Materials

1 Introduction

Since the financial crisis that occurred in the wake of the collapse of the Lehman Brothers financial services firm in 2008, the extreme appreciation of the yen has been corrected, the revenues of the Japanese export industry, including vehicles, have improved, and the Japanese economy as a whole has continued to make a gradual recovery. Automotive materials are still the key element for ensuring basic vehicle quality. To reduce the cost of these materials, the local procurement of materials has greatly expanded, especially in emerging markets, and automakers have reduced the use of scarce resources. Furthermore, manufacturers are actively pursuing technological developments, such as reducing body weights, making engines and transmissions more fuel efficient, and the electrification of the powertrain, in an effort to reduce CO_2 emissions. This article explains the technological trends in automotive materials in 2014.

2 Ferrous Materials

2. 1. Steel sheets

Changes in society's perceptions have created demands for lighter and safer vehicles. In recent years the technological development of alternative lightweight materials to replace steel sheets has been advancing. However, steel sheets remain the main automotive material and account for approximately 40% of the entire vehicle weight due to good cost performance and a comprehensive production base. Consequently, the technological development of steel sheets is being widely promoted to meet customer requirements. The uses of steel sheets can be broadly classified as follows: (1) parts for the vehicle frame, (2) outer panels, (3) chassis and drivetrain parts, and (4) motor parts.

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 (i.e., to absorb energy and secure cabin space after a collision occurs). The main technologies are high-strength steel sheets for cold and hot stamping.

The first high-strength steel sheets for cold stamping that were developed and applied were in the 590 MPa class. Since then, even higher strength steel sheets in the 980 MPa and 1,180 MPa classes have also been developed. These materials have been increasingly adopted to reinforce side members, center pillars, and roof side members. In recent years, as the strength of these materials continued to increase, it has also become necessary to ensure formability. This led to the development and partial adoption of ultra-high-strength 1,180 MPa class steel sheets with ductility at least equal to that of 980 MPa class high-strength steel sheets (1)(2). Another development is 980 MPa class high-strength steel sheets and 1,470 MPa class ultra-high-strength steel sheets with almost the same formability as 590 MPa class steel sheets (3). In the future it is expected that the number and application of even stronger steel sheet materials will only continue to expand.

In contrast, the use of hot stamping has allowed for high-strength steel members in the 1,470 MPa class to be produced. In this case, it is necessary for the metal to be formed while it is extremely hot and then quenched through contact with the die. Post-processing of the material via laser cutting is also necessary. Concerns about the low productivity of this material have been addressed by the development of a direct cooling method that passes cooling water between the surface of the die and the sheet and also a hot shearing method (4). The development of these methods has allowed this material to be adopted in a growing number of applications (5). A method of hot stamping steel sheets with different strengths that have been formed into a tailored blank has also been put into practical use. This method is increasingly being employed for center pillar reinforcement and door rings. In addition, the hot stamping of high-strength 1,800 MPa class steel sheets to form bumper beams has also been adopted, indicating a growing trend of using hot stamping to form high-strength steel into parts for the vehicle frame.

In addition, high-frequency induction hardening technology has been developed for three-dimensional hot bending of 1,470 MPa class steel pipes (6). This material has been adopted for cross member frames. Technologies such as this, which do not require a die, will likely become noteworthy trends in the near future.

2. 1. 2. Outer panels

To create an appealing vehicle design, outer panel parts must have stylish shapes and the forming process for those complex shapes is very difficult. Therefore, interstitial free (IF) steel has been widely adopted to meet these requirements due to the low amount of impurities and the high degree of formability of IF steel sheets. In the case of parts that must have specific characteristics to prevent denting (i.e., tensile stiffness and dent resistance), bake-hardened type high-strength steel (340 MPa class and 440 MPa class), which increases yield strength through a paint baking process, has been adopted. This steel material helps to reduce weight due its thinness, while also maintaining good formability and performance.

