MATERIALS

1 Introduction

The materials used in automobiles are evolving to meet needs that include reducing the vehicle weight, lowering cost, improving appeal and sales, pursuing higher levels of safety, reducing the amount of CO_2 produced during driving, and staying in compliance with ever more stringent exhaust emissions regulations. These needs have recently been growing even more diversified to encompass decreasing the amount of CO_2 produced during vehicle manufacturing and making more effective use of scarce resources. In response to this great variety of demands from society and vehicles, not only are the properties of the materials themselves being improved, but the applicable range of high-performance materials is also being expanded by devising new manufacturing and processing techniques.

Research and development to refine technologies that join together different materials in combination parts that possess complex functions, as well as other fine-tuned technologies, is also being vigorously pursued. A great deal of research and development is also being carried out on materials for the powertrains of electric vehicles. The following sections will summarize the technological trends seen in the field of automotive materials during 2016.

2 Ferrous Materials

2. 1. Steel Sheets

The social environment surrounding automobiles is severe as consumers are demanding lower cost, while insisting on safe and lightweight vehicles at the same time. Recently, manufacturers have been moving away from steel sheets toward alternative materials with low specific gravity to achieve high vehicle fuel economy targets. However, ferrous materials offer excellent cost performance and are a mature solution technology, and therefore remain the main material of choice for automobiles. In recent years hybrid electric vehicles (HEVs) and electric vehicles (EVs) have expanded greatly in popularity and so the importance of ferrous materials as magnetic materials has increased all the more. The main portions of an automobile to which ferrous materials are applied can be divided as follows: (1) vehicle frame parts, (2) outer panel parts, (3) chassis parts, and (4) motor parts.

2. 1. 1. Vehicle Frame Parts

Vehicle frame parts have been developed to have extremely high levels of strength so that they can provide both good collision safety (absorbing energy in a collision and ensuring the interior cabin space is protected) and also reduce vehicle weight. The main technologies involved are cold-formed high-tensile strength steel sheet and hot stamping. Cold-formed high-tensile strength steel sheets (high-tensile steel) in the 590 to 780 MPa class have been developed and applied to the energy absorption members in the front and rear frame (members that deform in a collision), while an ultra high-tensile steel material in the 980 to 1,180 MPa class has been developed and applied to the members that ensure the interior cabin space is protected (members that do not deform in a collision)[(1)(2)]. In recent years, a 980 MPa class high-tensile steel featuring both ductility and localized bendability was developed to suppress material rupture during collision deformation and it was adopted for in some energy absorbing members[(3)]. In addition, the applicable locations for that material are expanding in conjunction with improvements in formability and stamping technology, as well as advances in the development of spot welding techniques[(4)] and prediction technologies such as CAE[(5)].

Ultra high-tensile steel material is also produced on a global scale[(6)], which helps to expand its usage.

The use of hot-stamped materials, where molding and quenching are performed simultaneously within the die after heating the steel sheet, is also increasing, and there is a transition from the conventional 1,470 MPa class to an even stronger 1,800 MPa class material. At the same time, hot stamp molding simulation technologies are being developed for use in combination with both tailor welded blanks (TWB), which are formed by joining together individual sheets of steel of different thicknesses and strengths, and the tailor rolled blank (TRB) method, in which the steel sheet has a continuous thickness transition in the rolling direction. The development of these techniques, as well as various other molding technologies, such as steel sheet with different levels of strength in different portions due to fine temperature control during cooling in the mold[7][8], are enabling the forming of integrated, large-size members that are normally very difficult to mold. The possible application of these members to the energy absorption regions of the vehicle frame are being examined[9]. These members have been applied to large-size parts, such as the door ring structure, as well as to portions of the front and rear frame[10]. In the future the application of these parts is expected to expand even further.

2. 1. 2. Outer Panels

Ultra-low carbon steel is widely used for outer panels due to its high level of formability and surface quality, which are required to realize distinctive styling. These outer panels dominate the external appearance that constitutes one of the crucial aspects of the product appeal of an automobile. Bake-hardened type high-strength steel, which increases yield strength through a paint baking process, has been adopted for outer panel parts with a large surface due to its significant weight reduction effect. This results in lighter panels that also retain formability and performance. Although sheets with a strength class of 340 MPa used to predominate, the recent development of 440 MPa class material has led to even thinner parts[11] that have started to be used for door outer panels. At the same time, the use of highly lubricated steel sheets is also continuing to expand because the ability to form complex shapes with lower molding grade materials reduces cost.

