Use of gamma titanium aluminide for automotive engine valves

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Abstract

Titanium aluminade is considered an interesting material for the automotive industry when applied to light hot components because of their peculiar properties.
In particular the tensile strenght which is higher in the 700-800 °C range there at room temperature.
Compared with special steel used at high temperature (21-2N) the titanium aluminide is 50% lower in density and the termal expansion is also interestihgly lower.
A suitable casting technology has been developed with the goal of having a low cost transformation process. Unalloyed TiAl has been proven adequate for automotive valves.

Riassunto

Gli alluminiuri di titanio vengono considerati una famiglia di materiali inter metallici di interesse per applicazioni automotive viste le loro particolari proprietà.
La resistenza a rottura in temperatura 700-800 °C risulta superiore rispetto a quella a temperatura ambiente.
La resistenza a fatica in temperatura (800 °C) mantiene livelli superiori ai materiali normalmente usati per applicazioni a caldo (valvole di scarico).
A confronto con tali materiali (es. 21-2N) gli alluminiuri di titanio presentano un peso specifico ridotto del 50% e un coefficiente di espansione termica sensibilmente più bassi.
Ad oggi è disponibile una tecnologia di trasformazione qui descritta in grado di produrre componenti a costi competitivi (es. valvole motore).

BACKGROUND

General

Titanium and aluminum form three principal compounds called titanium aluminides, TiAl, TiAl2, TiAl3,. The TiAl compound, called gamma, is the one which has the highest melting point and other properties that make it useful for engineering purposes. It is nominally 50 atomic percent (35 weight %) aluminum. As with other metals, elements may be added to improve properties. The nature of these alloys is such that hot forming is not practical, so essentially all parts tested have been in cast form. All properties and parts mentioned in this paper are from the investment casting process, which is being used extensively in automotive applications today. For automotive engine poppet valves, unalloyed TiAl has been proven adequate for three engines, but small additions of chromium, silicon, and/or niobium (a percent or less) may be required to improve creep resistance, oxidation, and ductility for other engines. Niobium is the only element that increases cost significantly.

Properties

The properties of TiAl that make it interesting for a valve can be seen from the following side by side comparison with 21-2N, a commonly used exhaust valve steel:

	TiAl	21-2N
Density, grams/cc	3.9	7.7
Tensile strength, Mpa (ksi)		
Room Temperature	560 (80)	1090 (150)
760°C (1400°C)	600 (86)	400 (57)
Therm.Cond. (W/M.K) at 1400°F	28	25
Fatigue str., 10^8 cycles, smooth		
440°C MPa (ksi)	326 (46)	--
816°C MPa (ksi)	220 (31)	165 (24)
Hardness, BHN		
Room Temperature	260	300
760°C	240	140
Modulus, GPa (10^6psi), 75°F	170 (24)	200 (29)
Coefficient of thermal expansion, microns/meter	12.2	18.4

In air, the oxidation resistance of TiAl is quite good to 70°C (1300°F), and has been proven satisfactory in the combustion atmosphere of two engines. If not, an addition of 1% niobium makes it satisfactory up to 870°C (1600°F). While the ductility of the TiAl alloys is only around 1%, it should be adequate for valves, since Si3N4 has run well as a valve material. Even the lowest ductility alloy can easily be processed and handled.

Microstructure

Figure 1 shows the macroetch of the head and a section of the stem of an engine valve. It is possible to get equiaxed structures with low casting temperatures, but as with all titanium casting, temperature control is difficult. The fine columnar structure becomes equiaxed in the part center. The part showed in Fig. 1 was gated into the head of the valve, which is sound as cast. The stem contains varying amounts of centerline shrinkage, depending on the alloy. Thus, it is normal to Hot Isostatic Press the valves to close all internal porosity. That is very expensive due to the high temperatures involved, so tests in which the centerline shrinkage is left in the valve are underway.