2. 1. 3. Chassis and drivetrain parts

Since chassis parts form the foundation of a vehicle's performance and safety, it is unsurprising that many of these parts are considered to be safety-critical. In addition to specific functions, these parts have strict requirements to ensure reliability, such as strength, stiffness, durability, and corrosion resistance. Consequently, the use of high-strength steel is not as widespread in these parts as in vehicle frame parts. 590 and 780 MPa class high-strength steel is used in some lower suspension arms due to its good hole expansion capabilities, while 980 MPa class high-strength steel has been adopted for use in steel wheel rims. However, 440 MPa class steel sheets are still the main materials used for chassis parts. Several types of steel sheets have been developed as high-strength materials for chassis parts since these materials are required to have a variety of formability characteristics, including stretch flanging and hole expansion (7). In the case of drivetrain parts, hydroforming technology has been used to form an integrated axle housing from a single steel pipe and reduce weight (8). The use of triple tube expansion technology to integrally form welded structural components with steel pipes has achieved a 10% reduction in weight. The development of high-strength steel sheets and the applicable technologies that make full use of these materials will continue to be a major target for manufacturers in the future.

2. 1. 4. Motor parts

Electromagnetic steel sheets are used for the motors in electric vehicles. These motor parts are being developed with high magnetic flux density, low iron loss, very thin profiles, and high strength to increase the efficiency and speed rotation speed of electric motors. Precipitation strengthening using nano-copper particles was reported as technique that helps achieve both low iron loss and high strength (9). In addition, other research is attempting to reduce the iron loss during the core processing stage and determine the level of impact this has on the finished product (10). Applied research into a nanocrystalline soft magnetic material is also underway as a possible yoke material for high-speed electric motors in the future. This material has already succeeded at improving the efficiency of small electric motors in home appliances by 6% in comparison to electromagnetic steel sheets (11).

2. 2. Structural steel

Structural steel is a material that can obtain the required strength through forging and heat treatment, and it is mainly used for powertrain and chassis parts. While it is possible to achieve weight reduction by using high-strength, special steel containing rare metals such as molybdenum and vanadium, the application of more balanced materials that contain reduced amounts of expensive elements are also being promoted, to help reduce the material sourcing risk.

2. 2. 1. Engine parts

In the case of some engine parts, such as crankshafts and connecting rods, a non-heat treated steel material made by adding vanadium to carbon steel is being used to help save energy and lower cost. The use of vanadium to carry out precipitation strengthening of the steel makes it possible to omit the quenching and tempering process. Usually, a surface rolling process was used to increase the bending fatigue strength of the fillet parts of crankshafts through the application of compressive residual stress. However, recently, high-frequency induction hardening has come to be used to increase the hardness and residual stress of these parts. Consequently, it has become possible to return to the use of standard materials instead of high-strength materials. Similarly, molybdenum was often added to high-strength crankshaft parts manufactured with a gas soft nitriding process. However, it was found that if the amount of general purpose manganese was increased and manganese nitride was used to carry out precipitation strengthening of the steel, then a high-strength steel manufactured via gas soft nitriding could be realized without having to rely on the addition of molybdenum (12).

Reducing the weight of connecting rods also helps to lower the weight of peripheral components due to the reduction in the inertial force. This ripple effect can be extremely significant. It was reported that a high-strength steel for use in connecting rods was achieved by increasing the amount of vanadium added to the steel and also by optimizing the component elements and structures to suppress deterioration in machinability (13).

2. 2. 2. Drivetrain parts

In general, carburized gears are used for transmission gears since these have the required dedendum (root of a gear tooth) fatigue strength, impact strength, and resistance to pitting. Surface reforming techniques, such as high-concentration carburization and shot peening, are also applied. In recent years, a high-strength gear material was developed that maintains the strength of conventional gear materials but without rare metals (14). This was accomplished by reducing the amounts of rare metals, such as nickel and molybdenum, optimizing the component elements, and reviewing the carburizing and quenching process. Vacuum carburizing has also been introduced in Japan as a method to streamline the heat treatment line. A small-lot heat treatment furnace was developed that makes it economically viable to carry out heat treatments on small amounts of parts in a short time (15).