Thicker high-tensile steel in the 440 MPa class or higher, rather than thinner sheets, are starting to be used in side outer panels as vehicle frame part functions are being integrated in the side outer panels to decrease the number of reinforcement parts required to protect the interior cabin space and thereby reduce vehicle weight. The development of TWB technology to produce 590 MPa and 780 MPa class outer panels has allowed their partial adoption on some vehicles[12].

2. 1. 3. Chassis Parts

Since chassis parts are critical safety parts in terms of vehicle functionality, they have strict strength, durability, corrosion resistance and other requirements and do not use of 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 applied to steel wheel rims.

Chassis parts are required to have various forming characteristics, such as stretch-flanging ability and hole expandability, and several types of steel sheets different from those for vehicle frame members have been developed as high-tensile steel materials for chassis applications[13].

2. 1. 4. Motor Parts

The growing popularity of HEVs and EVs is pushing the development of high-performance steel sheet materials for automobiles into the new area of electromagnetic steel sheets for use in the iron cores of motors for EVs.

Motor efficiency improves as the iron loss of the electromagnetic steel sheet decreases and torque also improves as the saturation magnetic flux density increases. This means electromagnetic steel sheets with low iron loss and high saturation magnetic flux density are required, but these two properties generally have a trade-off relationship. There are also growing demands for materials with both high strength and low iron loss to make reducing the size and increasing the speed of electric motors possible, and various types of electromagnetic steel sheets have been developed and put into practical use in accordance with different usage conditions[14].

2. 2. Structural Steel

Structural steel is a material that can obtain the required strength through forging and heat treatment. It is mainly used in high-strength parts such as powertrain and chassis parts. Although elements such as molybdenum or vanadium have been added to steel to strengthen material while reducing its weight, concerns about cost reduction and material risk have shifted efforts toward the development of materials with lower quantities of these expensive 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 used to reduce heat treatment costs and energy consumption.

In the past, the bending fatigue strength of the fillet parts of crankshafts was increased by applying compressive residual stress via a surface rolling process. More recently, however, the use of high-frequency induction hardening to increase the hardness and residual stress has made it possible to return to the use of standard materials instead of high-strength materials. At the same time, a material that achieves the same strength as the current high-strength materials by increasing the amount of general purpose manganese and decreasing the amount of carbon without relying on the rare metal molybdenum has been developed and put into practical use for non-heat treated crankshafts manufactured via gas soft nitriding. The amounts of these components can be adjusted to increase the hardness in the vicinity of the surface after soft nitriding and suppress the cracking that occurs during straightening[15][16].

Efforts to reduce inertial force and friction loss through weight reduction have been complemented with the addition more vanadium to improve the strength and yield ratio, and the optimization of the structure and component elements to develop a high-strength steel with good machinability for connecting rods[17].

2. 2. 2. Drivetrain Parts

Due to the requirements of a high level of dedendum fatigue strength, impact strength, and resistance to pitting, carburized gears are generally used as the gears constituting the main component of the transmission. Cold forging is used to form these gears to rationalize the manufacturing processes and reduce costs, but the subsequent carburizing process tends to be prone to abnormal austenite grain growth.

As a countermeasure, the component elements were adjusted and a material that achieves the same level of required strength while also suppressing the abnormal grain growth was developed by replacing the expensive additive elements conventionally used to give the gears high strength, such as molybdenum and nickel, with other general-purpose elements[18][19].

A different approach involved focusing on nitriding technology, which causes little heat treatment strain in lower temperature treatments, and optimizing the amount of elements such as carbon, chromium, and vanadium to develop a steel material for nitrided gears that possesses the same level of strength as carburized gears[20].

2. 2. 3. Chassis Parts

Spring and bolt wire rods are used for springs and bolts, and the proactive addition of alloying elements has been the primary approach to improving properties in response to the demand for higher strength aimed at reducing weight.

