

Development of Lightweight Valve Spring Retainer Made from Aluminum Powder Metal for Motorcycle Races

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ABSTRACT

In order to enhance the engine performance of racing motorcycles, by aiming to increase critical engine speed, a valve spring retainer made of lightweight powder aluminum alloy has been developed. The high strength abrasion resistance aluminum, “NCP 400” (Nano Crystal Powder metal with crystal grain size of 400 nm), was created through blending optimum amounts of hard grains to provide abrasion resistance to the Nano Crystal Powder aluminum alloy consisting of Nano-sized crystal grains. Optimum temperature control and a forging method for the material property established the warm-precision-closed-forging technology where post-machining is unnecessary in parts manufacturing. The safety factor (the ratio of the margin of a part to the maximum stress when in use) verification method was set up, where the retainer load could be evaluated quantitatively based on the movement of the valve train during operation.

1. Introduction

Recently even factory machines in the MotoGP class, which is the pinnacle of motorcycle racing, are shifting from conventional 2-stroke engines to 4-stroke engines with valve systems. This has created an extremely high need for lightweight valve systems that allow high engine speeds. In response to this need, valve spring retainers made from titanium alloy have been adopted in place of the steel retainers used in mass production vehicle engines in order to reduce the inertia force of reciprocating motion parts. However, in consideration of the ratio of fatigue strength to weight, there are limits as to how far the weight with titanium alloy can be reduced. As a means of further reducing the weight, the authors have manufactured aluminum valve spring retainers since the mid-1990s for application to factory “works” racers and as kit parts. (Fig. 1) This paper presents the design of aluminum powder metal materials developed for retainers, and describes the manufacturing technology and a method for verifying the safety factor in parts manufacturing.

2. Development Targets

The development targets for the lightweight valve spring retainer were set as follows.

- (1) A weight reduction of 20% or more compared to the conventional titanium alloy retainer.
- (2) Abrasion resistance should be assured without surface treatment (hard anodizing coating, etc.).

3. Materials Technology

Conventional aluminum valve spring retainers were manufactured using a composite material made of hard particles mixed into rapidly solidified powder. Honda introduced retainers with Al-14.5%Si powder metal + ceramic powder composite material specifications to mass production vehicle engines in 1989. In addition, retainers with 2000 type aluminum powder metal + alumina + hard alumite specifications are currently used in other companies' motorcycles.

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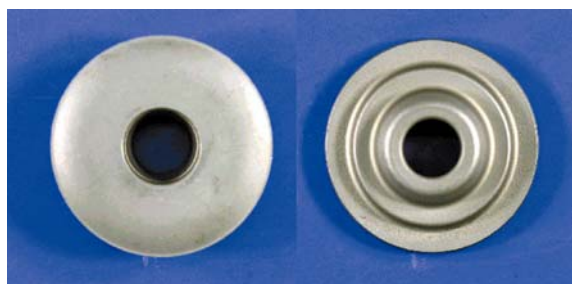


Fig.1 Valve spring retainer made from aluminum powder metal

Similar specifications were also considered in this development, but the conclusion was reached that they were not better for racing, mainly due to strength issues. Therefore, the decision was made to use Nano Crystal Powder aluminum metal developed by Honda's Basic Research Division as a metal with characteristics surpassing those of conventional rapidly solidified powder metals.

3.1. Ensuring Strength by Controlling the Structure of Rapidly Solidified Powder

In contrast to the conventional approach of expanding the limit of solid solution and grain refining by rapid cooling, Al base amorphous metals have been discovered in addition to La base, Zr base and other amorphous metals. Research on super-cooled metals that allow the manufacture of bulk amorphous metals is currently the focus of attention around the world, and various research institutions are continuing studies with the aim of practical application. Nano crystal aluminum metal has a structure comprised of nano-size crystal particles obtained by controlling the structure utilizing the crystallization from the amorphous phase and an intermetallic compound. The newly developed Nano Crystal Powder aluminum metal is already in the crystal phase in its powder state, but the structure is obtained through homogeneous nucleation from the super-cooled liquid state, so it is homogeneous. The metal composition was selected from the following viewpoints.

- (1) Manufacture should be possible using existing air atomizing facilities.
- (2) The metal should be comprised of low-cost elements.
- (3) Increases in the specific weight of the metal should be kept to a minimum.

