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Application of Titanium for Automotive Use in Japan

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Abstract:

Application of titanium for automotive use started with racing car engine parts at the beginning of the 1980s, then gradually expanded, and came to include high-class limited-production cars in 1989. This paper identifies the automobile parts for which the application of titanium is explored in the automobile industry, a newly growing field of titanium application, are reviewed, and outlines the problems associated with the titanium application to high-class mass-production cars.

1. Introduction

The 1991 Tokyo Motor Show exhibited new automobiles from Japan and abroad under the theme "earth-friendly cars". The automakers' attempts to protect the global environment by reducing the weight of their cars drew the attention of the visitors to the show. Aluminum alloys, magnesium alloys, titanium, and new materials were used extensively as weight-saving materials in the cars exhibited. These moves were prompted by not only the current global environmental issues but also the deliberations made on the Corporate Average Fuel Economy (CAFE) bill in the United States Congress, plus the automakers' strategy to produce automobiles of high functionality and distinction.

Historically, titanium has been used as a lightweight and high-strength functional material in the aerospace industry and as a corrosion-resistant functional material in various other manufacturing industries. In recent years, it has been finding increasing use in the construction and civil engineering fields.

This article takes a look at the automotive parts for which the use of titanium is being explored and provides an overview of the problems that must be solved before titanium can be used in such automotive parts on a mass-production basis.

2. Impact of US CAFE Bill on Japanese Automakers

In June 1989, Senator Bryan introduced a new CAFE bill in the United States Senate that greatly shocked those in the automotive industry. The new CAFE bill was designed to improve automobile fuel economy as a means of first dealing with the problem of national security and then addressing the worldwide environmental issue. The bill proposed that the 1988 CAFE values be reduced by 20% in 1995 and by 40% in the year 2000.

A penalty will be imposed on any automobile maker who fails to meet the minimum CAFE requirement of 27.5 miles per gallon. At that time, Japanese automakers had been exporting mainly compact cars to the United States, and the 1988 CAFE values of their models were 20 to 30% higher than those of American counterparts.

As Japanese automakers have since shifted to larger cars and intensified automobile safety and passenger comfort, however, their CAFE values are now declining. The new CAFE bill thus had a shocking impact on the Japanese automakers.

Fig. 1 shows the needs for automobile weight reduction with underlying factors. The subsequent steep declines in the profitability of Big Three automakers of the United States appeared to have put the Bryan CAFE bill on hold and braked the efforts at higher automobile fuel economy in the United States.

In September 1993, however, the United States government and the Big Three set the goal of developing 80-miles/gallon (34.0-km/l) fuel economy cars in a 10-year program and moved again to improve automobile fuel economy.

3. Recent CAFE Values and Fuel Economy-Improving Technologies

Fig. 2 shows changes in the CAFE values of Japan's leading

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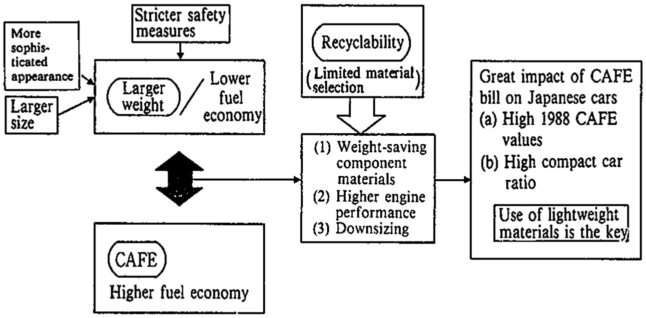