In contrast, high-strength steel with few alloying elements for use in suspension springs[21] and a medium carbon steel wire rod for cold forging, which has improved formability due to controlling the structure using isothermal transformation[22], have both been developed from the standpoints of reducing the cost, ease of raw material procurement, and increasing the level of functionality.

2. 3. Stainless Steel

Stainless steel is a material that combines iron with at least 11% chromium. It has excellent heat and corrosion resistance and is often used in the exhaust systems of vehicles and for decorative molding. The most common types are ferritic and austenitic stainless steels. Ferritic stainless steel is relatively 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. As the need to further improve fuel economy keeps increasing, the demand for a material that can withstand the higher exhaust gas temperatures in lighter weight vehicles and engines with improved combustion efficiency has been growing. Typical heat-resistant ferritic stainless steel materials used in vehicle exhaust systems include SUS429, which has strong high temperature characteristics thanks to the use of niobium, and SUS444, which is steel with molybdenum added for applications requiring even higher heat resistance. 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 SUS429 by substituting copper as the additive, and another type of steel that uses far less molybdenum than SUS444 was developed by combining niobium, copper, and trace amounts of molybdenum as additives[23][24].

In contrast, austenitic stainless steel is mainly used for flexible tubes that are required to have good corrosion resistance, high temperature strength, and machinability. A new type of austenitic stainless steel that adds a combination of silicon and molybdenum to achieve corrosion resistance at high temperatures superior to that of the existing SUS316L and SUSXM15J1 has recently been developed[25].

2. 4. Cast Iron Materials

Castings are widely used for many vehicle parts because they not only offer a high degree of freedom in shape design and enable the mass-production of parts with complex shapes, but also have excellent workability, wear resistance, vibration damping properties, and a low cost.

Cast iron is used for engine parts such as camshafts, manifolds, and turbocharger housings, as well as chassis parts such as knuckles, brake rotors, and various types of arms.

The design requirements for cast iron parts are becoming increasingly stringent, and issues such as optimizing heat treatments and the adjustment of components to obtain even higher levels of strength and toughness need to be addressed[26]. One of these issues is developing cast iron materials for exhaust system parts in downsized turbocharged engines. These parts require good heat resistance, and research into the manufacturability of austenitic heat-resistant cast iron, which has been identified as a candidate material, is underway[27].

At the same time, a new spheroidal graphite cast iron material with high strength in the 700 MPa class aimed at reducing the weight of chassis parts has been developed and put into practical use to manufacture thinner knuckles[28].

2. 5. Iron-Based Sintered Materials

Since sintering fills the mold in the shape of the product with metallic powder and heat hardens it after compacting, it is superior to other processes in terms of producing products in their final or almost final shape. These special characteristics are used to manufacture parts that require good wear resistance, such as sprockets or bearings, as well as parts that also require good heat resistance, such as valve seats or valve guides. In addition, research on sintered materials suitable for sintered carburized gears intended for use in automotive transmissions is also being carried out[29].

Magnetic materials are another product manufactured with the sintering process. Highly efficient and high-output magnetic materials are required in the electric motors that provide the drive power in HEVs and EVs.

Neodymium magnets are widely used as the magnetic material in electric drive motors. Adding dysprosium is an effective means of securing the magnetic properties and improving the heat resistance, which is essential. However, it is rare and expensive and, as with other rare metals, alternate technologies are being developed to reduce material risk. Consequently, it is also essential to elucidate the coercive force mechanism of magnets and research to clarify this issue is now being undertaken[30].

3 Nonferrous Metals

3. 1. Aluminum Alloys

The aluminum materials used for automotive parts have been applied to various different parts as replacements for steel materials due to the growing desire to reduce vehicle weight.

The reason for this is that compared to other nonferrous materials, aluminum can be used in a larger array of forming and machining processes, such as rolling, forging, extrusion, and various casting methods, making it a viable candidate for use in a wide range of parts. In addition, a stable supply of raw material is available, and the formation of a passive film on the surface gives it excellent corrosion resistance.

In particular, the amount of aluminum closure parts (lids) used on automobile bodies has been increasing on a global scale[31].

