MATERIALS

1 Introduction

The automotive industry is facing a wave of change described as a once in a century event. Underlying this wave are technological innovations such as electrification, intelligent systems, and information technology. The value associated with automobiles continues to expand from simple "ownership" to "usage", and various new non-automotive businesses are entering the Mobility as a Service (MaaS) industry, which is best known for its ride- and car sharing services. In the field of automotive materials, the existing focus on developing the fundamental basic technologies required to achieve higher performance, manage the risk associated with scarce resources, and reduce environmental impact is now being complemented with the development of materials informatics (MI) and other new technologies that draw on big data and artificial intelligence (AI). The following sections introduce the trends in automotive materials seen in 2018.

2 Ferrous Materials

2. 1. Steel Sheets

Recent efforts to reduce vehicle weight have focused on the use of multi-materials, which combine steel sheets with other materials and enhance various characteristics and functions, to improve automobile fuel efficiency. Although the amount of iron used in automobiles is anticipated to decrease between now and 2040(1), it is an abundant resource with many advantages such as recyclability and cost, and the inclination to use it to the fullest remains strong in Japan(2). In fact, as shown by the Innovative Structural Materials Association (ISMA), iron with a high degree of functionality is still actively researched and developed(3). The application of steel sheets can be broadly classified as follows: (1) parts for the body structure, (2) outer panels, and (3) chassis parts and (4) motor parts, which have become the object of rising expectations with the rapid shift toward greater electrification.

2. 1. 1. Body Structure

In terms of protecting occupants in the event of a collision, body structure parts are classified into energy absorption parts, deformation control parts, and undeformed parts for cabin, where a suitable grade of steel is applied to each of these parts(4).

1,180 Mpa-class steel is recently often used for cold press forming(5), and 1,310 MPa-class steel is also found in some applications(6).

Reports of the use of transformation induced plasticity (TRIP) steel to achieve high levels of both strength and formability have been followed by reports discussing liquid metal embrittlement (LME) cracks occurring in spot welds attributed to large amount of additive element content. There is also a growing need to develop application technology in conjunction with the development of materials(7).

Hot stamping, in which a heated steel plate is pressed with a die and simultaneously cooled and quenched while the upper and lower dies are still closed, is also used for many parts(8). Higher tensile strength steel in the 2,000 MPa-class(9) has been developed. Most products manufactured using hot stamping are subject to laser trimming because delayed fracture due to the residual stress generated by trimming in case of mechanical trimming, and the implementation of a trimming process that avoids delayed fracture is eagerly awaited to reduce manufacturing costs(8).

2. 1. 2. Outer Panels

Outer panel parts require a high degree of formability and excellent surface quality to realize beautiful designs. Until now, ultra-low carbon steel was widely used because it possesses the required formability, but aluminum or plastic is being used in an increasing number of vehicles. Nevertheless, there are also examples of reducing weight by making steel sheets thinner, or conversely, eliminating reinforcement parts by making them thicker[10]. In addition, 440 MPa-grade and 1,180 MPa-grade steel sheets have been used, and forming technology with excellent part design flexibility that takes advantage of the properties of mild steel are being developed[11].

2. 1. 3. Chassis Parts

Chassis parts have strict strength, durability, corrosion resistance, and other requirements to ensure their reliability as safety-critical parts in terms of vehicle functionality. They do not use high-strength steel as extensively as vehicle frame parts. However, 590 and 780 MPa-class high-strength steel is increasingly used in parts such as lower suspension arms, and 980 MPa-class high-strength steel has been adopted for use in steel wheel rims and some frame parts. In addition, chassis parts are required to have various forming characteristics, such as stretch-flangeability and hole expandability. Consequently, high-tensile steel materials suitable for chassis applications have been developed, and efforts are also being made to improve the rust prevention performance of arc welded portions[12].

