Consequently, ultra-high-tensile strength steel is not used for these parts as extensively as it is for vehicle frame parts, but 590 and 780 MPa class steel is increasingly used in parts such as lower suspension arms.

High-tensile steel specifically suited for use in chassis parts is being developed in response to the need for various characteristics, such as stretch flange capability and hole expansion properties. In addition, there have been advances in the development of new molding technologies, such as the use of continuous flange forming to achieve more rigid cross members, aimed at improving vehicle performance[9].

### 2. 1. 4. Motor Parts

The electrical steel sheets widely used as the core material in the electric motors that provide the drive power in electric and hybrid vehicles are required to have high magnetic flux density and low iron loss. Besides their magnetic properties and excellent stamping and punching workability, these steel sheets must also have a high level of strength because of the large centrifugal forces that act on the rotor during high speed rotation. Development aimed at improving performance by adjusting the amount of added alloy or controlling texture is being carried out to satisfy these diverse demands.

At the same time, the goal of further reducing iron loss is drawing attention to nanocrystalline soft magnetic materials, and a magnetic property measurement method applicable under stress is being researched to address the problem of increased iron loss caused by the residual stress and strain introduced during iron core processing[10].

### 2. 2. Structural Steel

Structural steel is a material characterized by its ability to obtain the required strength not only via the raw base material, but also through processing processes such as forging and heat treatments or surface hardening treatments. This material is often used in high-strength parts, such as powertrain and underbody parts. Until now, steel materials have been designed using comparatively expensive added elements, such as molybdenum and vanadium, but cost reduction and material procurement concerns are promoting the development of materials with fewer types and lower quantities of added elements.

### 2. 2. 1. Engine Parts

In crankshafts and connecting rods, which are primary engine component parts, vanadium is added to carbon steel, and non-heat treated steel that causes vanadium carbide precipitation is generally used in an effort to reduce heat treatment costs and the amount of energy consumption.

The high fatigue strength requirement of the fillet portions of the crankshaft has been met by applying compressive residual stress via a surface rolling process to increase bending fatigue strength. More recently, partial induction hardening has made it possible to improve the fatigue strength even when using standard materials. Furthermore, steel with a higher manganese content is used in cases involving a gas soft nitriding treatment without adding the molybdenum rare metal. This achieves fatigue strength equivalent to that of conventional high-strength material while contributing to a reduction in cost. In addition, issues such as cracking during straightening can be mitigated[11].

The weight of the connecting rods is being reduced to decrease inertial force. New forging technologies capable of imparting different levels of strength within the same part that make it possible to ensure the strength and workability at the required locations have been developed and put into practical use[12]. Furthermore, a high-strength steel with good machinability for connecting rods has been developed by optimizing the structure and component elements[13].

#### 2. 2. 2. Drivetrain Parts

For gears, a primary component part, carburized gears, which have the required dedendum fatigue strength, impact strength, and resistance to pitting, are generally used.

Although forming these gears via cold forging and raising the carburizing temperature thereafter has been favored to streamline the manufacturing process and reduce costs, this approach is prone to abnormal austenite grain growth. To address this issue, the component elements that suppress abnormal grain growth were adjusted, and a material that achieves the same level of required strength was developed by replacing the expensive additive elements conventionally used to give the gears high strength with other general-purpose elements[14].

A different approach focused on using a nitriding technique that has a lower processing temperature and causes less strain than carburizing to develop a nitrided steel for gears[15] with strength characteristics equivalent to those obtained from the carburizing treatment.

#### 2. 2. 3. Chassis System Parts

Spring and bolt wire rods are used for springs and bolts.

The active addition of alloying elements has been the main means of increasing strength. However, medium carbon steel wire rod with improved formability due to isothermal transformation[16] and non-refined wire material that allows a simpler heat treatment process by suppressing dynamic strain aging[17] have both been developed from the standpoints of cost reduction and ease of material procurement. In addition, a non-phosphorylation technology for lubrication coatings[18] has also been developed to improve the delayed fracture characteristic that become a concern with high-strength materials.

### 2. 3. Stainless Steel

Stainless steel is steel with a carbon content of 1.2% or less and a chromium content of 10.5% or more. It is most often used in exhaust manifolds, mufflers, exhaust gas recirculation (EGR) related parts or other exhaust system parts due to its excellent heat and corrosion resistance properties.

