

Development of Lightweight DLC Coated Valve Lifter Made from Beta Titanium Alloy for Motorcycles

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ABSTRACT

An ultra lightweight valve lifter made from titanium alloy was developed for high performance motorcycles. A beta titanium alloy that was fulfilling not only higher strength but also cold forgeability was selected among several types of titanium alloys. A solution treatment and aging combined with the cold forging made a refinement of the grain size of beta phase. As a result, a tensile strength and an elongation of the alloy were reached to 1170MPa and 10.3% respectively. During the solution treatment, oxygen diffusion (OD) treatment was also performed on the beta titanium alloy. The surface hardness of OD layer was increased up to as high as 600 HV. Subsequently, a diamond like carbon (DLC) layer having a hardness value of around 2500HV was formed on the titanium substrate in order to provide a superior tribological property. In between the DLC layer and the substrate, a sputtered Ti layer was formed as an intermediate adhesive layer. The intermediate layer resulted in preventing from any damage for example flaking or pitting of the DLC layer and realized a good bonding strength. The high durability and superior tribological properties were proved by endurance test with using an actual motorcycle engine. The developed valve lifter achieved more than 30% of weight reduction compared to a conventional steel valve lifter.

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INTRODUCTION

On the recent development of high-powered motorcycles, a higher power output is demanded especially in a super-sport category. Therefore, the critical engine speed tends to be increased to generate more power year by year. When the engine speed is increased, it is necessary to decrease the inertial force of moving components by reducing its weight. Weight reduction of reciprocating components, especially valve system components, is quite effective for enhancement of the critical engine speed.

A double overhead camshaft (DOHC) type of valve system is widely used in the engine of the super-sport category. The weight of valve system components mainly consists of each weight of springs, valves, valve lifters and retainer caps. Among these components, as reported on several papers (1-5), the weight reduction of the intake and exhaust valves and the retainer cap are already achieved by replacing the material from steel to titanium alloy. However, since the valve lifer (Figure 1) is still made from steel, the weight of valve lifter accounts for the large proportion of the total weight of valve system. Considering the total weight

reduction of the valve system, the weight of valve lifter is playing an important role.

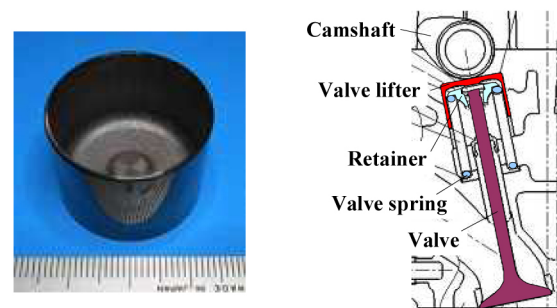


Figure 1. Valve lifter for high performance motorcycle.

With regard to the challenges for the weight reduction of valve lifter, the application of aluminum alloy for the valve lifter of an automobile engine was previously investigated (6). But the aluminum valve lifter needs a steel shim put on the crown of the valve lifter to protect the sliding surface from wear. Because of this structure, it cannot get so large

Table 1. Chemical composition of candidate materials.

	V	Cr	Al	Sn	Mo	Zr	Fe	Ti	Alloy type
Ti-15V-3Cr-3Al-3Sn	15	3	3	3				REM.	beta
Ti-3Al-8V-6Cr-4Mo-4Zr	8	6	3		4	4		REM.	beta
T-22V-4Al	22		4					REM.	beta
Ti-15V-6Cr-4Al	15	6	4					REM.	beta
Ti-5Al-2Fe-3Mo			5		3		2	REM.	alpha+beta

weight reduction compared to the conventional steel valve lifter.

In order to maximize the weight reduction, titanium alloy is suitable material for the lightweight valve lifter from the viewpoints of its superior mechanical properties and low density. So, we have decided to develop a lightweight valve lifter made from titanium alloy, which would be more than 30% lighter than conventional steel one.

Generally valve lifter has several functions as a valve system component;

- a. Contacting with cam lobe at a lifter crown and keeping a smooth sliding.
- b. Bearing a load from cam lobe and compressing a valve spring.
- c. Reciprocating smoothly in a lifter hole.