Fig. 1 Needs for automobile weight reduction and underlying factors

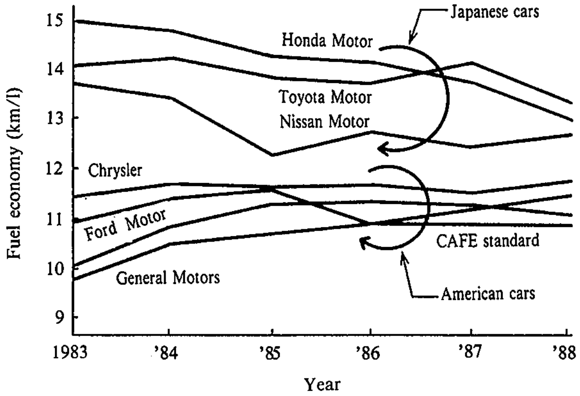


Fig. 2 CAFE value by automaker[1]

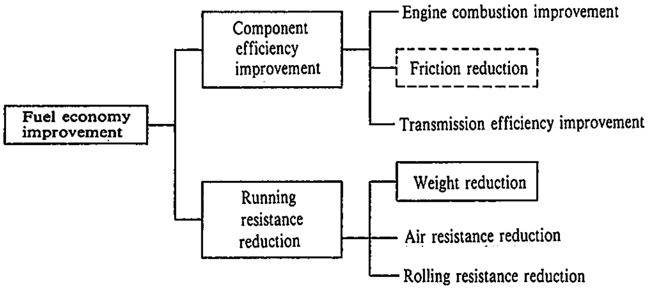


Fig. 3 Fuel economy improving technologies[2]

automakers. For the reasons noted above, the Japanese automakers must make greater efforts than their American counterparts to improve the fuel economy of their passenger cars.

Fig. 3 schematically shows the technologies studied by the Japanese automakers to improve the fuel economy of their passenger cars. In reciprocating gasoline engines, the principal type of engine used in today's automobiles, there is a limit to the improvement of fuel economy by way of improving fuel combustion and power transmission efficiency. Japanese automakers are therefore placing importance rather on car weight-reducing technologies.

4. Weight Reducing Technologies and Shift to Lightweight Materials

The weight of passenger cars can be reduced by: 1) switching to lightweight materials; 2) making parts hollow or thinner; and 3) consolidating parts. Since these weight-saving technologies differ in fuel economy gain that can be achieved, their benefits must be evaluated in the three categories of body parts, moving engine parts, and undercarriage parts.

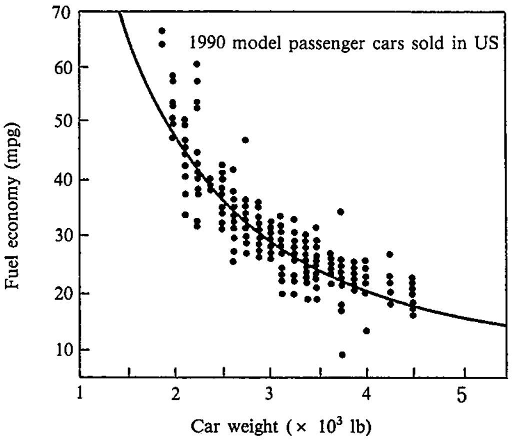


Fig. 4 Effect of car weight on fuel economy[2]

Fig. 4 shows the effect of car weight on fuel economy. A weight reduction of 1% produces an almost equal gain in fuel economy. Weight reduction in such engine parts as connecting rods and valve train is much more effective in improving fuel economy than in body parts.

A valve lifter weight reduction of 13 g through a material changeover to aluminum was reported to have improved fuel economy by 1%. This is because the weight reduction of valve lifters had the incidental effect of reducing the valve spring load. This is worth noting as an effective weight reduction approach.

Let us now briefly touch on the ongoing shift to lightweight materials. Generally speaking, this trend takes the direction from higher to lower specific gravity, that is, from steel to aluminum, and then to magnesium or plastics.

First, take a look at aluminum as a typical lightweight material. In the 1970s, aluminum was used in such engine parts as pistons, cylinder heads covers, and such drive train parts as clutch housings and transmission cases. In 1980, the substitution of aluminum expanded to rocker arms and cylinder blocks. Heat exchangers, such as radiators and coolers, were also made of aluminum, and the use of aluminum then spread to wheels and other undercarriage parts. Aluminum was used for hoods, fenders, and other outer panels of sports cars in the late 1980s. Honda introduced its all-aluminum body sports car NSX in 1990.