Based on metallurgical structure, stainless steel is classified into the five categories of ferritic, martensitic, austenitic, duplex (50% ferritic and 50% austenitic), and precipitation hardening, with the first two categories most commonly used in automobiles. The main elements added to stainless steel are chromium, nickel, and molybdenum, which are all designated as rare metals and prone to price fluctuations, leading to ongoing efforts to find of reducing the quantities of those elements.

Due to its lower thermal expansion coefficient than austenitic stainless steel, and excellent thermal fatigue strength, ferritic stainless steel is widely used in exhaust system parts because it does not contain nickel and is therefore relatively inexpensive compared to other stainless steels. Currently, the main type of steel used is the SUS 429 series which is strengthened by adding niobium. When a higher level of heat resistance is required, the SUS 444 series, which contains molybdenum, is applied. However, both niobium and molybdenum are rare metals, making it necessary to reduce their use and find alternatives. Consequently, a type of steel that contains no niobium was developed as an alternative for SUS 429 by substituting copper as the additive. With respect to SUS 444, a new type of steel containing far less molybdenum was developed by adding niobium and copper, and a completely molybdenum-free type of stainless steel was also developed by adding a combination of niobium, copper, and aluminum[19][20].

### 2. 4. Cast Iron Materials

Castings are widely used for engine and chassis parts because they can be easily shaped into a variety of forms, have excellent strength, wear resistance, vibration damping properties, and workability, and are also inexpensive.

Castings are used for sliding parts in the engine, such as camshafts and cylinder liners, heat-resistant parts, such as exhaust manifolds and turbocharger housings, and also for chassis parts, such as knuckles, brake rotors, and arms. Engines are increasingly being downsized in an effort to reduce $CO_2$ emissions, which has resulted in higher exhaust gas temperatures and intensified the demand to further increase the heat resistance of exhaust system parts. To address this issue, austenitic heat-resistant cast steel is being commercialized, and research into ferritic heat-resistant cast steel is also being carried out[21][22].

### 2.5. Ferrous Sintered Materials

Sintered materials are obtained by pouring the raw material in powdered form into a mold in the shape of the desired part, compacting it, and then sintering it. This results in a product that is in its final or almost final shape and therefore has excellent material yield, and also reduces the labor required during the machining process. In addition, these materials offer a great deal of freedom in terms of formulating different compositions of alloys, which makes it possible to obtain a variety of characteristics. These features are leveraged to manufacture mechanical structural parts such as connecting rods, clutch hubs, and sprockets, as well as wear resistant parts, such as valve seats and various bearings. Magnetic materials are another product manufactured through sintering. Neodymium magnets are a widely used magnetic material in electric motors that provide drive power in electric and hybrid-electric vehicles. Although heavy rare earth elements such as dysprosium, are added to this material to improve heat resistance, their rarity and highly uneven geographic distribution are stimulating the development of alternative technologies. The improved heat resistance obtained by reducing the size of the main phase crystal grains is drawing attention to a hot forming method that achieves better crystal growth suppression than conventional sintering, and has led to the development of a manufacturing technique that lowers the processing temperature, while also optimizing processing speed and the selection of component elements. Consequently, the size of the main phase crystal grains was reduced to several hundred nanometers, which is less than one tenth of their previous size, and magnets containing no heavy rare earth elements and usable in drive motors have been commercialized[23].

## 3 Nonferrous Metals

### 3.1. Aluminum Alloys

Aluminum materials are replacing steel materials in a large variety of automobile parts to reduce vehicle weight. Reasons for this include the ability to use aluminum in a larger array of forming and machining processes, such as rolling, forging, extrusion, and various casting methods, than other nonferrous materials, which makes it a viable candidate for use in a wide range of parts, as well as the availability of a stable supply of the raw material. The formation of a passive film on the surface also gives it the advantage of having excellent corrosion resistance. With the demand to further reduce weight intensifying year after year, the quantity of aluminum per vehicle will continue to increase[24].

The increasing use of multi-materials in which aluminum is combined with steel materials and CFRPs or other plastic materials, has also spurred the evolution of peripheral technologies such as methods to join dissimilar materials and technologies to prevent electrolytic corrosion.

There has also been an increase in the number of cases where thin, large-sized casting parts manufactured via high pressure die casting (HPDC), such as rear side frames, have been applied to vehicle frame parts and chassis parts[25][26]. This technology has made it possible to reduce costs via part consolidation and also made the design of highly space efficient and high rigidity parts possible via the application of rib structures and hollowing.