The developed valve lifter should fulfill above mentioned functions and long-term durability. Titanium alloy generally has higher mechanical properties. But on the other hand, its low thermal conductivity makes frictional heat accumulate on a sliding surface. For this reason, tribological problems such as a seizure and a severe wear are often observed on the sliding surface of a titanium alloy. So, it is an important issue to make a surface on the lifter crown having superior tribological properties.

In this paper, elemental technologies enabling the lightweight titanium valve lifter was discussed. At first, the composition of titanium alloy was selected from the viewpoints of forgeability and surface hardening by an oxygen diffusion treatment. And then, a heat treatment and a surface treatment were investigated in order to improve the strength and tribological properties on the lifter crown. At the end, the performance and durability of the developed titanium valve lifter was verified through an engine testing.

EXPERIMENTAL

Materials

Generally, titanium alloys are categorized into 3 types, alpha, alpha + beta, beta type, corresponding to the phases at the ambient temperature. The alpha type alloy shows a good ductility at low temperature and a higher corrosion resistance. The alpha + beta type alloy is popular titanium alloy which has a high strength and good ductility. The beta type alloy can control its strength with the appropriate heat treatment condition consisting of solution treatment and aging. At the same time, the beta type alloy also shows superior cold forgeability. The superior forgeability enabling a near-net-

shape forming leads to minimize the following machining process, and consequently realize the cost effective manufacturing process.

Based on the above-mentioned properties, 4 beta type alloys and 1 alpha + beta type alloy were selected for candidate material for the lightweight valve lifter. Chemical compositions are listed in Table 1. Among the constituents of the chemical composition, Al stabilizes the alpha phase. On the other hand, V, Mo, Cr and Fe act as a stabilizer of the beta phase. Sn and Zr are neutral elements which have minor influence on the beta transus temperature (7). Regarding Sn, the phase diagram of Ti-Sn is categorized as an alpha stabilized type, however generally Sn is recognized as a neutral element same as Zr because Sn does not affect the beta transus (8). The final material for the developed valve lifter was selected through following evaluations.

Upsetting

The wall thickness of the periphery of a valve lifter, so-called skirt, is below 1mm thickness. So, it is desirable for reducing production cost to forge as thin as possible. In order to select the material having good forgeability, upsetting tests were carried out.

A specimen for the upsetting test was a columnar shape having 16mm diameter and 32mm height, and 1.0mm chamfering was added at the peripheral edge. The outer surface of the specimen was polish finished. Before the upsetting test, lubricant for cold forging was applied on the both ends of the specimen in order to prevent seizure between the die and the specimen. The specimen was cramped at its both ends with a forging press and then applied a compression force at the rate of 4.4mm/sec until cracks were observed on the outer surface. During the upsetting test, the applied force and the displacement were monitored.

Comparing to the candidate titanium alloys, a conventional annealed SKD11 were also prepared. All of titanium alloys were solution treated. The forgeability was evaluated by comparing the upsetting limit value defined as $(L_0-L_1)/L_0$. L_0 is the initial height of the specimen, L_1 is the height when a crack is observed on the specimen. And $(L_0-L)/L_0$ is defined as the upsetting ratio. L is the height of specimen before a crack is observed.

Heat Treatment

The surface hardness of titanium alloy is necessary for sufficient tribological durability. In this study, as a surface hardening treatment of the titanium alloys, oxygen diffusion (OD) treatment was investigated. The OD treatment is a

Table 2. OD treatment condition.

