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Technical Report

Applications of Titanium for the Automotive Sector

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Abstract

The application of titanium to automotive parts began with the use for race cars, and now its use in mass-produced cars has started to increase. Nippon Steel Corporation has been expanding the type of applicable parts by utilizing the characteristics of titanium such as workability, heat resistance, and design in addition to its light weight, high mechanical strength, and corrosion resistance. This paper describes the recent examples of the application of titanium for automotive parts and those parts for which titanium is expected to be applied in the future.

1. Introduction

Titanium, as a lightweight, high-strength, and highly corrosion-resistant material, has been used in aircraft, heat exchangers using seawater as a refrigerant, and seawater desalination plants. Furthermore, its application has been expanded to consumer products, sports and leisure applications, and construction materials because of its heat resistance, biocompatibility, design, and amenity.[1)]

In addition, the number of applications in automotive parts is increasing due to these titanium characteristics. In particular, motorcycles and automobiles which are required to have high dynamic performance, such as racing cars, need to improve the time on the circuit and have a good response. Therefore, titanium is often applied to thoroughly reduce weight and increase output. In this paper, examples of titanium applications in automotive parts are introduced and parts, for which titanium is expected to be used in the future, are described.

2. Examples of Titanium Applications in Automotive Parts and Future Expectations

2.1 Fuel tanks

The weight reduction of fuel tanks is an important issue because it leads to the improvement of fuel economy and dynamic performance by lowering the center of gravity, especially for motorcycles. High-density polyethylene, which has been widely used as a lightweight material in recent years, needs to be multilayered with ethylene-vinyl alcohol copolymer (EVOH) resin as a barrier layer due to stricter fuel gas permeation regulations in EURO 5, which has been applied to motorcycles since 2020. As a result, the increase in mass due to the increase in thickness (approx. 4–7 mm) is inevitable. On the other hand, metallic materials have low fuel gas permeability, therefore the application of lightweight metals, namely aluminum and titanium, is being considered. Aluminum alloys, mainly the 5000 series, are possible candidates; however, they have issues of weldability and press formability. Since aluminum has a low melting point and high thermal conductivity, it is difficult to concentrate the welding heat input during arc welding, and burning through is likely to occur. In addition, spot welding of aluminum requires high pressure, high current, and short energizing times, which increase the initial cost of installing dedicated equipment. Furthermore, because of its low ductility and small Lankford value (r value), aluminum does not have good press formability for shapes that require deep drawing, such as fuel tanks. These facts indicate that it is difficult to make fuel tanks with thin walls using general-purpose equipment that is mainly used for manufacturing steel.

In contrast to this, titanium has almost the same melting point as iron and low thermal conductivity equivalent to stainless steel, which makes it difficult for burning through to occur during welding. In addition, spot welding can be performed only by adjusting the operating conditions, and no special equipment is required.[2)] In terms of press formability, titanium has excellent deep draw formability because it is a material with a high r-value. JIS Class 1 and ASTM Grade 1 commercially pure (CP) titanium, which has low O content, has overhang formability equivalent to that of low carbon steel for press forming, so this type of titanium is suitable for fuel tanks. However, unlike steel, it is prone to galling, and lubrication during press forming is an issue. In conclusion, titanium is considered to have lower application barriers for fuel tanks than aluminum alloys. In fact, after solving the mass-production issues including the optimization of conditions, the installation of a titanium fuel tank on a mass-produced motorcycle (**Photo 1**, Honda Motor Co., Ltd. 2017 model CRF450R) was realized for the first time in the world.[2)] The use of titanium has resulted in a significant weight re-

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Photo 1 Titanium fuel tank

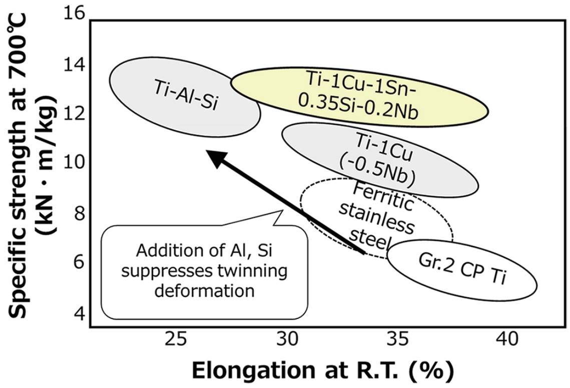

Fig. 1 Image of design concept of Ti-1Cu alloys

duction effect, which greatly contributes to performance improvement. Since titanium excels in corrosion resistance, it does not need to be painted to prevent corrosion. It is also expected to be applied to the fuel tanks of automobiles, which are close to the ground and require higher corrosion resistance.