2. 1. 4. Motor Parts

The electromagnetic steel sheets that are widely used as the iron core material in electric vehicle drive motors are required to improve the magnetic flux density that contributes to motor performance, as well as to reduce the iron loss that affects efficiency. They must also have a high level of strength because of the large centrifugal forces that act on the rotor during high speed rotation. Thinning, adjusting the amount of added alloys, controlling the texture and crystal grain size, reducing the amount of impurities, and other techniques are being applied to develop materials that satisfy these diverse demands[13][14].

At the same time, amorphous magnetism and nanocrystalline soft magnetism are also garnering attention from the standpoint of further reducing iron loss, and their potential application to electric vehicle motors is being examined[15][16].

2. 2. Structural Steel

Structural steel is a material that obtains the required characteristics by combining processes such as forging, heat treatment, and surface treatment. It is widely used in high-strength parts such as the powertrain and chassis parts. Various advances in these technologies have made spread the adoption materials and processes that mitigate the quantity of rare elements such as molybdenum and vanadium required to ensure the necessary characteristics.

2. 2. 1. Engine Parts

Non-tempered steel with added vanadium is generally used for primary engine component parts, such as crankshafts and connecting rods, in an effort to reduce heat treatment costs.

Partial induction hardening is used to improving the fatigue strength of the crankshaft fillets to the high levels they require. High strength has also been achieved by gas soft nitriding in some cases[17]. At the same time, the weight of the connecting rods is being reduced to decrease inertial force. New forging technologies capable of imparting different levels of strength in the same part by controlling the temperature and cooling rate to ensure the strength and workability at the required locations have been developed and put into practical use[18]. Furthermore, a high-strength steel with good machinability for connecting rods has been developed by optimizing the structure and component elements[19].

2. 2. 2. Drivetrain Parts

Gears, the main components of the transmission, are usually carburized gears due to the high level of dedendum fatigue strength, impact strength, and resistance to pitting that are required.

Although forming these gears via cold forging and high-temperature carburizing has been favored to rationalize the manufacturing process and reduce costs, this approach is unfortunately prone to abnormal austenite grain growth. To address this issue, the component elements that suppress abnormal grain growth, such as Ti and Nb, 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 less expensive elements[20].

At the same time, a new heat treatment that combines induction and vacuum carburizing was developed to make the heat treatment, simpler, shorter, and more energy-efficient. The use of special materials both reduced the usage of alloys and improved strength[21].

2. 2. 3. Chassis Parts

Spring and bolt wire rods are used for the suspension springs and bolts, whose characteristics have been improved by adding alloys to increase their strength and for light weight. Recent efforts to reduce cost and simplify material procurement particularly for suspensions springs, have led to the development of materials that allow the softening and annealing process to be omitted thanks to adjustments to the component elements controlled rolling during wire manufacturing(22). This has been combined with composite shot peening, to enable the use of low nickel content, vanadium-free low cost springs with a 1,300 MPa shear strength.

2. 3. Stainless Steel

Stainless steel is widely used in many automobile parts because of its excellent heat and corrosion resistance. In particular, ferritic stainless steel is often used for exhaust system parts because it does not contain nickel, has a low coefficient of linear thermal expansion, and has excellent heat fatigue characteristics. Many manufacturers have begun switching to steel types with lower amounts of molybdenum, niobium and other rare metals to reduce costs(23).

In contrast, austenitic stainless steel contains nickel and is used in parts that require more corrosion resistance, such as exhaust gas recirculation (EGR) coolers. More recently, it has also been applied to components (e.g., receptacles, high-pressure hydrogen piping, and pressure reducing valves) used in the high-pressure hydrogen gas environment of fuel cell vehicles (FCVs). However, cost is an issue for SUS316L, which suppresses the generation of work-induced martensite and δ ferrite by increasing the nickel equivalent through the addition of molybdenum to withstand hydrogen embrittlement in a high-pressure hydrogen environment at −40℃. Therefore, low-cost stainless steel materials with reduced amounts of rare metals are being developed to popularize FCVs(24).

