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Technical Report

Applications of Titanium and Its Alloys for Weight Reduction of Automobiles

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Abstract

Recently, weight reduction of automobiles is an important problem because of various regulations for automobiles. Therefore, automobiles comprising multiple materials, such as high-strength steel, titanium, aluminum, magnesium, and carbon-fiber-reinforced plastic (CFRP), have been produced. For the weight reduction of automobiles, titanium is a material used for a long time. This paper describes applications, remaining tasks, and the future of titanium for weight reduction of automobiles.

1. Introduction

The weight of automobiles has been increasing due to installed safety devices and other reasons, while there is demand for regulations on exhaust gas emissions to be stricter, so reducing the weight of automobile bodies is an important task. To that end, improving the specific strength of materials is important. Regarding steel, high-strength steel has been developed[1] and combined use of multiple types of materials has been promoted using lightweight metals (e.g., titanium, aluminum, and magnesium) and carbon-fiber-reinforced plastic (CFRP).[2] The use of titanium for weight reduction of automotive parts began in the 1980s mainly targeting racing cars. Titanium has been applied mainly to connecting rods, engine valves, and suspension springs. However, although the performance of titanium is high, the cost is also high, so it is used only for racing cars and high-class automobiles even now.

To reduce the costs of materials, Nippon Steel Corporation has replaced expensive alloying elements (V and Mo), which have been used for general-purpose titanium alloys, with inexpensive general-purpose elements and has developed the Super-TIX™ series.[3] This series has been used for automotive parts. In addition, to further reduce costs, Nippon Steel has been developing innovative processes for refining titanium sponges (raw material).[4] Meanwhile, the processing cost accounts for a larger portion in the parts production than the raw material cost, so measures to reduce such processing cost is required. Examples are the development of materials with better machinability[5] and stamping techniques considering the anisotropy specific to titanium. This paper introduces automotive parts for which titanium is used as a result of our past work, remaining tasks, and future prospects. For parts not mentioned in this paper, please refer to past reports and explanations.[6–8]

2. Automotive Parts for which Titanium is Used

2.1 Engine valves

Figure 1 shows the relationship between the tensile strength of various types of titanium alloys and temperature. Weight reduction of drive system parts also improves the responsiveness and reduces loads to peripheral parts, bringing further effects in addition to mere weight reduction of parts. Ti-6Al-4V is commonly used as intake valves that are used at approximately 300 to 400°C. Higher-strength Super-TIX™ 523AFM (Ti-5Al-2Fe-3Mo) developed by Nippon Steel has also been applied. Meanwhile, when the temperature exceeds 500°C, the strength of titanium rapidly decreases, so the material quality usable for exhaust valves that are used at approximately 700°C is limited. Ti-1100 (Ti-6Al-2.75Sn-4Zr-0.4Mo-0.45Si) and Ti-6Al-2Sn-4Zr-2Mo-0.1Si (hereinafter Ti-6242S) have been adopted in this case. They can resist high temperatures exceeding 500°C and their high-temperature strength is equivalent to that of heat-resistant steel SUH35. For exhaust valves, creep strength is also important besides fatigue strength, so they are often used as the acicular structure with excellent creep resistance.

As other heat-resistant titanium alloys, there is Ti-5.8Al-4Sn-3.5Zr-2.8Mo-0.7Nb-0.35Si-0.06C and the recently developed Ti-7Al-2Mo-0.2Si-0.15C-0.2Nb. Their grade is equal to that of Ti-6242S.[9] In addition, engine valves have sliding sections, but titanium's wear resistance is low, so it is enhanced by CrN and atmospheric oxidation. However, CrN is expensive, and, in addition, when inexpensive atmospheric oxidation is applied, creep deformation occurs during oxidation and an oxygen-hardened layer deterio-

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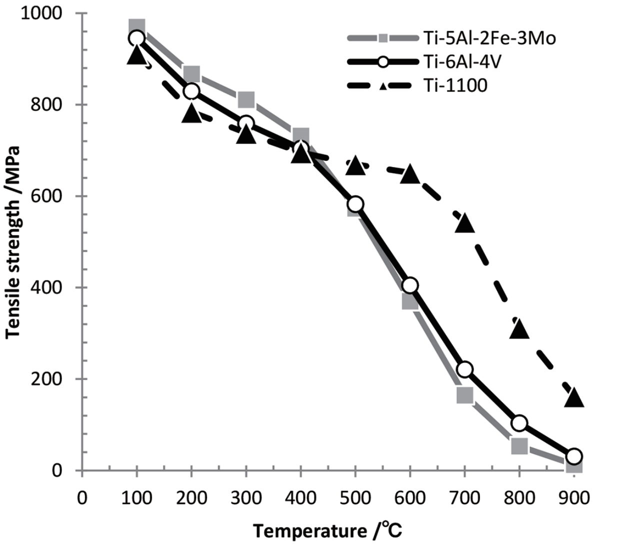