2.2 Exhaust pipes

Since exhaust system parts use a large number of materials, the weight reduction effect obtained by using titanium is significant. Particularly in motorcycles, titanium, which is considerably aesthetic, has been used for a long time because the exhaust system (especially mufflers) parts are exposed. When titanium was first applied, JIS Class 2 and ASTM Grade 2 CP titanium was mainly used; however, as stricter emission control regulations made catalytic converters mandatory and thereby raised the exhaust gas temperature, heat resistance (mainly high-temperature strength and oxidation resistance) was required. Meanwhile, high formability is required due to the need to realize complex shapes.

To improve the strength at high temperatures, solid solution strengthening is effective, and Al, which has a high solid solution strengthening performance at high temperatures, is often added. Also, in order to improve oxidation resistance at high temperatures, a small amount of Si is often added. Thus, for designing titanium alloys for exhaust systems, Al and Si are commonly added. On the other hand, the addition of these elements also increases the room-temperature strength and decreases ductility. In particular, Al suppresses twinning deformation at room temperature, which could deteriorate formability. In contrast, the addition of Cu, which has a high solution strengthening effect at high temperatures but does not affect twinning deformation at room temperature and maintains formability, was found to be effective in achieving both high-temperature strength and high formability, two contradictory properties.[3]

Based on this fact, Super-TIX™ 10CU (Ti-1Cu) was developed with approximately 1% Cu added. Super-TIX™ 10CUNB (Ti-1Cu-0.5Nb) was also developed with the addition of Nb to improve oxidation resistance at high temperatures. Nb improves oxidation resistance because it suppresses oxygen diffusion on the titanium oxide scale, and also does not affect the solid solution of Cu. Nb addition does not reduce the high-temperature strength and does not deteriorate the formability at room temperature. In addition, Super-TIX™ 10CSSN (Ti-1Cu-1Sn-0.35Si-0.2Nb)[4,5] with improved high-temperature strength has been developed (**Fig. 1**). These alloys have been applied to motorcycles and automobiles (**Photo 2**, Nissan Motor Co., Ltd. GT-R) for use up to 700–800°C.

2.3 Engine parts

Engine parts are relatively small, and weight reduction is not considerably significant. However, weight reduction can reduce the inertia force generated when rotational or reciprocating motion is involved, which can improve the response performance. In addition, titanium is superior to other metals in terms of specific strength in the operating environment of engine parts and it is especially applied to connecting rods and engine valves, where the cost performance of using titanium is high.

Photo 2 Ti-1Cu muffler

2.3.1 Connecting rods

The connecting rod is an engine component that converts the reciprocating motion of the piston into rotational motion. Reducing the weight of the connecting rod is highly effective in improving engine response, increasing power output by reducing friction loss, and further reducing weight by making peripheral parts smaller and simpler.[6] So far, Ti-6Al-4V has been used for connecting rods in motorcycles,[7] and Ti-3Al-2.5V-REM has been used in automobiles.[8] Since the V, which is contained in these alloys, is expensive, Super-TIX™ 51AF (Ti-5Al-1Fe) was developed, which contains Fe, a less expensive material than V. This alloy has almost the same fatigue strength as the conventionally used Ti-6Al-4V, while it shows good hot workability and is also easy to adopt the FS (Fracture Splitting) method, which is commonly used for steel connecting rods.[9] With these features, Ti-5Al-1Fe contributed to the world's first mass-produced titanium connecting rods using the FS method, and has been used in the 2015 model of the YZF-R1 and other models of Yamaha Motor Co., Ltd. (**Photo 3**). This alloy is also characterized by its excellent machinability, contributing to cost improvement in the production of connecting rods.

2.3.2 Engine valves

Engine valves are reciprocating motion parts, and as with connecting rods, weight reduction has a significant effect on improving response in the high rpm range. In addition, reducing the size of peripheral parts is possible. Titanium material has to have sufficient fatigue strength to withstand the stresses from the camshaft and

(a)

(b)

Photo 3 (a) Yamaha Motor Co., Ltd. YZF-R1, (b) Ti-5Al-1Fe connecting rod

Photo 4 Titanium engine valve

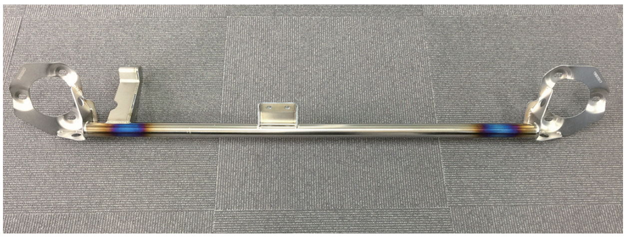

Photo 5 Titanium strut bar

valve seat at each opening and closing when it is used for engine valves. Furthermore, since exhaust engine valves are directly exposed to exhaust gas, fatigue strength and creep resistance at high temperatures are required. Titanium alloys that satisfy these characteristics are used for intake and exhaust engine valves (**Photo 4**).

