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Application of Titanium and Its Alloys for Automobile Parts

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Abstract

Some of the R & D activities by Nippon Steel on the application of titanium materials for automobile parts were introduced. Regarding exhaust pipes and mufflers, various material data needed to successfully handle commercially pure titanium was extensively accumulated while the manufacturing process by which products can show high performance inherent in titanium such as surface appearances was established. Regarding engine valves, both intake and exhaust valves having high wear resistance, high fatigue strength and high heat resistance were developed, which can be applied even in motorcycles with higher power engines. As a result of those activities, a lot of advantages of titanium usage including lightweight and high strength have become utilized in both many motorcycles and four-wheeled vehicles. In addition, to further enhance the use of titanium in automobiles, low-cost alloys such as Super-TIX series were newly developed, and it is strongly expected that more automobile parts will be made of titanium and its alloys in the very near future.

1. Introduction

Because of their excellent corrosion resistance and high specific strength (strength/density), titanium and its alloys have been widely used for chemical, electric power, and aerospace industries as major metal materials by taking advantage of their characteristics. On the other hand, their applications to automobile industry have been limited except for racing cars and special-purpose cars because of their high cost despite the strong interest shown in titanium materials by the industry in terms of lightweight, fuel efficiency, and performances.

In recent years, however, titanium and its alloys have come to be actively used for various parts of the general mass-produced cars due to the following factors:

1)The demand for lightweight parts has become increasingly strict for the prevention of global warming though reduction of CO_2 emission;
2)Remarkable progress has been made in the development of technology for the manufacture of low-cost titanium; and
3)The appearance and fashionableness peculiar to titanium have come to appeal to the public.

Nippon Steel has also been developing related technology in compliance with the above trend as summarized in the previous report[1]. Since the examples of actual applications of titanium to automobile parts and the principal advantages in the use of this metal material were introduced in the previous report, they are omitted from this paper. This paper deals concretely with part of the company's recent activity.

2. Exhaust pipes and mufflers

In addition to plain carbon steel and stainless steel, aluminum and FRP have also been used thus far for exhaust pipes and mufflers. Since those parts are large-sized structures for auto-bodies, the effect of reducing their weight is significant, contributing not only to the reduction of fuel cost but also to the improvement of engine and

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Table 1 Comparison of the standardized stress (coefficient of thermal expansion × Young's modulus #) due to thermal expansion

Material	Standardized of stress induced by thermal expansion (coefficient of thermal expansion × Young's modulus #)
Ferritic stainless steel	1
Austenitic stainless steel	1.5
Titanium	0.45

: Standardized value with ferritic stainless steel set as 1

running performances. Furthermore, because of its higher specific strength than that of steel and its higher heat resistance than that of aluminum, titanium is best fitted as a material to exhibit the effect of weight reduction in light of the fact that those parts are exposed to high temperature of over 400 °C in contact with exhaust gas[2]. For example, the weight of a two-wheeled vehicle can be reduced by about 3 kg and that of a four-wheeled vehicle by about 8 kg when steel is replaced by titanium.

Again, titanium is lower than steel (ferrite) in its coefficient of thermal expansion and Young's modulus, and can be expected to halve the strain induced by thermal expansion and contraction, as **Table 1** shows. This also renders titanium more advantageous in thermal fatigue property. Moreover, cold workability is required for the materials used for those parts, because they are manufactured through various forming steps, such as cold press or bending. In this respect, commercially pure titanium of JIS Class 2 can fully satisfy the above requirements.

In addition to the above functions, titanium is required to exhibit freshness and fashion particularly when used for a muffler, a part with its design targeted of the outward appearance of an auto-body a prime selling point of the use of titanium. The surface appearances inherent in titanium and not found in other metals is also welcome in the market [2-4]. Titanium also appeals to the public not only in a variety of changes in interference color of its surface when used but also in a unique exhaust sound, peculiar to titanium and not found in steel.

As above-described, the use of titanium for those parts is rapidly expanding because of the advantages of titanium over a wide range as seen in weight reduction, processability, freshness, and fashionableness.