Even as the strength of these automotive materials is being increased, component design and processing technologies addressing the contradictory demands of good formability and maintaining material toughness are being developed. Furthermore, structural designs for parts and application methods that take stress corrosion cracking (SCC) into consideration are also being examined.

The superior recyclability of aluminum and advances in recycling technology is making it possible to complement the conventional approach of using the recycled mass to form secondary aluminum alloys, with the recycling of aluminum into a product of the same grade that maintains the same level of material performance.

### 3.2. Magnesium Alloys

Magnesium alloys have the highest specific strength and specific rigidity among practical metal materials, making them promising lightweight structural materials for automobiles. However, issues such as poor corrosion and heat resistance, inferior plastic formability, and high material cost have limited their use in comparison to aluminum alloys.

The automotive parts that involving the practical use of magnesium alloys are mainly die cast or other cast parts such as steering wheel cores, cylinder blocks, cylinder head covers, and oil pans. Magnesium alloy sheets have been formed into vehicle hoods and roofs using superplastic forming (SPF), but so far these applications are limited.

To overcome these problems, industry, academia, and the government are collaborating on the development of alloys with excellent heat resistance for die casting[27] and alloys with greatly improved formability for plastic working[28].

## 4 Nonmetallic Materials

### 4. 1. Ceramics

The ceramic materials used in automobile parts are divided into structural ceramics, electroceramics, and coatings, depending on the characteristics and applications of the material.

The main structural ceramic materials are silicon nitride, used in parts such as the turbine rotors in turbochargers and the tips of rocker arms due to its excellent abrasion resistance, heat resistance, and corrosion resistance, cordierite, used for the carrier of the exhaust gas purification catalyst due to its excellent resistance to elevated temperatures and thermal shock resistance, and silicon carbide, used for fine particulate filters due to its excellent heat resistance.

Among electroceramics, zirconia is used for oxygen sensors and NOx sensors, alumina is used for spark plugs, silicon nitride is used for glow plugs, and lead zirconate titanate (PZT) is used for knock sensors and fuel injection actuators. In addition, research and development of all solid-state ceramic batteries has attracted attention recently for its potential to realize high capacity, high output secondary batteries[29].

In terms of ceramic coatings, chromium nitride and diamond-like carbon are used for parts such as piston rings, valve lifters, and piston pins to improve wear resistance and reduce friction in engine parts[30]. Furthermore, a technique for forming a silica-reinforced, porous anodic oxide film on the upper portion of the piston, aimed at improving the thermal efficiency of the engine, has also been developed[31].

### 4. 2. Plastics

Plastic materials are being used more and more in automobiles due to their low specific gravity and the ease with which they can be formed into nearly any shape. Increasing sophisticated and complex performance, including higher quality external appearance, better recyclability in the context of environmental preservation, and the use of natural raw materials are being imposed on plastic in addition to improvements in physical properties. Consequently, mixed composite plastics, increased performance through foaming, and even composite materials that use carbon fibers are being developed and commercialized at an accelerated pace.

#### 4. 2. 1. Exterior Parts

Polypropylene (PP) is a plastic material with low specific gravity and excellent cost performance that has been widely adopted for exterior automobile parts such as bumpers. Talc and other fillers are mixed into it to improve rigidity and heat resistance, and reformulation, such as the addition of elastomer, is often carried out to improve impact resistance. However, the use of plastic with a high talc content to realize a bumper material that is thin, lightweight, has high rigidity, and is easy to produce in mass quantities is coming to an end as foam molding is expected to take over as the main means of achieving weight reduction. The major issue of appearance defects caused by the rupture of bubbles had meant foam molding was almost never used for exterior plastic parts requiring a high-quality external appearance, but vehicles featuring side sill protectors and over fenders manufactured via foam molding went on sale in 2017[32]. CFRP, which is used on large airliners and expected to spread to automobiles, has not been used on vehicles with large production volumes due to economic factors, but it has been adopted as the back door frame material for some vehicles a relatively high production volume[33]. At the same time, bioplastics made from natural materials are being employed for the pillar garnish and others parts[34], and environmental concerns are expected to gradually expand the use of natural materials.