For intake engine valves, Ti-6Al-4V and Super-TIX™ 523AFM (Ti-5Al-2Fe-3Mo)[10] with various anti-wear treatments[11] are used. The latter is an alloy designed to have a higher beta-stabilizing ability and higher strength than Ti-6Al-4V, and its use in intake engine valves is increasing because of its high strength and high fatigue properties.

For exhaust engine valves, near α-type alloys developed for aircraft engines (Ti-6Al-2.7Sn-4Zr-0.4Mo-0.45Si, Ti-6Al-2Sn-4Zr-2Mo-0.1Si (Ti-6242S), etc.) are mainly used.[12] This is because (i) the proportion of α-phase, which is effective for high-temperature strength, is maintained high up to the high-temperature range, so that they have higher strength than that of Ti-6Al-4V and Ti-5Al-2Fe-3Mo in environments above 500°C, (ii) the fatigue strength at 800°C is equivalent to that of heat-resistant steel SUH35 (Fe-0.55C-9Mn-21Cr-4Ni-0.45N), and they have a high specific strength (fatigue strength/density). As for the fatigue properties of engine valves, the effects of microstructure and surface treatment are described in another article in detail and referring to that paper is recomended.[13]

2.4 Reinforcing and stiffening parts, subframes

Reinforcing and stiffening parts are sometimes installed to improve the rigidity of the vehicle body when a good response is required. Typical examples are the parts that connect the strut towers that support the left and right suspensions (strut bars) and the parts that connect various parts under the car body (under braces), which are mainly made of steel. On the other hand, weight reduction is effective in controlling an increase in mass caused by the installation of additional parts.

Since these parts need to be installed in a limited space, high Young's modulus and high formability are required. From that perspective, titanium is a suitable material because it has a relatively high Young's modulus and good formability among lightweight materials. Recently, titanium has been applied to strut bars (**Photo 5**, Okuyama Co., Ltd.). While the need to reduce the environmental burden is increasing for the future, titanium contributes to this matter by the reduction of painting thanks to its high corrosion resistance. Therefore, we expect to see more applications of titanium in lower body parts such as subframes and braces.

2.5 Body panels

With the increasing need for weight reduction in automobiles, weight reduction of body panels (roof, hood, doors, etc.) is effective because of their large mass. In particular, weight reduction of the roof, which is located at the top of the vehicle body, can improve the dynamic performance by lowering the center of gravity. When a vehicle is manufactured, the roof is jointed to the body frame, which is mainly made of steel, and goes through the painting process. In the painting process, the paint is baked at approximately 170°C, which is considered to distort if the coefficient of linear expansion is large. The coefficient of linear expansion of titanium is 8.4×10^{-6}, which has a relatively small difference from that of steel (12×10^{-6}), and applying titanium to roofs could achieve weight reduction while suppressing the occurrence of distortion. In the future, to solve the problems of dissimilar metal bonding and mass production through technological development, application of titanium to body panels is desired.

2.6 Fuel cell components and electrification components

As the world aims to reduce carbon dioxide emissions as a countermeasure against global warming, electric vehicles powered by motors are being developed in the automotive field. There are two methods of supplying electricity to a motor: one is to store electricity in a battery from outside, and the other is to use a fuel cell (FC). In particular, vehicles that use fuel cells are called fuel cell vehicles (FCV). FCs are one of the clean energy sources that generate electricity by the electrochemical reaction of hydrogen and oxygen, and produce only water. Among them, polymer electrolyte fuel cells

(PEFC) have been applied not only to automobiles, but also to distributed power sources for households because of their high power density, light weight, and compactness. As shown in **Fig. 2**, a PEFC is composed of a number of layers of membrane electrode assemblies (MEA), which consist of a solid polymer membrane, electrodes, and a gas diffusion layer, and a structure (cell) with separators gripping both sides of the MEA. The separator is formed to have a gas flow path that supplies hydrogen and oxygen, and has the role of transmitting the current to the outside without allowing the gas to permeate. In addition, a large number of sulfate groups are coordinated in the polymer membrane to ensure conductivity, and sulfate ions may be leached into the produced water as the membrane degradation progresses. Therefore, when metal materials are applied to separators, formability for the gas flow path, low contact resistance with electrodes, and corrosion resistance under an acidic sulfuric acid environment are required.