2. 2. 3. Chassis parts

Wire rod for springs and bolts are used for these parts in the suspension. The development of high-strength wire rods to reduce weight is advancing. Recently, an inexpensive steel spring with shear strength in the 1,200 MPa class, which contains low amounts of nickel and no vanadium, was realized by optimizing the component elements of high-strength suspension spring steels (16).

2. 3. Stainless steel

Stainless steel is a material that combines iron with at least 11% or more chromium. It has excellent heat and corrosion resistance and is often used in the exhaust systems of vehicles and for decorative molding. Ferritic and austenitic stainless steels are the most common materials. Ferritic stainless steel is inexpensive because it does not contain nickel. It also has excellent heat fatigue characteristics, which is why it is often used for parts in the exhaust system. In recent years, as the need to further improve fuel economy has increased, there are growing demands for a material that can withstand the higher exhaust gas temperatures in lighter weight vehicles and engines with improved combustion efficiency. One of the representative heat-resistant ferritic stainless steel materials often used in vehicle exhaust systems is SUS444. It was found that a new steel material with heat-resistance capabilities equal to or better than SUS444 could be realized without adding any of the rare metal molybdenum by precipitation strengthening the steel with copper and utilizing solid solution strengthening of aluminum (17).

Austenitic stainless steel is used in places such as the interior of double-pipe exhaust manifolds, exhaust gas recirculation (EGR) coolers, and heat-resistant gaskets, where even higher high-temperature strength and corrosion resistance characteristics are required.

2. 4. Cast materials

Castings can be easily shaped into a variety of forms, and parts with complex shapes can be mass-produced. Castings are also inexpensive and have excellent workability, wear resistance, and vibration damping properties. As a result, these materials are widely used for powertrain and chassis parts.

Castings are used for powertrain parts such as cylinder sleeves, camshafts, and flywheels, as well as chassis parts such as knuckles, brake rotors, and various types of arms. For chassis parts, a 600 MPa class spherical graphite casting material with high strength and toughness has been adopted for suspension arms, greatly reducing the weight of parts that used 380 MPa class material (18). This material has improved strength, good bending deformation, and impact resistance by adjusting the component elements, such as silicon, manganese, and copper, and optimizing the application of heat treatments.

2. 5. Ferrous sintered materials

In the case of a sintered body, the powder material is placed into a die in the shape of the desired part and then the powder is compacted and formed into a solid mass using pressure. The sintering occurs after molding so the machining allowance is small and the cost of the process can be held down by using specific raw material powders only on the required portions. Powder materials also enable a large degree of freedom in the design of the parts. Currently, these materials are mostly used as structural materials for powertrains and magnetic materials for electric motors. In engines, these materials are used for parts that require good wear resistance, such as valve seats, valve guides, sprockets for chains with complex shapes, synchro hubs, parts for the variable valve timing mechanism, and parts that require good strength, such as connecting rods. Recently, research has been conducted on sintered materials that are strengthened by combining the sintering process with carburizing and rolling methods, which was previously considered to be difficult (19). These new sintered materials are intended for use in gears that are required to have good fatigue properties under high surface pressure.

Sintered neodymium magnets are used in the motors of electric vehicles and rare earth elements are added to these magnets to improve heat resistance. Development of new technologies to reduce the amount of rare earth elements needed in these magnets is advancing and research is being conducted on the microstructure and magnetic properties of these materials to improve heat resistance and identify the coercivity mechanism (20)(21). In addition to sintered neodymium magnets, NdFe12Nx magnets have attracted attention as a possible new material structure (22).

3 Nonferrous Metals

3. 1. Aluminum alloys

The use of aluminum alloys is only expected to increase as demand for lighter and more fuel efficient vehicles to help reduce CO_2 emissions continues to grow around the world. The specific gravity of aluminum alloy is approximately one-third that of steel and, in general, the weight can be reduced by about 30% to 50% compared to steel materials. In North America a pickup truck model has been introduced to the market that makes heavy use of aluminum alloy materials.

There are many different forms of aluminum alloy materials, including sheets, castings, forgings, extrusions, and so on. For example, aluminum sheets have replaced steel sheets for use in engine hoods, and steel sheet press welded structures for suspension members and sub frames have been changed to aluminum castings using different methods and shapes to accommodate aluminum alloys.