Fig. 1 Tensile strength of Ti-5Al-2Fe-3Mo, Ti-6Al-4V and Ti-1100 as a function of temperature
Materials were round bars hot rolled of area reduction of 95% or more in $\alpha+\beta$ region. Ti-5Al-2Fe-3Mo, Ti-6Al-4V were treated at 750°C for 1 h followed by air cooling. Ti-1100 was solution treated at 1 100°C for 20 min and 750°C for 1 h followed by air cooling.

Photo 1 Ti-5Al-1Fe connecting rod

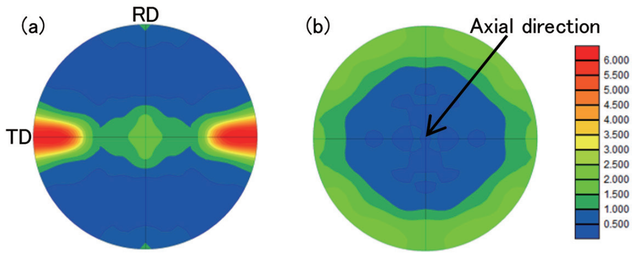

Fig. 2 (0001) pole figures of Ti-5Al-1Fe (a) Hot-rolled to sheet and (b) Hot-rolled to round bar

rates the fatigue strength. Therefore, when wear resistance is improved by oxidation treatment, appropriate oxidation conditions are set to minimize the deterioration of the fatigue strength.[10] Low-cost surface treatment technologies to attain both wear resistance and fatigue strength are required in addition to improvement of the high-temperature properties of titanium alloys in the future toward application in severer environments.

2.2 Connecting rods

Reducing the weight of connecting rods can enhance the responsiveness and increase the engine speed. The engine speed of motorcycles is particularly high, so a high specific fatigue strength (fatigue strength/mass) is required.[11] Meanwhile, the cost of processing titanium, such as hot working, cutting, and grinding, is high so the costs of raw materials and production need to be reduced in addition to improving its properties. For example, the hot deformation resistance of Nippon Steel's Super-TIX™ 51AF (Ti-5Al-1Fe) for which inexpensive general-purpose alloying elements are used is equal to or slightly higher than that of SCM420 and lower by 15 to 20% than that of Ti-6Al-4V. In addition, the machinability by a drill (maximum cutting speed at which cutting holes with a desired length can be bored) has been improved by approximately 15%.

In addition, its manufacturability is high and thereby the fracture-splitting (FS) method can be used. The method is used for steel connecting rods that can secure resistance to bearing stress in sliding sections. On general-purpose Ti-6Al-4V, the brittle fracture appearance required for the FS method is difficult to obtain since it is highly tough.[12] Meanwhile, the toughness of Ti-5Al-1Fe is lower than that of Ti-6Al-4V, so a brittle fracture appearance can be easily obtained. Yamaha Motor Co., Ltd. manufactured connecting rods using Ti-5Al-1Fe by the FS method and equipped YZF-R1 with them in 2015 (**Photo 1**). This reduced the weight by approximately 20% compared to steel connecting rods.

However, the Young's modulus of titanium is approximately half that of steel, so the thickness needs to be increased for titanium to secure rigidity of a similar level to that of steel and thereby weight reduction effects by the use of titanium have not been fully obtained. As a solution to this problem, controlling the orientation of titanium crystals with high anisotropy is effective. Orienting [0001] of the α phase (hcp structure) (main phase) can increase the Young's modulus.[13] In fact, for hot-rolled sheets, [0001] of the α phase can be oriented in the width direction (**Fig. 2**(a)) by heating in a range of a single β phase to perform unidirectional hot rolling, which can improve the Young's modulus in the width direction to 140 to 150 GPa. However, 150 GPa is only approximately 70% of that of steel and there is demand for an even higher Young's modulus. In addition, for many mass-produced round bars, [0001] of the α phase has not been oriented in the axial direction (Fig. 2(b)), so the Young's modulus of round bars in the axial direction is approximately 100 to 110 GPa. Thus, a high Young's modulus by controlling the crystal orientation has not been achieved. Possible future tasks required for materials are improvement of hot workability, machinability, and grindability from the perspective of costs and a higher Young's modulus from the perspective of properties.