2.2 Characteristics required and Nippon Steel's stance

Nippon Steel provided for sufficient original data in which titanium was compared with the conventional material, i.e. heat-resistant stainless steel used for an exhaust system, so that not only automakers and parts makers, well versed in titanium, but also other makers not experienced in handling titanium can fully master it. The data cover a wide range of characteristics including tensile properties at room temperature, n-value, r-value, tensile properties at high temperature, fatigue strength, oxidation resistance, and thermal fatigue.

The tensile strength at a level of pure titanium in JIS Class 2 at room temperature is almost equal to that of heat-resistant stainless steel used for an exhaust system. According to Marui et al.[5], materials should have tensile elongation of about 30% to be successfully manufactured to exhaust pipes and mufflers through various processes. Commercially pure titanium at a level of JIS Class 2 can achieve tensile elongation of 30%. It is difficult, however, for high strength pure titanium of JIS Class 4 to achieve this figure. Even Ti-3Al-2.5V alloy can attain the tensile elongation only to the extent of 20%. This accounts for a major use of pure titanium at a level of class 2.

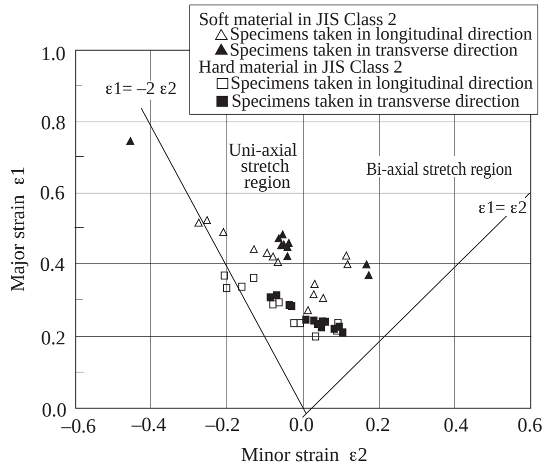


Fig. 1 Forming limit diagram of JIS Class 2 commercially pure titanium

The forming limit diagram, FLD, was prepared as **Fig. 1** shows while evaluating various characteristics including stretch-expand forming and bore expanding with the intention of grasping the formability of titanium reflecting the actual forming, and the basic data were put in order to enable to predict a forming limit against a wide variety of routes of forming various part shapes. It can be said that those data on formability were helpful in establishing the processes of manufacturing titanium mufflers and exhaust pipes promptly and accurately.

The oxidation limit temperature of heat-resistant stainless steel for an exhaust system is believed to be around 850 to 1,050 °C[6]. However, titanium is abruptly oxidized at a temperature of around 700 °C, which is lower than the above temperature range. Although this poses no problem at present, it is very likely that titanium should be as oxidation-resistant as heat-resistant stainless steel for an exhaust system in light of the assumption that this oxidation limit temperature will become higher due to the demand for a higher output and the regulations governing exhaust gas.

Beside the foregoing, titanium is required sometimes to be given a surface peculiar to this metal by surface conditioning, such as shot-peening[3] and atmospheric oxidation[2-4], so that a value is added to this metal in terms of a design. The uniformity of material surface is therefore required. With the highly advanced surface control techniques[7] acquired in the manufacture of building materials (walls and roofs) in which emphasis is placed on surface design and uniformity, Nippon Steel is fully taking advantage of those techniques for the manufacture of titanium mufflers.

2.3 Examples of applications

The application of titanium started with the aftermarket of large-sized motorcycles in 1997, ending up in mounting on mass-produced large-sized motorcycles in 1998. The above market has now grown into a scale of 400 tons. Recently, we have become familiar with the sight of motorcycles with titanium exhaust pipes and mufflers mounted thereupon, as shown in **Photo 1**. Although four-wheeled vehicles using titanium parts are mostly seen in the market, the effects of weight reduction and good design have increased the number of applications of titanium to new cars on the market as **Photo 2** shows.

Photo 1 Motorcycles in which titanium mufflers are used


Photo 2 Example of application of titanium muffler to four-wheeled vehicle

3. Engine valves

The weight reduction of engine parts is more effective than that of other parts in terms of the improvement of fuel consumption, lower noise output, and higher power output. In particular, the effect is significant in engine valves, and the application of titanium has been studied since early days as the parts for which the characteristics of titanium can be exhibited to a maximum.