Changing the hood material has another advantage in that the manufacturing process does not have to be changed greatly. The price of aluminum bullion is higher than that of iron, so various creative methods have been used to hold down the rise in cost per each 1 kg in weight reduction. For example, the use of 6000 series alloy sheets that are age hardened using the heat of the painting process has become mainstream since this method reduces the amount of aluminum compared to non-age hardened 5000 series alloy sheets.

In the case of suspension members, initial investment is large because aluminum casting equipment is required. However, since aluminum castings, such as high vacuum die castings, enable the integral molding of large parts, the number of parts can be reduced significantly in comparison to parts made from press-welded steel sheets, which helps hold down increases in cost. Two-cavity technology for large-scale aluminum die castings has been developed, which reduces cost while maintaining high quality. This kind of technology will enable the aluminum die casting of parts to be adopted in even more mass production models (23).

The key to expanding the application of aluminum alloys to even more vehicles is to reduce cost. Large-size parts welded using friction-stir welding (FSW) instead of arc welding have been developed. FSW requires only one-tenth of the electricity of arc welding, thereby reducing energy usage. A technique was also devised that prevents electrolytic corrosion from occurring, enabling the practical adoption of structures that join together steel and aluminum alloys on mass-production vehicles (24). Reducing the weight of the vehicle is not solely for improving fuel economy. Reducing the weight of parts that are further away from the center of the vehicle also helps to improve vehicle handling, so the portions of the vehicle that are selected for the application of aluminum alloys is also made from this standpoint (25).

Smelting aluminum from bauxite requires a large amount of electricity. However, recycling aluminum alloys does not require electricity for refining. Therefore, even though some energy is used to dissolve the material, the amount of energy is extremely small compared to the energy needed for smelting. Consequently, parts such as engine blocks and transmission cases are often made from waste aluminum material as cascade recycling systems have become widely adopted.

Currently, Nissan Motor Co., Ltd. is working with recycling businesses all across Japan to separate and recover aluminum wheels for use in suspension parts and the like, as a measure to help minimize the amount of natural resources that have to be newly mined (26). In the ASEAN region, aluminum alloy wheels for motorcycles formed using high-pressure die casting (HPDC) were developed and the aluminum alloy used in these wheels is made from recycled secondary aluminum alloy ingots. This helps to reduce the amount of CO_2 emissions during the material production process (27).

3. 2. Magnesium alloys

Magnesium alloys have a specific gravity of 1.74, which is approximately one-quarter that of steel and two-thirds that of aluminum alloys. Among the various alloys being put into practical use in vehicles, magnesium alloys have a high specific strength and specific stiffness, which makes lightweight designs possible. Magnesium alloys are widely expected to be the next lightweight material to be commonly used in vehicles after aluminum.

The main automotive applications for magnesium alloys are as alloys for casting, such as die casting. Some examples of magnesium alloy parts that have been adopted are interior parts, such as steering wheel cores and steering members, and powertrain parts, such as cylinder head covers and transmission cases (28)(29).

However, there are only a few examples of magnesium alloys used as wrought materials, but in 2014, magnesium alloy sheets were newly applied to interior body parts (30).

As demand for even lighter vehicles has been growing, a wide range of research and development has been pursued in this area. Research has examined how to improve formability by controlling the texture of magnesium alloy sheets (31) and another report examined the impact energy absorption characteristics of circular pipes made from magnesium alloy (32). In addition, a technique for joining together aluminum alloys and magnesium alloys via forge welding was developed (33). In the future, a wide range of problems and issues will need to be resolved, including those of peripheral technologies, in order to expand the automotive uses and applications of magnesium alloys. These issues include lowering the cost of materials and manufacturing methods, finding techniques to join magnesium alloys to other materials, the development of techniques to help prevent electrolytic corrosion, and the development of materials technologies and mechanisms to enable recycling.