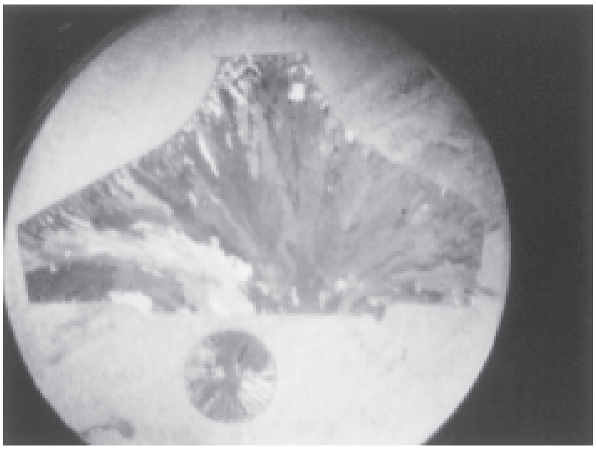

Fig. 1: Macro etch, about twice size, of the cross section of the head and stem of a typical automotive valve. Structure is not refined by heat treatment.

Figure 2 shows a valve with some microstructures at different magnifications, after HIPping. There is some recrystallization where the pores are closed, but the structure is about the same as cast, almost fully laminar, which is the desired structure.

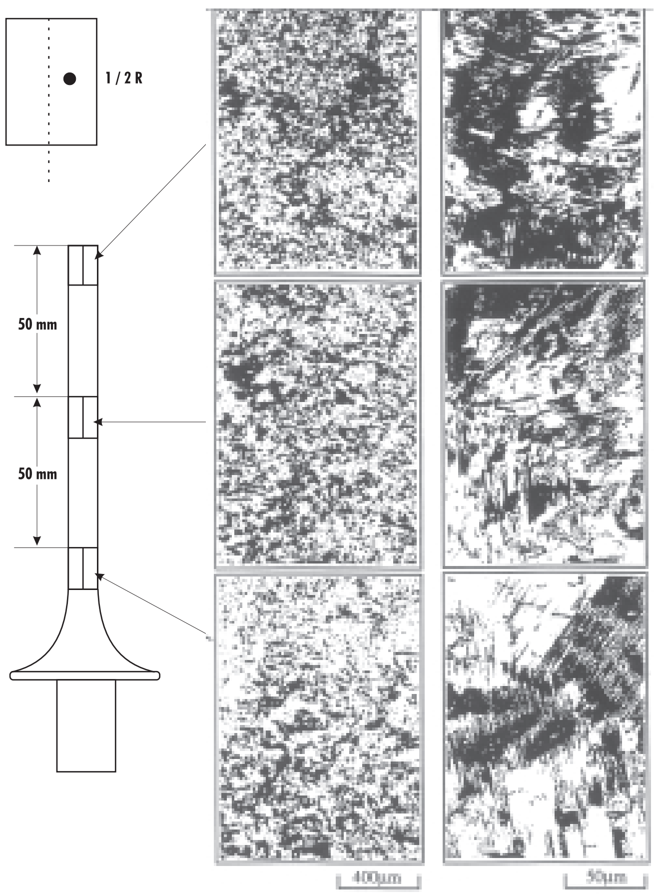

Fig. 2: Microetches, at different places in a TiAl valve after HIPping at 1200°C and 1200 Kgf/cm² for one hour.

Status of development

The potential for light weight valves was recognized as early as 1994. Calculations showed that the use of solid TiAl valves to replace solid steel valves would permit increasing the limiting speed of a push rod engine from 6000 rpm to 6900 rpm in a large engine. Recent works [1] showed that in a smaller overhead cam engine, the limiting speed could be increased from 13,700 rpm, to 14,400 rpm. During this time frame, valves were run in several engines, including stoichiometric operation and excellent performance was obtained. In some cases, plasma carburizing was used to improve wear resistance, but in others, the valves were tested uncoated. Very wear resistant coatings can be applied to TiAl, if engine test shows they are required. All valves tested to date have been hot isostatically pressed to eliminate all internal porosity in the cast valves.