2.3 Exhaust system parts

For exhaust system parts, titanium has been mainly used for motorcycle mufflers for surface design and weight reduction. However, as an environmental measure, there is demand for the temperature of exhaust gas to be increased, so it is becoming difficult for JIS Class 2 industrial pure titanium that has been used so far to resist such heat sufficiently. Therefore, various types of heat-resistant titanium alloys have been developed. Exhaust system parts are manufactured by forming thin plates, so workability at room temperature and high-temperature properties are required at the same time. Usually, when Al is used to enhance the high-temperature strength of titanium alloys, Al suppresses twinning deformation that significantly contributes to the workability of titanium. Therefore, although the high-temperature strength is enhanced, the workability deteriorates.

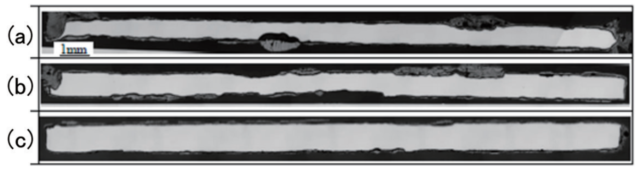

Fig. 3 Cross-section micrographs of specimens after the 5-cycle high-temperature salt damage tests at 700°C
Specimens are (a) Commercial pure titanium (CP-Ti), (b) Super-TIX™ 10CUNB and (c) Super-TIX™ 10CSSN. Specimen was grinded by emery paper #400. A test cycle was followed; 1) Dipped for 1 h in 5%NaCl aqueous solution, and 2) Oxidation at 700°C for 23 h in air.

Meanwhile, in Cu, the solution strengthening performance at high temperature is high and the degree of suppression of twinning deformation is small, so it is possible to retain workability at room temperature.

Therefore, Nippon Steel has developed Super-TIX™ 10CU (Ti-1Cu), Super-TIX™ 10CUNB (Ti-1Cu-0.5Nb), and Super-TIX™ 10CSSN (Ti-1Cu-1Sn-0.35Si-0.2Nb) using Cu that can maintain workability at room temperature while enhancing the high-temperature strength.[14, 15] In addition, for materials for exhaust systems, it is sometimes necessary to evaluate high-temperature salt damage resistance using snow melting agents used to prevent road surfaces from freezing. It has been reported that the Cu used by Nippon Steel for the developed materials accelerates high-temperature salt damage while Si and Nb suppress such damage.[16] It has also been reported that high-temperature salt damage is promoted by repetition of the following phenomena: 1) a reaction of NaCl steam and titanium oxide films produces Cl gas; 2) a reaction of the Cl gas and base material elements produces volatile chlorides; and 3) oxidation of chlorides produces Cl gas.[17] Therefore, Nb and Si that are additive elements that suppress atmospheric oxidation may suppress the oxidation of chlorides by reducing the supply of oxygen.

Figure 3 shows cross-section micrographs after high-temperature salt damage tests. On CP-Ti (commercial pure titanium), local oxidation is seen. Local oxidation is less seen on Super-TIX™ 10CUNB than on CP-Ti and much less seen on Super-TIX™ 10CSSN. These results show that, even when a titanium sheet contains Cu that accelerates high-temperature salt damage, addition of Nb and Si (compound addition) can reduce such damage. To apply titanium to exhaust system materials in the future, although improving the high-temperature properties is important, cost reduction is a critical task. Titanium has been adopted only for high-class automobiles recently, such as Toyota Motor Corporation's limited-production model LEXUS LFA and GT-R by Nissan Motor Co., Ltd., which shows the importance of cost reduction.

2.4 Fuel tanks

Fuel tanks are placed at relatively high places on motorcycles, so reducing their weight may improve the maneuverability by lowering the center of gravity. As fuel tank materials, surface-treated steel sheets have been used and resin is also often used at present. However, resin sheets need to be thickened to meet regulations on the permeability of fuel and thereby the weight has not decreased much. Meanwhile, using titanium can reduce the weight by approximately 40% (**Photo 2**). Besides the application of titanium, using aluminum for fuel tanks is also being studied. However, when conventional mass-production equipment is used, aluminum easily melts and collapses by concentration of heat input due to its high thermal conductivity. Therefore, aluminum sheets need to be thick,

Photo 2 Titanium fuel tank

so using titanium can often reduce weight even more.