4 Nonmetallic Materials

4. 1. Ceramics

Ceramic materials used in vehicle parts are divided into structural ceramics, electroceramics, and coatings, depending on the characteristics and applications of the material. Structural ceramics include materials such as cordierite, which is used in the catalyst carrier to help purify exhaust gases, silicon carbide, which is used in diesel particulate filters (DPFs), and alumina, which is used in spark plugs. Electroceramics include materials such as zirconia, which is used in oxygen sensors in the engine, lead zirconate titanate, which is used as the piezoelectric element in knock sensors, silicon nitride, which is used in glow plugs, and alumina and aluminum nitride, which are used in IC packages. There have been no major changes in the parts listed above over the past several years.

One new trend seen in the field of ceramic materials is the application of chromium nitride coatings using the vacuum deposition method and also coatings made from a new material called diamond-like carbon. These ceramic materials are being applied to valve lifters (34), piston rings (35), and clutch plates (36) to reduce friction and improve the wear resistance of engine parts. In addition, research into a heat insulating film made from a ceramic coating to be applied to the component parts of the combustion chamber has been attracting attention as a means of possibly reducing engine cooling loss (37).

4. 2. Plastics

Plastic materials are lightweight and have excellent shape and design flexibility. The amount of plastic materials used in vehicles is increasing due to these characteristics and the relative ease of molding into various shapes compared to other materials. The material properties of plastics include high fluidity and high strength, which make it possible to reduce the thickness of parts. Furthermore, plastics can be turned into many different kinds of composite materials by using various reinforcing materials to optimize and adjust the material properties. More and more vehicle parts are taking advantage of lightweight plastic materials with excellent shape flexibility. This is driving the active development and application of plastics to improve the designs of parts and promote part modularization. In the future it is expected that the use of plastic materials in vehicles will only continue to increase.

At the same time, the use of recyclable and plant-derived plastics is also increasing. These materials can be collected within manufacturing processes and from the market when vehicles are scrapped. These materials are seen as environmentally friendly and a way for automakers to address both environmental and energy issues.

4. 2. 1. Exterior parts

Polypropylene (PP) has superior material properties and formability, and also good cost performance. As a result, PP has been adopted for use in bumpers and a wide range of exterior parts. PP-based composite materials and PPA-based composite materials have also been adopted in some vertical portions of exterior panel parts, such as fender panels and back door panels (38).

In addition, sheet molding compounds (SMCs) and carbon fiber reinforced plastics (CFRPs) are being adopted for use in some parts with horizontal surfaces that require good stiffness to help resist sagging, such as hoods and roofs. CFRP, in particular, is even being applied more and more to the structural members of vehicle bodies (39). In the future, further technological development is expected to help reduce the material cost and shorten forming cycle times, which will help to expand the application of CFRP to more mass-production vehicles (40).

4. 2. 2. Engine parts

The development of polyamide (PA) materials with excellent heat resistance has enabled the wide application of these materials to many engine parts, such as the intake manifold, cylinder head covers, and radiator tank. In recent years, there has also been greater application of these materials to air intake and cooling system parts to help reduce weight. PP materials have also been widely adopted for parts that do not require good heat resistance, such as radiator supports and air cleaner cases.

So-called super engineering plastics that possess excellent durability performance, such as polyphenylene sulfide (PPS), are increasingly being adopted for use in functional parts, such as parts located around the engine and electronics-related parts. The use of these materials is likely to expand in the future, especially in hybrid and electric vehicles.

4. 3. Interior materials

Since materials used for vehicle interiors come into direct and long-term contact with vehicle occupants, these are critical materials that have a direct effect on consumers. The following is a list of the three highest priority demands of vehicle occupants for the vehicle interior: (1) ease of driving operations, (2) a comfortable interior even when driving for long periods of time, and (3) interior materials that impart a feeling of luxury. The following paragraphs describe the material technologies related to each of these three demands.

Thinner profile seats and other parts that use urethane to reduce weight while maintaining ride comfort are being examined to help promote the ease of driving operations. The adoption of urethane foam that uses biopolyols that are manufactured from castor oil is one example of a carbon-neutral material that is being used in vehicle interiors (41).