In recent years, multi-material design has become more prevalent in automobiles, and plastic materials are also increasingly used in combination with other materials, including steels and carbon fiber reinforced plastics (CFRP). There has been remarkable technological advancement in the techniques required to join together these different materials, as well as in electrolytic corrosion prevention techniques[32-37].

There has also been an increase in the number of cases where thin, large-sized casting parts manufactured via high pressure die casting (HPDC) were applied to vehicle frame parts and chassis parts. This is due to the reduction in costs resulting from part consolidation and the new possibilities in part design afforded by the application of rib structures and hollowing to produce parts with high space efficiency and high rigidity[38].

These manufacturing methods have been raising the overall strength of aluminum materials. At the same time, component design, processing technologies, as well as structural design and usage of parts that takes stress corrosion cracking (SCC) into consideration are all being developed to cope with the contradictory demands of good formability and maintaining toughness.

In addition, the superior recyclability of aluminum is leading to a transition away from the conventional uses of secondary aluminum alloy ingots from the recycled mass toward the expansion of recycling technologies that maintain the same level of material performance[34].

3. 2. Magnesium Alloys

Magnesium alloys have a small specific gravity in comparison to the other metal materials used in automobiles and are mainly used as a lightweight structural material for cast parts. However, despite their advantages of high specific strength and high specific rigidity, magnesium alloys have seen limited application as a material for panels such as outer panels due to their low corrosion resistance and the poor plasticity and formability caused by their crystalline structure.

The recent development of a wide range of new rolling techniques have led to the introduction of vehicle models with large outer panels, such as hoods and roofs, formed using superplastic forming (SPF)[39].

Magnesium alloys are often used as cast members due to their poor formability. Consequently, flame retardant technologies that do not use rare earth metals and surface treatment technologies that provide high corrosion resistance and high durability have been developed to address the issues limiting the application of these alloys[40][41].

Lithium ion batteries have become the main type of secondary battery used in the electric power plants of automobiles. Magnesium secondary batteries, which offer the promise of further improvement in battery performance, are also being developed, but large hurdles, such as the electrode material and electrolyte, must still be cleared[42][43].

3. 3. Titanium Alloys

Titanium alloys are lighter than steels, and also have excellent high temperature strength, and high corrosion resistance, making them valuable in a broad range of fields that includes aerospace technology, chemical plants, and even sporting goods.

An increasing number of mass-production automobile parts that capitalize on these material characteristics, including motorcycle exhaust pipes, mufflers, and fuel tanks, are being produced[44]. Fracture-split (FS) titanium connecting rods have also been put into practical use in the same way as steel connecting rods[45][46]. However, the automobile industry has found that titanium leads to higher costs because it has a lower specific rigidity than steels, a higher raw material cost, and poor formability. Consequently, the application of titanium alloys has been limited to racing vehicles and a subset of sports cars.

4 Nonmetallic Materials

4. 1. Ceramic Materials

The ceramic materials used in vehicle parts are classified into ceramics for exhaust gas purification catalysts, electroceramics, which are used in various sensors, and a wide variety of coatings.

In the exhaust catalyst, honeycomb ceramics made of cordierite are used as catalyst supports because of their excellent thermal shock resistance, and the honeycomb structure is coated with a functional ceramic powder, such as alumina or ceria, which contains precious metal to act as the catalyst. In addition, cordierite and silicon carbide are molded into a filter structure and used to capture particulate matter.

Electroceramics are selected based on their functions and electrical characteristics. For example, zirconia is used for NO_x sensors, alumina is used for spark plugs, silicon nitride is used for glow plugs, and lead zirconate titanate is used for knock sensors. Recently, lead-free ceramics materials have also been developed.

In terms of ceramic coatings, hard thin-film treatments (CrN, TiN, and DLC) have been applied to parts such as the piston rings, valve lifters[47], and piston pins[48], to improve the friction and wear characteristics of the engine. In addition, a technique that forms a silica-reinforced, porous anodic oxide film on the upper portion of the piston in an aim to improve the thermal efficiency of the engine has been developed[49].

4. 2. Plastic Materials

Since plastic materials are lightweight and have excellent shape flexibility, the proportion of plastic used in vehicles has been rising, and the amount of plastic materials used is expected to increase as their applications extend to more and more locations.

At the same time, to address both environmental and energy issues the use of plastics derived from recyclable materials or plants is also being promoted.