3.1 Intake valves

Titanium alloy intake valves have come to be mounted on many of the motorcycles and four-wheeled vehicles by this time, and most of them use Ti-6Al-4V, an alloy most commonly used among the titanium alloys. With a concept that Ti-6Al-4V is optimal in consideration of the environment to be used and the ease of mass production of intake valves, Nippon Steel has also started the research and development jointly with Asian Industry Co., LTD. relative to the application of this alloy to the intake valves of motorcycles in the light of the immediate needs of lightweight and higher output[8].

The most difficult problem in the application of titanium alloys to intake valves is how to develop wear-resistant surface treatment technology because it is well known that titanium alloys are low in wear resistance. Surface treatment, including hard TiN coating, Mo thermal spray coating, and Cr plating, is employed in many cases. However, all these methods are costly and found unfit in maintaining a prolonged wear resistance. Accordingly, it was decided to employ “oxidizing treatment” utilizing solid-solution hardening of oxygen, a treatment characterized by producing a comparatively thick hardened layer in which highly concentrated oxygen is diffused into titanium surface layer to enhance hardness[9,10].

The oxidizing treatment is basically a heat treatment to heat to high temperature in air. It is necessary, however, to prevent the valve from being deformed by self-weight during oxidizing treatment, because the creep resistance of Ti-6Al-4V is not completely satisfactory at high temperature. This led to the adoption of an acicular structure most excellent in creep resistance instead of equiaxed or mill-annealed microstructures, both of which are particularly inferior in creep resistance. **Photo 3** shows the microstructure of the cross section of the stem of a valve. It was rendered possible to avoid the deformation during heat treatment by converting the valve wholly into an acicular microstructure.

The acicular microstructure is generally believed to be low in ductility and fatigue strength. It is possible, however, to secure high ductility and fatigue resistance equal to those of an equiaxed structure by converting fully into an acicular microstructure without allowing the coarse phase to precipitate along the α grain boundaries[11]. Tensile strength over 980MPa with elongation over 12% was confirmed by tensile tests using test pieces taken from the stem portion of the valves. As **Fig. 2** shows, it was confirmed that even the acicular microstructure has fatigue strength almost equal to that of an equiaxed microstructure.

In general, wear resistance increases when an oxygen-hardened layer is given, whereas fatigue strength is known to decrease when the oxygen-hardened layer is given[9,10]. It therefore becomes neces-

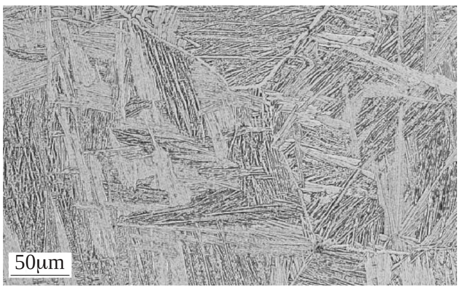


Photo 3 Optical microphotograph of intake valve made of Ti-6Al-4V

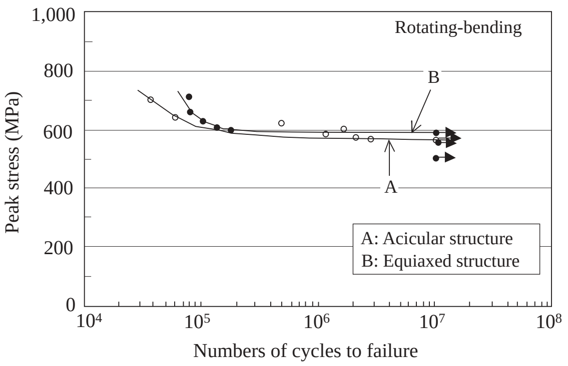


Fig. 2 Rotating-bending fatigue properties of Ti-6Al-4V with equiaxed and acicular microstructures

sary to grasp the optimal heat treatment conditions in which these two conflicting properties are balanced, and apply them. Therefore, the measurement of surface properties and hardness distribution near the surface was made after heat treatment in a temperature range of 670 to 820 °C for 1 to 16 hours in air.