Reducing the amounts of volatile organic compounds (VOCs) that are present in the vehicle interior is necessary to realize a comfortable interior over long periods of use. Consequently, paint and adhesive solvents and other materials that do not volatize aldehydes have been adopted.

Materials with strong color intensities that usually were used on vehicle exteriors, such as high gloss piano black paints and coatings, are being adopted more often on interior materials to help impart a sense of luxury. There are also an increasing number of examples of paint and coating-free decorations being achieved through spin dyeing (42). The number of luxury vehicles with bright interiors has been increasing and so skin materials that have been given water repellent and hydrophilic properties have been adopted as a way of protecting these interiors from dirt and staining.

4. 4. Rubber

Rubber materials have crosslinking points that create the unique viscoelastic properties that makes rubber an irreplaceable material for functional parts. For example, rubber is used not only for tires and hoses, but also in mounts and bushings to absorb vibrations, and in parts that provide seals against water and oil, such as weather stripping and O-rings.

Since the fuel efficiency and wet grip performance of tires have a trade-off relationship, a new additive technology was developed to improve the dispersing quality of the silica filler in the tire rubber, to help enhance both performance aspects. Recently, tire manufacturers have begun adopting this new rubber material with increased amounts of additives (43).

More and more automakers are adopting smaller engines with turbochargers. The usage environment (high pressure and high temperature) of the rubber hoses that connect the turbo to the intercooler has become even more severe. Consequently, fluororubber (FKM) is being used for these turbo hoses to improve durability because it can maintain a high elongation rate even under high-temperature environments that exceed 180° C.

There is increasing demand for smaller and lighter rubber parts to absorb vibrations, such as mounts and bushings. Consequently, research and development of a rubber material with improved heat resistance and high durability is being actively promoted.

Demands for reduced weight have also reached rubber weather strips. A low-foaming ethylene-propylene-diene-monomer (EPDM) rubber material has been developed that achieves a low specific gravity while also maintaining the required rubber properties, such as hardness. This material is being used on more and more vehicles and the cross-sectional shape of these parts is also being optimized.

4. 5. Glass

The basic functions of automotive glass have not changed and include collision safety and visibility. The application of additional, occupant-friendly functions, such as the blocking of ultraviolet and infrared light, are now being applied to both windshield glass and front door glass in a growing number of vehicles, from standard mid-size vehicles to small and mini-vehicles. In addition, in recent years, the infrared light blocking performance of vehicle glass has been attracting more attention. Demand for antifogging and heat insulating properties in vehicle glass is also increasing from the standpoint of improving the driving range of electric vehicles and improving practical fuel economy. Dimming glass, which can control the amount of light that passes through it, is both functional and useful for design purposes. Its use is expanding from some luxury models to aircraft (44). It is expected to offer new value in the field of automotive glass.

4. 6. Paints

The adoption and use of design-specific paint colors for vehicles, such as two-tone roofs (45) and even more vivid reds (46), to help attract more customers is continuing to expand. New painting technologies that improve the quality of the paint appearance are also being employed (47). The contribution that the paint makes to the overall product competitiveness and appeal of a vehicle is only continuing to grow and become more important.

In the case of primer and top coat vehicle paints, a water-based 3-wet painting process (the primer drying oven is eliminated), which is a more environmentally-friendly painting technology, is increasingly being adopted to help reduce VOC and CO_2 emissions. Furthermore, additional development is being carried out to improve the quality of the paint appearance using this same process (48).

In the case of electrodeposition coatings, fundamental research is continuing to be pursued on the topics of materials with high throwing power, paint analysis methods, and degradation analysis technologies. The aim is to help stabilize the quality of electrodeposition coatings and optimize the amount of material that is used. Steady progress is being made to both maintain and improve the durability and quality of automotive paints and coatings (49)-(51).

4. 7. Electrical insulating polymeric materials

Product development is being promoted to obtain an enamel resin with a low-dielectric constant and improved adhesion and flexibility. This enamel resin being developed as a technology for the coils used in the motors of electric vehicles to help meet the need for smaller systems that operate at high voltage (52)(53).

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