	Temperature(K)	Duration(min)	beta transus(K)
Ti-15V-3Cr-3Al-3Sn	1063	60	1023-1043
Ti-3Al-8V-6Cr-4Mo-4Zr	1073	60	988-1018
T-22V-4Al	1023	60	1003
Ti-15V-6Cr-4Al	1023	60	1003
Ti-5Al-2Fe-3Mo	1123	60	1223

surface hardening process of a titanium alloy by means of oxygen diffusion into the titanium substrate in an air furnace at the temperature just above or below beta transus temperature determined by the chemical composition. The treatment condition was planned as shown in Table 2. And also the beta transus temperature of each alloys are shown in Table 2. Test specimens having 16mm diameter and 5mm thickness were machined and then one flat surface of the specimens were polished in mirror finish. The specimens were degreasing with acetone, subsequently OD treated at predetermined time and temperature in an air furnace. After the treatment, each specimen was aged in order to adjust the hardness of the inner part as high as 400HV. Then the hardness profile was measured in Vickers (0.25N). Comparing the hardness profiles and also considering the condition of oxidized scale generated on the surface, the material and treatment condition which showed the hardest surface was selected.

Then, in order to improve mechanical properties, the condition of solution treatment and aging was investigated. At this time, if the solution treatment and aging could be combined with the OD treatment, it would be the cost effective process. However the aging condition is too low to diffuse oxygen into titanium substrate. So, in order to optimize the condition of the solution treatment combined with the OD treatment, the solution treatment temperature was set just above or below beta transus.

The specimen was much the same as that for upsetting test. The upsetting ratio of the specimen was 0.8. The specimen was solution treated at two different temperatures, above beta transus and below, specifically at 1073K and 968K, and also solution treatment times were fixed for 4hrs and 1hr respectively by considering keeping the surface hardness above 600HV. Subsequently the specimen was aged at 748K for the predetermined time up to 24hrs. The internal hardness values of HRC were measured on each steps of the heat treatment.

After the heat treatment condition was fixed, X-ray diffraction analysis was carried out. From the result, what kinds of phases, for example alpha, beta and omega and so on, were precipitated was investigated. Also tensile test was carried out with using columnar test bars having 5mm diameter and 20mm gauge length in order to confirm the ultimate tensile strength, yield strength and elongation of the selected titanium alloy with the determined heat treatment process.

Surface Treatment

The valve lifter requires anti-wear and anti-seizure properties because it slides against a cam lobe, a shim and also a lifter hole. Conventionally several surface treatments such as Ni-P plating, PVD and/or CVD coating and thermal spray coating are proposed as countermeasures for before-mentioned tribological problems on a titanium alloy. Among these surface treatments, DLC (Diamond-like carbon) has recently drawn considerable attention for its superior tribological properties, that is to say, not only wear and seizure resistant but also quite low frictional property (9). In this study, we selected a-C:H type DLC having a hardness value of 2500HV as a promising surface coating which has not only larger growth rate of coating thickness but also superior tribological properties as widely used for automotive application (10). The OD treatment was applied on the substrate. As an intermediate layer, Cr or Ti was deposited on the OD layer. Evaluated configuration of surface coatings were shown in Figure 2. These coatings having around 4 μm thickness were applied on test coupons and also actual valve lifters with using PACVD (Plasma Assisted Chemical Vapor Deposition) process.

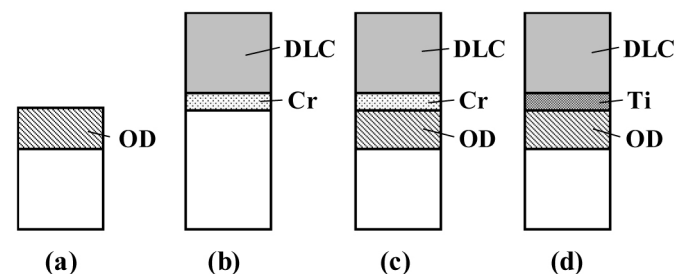


Figure 2. Schematic illustration of the configuration of surface coating layer. (a) OD treated only, (b)DLC with Cr intermediate layer on the Ti substrate, (c)DLC with Cr intermediate layer on the OD treated Ti substrate, (d)DLC with Ti intermediate layer on the OD treated Ti substrate.

Pin on Disk Wear Test

The anti-wear and anti-seizure properties of surface treated titanium alloys were evaluated using a pin on disk type wear tester having 3 pins against a disk. The disk material was carburized SCM420 same as the cam lobe material. The pin material was a titanium alloy that was