Fig. 3 shows the distribution of Vicker's hardness near the surface of the specimens heat-treated at respective temperatures for one hour. Again, **Fig. 4** gives the distribution of Vicker's hardness near the surface of the specimens oxidized at 670 and 820 °C respectively by changing the time of the treatment. In proportion to an increase in treatment temperature or in treatment time, the distance of diffusion of oxygen into the titanium alloy becomes longer with the hardness deeper inside becoming higher. It was confirmed that the specimen heat treated at the highest temperature of 820 °C and for the longest time of 4 hours in this test was hardened to the extent of 50 μm from the surface, and the specimen heat treated at the lowest temperature of 670 °C and for the shortest time of 1 hour in this test was hardened to the extent of 10 μm from the surface. Undoubtedly, an oxidized scale of TiO_2 is formed on the surface, from which oxygen diffuses inside the matrix. This indicates that the hardness on top of the surface immediately below the scale is equal independent of the heat treatment conditions. However, a marked difference in hardness was found at a depth of several μm from the surface, a depth to enable to measure hardness, depending on respective heat treatment conditions. Meanwhile, in some conditions of heat treatment at high temperature and for a long time, the oxygen-hardened layer was found cracked. Those conditions are unfit for oxidizing treatment, and

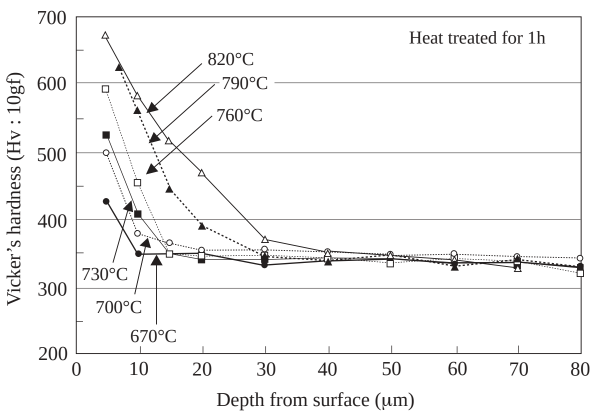


Fig. 3 Depth profile of Vicker's hardness of Ti-6Al-4V heat treated at 670 - 820 °C for one hour in air

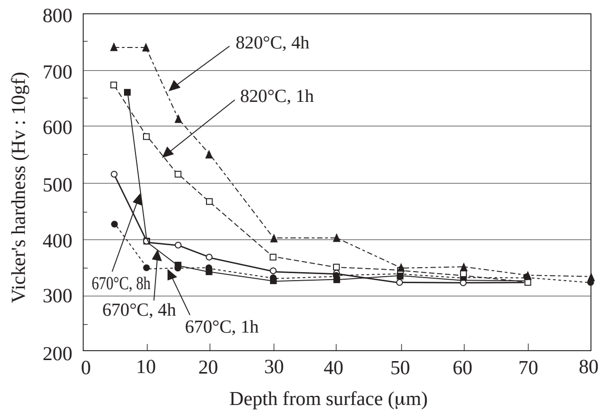


Fig. 4 Influences of heat treatment time on the depth profile of Vicker's hardness of Ti-6Al-4V heat treated at 670 and 820 °C in air

should be avoided in the actual manufacture of valves.

In this manner, the relationship between the thickness of the oxygen-hardened layer and the treatment conditions was established. Then, engine valves were manufactured after the actual oxidizing treatment to evaluate their fatigue properties and wear resistance. **Fig. 5** shows the S-N curves of valves after oxidizing treatment as measured by subjecting actual valves to repeated bending stress[8)] (by courtesy of Asian Industry Co.,LTD.). The thicker the oxygen-hardened layer, the higher is the fatigue strength. However, no significant difference was observed between the valves treated at 670 °C for one hour and 16 hours. Both of the valves are found to have high fatigue strength almost equal to that of the ones without oxidizing treatment. In the selection of oxidizing treatment conditions, wear resistance is also an important factor and both of the life expectancy by wear and the fatigue strength required should be taken into account.