Meanwhile, to adopt titanium for fuel tanks, it is important that titanium sheets have sufficient stamping performance. The anisotropy specific to titanium, seizure with dies, and springback due to low Young's modulus need to be taken into account. Seizure with dies is the largest problem when titanium is stamped, in particular. Lubrication sheets are sometimes used to avoid dies from coming into contact with titanium to prevent seizure, but, when considering mass production, conventional liquid lubricants are desirable. Thin titanium sheets are treated by two types of annealing—annealing/pickling or annealing in a vacuum atmosphere. Annealing in a vacuum atmosphere forms a thin oxide film on the surface and this reduces seizure with dies. In addition, partially modifying the material quality of dies has made stamping using liquid lubricants possible.[18] In addition, the blanking direction at the time of stamping is an important factor.

Figure 4 shows the relationship between the bulging height and blanking direction for JIS Class 1 pure thin titanium sheets. Generally, the elongation in a uniaxial tensile test is larger in direction L (parallel to the rolling direction) than that in direction T (width direction). However, in a bulging test, blanking a sheet with direction T taken as the longitudinal direction provides higher workability. In addition, although uniaxial stretching in direction L largely relies on the grain size, uniform biaxial stretching and uniaxial stretching in direction T do not significantly rely on the grain size.[19] Such unusual behavior is related to the structural texture and twinning deformation, but it cannot be said that such behavior has been sufficiently understood. Therefore, such behavior cannot have been uniformly incorporated into simulations and researchers have been using trial and error.

3. Future Prospects of Application of Titanium to Automotive Parts

Multiple types of materials have been used in combination for aircraft and high-class motorcycles. Regarding aircraft, for B787 manufactured by the Boeing Company and A350 made by Airbus SE, the composite material accounts for 50%, aluminum for 20%, titanium for 15%, and steel for 10% in the rough mass ratio. The ratio of applied composite material has increased to three to five times that of previous-generation aircraft.[20] As the ratio of the composite material increases, the ratio of titanium also increases from the perspective of contact corrosion of different types of materials and differences in thermal expansion. In the motorcycle sector, for 1 000-cc super sport motorcycles, steel accounts for 40%, aluminum for 35%, resin for 10%, and other metals (titanium and magnesium) for 8% in

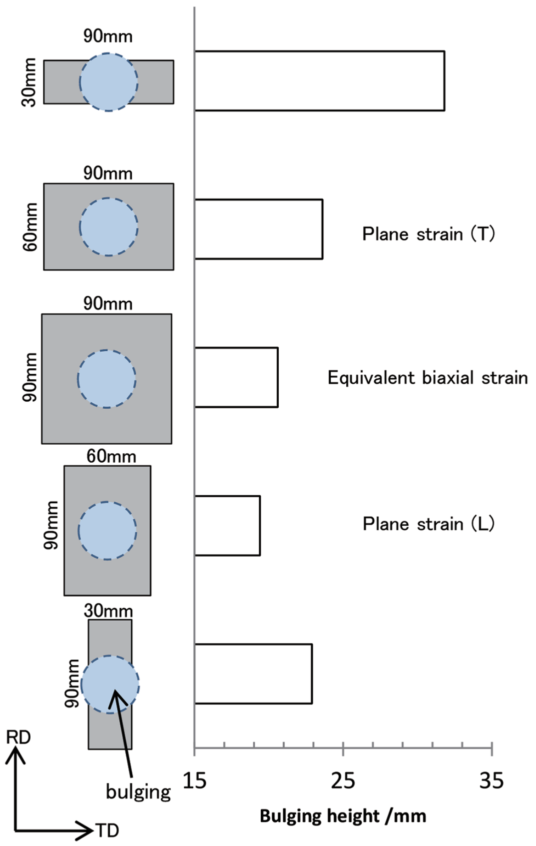

Fig. 4 Bulging height of JIS Class 1 commercially pure titanium sheet in spherical bulging test
50 μm-thick teflon sheet was used for lubricant of bulging test.

the mass ratio. For a 125-cc commuter motorcycle, the ratios of aluminum and other metals (titanium and magnesium) have been increasing and, when combined, their ratio exceeds that of steel.[21, 22] This may be because aircraft and high-class motorcycles have been seeking weight reduction while attaching importance to fuel efficiency in the aeronautics industry and maneuverability (e.g., engine performance and steering performance) in the motorcycle sector.

The density of titanium is a little less than 60% of that of steel, so, when comparing the specific strength, a 440-MPa general-purpose industrial pure thin titanium sheet with elongation of 30% is equal to 780 MPa in the case of steel sheets; and an 800-MPa high-strength thin titanium sheet with elongation of 20% is equal to 1.4 GPa in the case of steel sheets. In addition, the strength of Ti-6Al-4V mainly used for aircraft and Ti-5Al-1Fe used for golf club heads and connecting rods are 900 to 1 000 MPa. They are equal to 1.6 to 1.7 GPa in the case of steel, having high potential.