In this way, the substitution of aluminum for steel extended from engine parts to accessory parts and is now expanding throughout the entire car body. Magnesium alloys, the lightest of all structural metals, were initially used as die-cast parts of complex shapes utilizing their excellent castability. The use of magnesium alloys is still restricted to steering system parts for limited-production luxury cars. It should be noted that magnesium was introduced also to cope with the weight increase of steering wheel parts involved in the installation of air bags.

It is well known that weight reduction through the use of plastics is making steady progress.

5. Characteristics and Automotive Uses of Titanium

In **Table 1**[3], the basic properties of representative titanium alloys whose use is explored in the automotive industry are com-

Table 1 Comparison in basic properties of representative titanium alloys and conventional materials

Material	Density (g/cm^3)	Yield strength (MPa)	Young's modulus (GPa)
Low-carbon steel	7.8	350-450	200
Stainless steel	7.8-8.00	200-300	193-200
Aluminum alloy	2.8	50-450	69-71
CP Ti	4.51	220-550	103-107
Ti-3Al-2.5V	4.48	600	91-103
Ti-6Al-4V	4.43	1,030	114
TIMETAL 62S	4.43	1,100	117-124
Ti-6-2-4-2S	4.54	920	114
TIMETAL-1100	4.51	900	114
Beta-C (Ti-38644)	4.82	1,240-1,620	103
TIMETAL-LCB	4.63	1,070-1,460	
Ti-15-3-3-3	4.76	960-1,400	103-107
Ti-22V-4Al	4.62	-950	
TIMETAL-21S	4.93	960-1,400	100-103
Gamma-Ti-Al	3.96	390-480	168

pared with those of conventional materials. The specific gravity of titanium is 4.5, which is about 60% of that of steel.

Titanium is higher in specific gravity than aluminum and magnesium alloys, but is by far stronger than them. It therefore exceeds aluminum alloys in specific strength, particularly in the medium temperature range. Titanium is also advantageous over various steels and aluminum alloys in terms of specific toughness (toughness/specific gravity) and specific fatigue strength (fatigue strength/specific gravity), two important factors in the use of titanium for automotive parts[4].

For any material used in outer panels and fittings, corrosion performance is a problem. Titanium outperforms most materials when exposed to saline or marine air. Titanium is expected to be favorably accepted in the Untied States and Northern Europe where deicing salt is spread on highways to prevent skidding in winder.

Young's modulus of titanium is about 50% of that of steel. Therefore, when titanium is used to make a coil spring, the number of coils can be reduced to make the spring more compact and lighter.

Titanium has many advantages as noted above, but it is expensive to fabricate it because it is difficult to machine or form. Also, some titanium automotive parts must be specially treated to prevent wear. Titanium thus has problems still to be solved.

What automotive parts can be made of titanium? **Fig. 5** shows the automotive parts for which the use of titanium is being studied. **Table 2** lists the weight reduction of some automotive parts expected from the substitution of titanium for steel and their development stage. Titanium offers the greatest possibility of replacing steel in reciprocating engine parts, such as valve springs and retainers, followed by such rotating parts as connecting rods and in the various suspension system parts that would have the greatest weight reducing effect.