2. 4. Cast Iron Materials

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

Specifically, castings are used for engine parts such as turbine housings, camshafts, and exhaust manifolds, drivetrain parts such as differential cases, and chassis parts such as brake rotors and various types of arms.

New materials that are both inexpensive and possess excellent heat resistance properties have become the focus of development aiming to meet the demand for highly heat-resistant materials for modern, downsized, supercharged engines, as well as to further improve fuel efficiency(25).

Although cast iron materials are known to be brittle and difficult to weld, more recent development has achieved a reduction in weight using laser welding to join dissimilar materials such as the ring gear and differential case in drivetrain parts(26).

2. 5. Ferrous Sintered Materials

Sintered materials are created using powder metallurgy, a process in which the metal material in powdered form is poured into a mold in the shape of the desired part, compacted at high pressure, and then sintered. This results in a product that is in its final or almost final shape and therefore it has excellent material yield, and provides a high degree of freedom in the material design. These advantages are leveraged to use iron-based powders to manufacture mechanical structural parts such as connecting rods and planetary gears, as well as wear resistant parts, such as valve seats. Recently, lasers have been used to melt the powder, with a copper-based powder used for laser-clad valve seats formed directly onto the cylinder head in an effort to improve engine performance(27). At the same time, many magnetic parts are manufactured by sintering. For example, neodymium sintered magnets that possess a high level of saturation magnetization are widely used for in-vehicle motors, including the drive motors for electric vehicles. Until now, heat resistance has been improved by adding expensive heavy rare earth elements such as dysprosium to increase coercivity, which serves as an index of heat resistance. Due to resource and other risks, however, research is being actively conducted to develop alternative technologies and better understand the underlying coercivity generation mechanism(28). In particular, the development of grain boundary diffusion technology, grain boundary phase modification, and grain refinement technologies has made it possible to produce neodymium magnets that possess high coercive force in which the addition of heavy rare earth elements is either greatly reduced or even eliminated(29)(30).

3 Nonferrous Metals

3. 1. Aluminum Alloys

Aluminum materials are replacing steel materials in various automobile parts to reduce vehicle weight. Aluminum can be used in a large array of different forming and machining processes, such as rolling, forging, extrusion, and various casting methods. The stable supply of raw material also makes it applicable to a wide range of parts. With the demand to further reduce the vehicle weight intensifying year after year, the quantity of aluminum used per vehicle continues to increase[31].

The increasing shift toward a multi-material composition in vehicles requires a body structure that incorporates the joining of dissimilar materials such as steel and plastic, including carbon fiber reinforced plastics (CFRPs). This structure has come into use as a result of the development of joining techniques for dissimilar materials and of technology 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, such as suspension frames and suspension towers, have been applied to chassis and body structure parts. Integration and highly rigid part designs enable rib structures to reduce the number of parts in comparison to structures made from welded steel sheets.

In parallel with increases in the strength of the materials themselves, the conflicting problem of stress corrosion cracking is being taken into consideration in the development of chemical composition and the reexamination of design structures for bumper reinforcement extrusion parts that use high strength materials.

Advances in aluminum recycling technology are making it possible to move from the conventional cascade recycling approach, in which the aluminum ingot reclaimed from waste aluminum is used for engine blocks and other purposes, to a new type of recycling where the same aluminum material is turned into a product exhibiting the same level of quality.

3. 2. Magnesium Alloys

With a specific gravity one-quarter that of steel and two-thirds that of aluminum, magnesium is the smallest of the metals used in vehicles, and has been used in some automotive parts for the lightweight designs made possible by it high specific strength and specific rigidity. However, the many technical issues that arise in actual use, such as corrosion resistance, including galvanic corrosion with dissimilar metals, heat resistance, and plastic workability, has limited the number parts where it is applied. Magnesium is mainly used in die cast parts such as steering wheel frames cylinder head covers and engine oil pans, and can also be found in the expanded material of a few sports car roofs. In 2018, Audi used die cast parts made from a magnesium alloy called AZ91 for strut braces[32]. Industry and academia are also collaborating on research into flame-retardant expanded materials aimed at broadening the applications of magnesium[33], creating expectations that solutions extending to problem in plastic working, as well as in other peripheral technologies such as bonding and surface treatments, will be found.