Particularly in terms of (1) above, a combination of elements with a high amorphous forming ability was required due to limitations on the cooling speed and melting temperature. Figure 2 shows groups of elements with high amorphous forming abilities with aluminum as the main element. It has already been found that high amorphous forming ability can be obtained by adding one element from each of groups A and B shown in Fig. 2 to aluminum to create a three or more element system, so the addition elements were selected from these groups. Figure 3 shows a comparison of crystallizing temperature and material cost for three-element alloys that include a group A element. Fe was selected from group A due to its high crystallizing temperature and low cost. In addition, Fig. 4 shows a graph of the alloy density and the alloy cost for three-element metals including each representative element in group B. Ti was selected from group B because it has the lowest specific weight and is low cost. In order to enhance the amorphous forming ability, Si was added as the fourth element to the

H																			He
Li	Be											B	C	N	O	F	Ne		
Na	Mg											Al	Si	P	S	Cl	Ar		
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr		
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe		
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn		
Fr	Ra	Ac																	

Fig.2 Combination of elements which form amorphous

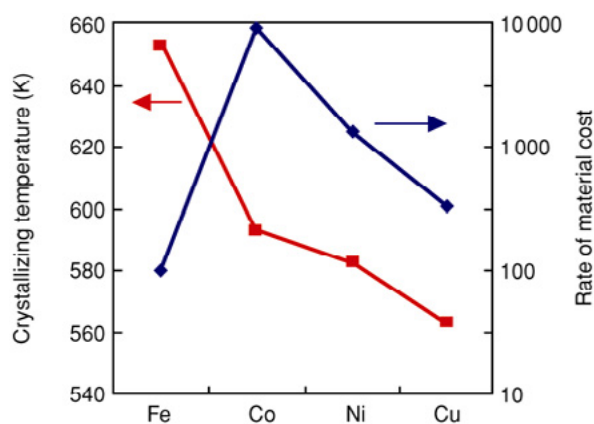


Fig.3 Crystallizing temperature of Al-(Gr. A element)-(Rare earth element) alloy and rate of material cost of Gr. A element

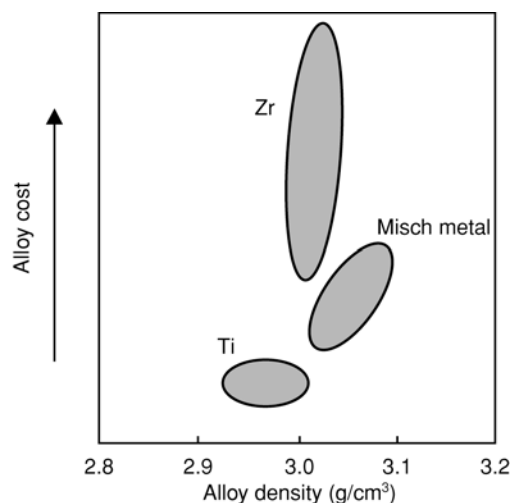


Fig.4 Relationship between alloy density and alloy cost (Al-Fe- Gr. B element alloy)

base of the Al-Fe-Ti alloy to create a four-element Al-Fe-Ti-Si alloy. Note that the interaction between Si and Ti worked to increase the amorphous forming ability, and had the effect of spheroidizing the Al-Fe compound which suppressed the drop in toughness.

Figure 5 shows the relationship between the Fe, Ti and Si addition amounts and the mechanical properties. The tensile strength increased together with the Fe addition amount, but at 6 atomic percent (hereafter, at%) or more the melting point became too high, making atomization difficult with existing mass production facilities. Ti also worked to increase the tensile strength in the same manner, but at 1at%

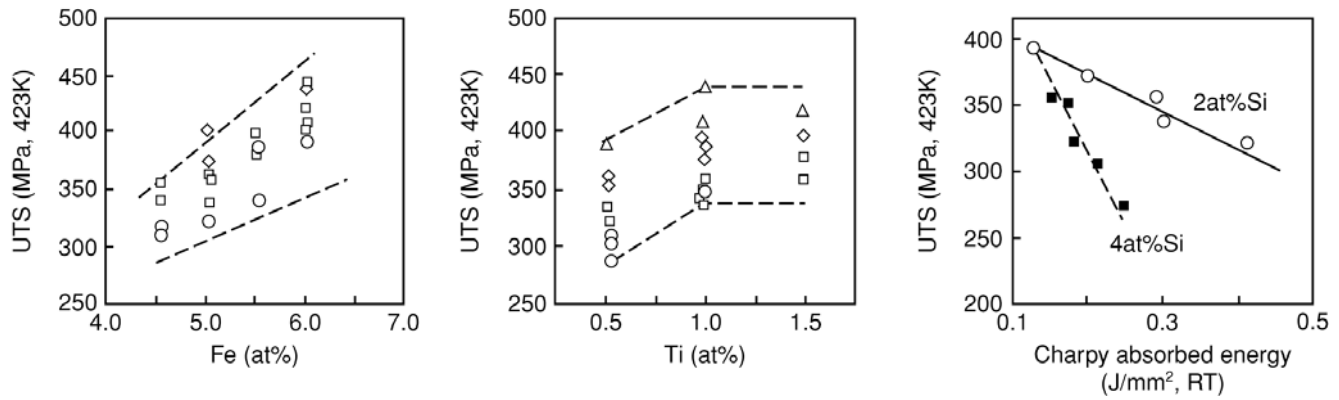


Fig.5 Relationship between amount of addition element and mechanical properties

or more there was no further increase in the tensile strength. Si shows a high impact value ratio with respect to tensile strength at 2at%. In consideration of these results, Al-6at%Fe-1at%Ti-2at%Si was determined as the optimum alloy composition.