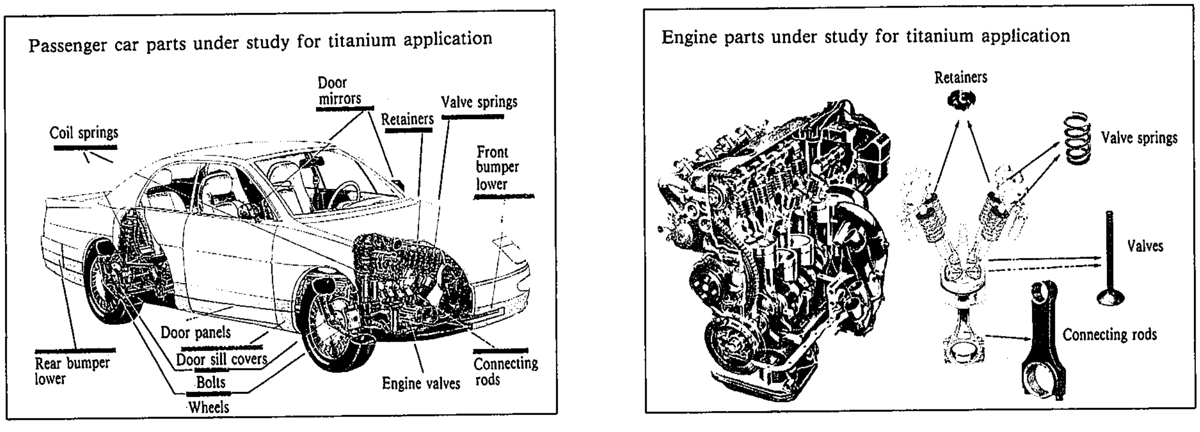
6. Titanium Applications in Automotive Field

The automotive industry first used titanium in the engine parts of Formula-1 racing cars at the beginning of the 1980s. Since F-1 racing cars must have high output, speed, and response, lightweight and high-strength titanium was adopted in engine parts. Titanium was then used by Mitsubishi Motors for valve spring retainers in the AMG engine of the Gallant model in 1989, and by Honda Motor for the connecting rods of the NSX sports car in 1990.

At the 1991 Tokyo Motor Show, Nissan exhibited the TRI-X with titanium underbody panels, and drew the attention of visitors.

(1) Engine parts: Valve spring retainers in the Gallant and connecting rods in the NSX

The valve spring retainers used in the Gallant are cold forged from a new beta titanium alloy, designated Ti-22V-4Al, and are given a low-cost oxidation treatment to protect them against wear. The use of titanium helped to reduce the weight of the retainer by 40% and to increase the engine speed by 300 to 400 rpm[5]. The connecting rods of the Honda NSX are made from a new free-machining titanium alloy designated Ti-3Al-2V+S+REM. Developed to reduce the amount of machining, a large cost factor, the new titanium alloy offers drilling efficiency about three times higher than that of the conventional Ti-6Al-4V alloy. The connecting rods are ion plated with chromium nitride (CrN) for wear protection. The CrN ion-plated coating is less expensive and more durable than the conventional molybdenum thermal spray coating. The substitution of titanium is reported to have reduced the weight of connecting rods by 30% and increased the engine speed


Passenger car parts under study for titanium application

Engine parts under study for titanium application

Fig. 5 Automotive parts for which substitution of titanium is being studied

Table 2 Achievable weight reduction by automotive part from titanium use; development phase

Part		Present material	Weight reduction (expected)	Development phase				Applicable material	Technical point
				Racing cars	Concept cars	High-class limited-production cars	Mass-production cars		
Engine	Connecting rods	Carbon steel	▽30% / ▽1.1kg	☐	☐	☐ ⬚		Ti-6Al-4V Ti-2Al-2V TIMETAL-62S	◦ Better machinability ◦ Less costly wear-resistant treatment
	Valves	Heat-resistant steel	▽40% / ▽0.3kg	☐	⬚	⬚	⬚	Ti-6Al-4V TIMETAL-62S Ti-1100	◦ Better machinability ◦ Less costly wear-resistant treatment
	Valve springs	Spring steel	▽55% / ▽0.7kg	☐ ⬚	⬚	⬚		Beta-C Beta-21S	◦ Less costly wear-resistant treatment
	Retainers	Cr-Mo steel	▽40% / ▽0.2kg	☐	☐	☐ ⬚		Ti-22V-4Al Ti-15-3	◦ Better cold workability ◦ Less costly wear-resistant treatment
Undercarriage	Suspension springs		▽50% / ▽5.3kg	☐	☐ ⬚	⬚		Beta-C Beta-21S TIMETAL-LCB*	◦ Lower Young's modulus
Power train	Drive shafts		▽30% / ▽2.4kg		⬚			Beta-C Beta-21S	◦ Higher shear strength ◦ Better machinability
Fittings and others	Door mirrors Outer panels		▽40% and corrosion performance		⬚ Outer panels	☐ Door mirrors Wheels		C/P	