3.2 Exhaust valves

For exhaust valves exposed to high temperature, Ti-6Al-2Sn-4Zr-2Mo-0.1Si(6242S), a typical heat-resistant alloy, is used in many cases though only a few examples of its applications are available. In case of mass-produced motorcycles, however, exhaust valves should desirably be made of a heat-resistant and reliable material to a higher degree, because they are exposed to higher temperature for a prolonged period of time. This led to the study on the application

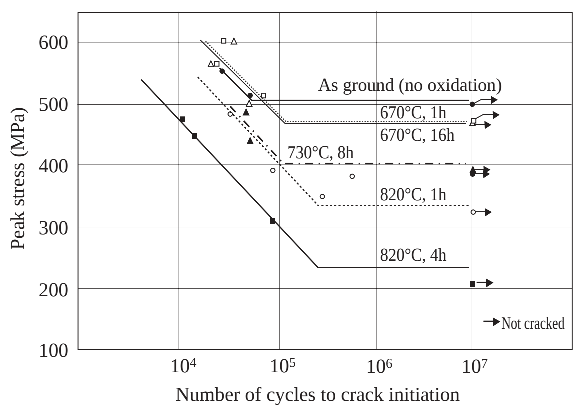


Fig. 5 Fatigue properties of intake engine valves made of Ti-6Al-4V oxidized under various conditions. Fatigue tests were conducted using actual valves

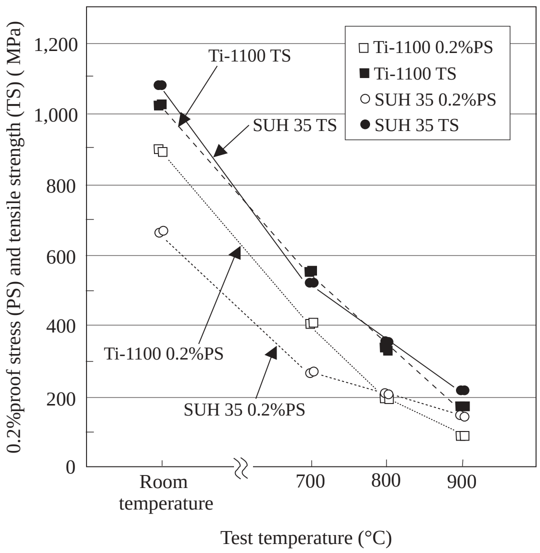


Fig. 6 Tensile properties of TIMETAL@1100(Ti-1100) and SUH 35 at room and high temperatures

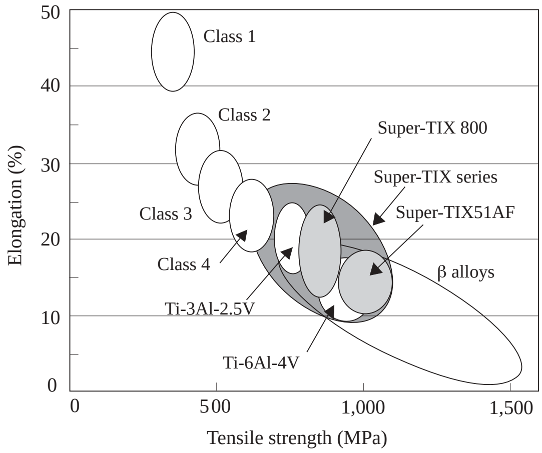


Fig. 7 Relationship between the strength and ductility of Super-TIX series and typical titanium materials (schematic diagram)

of TIMETAL@1100 (Ti-6Al-2.7Sn-4Zr-0.4Mo-0.45Si), one of the most excellent alloys in heat resistance among the titanium alloys. Although this alloy is considered to be excellent in heat resistance among the commercially available titanium alloys, its service temperature is only to the extent of 600 °C at best[12]. It is therefore necessary to be convinced of the heat resistance of the optimally heat treated material at around 800 °C because heat resistance up to about 800 °C is required in the case of the exhaust valves of motorcycles. Accordingly, materials heat-treated in various ways were prepared and their tensile properties and creep resistance at various temperatures from room temperature up to around 800 °C were evaluated so that the conditions can be established of enabling to realize the maximum balance of material characteristics. Then, engine valves were actually manufactured for evaluation.