4. 2. 1. Exterior Parts

Polypropylene (PP) has excellent formability and good cost performance, so it is widely used for vehicle exterior parts, such as bumpers. Plastic materials are also used in fenders and back door panels to expand the scope of weight reduction and shape flexibility. At the same time, CFRP, which has been introduced in airplanes, is also attracting attention despite cost and productivity issues. The benefits of its high strength and low specific gravity are being leveraged for use in vehicle roofs and hoods[50]. In addition, carbon fiber reinforced thermoplastics (CFRTP), which use thermoplastic resin in an effort to shorten cycle times and improve collision energy absorption performance in comparison to CFRP, are also attracting attention and their use is also expected to expand in the future.

4. 2. 2. Interior Parts

The vehicle interior is where passengers spend all their traveling time, so the materials used there are required to be comfortable and provide a high-quality feel. The methods used to express this high-quality feel start, of course, by improving the visual design, but the quietness of the interior obtained through the application of sound absorbing material and the textures of the parts touched by the occupants are also important. Especially in recent years, there has been a remarkable improvement in the interior textures due to the expanded use of soft pads as well as inexpensive but stylish raw materials, even in smaller cars.

At the same time, increased attention has also been paid to the smell of brand new vehicles, as well as to reducing the amount of volatile organic compounds (VOC) as means of providing a comfortable interior space. This is particularly true in China, which has now become the world's largest automobile market and where consumers have a high level of interest in the air quality of the vehicle interior. Consequently, it has becoming increasingly important to take volatile substances into consideration when selecting interior materials, from the raw materials stage all the way up to management of the manufacturing process.

4. 2. 3. Engine Parts

Polyamide (PA), a plastic material used in engine components, offers excellent heat resistance and has therefore been used for parts such as the intake manifold and the radiator tank. Newer variations of this material featuring low water absorption and resistant to calcium chloride have been developed, expanding their use to additional parts such as intercooler tanks or thermostats. In contrast, PP materials are adopted in parts such as radiator supports, air cleaner housings, and resonators to help reduce the weight and cost of engine parts[51].

4. 3. Rubber Materials

Rubber materials exhibit unique viscoelastic properties and are used in parts such as tires, hoses, weather strips, and vibration-absorbing rubber in mounts and bushings.

In tires, advances in technology have sought to achieve both good fuel efficiency and wet grip performance. Dispersant is now used to counter the increased silica content and nano-sized silica has also been adopted[52].

The engine compartments in modern vehicles are becoming more compact, subjecting engine parts to more severe usage environment. Materials with excellent high-temperature durability, such as ethylene propylene diene rubber (EPDM), acrylic rubber (ACM), and fluorocarbon rubber (FKM) are now being used for rubber hoses.

A low-foaming EPDM rubber material is now increasingly used to reduce the weight and cost of weather stripping, and new materials are being developed to achieve even greater environmental friendliness, new functionality, and additional properties.

Natural rubber is still the main material used for vibration-absorbing rubber applications and chloroprene rubber is also starting to be used for this purpose. However, the further electrification of vehicles in the years ahead has been prompting efforts to develop new vibration-absorbing rubber materials[53].

4. 4. Glass Materials

Automotive glass is designed to provide many functions, from blocking ultraviolet and infrared light, to soundproofing and repelling water. These glass materials are being applied not only to the windshield and front door glass, but also to the rear door and rear window glass.

In addition, the application of an interlayer, which allows text or maps to be displayed on the entire windshield to improve safety and provide smart-device interactivity in the vehicle interior, is expanding to more models[54]. This is expected to see even wider usage as automated driving becomes more commonplace.

At the same time, resin glass is also increasingly being adopted for use on automobiles for the purpose of reducing weight. Polycarbonate (PC) is typically used as a resin glass material due to its transparency and impact resistance, but since this material has poor weather and wear resistance, it requires the application of a hard coating, which leads to higher costs. Consequently, a transfer technique that can replace the hard coating with the application of a film with the ability to conform to curved surfaces is being developed[55].

Windshields that can generate heat and other innovative glass materials are anticipated to see wider adoption in the future to reduce electric power consumption in electric vehicles.