Note ☐ : Actually used, ⬚ : Under development, *: Under development

by 700 rpm[6].

(2) Body parts: Underbody outer panels in the TRI-X

Titanium is used in four areas of the Nissan TRI-X: door outer, side sill cover, front bumper lower, and rear bumper lower. These titanium parts are used for the purposes of weight reduction and salt damage protection as shown in **Fig. 6**. These outer panels are formed to very strict specifications and incorporate the results of joint development by the material and automobile manufacturers.

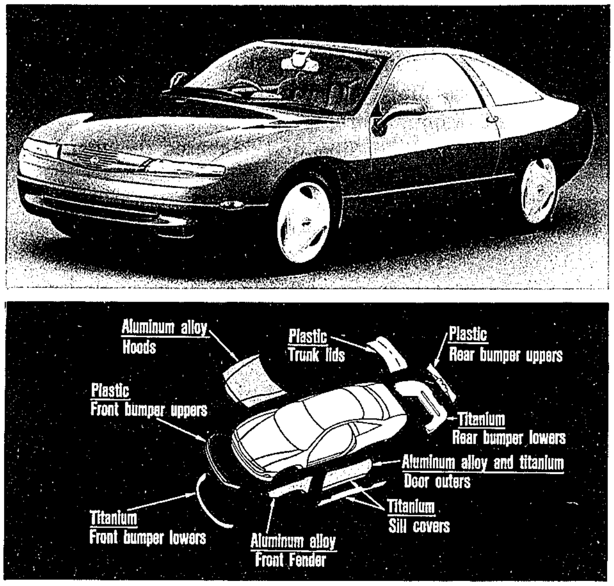


Fig. 6 Appearance of Nissan TRI-X exhibited at 1991 Tokyo Motor Show and its outer panels made of titanium

(3) Fittings: Ultrasonic water-repelling mirrors

The Toyota Lexus and Soarer are equipped with ultrasonic water-repelling mirrors. The back plates of the mirrors are made of titanium. The mirrors are developed to ensure good visibility in rain. Titanium was adopted for this application because its coefficient of thermal expansion is close to that of the mirror itself and because it has good ultrasonic transmission performance.

7. Problems with Use of Titanium as Material for Automotive Parts

The first problem with the use of titanium in automotive parts is how to reduce the material cost. The second is how to raise the upper limit temperature in the medium and high temperature range. The third is how to lower the wear-resistance treatment cost as well as forming and other fabrication costs. Measures taken in dealing with these problems are described below.

(1) Introduction of new low-cost, high-performance titanium alloys

The titanium material most extensively used in the automotive industry is the Ti-6Al-4V alloy. TIMET Corporation of the United States developed TIMETAL-62S as a low-cost substitute for the alloy. It is a Ti-6Al-1.7Fe-0.1Si alloy with the expensive vanadium replaced by iron. Strength characteristics of TIMETAL-62S in the connecting rod and intake valve operating temperature regions are shown in **Figs. 7** and **8**, respectively[3]. As TIMETAL-62S performs as well as the Ti-6Al-4V alloy, it is expected to find increasing use. Beta alloys are used as materials of valve springs and suspension springs on the strength of their cold workability and fatigue strength.