Furthermore, when looking at the specific rigidity as structural materials, the density is a controlling factor of flexural rigidity, so the balance of specific strength and specific rigidity in titanium is adequate among metal materials. In service environments, when it is 100 to 200°C or higher, the strength of aluminum alloys and magnesium alloys significantly decreases, so it can be said that titanium alloys are more advantageous. Thanks to these properties, titanium has been increasingly applied to the parts introduced above. In addition, automobiles have been becoming electric automobiles (EVs) and titanium needs to cope with changes due to such trend. Beside this, the largest task for applying titanium to automotive parts in the future is cost reduction. Whether this problem can be overcome is a key issue.

3.1 Surface design

Another strong point that produces added value for automobiles besides fuel efficiency, safety performance, and engine performance is surface design represented by design and decoration. The main targets of design including surface design are exterior, mufflers, and interiors of automobiles and even functional parts (fuel tanks, engines, suspensions, and brakes) for motorcycles. On titanium, various interference colors can be developed by controlling the thickness of oxide films by atmospheric oxidation and anodic oxidation unlike coating.

In addition, surface design specific to titanium can be given by combining an interference color and base metal and adjusting the texture and color tone. As another characteristic, natural gradation can be provided on interference colors depending on the curves of parts and light conditions. Titanium has been used for mufflers and bolts mainly for motorcycles as automotive parts for surface design, in addition to weight reduction. Nippon Steel provides surface design titanium brand TranTixxii for building roofs and walls and mugs that are easily seen and whose appearance is regarded as important in addition to the aforementioned items. In addition, color tones, which vary depending on the light conditions and the thickness of the oxide film, can be reproduced by computer graphics (CG) simulating cases where titanium sheets are used for various automotive parts, interiors, and exteriors.

3.2 Photocatalytic effects

General photocatalysts hold grains having photocatalytic effects with binders. When the photocatalytic effects are enhanced, the binders are decomposed, so the effect cannot be fully exerted. Nippon Steel has developed a titanium material that can exert the effects at maximum by advancing anodic oxidation, which forms oxide films, to form films having photocatalytic effects on the surface of titanium.[23, 24] It has been confirmed in ultraviolet light radiation that this material has photocatalytic activity (funginert and antibacterial properties, nitrogen oxide removal performance, and formaldehyde removal performance) exceeding the criteria specified by the Photocatalysis Industry Association of Japan. It has also been confirmed that the material works to kill influenza viruses. In addition, the KI method (evaluation of activity based on a change in the color of a solution by oxidation of I ions) and methylene blue degradation testing have confirmed that the materials show response to visible light.

3.3 Non-magnetism

For TRIP steel and metastable austenitic stainless steel, martensitic transformation occurs by cold working, so that such steel is more subject to cold working, the relative permeability increases, and the steel starts having magnetism. On the other hand, the relative permeability of titanium remains at 1.00 no matter how much it is subjected to cold working, remaining non-magnetic. Titanium is expected to be applied to parts that require non-magnetism combined with corrosion resistance and specific strength.

3.4 Increase of EVs

In keeping with the trend toward EVs, values may change or diversify in the future due to a decrease in the number of parts used, changes to the use of automobiles from the perspective of mobility (represented by car sharing), and consideration of life-cycle costs of parts and automobiles in a mature society. For example, when considering reuse by extending the service life of parts and standardization in place of recycling, high-corrosion-resistance titanium may be suitable for parts to be reused because it does not require anticorrosion coating under normal service environments.

4. Conclusions

This paper has introduced cases where the weight of automotive parts has been reduced by the use of titanium as well as tasks for the future. New titanium connecting rods and fuel tanks that have recently been adopted for mass-produced vehicles can be developed not only by Nippon Steel using inexpensive elements and considering low processing costs but also by cooperative projects with parts and automobile manufacturers. Titanium has excellent characteristics potentially, but these characteristics cannot be fully exerted in many applications purposes, so titanium needs to be further studied in cooperative development. In addition, titanium may fill an important role in changes (e.g., increase of EVs) by developing attractive products using surface design specific to titanium and characteristics that have not been focused on. Nippon Steel will issue more information on titanium as a material supplier and continue contributing to the growth of the automobile sector in the future by cooperative development with parts and automobile manufacturers.

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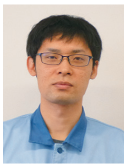

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