4. 5. Paints

Automotive paints have evolved into a shortened process paint system that aims to reduce the length of the painting process and thereby reduce the CO_2 emissions from the assembly plant. In addition to base coats that have good chipping resistance and provide a light blocking function to electrodeposition, there are base coats that express color and achieve both color variation and a quality finish, by using wet-on-wet technique to apply successive clear layers, followed by baking and curing. Other paint materials and systems that can help to further reduce CO_2 emissions are under consideration[56]. The successive layering of different color layers is also being employed to offer new value to customers. In addition to the application of an orientation technique for bright pigments via control of the amount of moisture transfer when the achromatic color is wet, specifying the lightness of the reflective layer and the light transmittance of the colored layer makes is possible to mass produce high-chroma saturation colors for chromatic colors as well. Moving forward, additional examinations will be carried out to help create even more value for the customer[57].

For electrodeposition coatings on the vehicle body, CAE is used as a technology to predict the throwing power of electrolytic coloring by simulating the film thickness distribution over the entire body. This is used to optimize the design of the vehicle body structure, and additional research to further improve the accuracy of that predictive technology is also being conducted.

References

(1) Ishiuchi et al., "Application development of the high formability 1.2GPa ultra high strength steel," JSAE Annual Congress (spring), No. 76-13, 20135420, pp.9-11 (2013)

(2) Fukuhara et al., "The World's First Development of 1.2GPa Ultra-High Strength Steel with High Formability," Nissan Technical Review 2015, No. 76, pp.5-9 (2015)

(3) "All of the HONDA CLARITY FUELL CELL", pp.25-26, San-eishobo Printing (2016)

(4) Kobe Steel press release, Development and adoption of Automotive cold-rolled high-tensile (2011.10.5)

(5) Ueda et al., JSAE Transactions Vol.46, No.3, pp.687-692 (2015)

(6) Nippon Steel & Sumitomo Metal press release, http://www.nssmc.com/news/20150525_100.html (2017. 4. 28)

(7) Fukuchi et al., "Development of High-productivity Hot Stamping Technology" (in Japanese), JSAE Journal, Vol. 68, No. 2, pp.111-112 (2014)

(8) Robert Zum Mallen, Joe Riggsby: AUTOMOTIVE ENGINEERING CONGRESS 2013

(9) Senuma et al., Transaction of ISIJ (Testu-to-Hagane) Vol. 100, No. 12, pp.49-57(2014)

(10) Nikkei Automotive Technology, No. 45 (November), pp.46-51(2012)

(11) JFE Technical Review, No. 30, pp.48-50 (2012)

(12) Nakao, 81st Japan Laser Processing Society Congress (2014.5)

(13) Uenishi et al., JSAE Forum, No. 20134363, pp.7-12(2013)

(14) Oda et al., JFE Technical Review, No.36, pp.6-11 (2015)

(15) Takahashi et al., "Development of Steel for High-strength Crankshaft by Precipitation Strengthening of Mn-nitride," Honda R&D Technical Review, Vol. 84, No. 2, pp.138-145 (2013)

(16) Takasu et al., Nippon Steel & Sumitomo Metal Technical Review, No.406, pp.2-7 (2016)

(17) Shinohara et al., JSAE Transactions, Vol.46, No.4, pp.825-829 (2015)

(18) Maruyama et al., SANYO SPECIAL STEEL Technical Review Vol. 22, pp.21-28 (2015)

(19) SANYO SPECIAL STEEL Technical Review Vol. 23, No.1 pp.74-78 (2016)

(20) Imataka et al., Nippon Steel & Sumitomo Metal Technical Review, No.406, pp.8-12 (2016)

(21) Masuda, Journal of ISIJ Vol. 20, No.12, pp.606-612 (2015)

(22) Okonogi et al., Nippon Steel & Sumitomo Metal Technical Review, No.406, pp.64-69 (2016)

(23) Kajimura, Journal of ISIJ Vol. 20, No.12, pp.621-626 (2015)

(24) Hamada et al., Materia Japan Vol. 56, No. 1, pp.3-35 (2017)

(25) Hirade et al., Proceeding of JSAE Annual Congress (autumn), pp.367-370 (2016)