Fig. 6 shows tensile properties at room and elevated temperatures of properly heat treated TIMETAL@1100. The 0.2% proof stress of Ti-1100 is higher than that of SUH 35, a conventional material of exhaust valves, at temperatures ranging from room temperature to 700 °C, and almost equal at 800 °C. The fatigue strength of Ti-1100 at 800 °C is also confirmed to be on a level with that of SUH 35[1], and the creep resistance is also confirmed to be rather excellent than that of SUH 35[1]. As described above, satisfactory characteristics for exhaust valves could be obtained by the application of proper heat treatment to this alloy.

Furthermore, an Al-containing titanium alloy is known to decrease ductility when exposed to a temperature zone of about 600 °C for a prolonged period of time by the formation of the ordered phase called α_2[13]. It is also verified, however, that TIMETAL@1100 retains its ductility even when exposed to a temperature zone of around 600 °C for as long as several thousand hours.

4. Development of new alloys for automobile parts and the study of their applications

The foregoing examples of titanium automobile parts are made of conventional titanium materials. Nippon Steel has also developed low-cost alloys with the intention of applying titanium alloys not only to automobile parts but also to utility goods with applications that are closer to our daily life, in large quantities. The research and development for the application of those alloys to automobile parts is now under way.

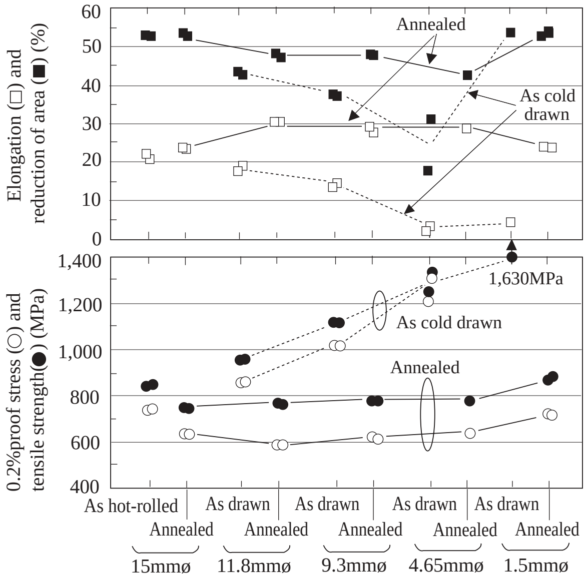
A series of alloys called Super-TIX is counted among the above alloys. **Fig. 7** gives a schematic diagram of the relationship between strength and ductility in comparison with other conventional titanium materials. Super-TIX series is broadly divided into Ti-Al-Fe and Ti-Fe-O-N alloy groups[14-19]. The former is a group of alloys in which V or Mo, an expensive β stabilizing element, is replaced by inexpensive Fe, and suitable particularly for applications which may be used at intermediate temperatures. Super-TIX51AF(Ti-5%Al-1%Fe) is a core alloy of the group and has tensile strength of around 1,000 MPa, equivalent to that of Ti-6Al-4V, and its application is now under study with emphasis placed on bars and wires.

On the other hand, the Ti-Fe-O-N alloy group is suitable for parts to be used at around room temperature without being exposed to high temperature, and provided with various high performances including hot workability with inexpensive Fe, O, and N blended in good proportion. Super-TIX800 (Ti-1%Fe-0.35%O-0.01%N) is a core alloy in the group and has tensile strength of around 800 MPa, which is intermediate in strength between Ti-6Al-4V and Ti-3Al-2.5V, in line with excellent hot and cold workabilities. This enables to manufacture various forms of products, including heavy plates, hot-and cold-rolled coil sheets, bars, and wires.

Since those alloy groups are detailed in the literature[14-19], it suffices to introduce the tensile and rotating-bending fatigue properties of annealed materials in **Figs. 8** to **10**. Those alloys are strongly expected to be applied to various automobile parts, such as valves, connecting rods, retainers, and fasteners, depending on their respective properties as the materials of what is called auto-grade.

It should be noted that there are some points in Super-TIX series to be careful in handling due to their specific composition of alloying elements selected for the reduction of manufacturing cost. It is recommended to refer to the literature 14) to 19) in which those points are described in detail.