#### 4. 2. 2. Interior Parts

Interior materials must both provide comfort and high quality textures within the vehicle interior, and contribute to weight reduction. The same high quality textures now also tend to be expected in compact cars as well, spurring the vigorous development of technologies to improve texture quality at a low cost, such as material coloring technologies that produce vibrant colors and surface materials that possess a luxurious feel. The use of decorative flourishes, such as simulated stitching (seams), on surface materials is also increasing. This includes a method of transferring the sewing line and the shape of the thread to the material using a die, and a method that sews in real threads after transferring only the sewing line[35]. In addition, the development of these materials must solve issues such as scratch resistance, wear resistance, and stain resistance to maintain the quality of the texture over the long term.

On a different note, weight reduction initiatives include the development of materials suitable for foam injection molding, which allows them to have a lower specific gravity, as well as of not only high-rigidity materials that can be made thinner, but also seat cushions that require less urethane thanks to the use of a foam resin core material and are designed to be lighter[36].

#### 4. 2. 3. Engine Parts

Polyamide (PA) is a plastic material that offers excellent heat resistance and has therefore been used for parts such as the intake manifold and the radiator tank. Parts such as radiator supports and air cleaner housings increasingly use PP materials to address the issues of weight and cost reduction. At the same time, the next-generation of polyamide plastics with high levels of heat resistance is being developed to replace heat-resistant crystalline plastics, such as aromatic nylon and polyphenylene sulfide (PPS) that are representative of super engineering plastics. Furthermore, highly functional polyamide plastics endowed with heat dissipation properties and high luminance[37] are also being developed. Such new plastics are expected to eventually be used in engine parts and elsewhere.

### 4. 3. Rubber

The unique viscoelastic properties of rubber materials make them irreplaceable for functional parts, which include tires and hoses, vibration-absorbing rubber in parts such as engine mounts and bushings, and seals in such as weatherstrips, O-rings, and gaskets.

For tires, advances have been made in technology to achieve both good fuel efficiency and wet grip performance. In particular, improved silica dispersion is being approached from two different angles, one involving the addition of a dispersant, and the other involving modifying the rubber raw material itself[38].

Materials with excellent high-temperature durability, such as ethylene propylene diene rubber (EPDM), acrylic rubber (ACM), and fluorocarbon rubber (FKM) are now used for rubber hoses to cope with the increasingly severe thermal environment resulting from the downsizing of engine compartments.

Vibration-absorbing rubber often requires anisotropic vibration damping characteristics in the vertical and horizontal directions. Consequently, a multi material molding technique was developed to combine materials that have different vibration damping characteristics.

Rubber for weatherstrips must maintain elasticity and flexibility at low temperatures. EPDM material with suppressed crystallization has been developed by modifying its molecular structure[39].

### 4. 4. Glass

The transparency of automotive glass has been leveraged to bring it in broad use in all vehicle windows, and is increasingly being given ultraviolet and infrared light blocking functions, as well as a sound insulation function. In addition, the use of special glass that allows text or maps to be displayed on the entire windshield to improve safety and interface with the growing use of IT in the vehicle interior is also becoming more common[40]. This glass is also being used to decorate the vehicle interior and act as an on-board display for styling and other purposes[41]. At the same time, using organic glass to achieve weight reduction is becoming more common. Polycarbonate (PC) is typically used as a plastic glass material due to its transparency and impact resistance. A hard coating technology has been developed for this PC glass to improve its weather and wear resistance when it is used for windows with large curved surfaces[42]. In the future, automotive glass materials are expected to include new functions, such as heat insulation, anti-fogging, and dimming, to create an even more comfortable vehicle interior.

### 4. 5. Paint

Reflecting the growing diversity in consumer preferences, the number of available high brightness and two-tone color options continues to increase. The development of new color ranges including orange[44] is providing high brightness color choices other than the conventional high brightness reds[43]. In addition, two-tone color schemes for the roof and body are making their way to additional models such as light-duty SUVs and minivans.

In the wake of ongoing efforts to reduce $CO_2$ emissions from plants, a shorter painting process resulting from the elimination of the intermediate coating step is gradually becoming standard[45]. Furthermore, various simulation technologies are being developed and applied to the painting process, including the use of fluid simulation and scale modeling to validate the development of a highly efficient paint dust collection system that significantly reduced energy consumption during the painting process[46].

In the field of rust prevention, focusing on the electrochemical behavior of corrosion led to a proposed method of evaluating corrosion resistance in a short time which has begun to be applied to the corrosion resistance quality development of mass production parts[47]. As corrosion resistance quality becomes even more important with the growing adoption of multi-material vehicle bodies, this method is expected to evolve into an efficient corrosion resistance evaluation technology that can replace the conventional tests involving actual rust.

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