(26) Hatate, Journal of ISIJ Vol. 20, No. 9, pp.423-428

(2015)
(27) Kawahata et al., Hitachi Metals Technical Review, Vol.32, pp.8-13 (2016)
(28) J. Nichols: Cost Competitive Light-Weighting Material Developments for Commercial Vehicle Applications, SAE Technical Paper 2013-01-2419 (2013)
(29) Nishida et al., Kobe Steel Technical Review, Vol. 66, No. 1, pp.61-67 (2016)
(30) Yano et al., JSAE Journal, Vol.49, No.11, pp.56-62 (2015)
(31) JAPAN ALUMINIUM ASSOCIATION, http://www.aluminum.or.jp/jidosya/japanese/07/07Localindex.html (2017.4.28)
(32) Automotive Circle International: EURO CAR BODY 2016, http://www.automotive-circle.com/Review/EuroCarBody-2016 (2017.4.1)
(33) Automotive Circle International: EURO CAR BODY 2015, http://www.automotive-circle.com/Review/EuroCarBody-2015 (2017. 4. 1)
(34) Automotive Circle International: AUTOMOTIVE CIRCLE, http://www.automotive-circle.com/Review/Insight-Edition-Ford-USA-2015 (2017.4.1)
(35) Automotive Circle International: AUTOMOTIVE CIRCLE, http://www.automotive-circle.com/Review/Insight-Edition-Daimler-AG-2015 (2017.4.1)
(36) Automotive Circle International: AUTOMOTIVE CIRCLE, http://www.automotive-circle.com/Review/Insight-Edition-General-Motors (2017.4.1)
(37) Automotive Circle International: AUTOMOTIVE CIRCLE, http://www.automotive-circle.com/Review/Insight-Edition-BMW-2016 (2017.4.1)
(38) A. Asami, T. Imanishi, Y. Okazaki, T. Ono, K. Tetsuka: Development of Aluminium Hollow Subframe Using High-Pressure Die Casting, SAE Technical Paper, 2016-01-0406 (2016)
(39) Thorsten Becker:z: Magnesium roof panel of the new Porsche911 GT3 RS, Aachen Body Engineering Days 2015, pp.260-272 (2015)
(40) Nikkan Kogyo Shimbun, 2016.8.4
(41) Kurimoto Ltd., News Release, http://www.kurimoto.co.jp/release/pdf/technology20160804-01.pdf (2017.4.28)
(42) Nihon Keizai Shimbun, 2016. 10. 9
(43) Saitama Industrial Technology Center (SAITEC) press release, http://www.pref.saitama.lg.jp/a0001/news/page/160119-01.html (2017.4.28)
(44) Honda Technical review, http://www.honda.co.jp/tech-views/tank/titantank/ (2017.4.28)
(45) Japan Institute of Light Metals, Lecture at the 51st Oyamada Memorial Award
(46) Kubota, Journal of SOKEIZAE Center, Vol. 50, No. 5, pp.2-8 (2009)
(47) Nobuo Sakade, Materia Japan Vol. 53 No. 12, pp.599-602 (2014)
(48) Oerlikon Nihon Balzers Coating, https://www.oerlikon.com/balzers/jp/ja/ (2017.4.27)
(49) Wakisaka, JSME Journal, Vol. 119, No. 1174, pp.525 (2016. 9)
(50) Nagai et al., JSAE Journal, Vol. 69, No. 4, pp.8-14 (2015)
(51) Kuraray, http://www.kuraray.co.jp/release/topics/2015/pdf/150825_jp. pdf (2017. 4. 27)
(52) Yokohama Rubber, http://www.yokohamatire.jp/yrc/japan/tire/brand/bluearth/bluearth1_ef20.html (2017. 4. 27)
(53) Bridgestone news release, http://www.bridgestone.co.jp/corporate/news/2015121701.html (2017.4.27)
(54) Sekisui Chemical, http://www.s-lecfilm.com/product/auto/hud/index.html (2017.4.27)
(55) Dai Nippon Printing news release, http://www.dnp.co.jp/news/10131364_2482.html (2017.4.27)
(56) Kojima, Proceeding of JSAE Annual Congress, No. 54-12, pp.5-8 (2012)
(57) Kojima, “Method for forming multi-la