3.2. Ensuring Abrasion Resistance with the Optimum Hard Particle Mixture

Possible methods for improving abrasion resistance are as follows.

- (1) Surface treatment such as hard alumite or hard plating
- (2) Creating a composite material by dispersion compounding of hard particles

The authors selected method (2) which endows the material itself with abrasion resistance. This is because method (1) increases the cost of parts manufacturing, and the advantage of powder materials is that hard particles can be dispersion compounded afterwards to the base powder metal. When creating a composite material, it is necessary to select

the hard particle size and amount, and to confirm the effects on the mechanical properties. In addition, if dispersion compounding is uneven, this may result in uneven mechanical properties or create a starting point for fatigue fracture. Figure 6 shows concept drawings of the effects of the alumina addition amount and particle size on abrasion resistance and strength. In general, larger addition material particle sizes and amounts tend to cause the strength to drop but the abrasion resistance to rise. Figure 7 shows the mechanical properties of actual composite materials. Based on these test results, an addition amount of 5% (average particle size of 3 μm) was selected to achieve a balance between strength and abrasion resistance. Abrasion tests were conducted using a pinion disk shaped friction abrasion tester as shown in Fig. 8. In addition, the mixing conditions for mixing alumina were set using a rotation and revolution type rotary mixer. Figure 9 shows the composite material structure. This shows that the alumina is evenly dispersion compounded. Table 1 shows the mechanical properties of the final composite material. This metal has a high fatigue strength and tensile strength even in the temperature range at which this metal is used as retainers (423 K). The authors named this high strength abrasion resistant aluminum material “NCP400” (Nano Crystal Powder metal). The “400” indicates a crystal size of 400 nm. The crystal particle size of this metal can be controlled from 20 nm to 1 μm by varying the heat history, but the balance between strength and toughness is best at around 400 nm.