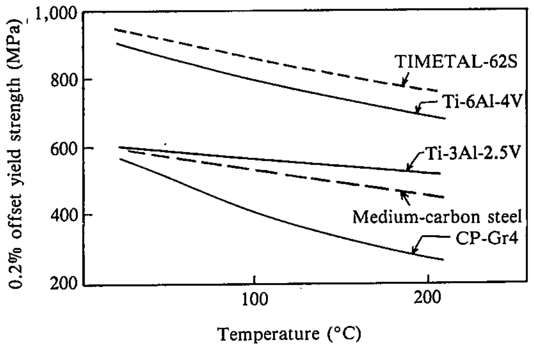


Fig. 7 Effect of temperature on yield strength of representative connecting rod materials

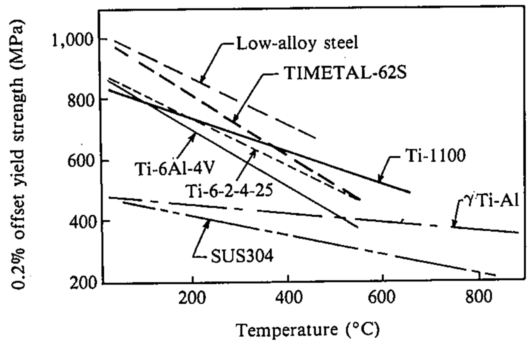


Fig. 8 Effect of temperature on yield strength of representative valve materials

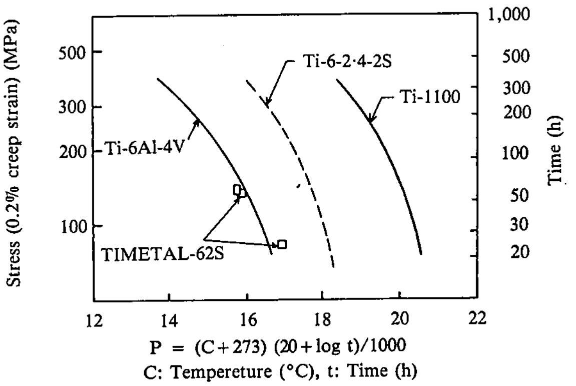


Fig. 9 Larson-Miller comparison of 0.2% creep strain for titanium alloys for valves

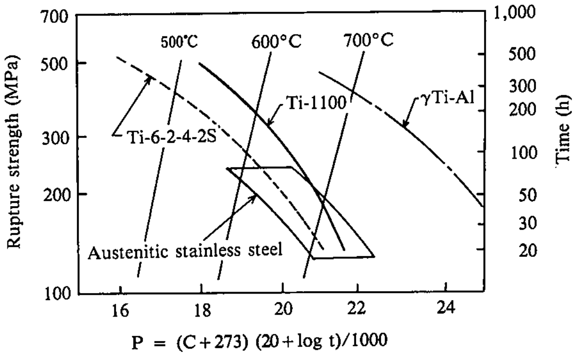


Fig. 10 Larson-Miller comparison of creep rupture strength for titanium alloys for valves

TIMETAL-LCB was developed as a low-cost substitute for the beta titanium alloys.

TIMETAL-LCB has the expensive vanadium replaced with the low-cost beta stabilizer ferromolybdenum, and is expected to find usage as a low-cost titanium alloy for springs[7].

Titanium alloys are generally used in the medium- and high-temperature regions of up to about 500°C. Titanium alloys were considered difficult to use in exhaust valves that reach operating temperatures of about 800°C. TIMET Corporation developed TIMETAL-1100 with superior high-temperature properties as an advanced version of the Ti-6Al-2Sn-4Zr-2Mo alloy used in the aircraft industry[3]. The high-temperature properties of TIMETAL-1100 are shown in **Figs. 9** and **10**, where those of Ti-Al intermetallic compounds are also included. There is also TIMETAL-21S developed as a beta alloy, featuring much better oxidation resistance in the medium- and high-temperature ranges. These new alloys are expected to find increasing application in valve train parts, a field where needs for weight reduction are strong.