Titanium has both formability and corrosion resistance, and titanium itself is electrically conductive. However, the passivation film formed on the surface has high electrical resistance, and improving the contact resistance with the electrode is an issue for separators. Therefore, technologies to achieve both corrosion resistance and low contact resistance have been studied, such as plating with precious metals including Au and Pt[14, 15] and deposition of C layers. As a result of these technological developments, a titanium separator has been adopted in Toyota Motor Corporation's MIRAI (FCV).

In addition to fuel cells, titanium is expected to be applied to motors, for which demand is increasing due to electrification. Motors, like engines, have rotating parts, and titanium alloys are suitable because of their light weight and high strength. Titanium is suitable for motor parts also because it is non-magnetic, and it is believed to contribute to the improvement of motor performance. In particular, Super-TIX™ 523AFM (Ti-5Al-2Fe-3Mo) can improve the strength and fatigue strength in the room temperature to medium temperature range (about 300°C) by appropriate heat treatment,[13] and its application is highly anticipated.

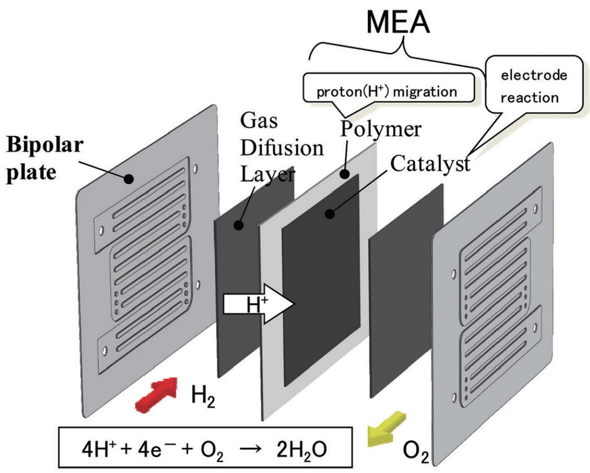

Fig. 2 Schematic diagram of PEFC

3. Conclusion

Taking advantage of the excellent material properties of titanium, the application of titanium to automotive parts has been steadily expanding, starting with racing cars and continuing to mass-produced cars. The variety of applications has expanded from engine parts such as connecting rods and engine valves to exhaust pipes, fuel tanks, and even fuel cell parts. In addition to its high specific strength, titanium has a combination of excellent properties such as high corrosion resistance, good formability, and low coefficient of linear expansion. This material has the potential to provide benefits other than weight reduction through material substitution. In the future, as mobility becomes more diversified, we would like to further promote the application of titanium to automobile manufacturers, parts manufacturers, and material manufacturers in order to expand the application merits afforded to automotive parts.

References

1) Tokita, M., et al.: Shinnittetsu Sumikin Giho. (396), 9 (2013)
2) Kawakami, A.: Ferrum (Bulletin of the Iron and Steel Institute of Japan). 23 (11), 6 (2018)
3) Fujii, H., et al.: Materia Japan. 48 (11), 547 (2009)
4) Otsuka, H.: Titanium Japan. 60 (2), 26 (2012)
5) Mori, K., et al.: CAMP-ISIJ. 27, 529 (2014)
6) Doi, K., et al.: Titanium Japan. 64 (1), 40 (2016)
7) Hagiwara, Y., et al.: Honda R&D Technical Review. 2, 229 (1990)
8) Masahashi, K.: Tokushuko (The Special Steel). 47 (11), 35 (1998)
9) Suzuki, T., et al.: Keikinnzoku (Journal of Japan Institute of Light Metals). 67 (2), 50 (2017)
10) Mori, K., et al.: Titanium Japan. 55 (2), 34 (2007)
11) Tominaga, T., et al.: Transactions of the Society of Automotive Engineers of Japan. 35 (1), 135 (2004)
12) Fujii, H.: Journal of the Japan Society for Technology of Plasticity. 56 (654), 530 (2015)
13) Mori, K., et al.: Nippon Seitetsu Giho. (418), 97 (2021)
14) Jung, H.-Y. et al.: Journal of Power Sources. 194, 972 (2009)
15) Wang, S.-H. et al.: Journal of Power Sources. 160, 485 (2006)

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