As the titanium alloy designed primarily for applications except for aircrafts like the above Super-TIX series, the β type titanium alloy, TIMETAL@LCB (Ti-4.5Fe-6.8Mo-1.5Al), is a good example. This alloy was developed by Titanium Metals Corporation (TIMET). and its application to suspension springs is now under study by taking advantage of the characteristics of this alloy, that is, low Young's modulus (about 80,000 MPa) and high strength (about 1,400 MPa).



Tensile test specimen:
GL=25mm, 6.25mmø for 15mmø hot-rolled bar
GL=14.2mm, 4.06mmø for 11.8mmø and 9.3mmø cold-drawn wires
GL=25mm, 4.65mmø for 4.65mmø cold-drawn wire
GL=25mm, 1.5mmø for 1.5mmø cold-drawn wire

Fig. 8 Tensile properties of hot-rolled bars and cold-drawn wires of Super-TIX800 (Ti-1%Fe-0.35%O-0.01%N)

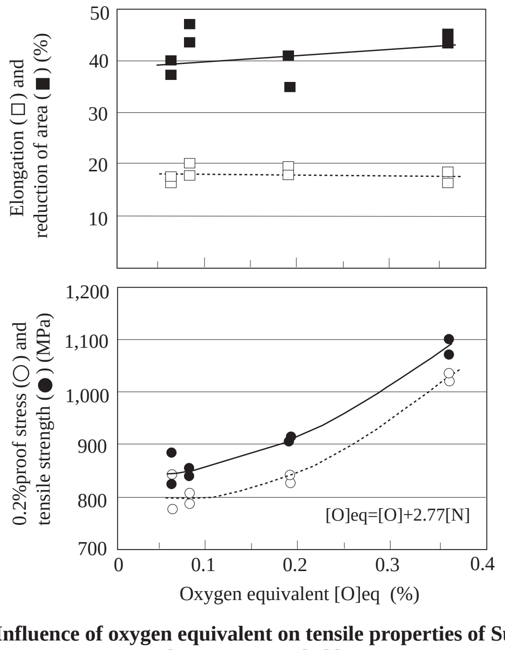


Fig. 9 Influence of oxygen equivalent on tensile properties of Super-TIX51AF (Ti-5%Al-1%Fe) annealed bars

It was actually adopted by Volkswagen Lupo FSI in 2001, and its debut in the Japanese market is strongly expected.

5. Conclusion

Titanium has come to be used for some parts of mass-produced automobiles by taking advantage of lightweight and high strength. It is necessary, however, to solve many problems still more for further utilization of this metal. One of them is the drastic reduction in cost of titanium which still looks like a high grade material in spite of the recent cost reduction. This does not necessarily mean material cost

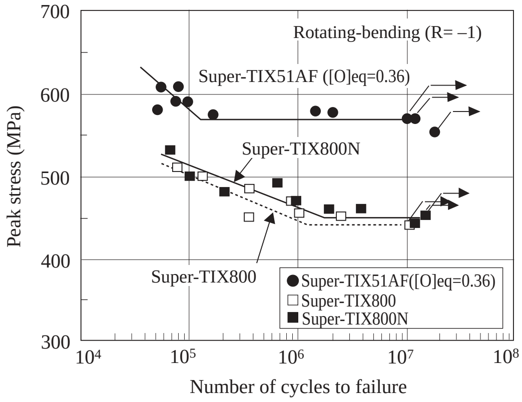


Fig.10 Rotating-bending fatigue properties of hot-rolled and annealed bars (15 mm in diameter) of SuperTIX800 and SuperTIX51AF Annealing was conducted at 750 °C for 1h followed by air cooling

reduction only. It should be noted that the reduction in cost of processing parts is also a very significant factor. In other words, it is necessary to try to reduce overall cost with the full understanding of the characteristics of the material in line with the development and application of appropriate methods of processing and post treatment while developing inexpensive materials for automobile parts. It is necessary for the realization of this objective to go ahead with research and development in close cooperation of the three parties, that is, we material manufacturer, parts manufacturers, and automobile manufacturers.

The authors would like to conclude this paper by praying that the characteristics of lightweight and high strength in titanium are made the best of in the auto industry in the future with the above-described cooperation promoted further.

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