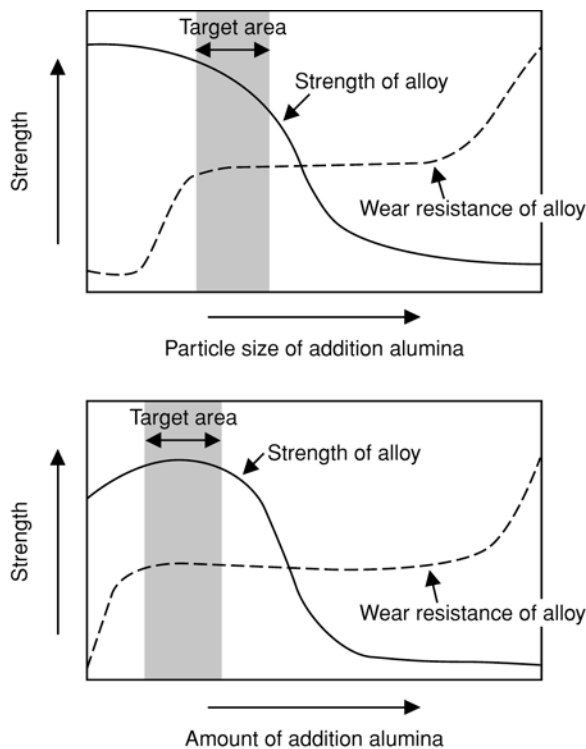


Fig.6 Amount and particle size of alumina

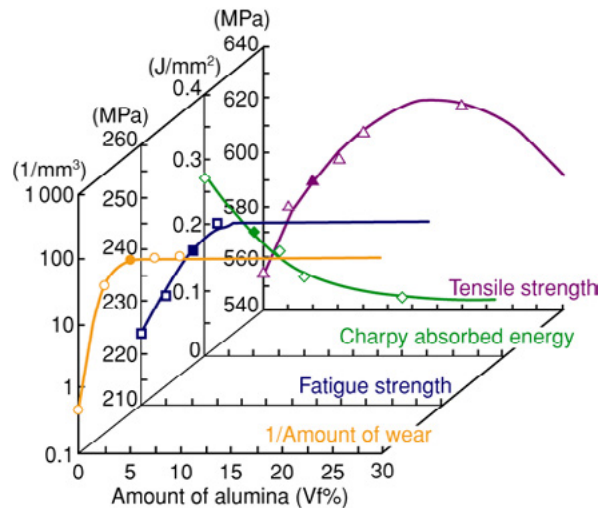


Fig.7 Mechanical properties of composite metal

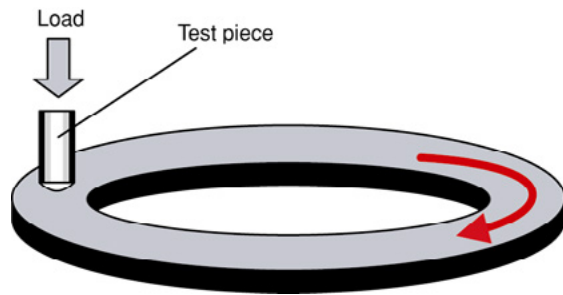


Fig.8 Abrasion test

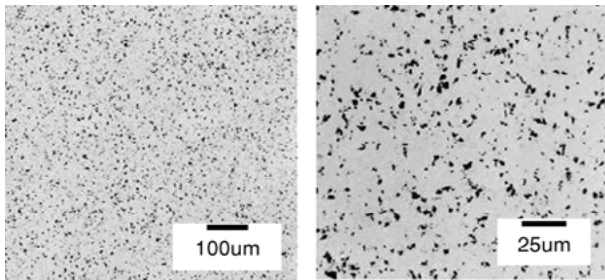


Fig.9 Microstructure

Table 1 Mechanical properties of NCP400

		RT	423K	473K
Tensile strength	(MPa)	590	485	445
Yield strength	(MPa)	484	412	374
Elongation	(%)	3.0	3.7	4.3
Fatigue strength	(MPa)	220	210	—
Charpy absorbed energy	(J/mm ²)	0.14	—	—
Young's modulus	(GPa)	97	94	89
Density	(g/cm ³)	3.04	—	—

4. Parts Manufacturing Technology

4.1. Precision Closed Die Forging

Precision closed die forging which does not require post-machining was attempted in order to enhance the strength and reduce the machining cost of the developed retainer. The nano crystal structure of NCP400 makes it easier to work than conventional aluminum powder metals, but compared to normal wrought products it has high strength at elevated temperatures, which gives it high deformation resistance when hot. In addition, it is also characteristic in that it experiences almost no work hardening. Therefore, special consideration must be given to the forging design, lubricant selection, work temperature, die temperature and other conditions. Of these, temperature control is a particularly important element.

4.1.1. Work temperature

The work temperature was determined from the relationship between the material properties of high temperature elongation and the recrystallizing temperature. Figure 10 shows the relationship between temperature and elongation for NCP400. In contrast to elongation of only a few percent at normal temperature, elongation begins to increase noticeably when 573 K is exceeded. Figure 11

shows the relationship between the work retention temperature and hardness. Here, structure growth starts and the product strength drops when 773 K is exceeded. Therefore, forging tests were conducted with the work heating temperature in the range from 573 K to 773 K, and as a result 623 K was selected as the optimum work temperature. There is no change in the hardness even after holding the work at 623 K for 100 hours, and there is sufficient heat resistance. Note that the work was heated using a mesh belt type continuous oven, and the belt speed and ambient temperature were set to stabilize the work at 623 K at the belt exit.

4.1.2. Die temperature

If the die temperature is too high, the product dimension accuracy deteriorates and concerns such as seizing, adhesion and a shortened die life occur. Conversely, if the temperature is too low, the temperature of the heated work drops, causing cracking and making it not viable to mold sound products. Figure 12 shows the positions where forging cracks occur, and Fig. 13 shows the relationship between the die temperature in molding and the occurrence rate of forging cracks. Periphery cracks and crown cracks both show a high correlation with die temperature, with the occurrence rate rising sharply at 473 K or lower. Therefore, 523 K was selected as the optimum die temperature. In addition, both the upper and lower dies were controlled using imbedded heaters to maintain a stable die temperature during forging.