4 Nonmetallic Materials

4. 1. Ceramics

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

Structural ceramics like silicon nitride possess excellent wear, heat, and corrosion resistance characteristics, and are used in parts such as the turbine rotors of turbochargers, the tips of rocker arms, and the vortex chambers of diesel engines.

Electroceramics like alumina and zirconia possess strong insulating characteristics, high electrical conductivity (ion conductivity), and piezoelectric properties, and are used in spark plugs, oxygen sensors, NOx sensors[34], and knock sensors.

Cordierite, with its excellent thermal shock resistance (low thermal expansion), and silicon carbide, with its excellent thermal shock resistance and high thermal conductivity, are the main ceramic materials used in catalyst carriers for exhaust gas treatment and in particulate collection filters.

4. 2. Plastics

Plastics have low specific gravity, can easily be formed into nearly any shape, and possess good workability, and are used more and more in automobiles to reduce weight, lower costs, and add functionality through enhanced performance. In addition to improved physical properties, a higher quality external appearance, better recyclability in the context of environmental preservation, and other increasingly sophisticated and complex performance requirements are being imposed on plastics.

4. 2. 1. Exterior Parts

Polypropylene (PP), a plastic with a low specific gravity and excellent cost performance, has been widely used in exterior automobile parts such as bumpers for a long time. Talc and other fillers are mixed into it to improve rigidity and heat resistance, and reformulation, such as the addition of rubber, is often employed to improve impact resistance. PP is still widely used in automobiles to this day and its use has also recently extended to back door outer panels.

Carbon fiber reinforced plastics (CFRPs), which are widely used in the aviation industry, are expensive and present challenges in terms of productivity. Consequently, their use in the automotive industry, where mass production is the norm, had limited their use to a few luxury cars and sports cars. However, they are gradually seeing greater adoption in vehicles with relatively larger production runs, as exemplified by the use of carbon sheet molding compound (C-SMC) in back door inner panels(35). Stampable thermoplastic CFRP materials have greater productivity than CFRPs that use thermosetting resins, but until now have only been used in the stack frames(36) of fuel cell vehicles. However, there are also plans to use them in truck cargo beds(37). These materials can be molded into more complex shapes than prepreg material consisting of continuous carbon fiber (CF) impregnated with resin. They can also be processed more quickly than with production methods that use an autoclave, and their application is expected to expand to a larger number of parts. Recycling carbon fiber (CF) has proven difficult, but the recent appearance of vehicles with frames that use recycled CF(38) is raising expectations for advances in this field.

Existing examples of hard-coated polycarbonate (PC) resin glass have been limited to back windows and quarter glass. However, the world's first automobile with a plastic front windshield was unveiled last year(39), and this new development will be watched closely.

4. 2. 2. Interior Parts

Interior materials must provide both a high level of comfort and a sense of high-quality to vehicle occupants. Recently, volatile organic compound (VOC) regulations, odors and other aspects of air quality are receiving an increasing amount of attention. China is moving toward establishing regulations in that respect, and there is a global shift toward low-odor and low-VOC materials for materials such as PP and urethane, which are used in large quantities in vehicle interiors.

High quality interior decoration now tends to be expected in light-duty vehicles as well, spurring the adoption of materials with more vibrant colors and surface materials that possess a more luxurious feel. In addition, the use of surface material decoration that simulates the appearance of stitching (seams) is increasing, and the development of technologies that can achieve both low cost and a high-quality texture is being pursued enthusiastically. In luxury automobiles, technologies that use three-dimensional decorations and shadows to promote a greater sense of luxury and texture have appeared(40). This trend toward genuine decorations will continue to draw attention.

Mobility as a Service (MaaS) initiatives to establish car sharing and other mobility-related services, are also intensifying. Unlike a conventional vehicle with a single owner, these services involve vehicles used by numerous unspecified people, and interior materials that are more damage resistant, stain resistant, and reduce odors will become more important. One of the challenges will be the development of materials that can maintain these characteristics over a long period of time.