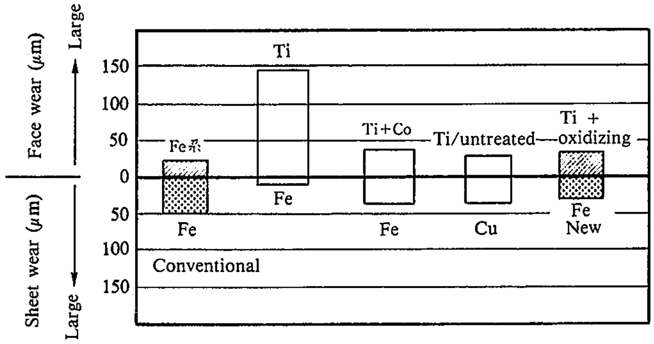
(2) Reduction in forming, machining, and wear treating costs

Titanium can be formed and machined on the same equipment as steel, but its yield must be improved because it is more expensive than steel. The yield improvement can be achieved by raising the forging efficiency through the optimization of heating temperature, temperature control during forging, and forging load distribution from rough to finish forging. Studies are under way on the utilization of beta alloys that have excellent cold workability, and on the employment of such new technologies as closed-die forging and powder metallurgy to produce near-net shapes. Since titanium is difficult to machine, it was formerly considered difficult to use titanium in automotive parts from the point of view of production efficiency and cost. Recently, however, high-efficiency machine tools of the high-pressure coolant type developed for difficult-to-machine materials have been found effective in machining titanium, thus eliminating one bottleneck in the mass production of automotive parts from titanium. When combined with the use of free-machining titanium and the application of neat net shape fabrication technology, such machine tools will become powerful tools for solving other problems associated with the use of titanium and titanium alloys in automobiles.

Since titanium is often used in moving automotive parts, it is essential to protect titanium sliding surfaces against seizure and wear. **Table 3**[8] shows hardfacing treatments for representative automotive parts. Of the hardfacing methods listed in **Table 3,**

Table 3 Methods of titanium parts treatment against seizure and wear

Method	Part
Plating Hard plating NiP	Valve lifters Springs
Thermal spraying Molybdenum Tungsten	Valves Connecting rods Clutches
Nitriding Oxidizing	Retainers Valves Connecting rods
Ion plating	Connecting rods



High-temperature valve seat wear test (accelerated test)

Fig. 11 Comparison of intake valve accelerated wear test results

oxidizing is considered the most cost-effective approach.

The oxidizing process is already applied commercially to connecting rods and retainers. **Fig. 11** shows the wear resistance of intake valves treated against wear by various methods. Oxidizing is found to be a powerful method.

It should be noted that the seizure and wear behavior of titanium greatly varies with the mating material, sliding system, and sliding pattern involved. The problem of titanium seizure and wear must be dealt with always in combination with the mating material specifications.

8. Expectations and Outlooks of Titanium Use in Automobiles

As discussed above, the use of titanium in automobiles has been gradually moving forward. More powerful cost-cutting measures are indispensable to shift the use of titanium from the field of sports cars for higher racing performance to that of passenger cars for improved fuel economy to meet the CAFE standards. Titanium manufacturers are called on to reduce the production cost of titanium and develop technology to lower the fabrication cost of titanium parts (for example, free-machining titanium alloys). Automotive part manufacturers, for their part, are expected to develop technology to use titanium in full utilization of its properties (for example, near net shape fabrication technology), while finished automobile manufacturers are expected to develop evaluation systems and design techniques to make the most of the advantages of titanium.

Over the medium and long terms, titanium has such potentiality that its use will expand from sports cars to high-class limited-production cars and then to high-class mass-production cars. To expedite this process, some pending problems must be solved, such as the combination of titanium with other materials, recycling of titanium, and assurance of a stable supply of titanium.

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