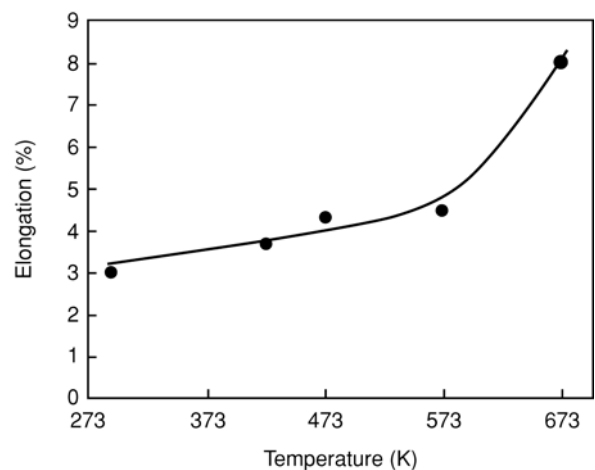


Fig.10 Relationship between temperature and elongation

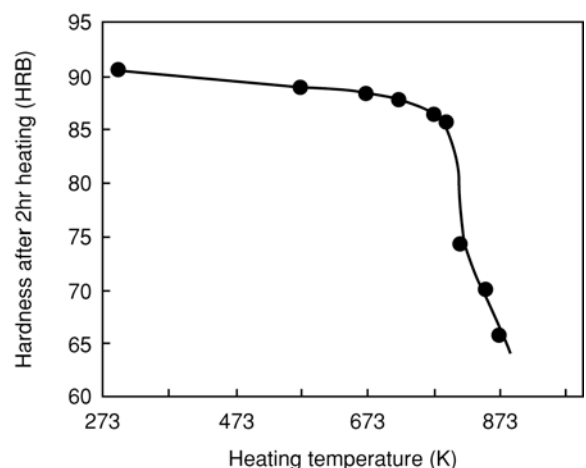


Fig.11 Tempering curve

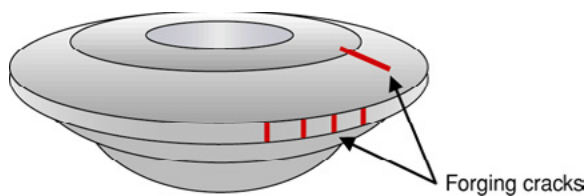


Fig.12 Position of forging cracks

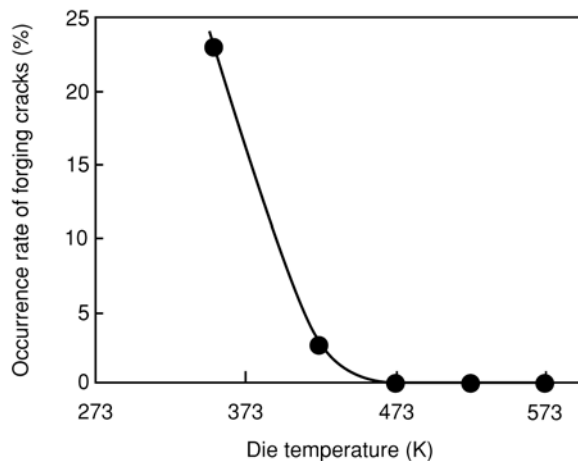


Fig.13 Relationship between die temperature and occurrence rate of cracks

4.1.3. Forging design

The nano crystal aluminum metal has superior plastic working characteristics compared to conventional aluminum powder metal. However, the structure is nanometer size so the working hardness is small and deformation easily concentrates in a single area. Therefore, the metal must be worked evenly and gently in each part during the molding process. For this reason, a holed billet was fabricated and closed die forging was performed by two-step molding. Figure 14 shows this design. The results of unit fatigue tests on the flange of forged parts showed a fatigue strength improvement of 20% compared to machined parts. This is thought to be due to the flow molding effects of forging.

4.2. Verification of Safety Factor

4.2.1. Loads received by the retainer

Most valve systems used in racing motorcycles are DOHC lifter types in which the cam drives the valves directly via a valve lifter. Figure 15 shows a model drawing of the portion around the lifter. The loads received by the retainer are as follows.

- (1) Flange bending load produced by the lift load from the spring and the dynamic inertia load
- (2) Longitudinal splitting impact load received from the cotter during valve bounce due to over-revolution, etc.
- (3) Bearing surface friction load produced by sliding with the valve spring

Unit motoring tests and engine evaluation verified that sufficient durability with respect to (3) was achieved by

optimizing the hard particle mixture as described in section 3.2 above. Therefore, (1) and (2) are discussed below.

4.2.2. Measurement of valve system motion

In order to quantitatively measure the loads received by the retainer during operation, it is important to understand the valve system motion. In the static state, the only load received by the retainer is the lift load from the valve spring. However, when engine rotation causes the spring to reciprocate between the installed condition and the lift condition, the inertia force of the mass of the spring moving parts (approximately 1/3 of the spring mass for a variable pitch spring) also applies in addition to the static lift load. When this inertia force of the reciprocating motion parts exceeds the valve spring load at high revolutions, the valve is no longer driven along the designed cam profile and instead exhibits motion such as bounce and jumping. As a result, the inertia force of this acceleration is also applied to the retainer, making it difficult to predict the load simply with calculations. Mass production vehicles are not used at revolutions in this range, but assuring durability in this range is important for racing vehicles.

Thus far there have been a number of reports concerning the measurement of valve system motion⁽¹⁾, but none which converted this motion to the load received by the retainer and performed quantitative evaluation. Therefore, the authors attempted quantitative evaluation using the valve gauge method which does not use laser measurement or other large scale facilities, and also does not require special machining of the cylinder heads. This is an extremely simple method in which two strain gauges are affixed in the axial direction of the valve stem as shown in Fig. 16, and measurement is performed on the cylinder head unit by a motoring device as shown in Fig. 17. Measurement is performed at two opposing points on the valve stem to eliminate strain in the valve bending direction. The average value of the two measurement values was taken as the axial strain, and this strain was converted into a load. Figures 18 to 21 show the waveforms obtained by this method. At extremely low speed (crank revolutions of 60 r/min or less), there is no inertia force and the waveform is straight as shown in Fig. 18.