4. 2. 3. Powertrain and Electric Drive Unit Parts

Among plastics, polyamide (PA) is offers a relatively high heat resistance and is therefore used for some engine parts such as intake manifolds and radiator tanks. The use of plastic to reduce weight has even been extending to side covers and other parts in the transmission(41), and is expected to expand even further over time.

Various plastic materials are also used in fuel cell (FC) units, which are anticipated to become next-generation powertrains. In particular, the majority of hydrogen tanks used to store high-pressure liquid hydrogen are made of CFRPs. Plastic materials are also used for the liner inside the type 4 hydrogen tanks used in some FC vehicles(42). Making FC vehicles more widespread calls for reducing the cost and increasing the performance of these materials.

4. 3. Rubber

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

The requirements for tires include a longer service life and balancing the contradictory demands of both reduced rolling resistance and improved wet grip performance. Tire manufacturers are tackling development from the raw material stage to achieve these required performance parameters for tires. In particular, technology that improves silica dispersion is key to improving these tire characteristics(43).

As engine compartments become more compact and the number of downsized engines with superchargers increases, engine parts are being subjected to an ever more severe thermal environment. Consequently, their rubber hoses are made from materials with excellent high-temperature durability, such as ethylene propylene diene rubber (EPDM), acrylic rubber (ACM), and fluorocarbon rubber (FKM). Vibration-absorbing rubbers, such as those used in engine mounts, have primarily been made from natural rubber (NR), but the development of more heat-resistant formulations is now underway.

4. 4. Glass

In addition to basic performance such as safety and visibility, the development of automotive glass is also expected to provide advanced functions such as weight reduction, appealing design, and greater in-vehicle comfort in response to vehicle electrification, the introduction of intelligent systems, and the use of information technology. Examples include the development of windshields and door glass with excellent sound insulation, front door glass with excellent UV blocking performance (approximately 99%) and infrared light blocking performance[44], windshields with excellent infrared light blocking performance, and windshields that can display information, all of which have now been put into practical use. There are also cases where the design characteristics of chemically tempered glass have led to applying it to interior decoration or onboard display screens.

Furthermore, plastic materials are starting to be used for large panoramic roofs, rear windows, and quarter glasses to reduce weight. At the same time, low-cost coating technologies are being developed to address issues such as weather, scratch, and wear resistance.

4. 5. Paint

In addition to the conventional requirements for product appeal and performance, automobile paints must now meet those for CASE.

Regarding paint design, multi-layer coatings are used to achieve "High chroma", "Deep feeling", and "Liquid metallic feeling".

Automakers have expanded their selection of optional brilliant new design colors. On the other hand matte colors are also used on some brands and vehicles. Bi-tone color schemes have also become increasingly common since the triggering of their popularity by European compact cars.

In terms of environmental impact, the focus has been on decreasing the emission of greenhouse gases such as CO_2 and regulating chemical substances, and new technologies (materials, processes, and equipment) tying into energy conservation will be necessary. The simple substitution of materials is no longer sufficient to reduce vehicle weight, and a radical reformation of the vehicle structure is becoming necessary. Studies are now underway to determine if the designs and functions that were previously provided by paints can be replicated with alternative wrapping films. The current trend involves expanding the application of designs and stripes with Bi-tone colors and decals.

Autonomous driving and safety technologies for CASE vehicles will also require adapting paints to the light or radio waves from LIDAR or radars (penetration and reflection).

References

(1) Nikkei Automotive, February 2018, pp. 58 to 61 (in Japanese)

(2) Nikkei Automotive, June 2018, pp. 58 to 61 (in Japanese)

(3) Innovative Structural Materials Association (ISMA) website, http://isma.jp/en/index.html (accessed March 11, 2019)

(4) Ureshino, Expectations on Steels for Automobile Weight Reduction, The Special Steel, Vol. 67, No. 5, pp. 8 to 10 (2018) (in Japanese)

(5) Ogawa et al., Journal of Society of Automotive Engineers of Japan, Vol. 72, No. 12, pp. 71 to 76 (2018) (in Japanese)

(6) Mazda web press release, Development of World's First 1310 MPA Ultra-High Tensile Strength Steel Sheet Cold Formed Component, https://www2.mazda.com, (accessed March 11) (in Japanese)

(7) Hirade et al., Application Development of the High Formability CR980MPa and GA980MPa Advanced High Strength Steel, Proceedings of the JSAE, Document No. 20175408 (in Japanese)

(8) Hayashi, Takao, Development of Material that Contributes to Weight Reduction and Adoption Trends, The Special Steel, Vol. 67, No. 5, pp. 11 to 14 (2018) (in Japanese)

(9) ArcelorMittal website, https://automotive.arcelormittal.com/products/By_region/2genphs (accessed March 11, 2019)

(10) Iizuka et al., Journal of Society of Automotive Engineers of Japan, Vol. 72, No. 12, pp. 19 to 24

(2018) (in Japanese)
(11) Fujii et al., Improvement in Press Formability by Stretch Preforming, JFE Technical Report, No. 41, pp. 41 to 46 (2018) (in Japanese)
(12) Tanaka et al., Development of High Argon Welding Technology, Mazda Technical Review, No. 34, pp. 122 to 127 (2017) (in Japanese)
(13) Oda et al., Recent Development of Non-Oriented Electrical Steel in JFE Steel, JFE Technical Report, No. 36, pp. 6 to 11 (2015) (in Japanese)
(14) Kaido, Chikara, Optimal Magnetic Properties of Non-oriented Electrical Steel Sheets and the Feasibility, The Magnetics Society of Japan, 221st Topical Symposium Proceedings, pp. 7 to 12 (2019) (in Japanese)
(15) Hitachi Metals press release, Developing a Higher-Efficiency Motor Technology Using Amorphous Metals, https://www.hitachi-metals.co.jp/e/press/news/2018/n1024.html
(16) Enomoto et al., Development of Extremely Efficient Motor That Uses a High Bs Nanocrystal Alloy, 2018 IEE-Japan Industry Applications Society Conference, 3-54, III 299-III 304 (2018) (in Japanese)
(17) Takasu et al.: Development of Moderate and High Strength Non-refining Steel for Crankshaft, Nippon Steel & Sumitomo Metal Technical Report, Vol. 406, p. 2-7 (2016) (in Japanese)
(18) Maeyama et al.: Development of New 1.0L Series and 3 Cylinders Gasoline Direct Injection Downsized Engine, Honda R&D Technical Review, Vol. 29, No. 1, p. 1-9 (2017) (in Japanese)
(19) Shinohara et al.: Journals of Society of Automotive Engineers of Japan, Inc., Vol. 46, No. 4, p. 825-829, 20154497 (in Japanese)
(20) Kaizuka et al.: Gear Steel for Cold Forging, Kobe Steel Engineering Reports, Vol. 66, No. 2, p. 36-41 (2017), http://www.kobelco.co.jp/technology-review/pdf/66_2/036-041.pdf (in Japanese)
(21) Obayashi et al., Development of Gear Steel MSB20 for the Hybrid Process of Vacuum Carburizing with Induction Hardening, Material Japan, Vol. 57, No. 2, pp. 72 to 74 (2018) (in Japanese)
(22) Chiba et al.: Wire Rod Capable of Eliminating Softening Annealing Treatment, Kobe Steel Engineering Reports, Vol. 66, No. 2, p. 26-30 (2017) (in Japanese)
(23) Nakamura, Tetsuyuki, Development of Mo Free-type Ferritic Heat-Resistant Stainless Steel, Ferrum, Vol. 22, No. 5, pp. 229 to 233 (2017) (in Japanese)
(24) Watanabe et al., Development of AUS305-H2 Stainless Steel for Use with High-Pressure Hydrogen, Aichi Steel Technical Review, Vol. 34, No. 1, pp. 9 to 14 (2018) (in Japanese)
(25) Ishikawa et al., Society of Automotive Engineers of Japan, Technical Presentation Proceedings of the 2018 Spring and Autumn Congresses, Document No. 20186024 (in Japanese)
(26) Kijima et al., Journal of Society of Automotive Engineers of Japan, Vol. 71, No. 9, pp. 70 to 74 (2017) (in Japanese)
(27) Aoyama et al., Journal of Society of Automotive Engineers of Japan, Vol. 72, No. 7, pp. 10 to 11 (2018) (in Japanese)
(28) Toyota press release, Toyota Develops New Magnet for Electric Motors Aiming to Reduce Use of Critical Rare-Earth Element by up to 50%, Toyota Motor Corporation, https://global.toyota/en/newsroom/corporate/21139684.html (accessed March 11, 2019)
(29) Nakamura, Hajime, Outlook for Nd-Fe-B Sintered Magnets and Expectations for New Magnets, Japan Institute of Metals and Materials Annual Fall Meeting (2018)
(30) Hirota, Koichi, The Trend of Development for Nd-Fe-B Sintered Magnets, The Magnetics Society of Japan, 221st Topical Symposium Proceedings, pp. 19 to 23 (2019) (in Japanese)
(31) Homepage of Automobile Aluminum Committee: Japan Aluminum Association, https://www.aluminum.or.jp/jidosya/japanese/02/02Localindex.htm (accessed May 13, 2018) (in Japanese)
(32) The Japan Magnesium Association Secretariat, 75th Annual IMA World Magnesium Conference and Investigation Report from North American Corporations, Magnesium, Vol. 47, No. 8, pp. 1 to 10, (2018) (in Japanese)
(33) Chino, Yasumasa, State of Research and Development on Flame-Retardant Aluminum Alloys in and outside Japan, Magnesium, Vol. 47, No. 4, pp. 10 to 11 (2018) (in Japanese)
(34) NGK Insulators website, http://www.ngk.co.jp/news/2008/0611.html, (in Japanese)