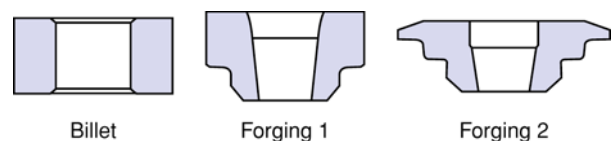


Fig.14 Forging design

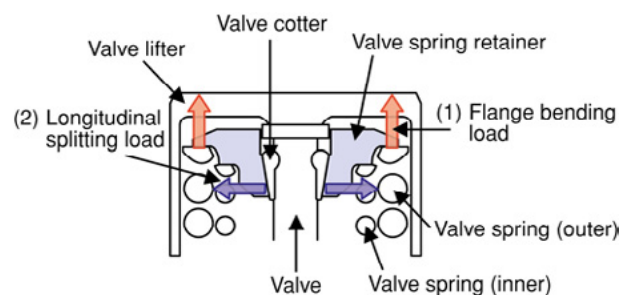


Fig.15 Valve system

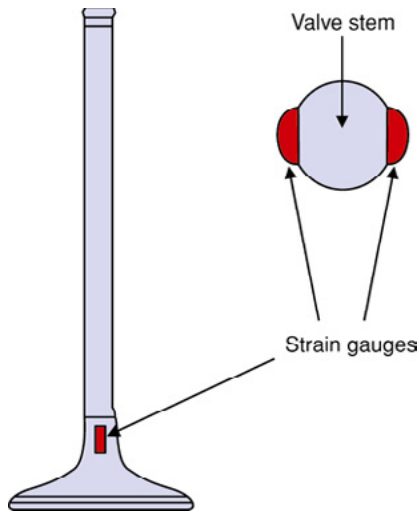


Fig.16 Sticking location of strain gauge

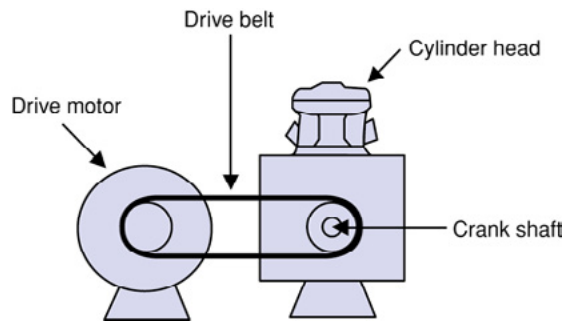


Fig.17 Motoring test

However, in the medium speed range (about 3 000 r/min), the inertia force caused a change in the waveform as shown in Fig. 19. Progressively increasing the speed resulted in a compressed waveform with a projection around the end of the lift as shown in Fig. 20, and then a tensile waveform as shown in Fig. 21. Figure 20 shows the compressed waveform produced when the parts from the valve to the valve lifter, which jump around the middle of the cam up-slope, land on the cam down-slope. Figure 21 shows the tensile waveform produced when the jump extends past the cam down-slope and the valve lands directly on the valve seat. The authors read the peak load at this time and obtained the acceleration of the reciprocating motion parts using the equation of motion shown in equation (1) below.

$$a = F_v / M \quad (1)$$

a : Acceleration of the reciprocating motion parts
 F_v : Measured load produced on the valve
 M : Inertia mass received at the strain gauge attachment positions (valve stem)

The retainer flange bending load ((1) in Fig. 15) can be expressed as follows.

$$F_{tuba} = F_{ol} + F_{ok} \quad (2)$$

$$F_{ok} = M_o \times a \quad (3)$$

F_{tuba} : Load applied to the retainer flange

F_{ol} : Lift load of the outer valve spring

F_{ok} : Inertia load of the outer valve spring

M_o : 1/3 of the outer valve spring mass

(Strictly speaking the lift load is not constant with respect to the time axis and there is a phase difference between F_{ol} and F_{ok} , but the load is expressed simply here as the sum of the two.)