(35) Urayama et al., Mass Production Development of the Car Shell Inner Parts Applied Sheet Mold Compounds, Journal of Society of Automotive Engineers of Japan, Inc., Vol. 72, No. 6, pp. 973 to 978 (2018) (in Japanese)
(36) Hayashi et al.,Development of Stampable Thermoplastic CFRP and its Application Stack Frame, Journal of Society of Automotive Engineers of Japan, Inc., Vol. 77, No. 6, pp. 10 to 11 (2017) (in Japanese)
(37) Nikkan Kogyo Shimbun, March 6, 2018, Teijin to Supply Composite Alloys to GM, First Use in Vehicle Body Structure in the World, https://www.nikkan.co.jp/articles/view/00464499 (in Japanese)
(38) BMW Japan website, https://bmw-i.jp/BMW-i3/Design/ (in Japanese)
(39) GLM press release, September 13, 2018, https://glm.jp/company/news/teijin_0913_release/ (in Japanese)
(40) Lexus Japan website, Hand-pleated door trim, https://lexus.jp/models/ls/features/craftsmanship/ (in Japanese)
(41) Maeda et al., Resinification of Side Cover (Transmission Parts), Toyoda Gosei Technical Review, Vol. 59, pp. 91 to 92 (2017) (in Japanese)
(42) Ube Industries press release, December 8, 2014, https://www.ube-ind.co.jp/ube/en/news/2014/20141208_01.html
(43) Japan Rubber Weekly, April 24, 2018, Special Feature: Basic Technologies Supporting the Development of Fuel-Efficient Tires, https://gomuhouchi.com/tire/13438/ (in Japanese)
(44) Mazaki et al., High Performance UV Cut Tempered Automotive Glass "UV verre Premium-TM", Research Reports Asahi Glass Co., Ltd., Vol. 61, (2011) (in Japanese)