Substituting equation (3) into equation (2) yields the following.

$$F_{tuba} = F_{ol} + M_o \times a \quad (4)$$

In addition, the retainer longitudinal splitting load ((2) in Fig. 15) can be expressed as follows.

$$F_{tate} = F_{tl} + (M_r + M_o + M_i) \times a \quad (5)$$

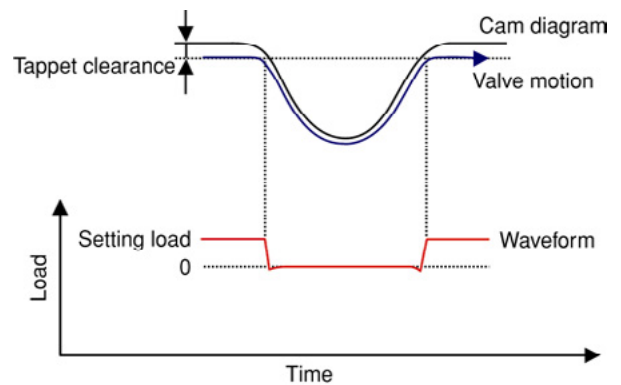


Fig.18 Waveform of load (under 60 r/min)

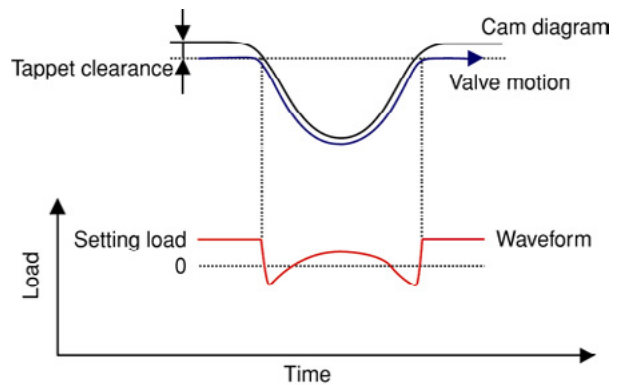


Fig.19 Waveform of load (about 3 000 r/min)

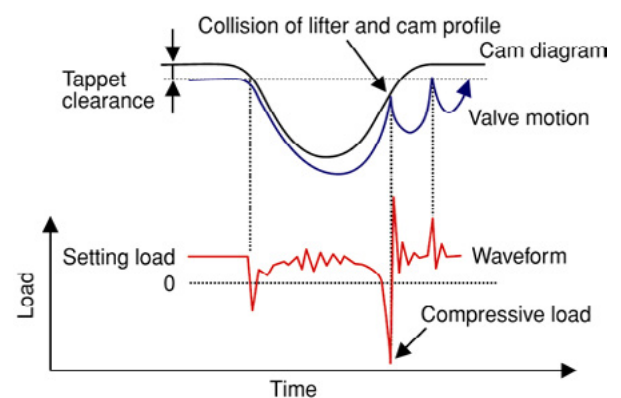


Fig.20 Waveform of load (high engine speed)

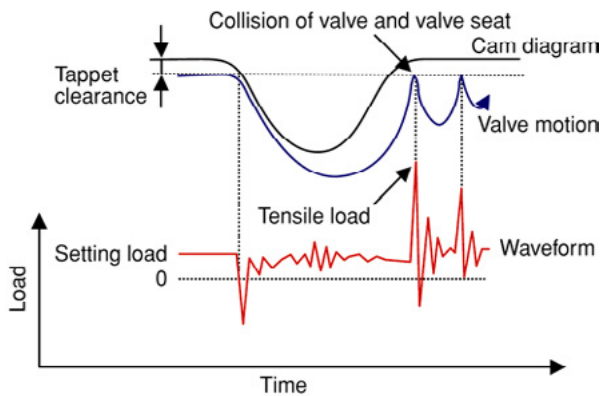


Fig.21 Waveform of load (high engine speed)

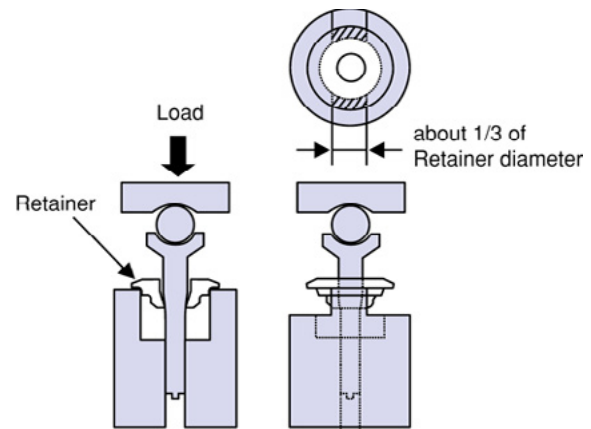


Fig.23 Component jig test

F_{tate} : Retainer longitudinal splitting load
 F_{tl} : Total lift load of the outer and inner valve springs
 M_r : Retainer mass
 M_i : 1/3 of the inner valve spring mass

Figure 22 shows a graph plotting the loads obtained by equations (4) and (5) against the engine speed on the horizontal axis.

4.2.3. Unit fatigue test and static destruction test

Since it became possible to measure the loads in an actual engine as described in section 4.2.2, unit tests were conducted to understand the actual forces acting on the retainer with respect to those loads. Two types of unit tests were performed in accordance with the destruction modes in an actual engine. These were a fatigue test with respect to the flange bending load, and a static destruction test with respect to longitudinal splitting. Figure 23 shows an example jig shape. Note that the valve spring seat does not evenly contact the entire surface of the retainer, and instead has a large surface pressure distribution at the spring end and directly opposite (180°) the spring end. Therefore, the jig was shaped to receive the retainer at two points to match these conditions. Based on these test results and the results shown in Fig. 22, the better retainer shape was set to provide a safety factor of 1.2 or more in an actual engine.

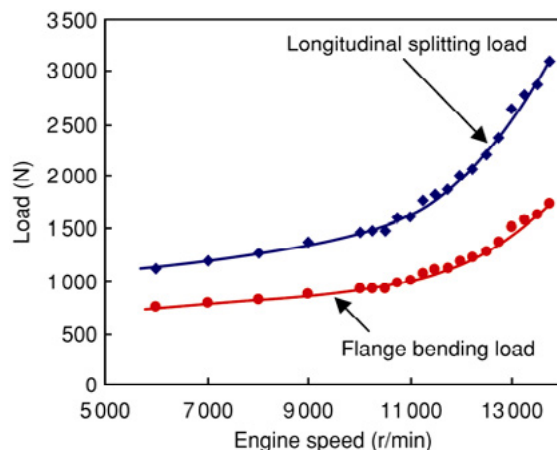


Fig.22 Relationship between engine speed and load which retainer receives

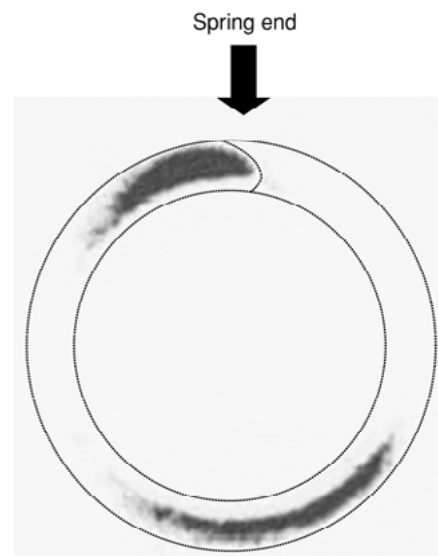


Fig.24 Pressure distribution of valve spring seating surface (by No carbon paper)

4.2.4. Analysis by computer-aided engineering

An attempt was made to clarify the correlation between the fatigue limit obtained by the unit fatigue test and the maximum stress obtained through analysis by computer-aided engineering for this retainer. The computer-aided engineering model used a 1/2 model, the unit fatigue test jig was used as is, and the contact conditions were set to accurately simulate the fatigue test. This improved the development efficiency by reducing the test man hours. Figure 25 shows an example simulation.

5. Effects in an Actual Engine

Weight reduction of 23% was achieved compared to conventional titanium alloy retainers. This stabilized the valve system motion, reduced the load on other valve system parts, and made it possible to increase the limit revolution speed of valve bounce by 220 r/min. As a result, the engine limit revolution speed increased, and the improved output led to greater competitive strength. This retainer had been applied to factory “works” racers in the super-bike class since the mid-1990s, and has contributed to six consecutive

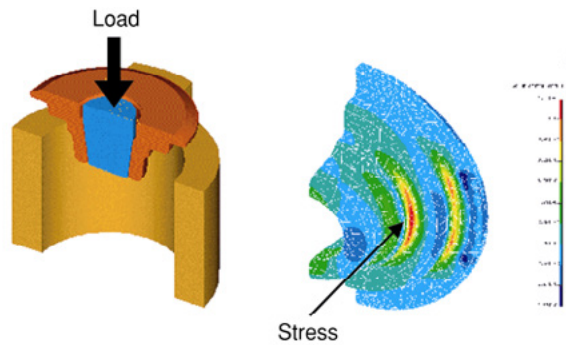


Fig.25 FEM simulation of component jig test

victories in the Suzuka 8-hour Endurance Road Race. In addition, it is also sold as a kit part.

6. Conclusions

- (1) Weight reduction of 23% was achieved compared to conventional titanium alloy retainers.
- (2) Nano Crystal Powder aluminum metal with high strength and high toughness was developed.
- (3) Technology for realizing the optimum hard particle mixture was established to provide abrasion resistance.
- (4) Precision closed die forging technology was established to reduce the parts supply cost.
- (5) A safety factor verification method was established which allows quantitative evaluation of the retainer load from the valve system motion.

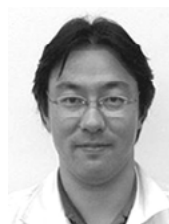
Acknowledgements

The authors wish to express their deep thanks to all related parties at Toyo Aluminium Co., Ltd. and Sumitomo Electric Industries, Ltd. for performing joint material development, and Tanaka Seimitsu Kogyo Co., Ltd. for parts manufacturing.

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