The tests to date show that the TiAl valves will give a power increase over steel valves of about 8% due to the increase in rpm allowed. In addition, if engines are improved to enable stoichiometric operation, further benefits might be obtained. Many other parts of the engine would also have to be changed due to higher temperature of stoichiometric operation.

CASTING TECHNOLOGY

As mentioned, casting is the most cost effective way to form TiAl parts. While some work has bean done in permanent molds and there is a potential for use of a modified sand casting process, only investment casting has been used enough to be called a reliable process. However, if TiAl valves made by investment casting go into production, more work would undoubtably be done to achieve success in the lower cost processes.

Hitchiner believes its CLIX process (US Patent 5,299,619) is currently the lowest cost way of preparing cast valve blanks. The process is shown schematically in Figure 3. Titanium scrap is preheated under vacuum, 3a. The chamber is backfilled with argon, the cover is removed and molten aluminum is poured into the hot titanium as shown in 3b. Power is applied to the charge, which soon causes the titanium and aluminum to exothermically react, forming the TiAl molten alloy, 3c. Quickly, before the melt has time to react with the ceramic crucible, a mold in a vacuum chamber with a fill pipe extending out is moved so the pipe extends into the melt and fills the mold when a vacuum is established in the mold chamber, 3d. Each time a mold is cast a new crucible with a new charge is loaded into the melting chamber. To date almost all valves have been cast in investment shell molds, but a few tests of permanent molds and sand molds showed promise. If either of these mold types could be used costs would be lowered by around 15%.

REACTION MELTING BY CLI PROCESS

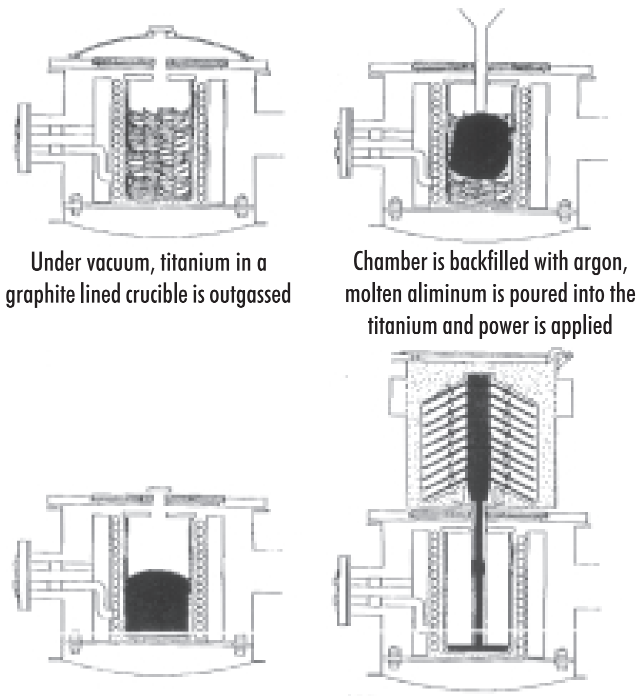

Fig. 3: a-d. Steps in melting and casting TiAl by the CLI process.

MACHINING

Some concerner on the machinig of titanium aluminides are still in place. Recent works [2] showed that if vitrified SiC wheels dressed with diamonds were used to grind TiAl, there was about a 34% increase in grinding costs as compared to stainless steel. However, if you increased the surface speed from 32 to 45 ft/sec and increased the machine stiffness from 15.6 to 24 Kw, the TiAl could be ground faster than stainless steel. Several companies have experience grinding TiAl valves and it is expected grinding could be done economically.

COATING

It is possible that a hard coating on the valve tips and a wear coating on the valve stems will be needed, depending on loads applied to the valve. There are a variety of coatings that have been used – nitriding, CVD coatings, plasma carburizing, and platings of various kinds. There are some indications that a carbon addition to the TiAl would increase its resistance to mushrooming on the tip, which might eliminate the need for a tip coating of some kind. Clearly, there is need for quite a bit of work, mostly testing, in this area to achieve the most economic process. Figure 4 shows some wear data obtained up to now.

COST

The cost per kilogram of the raw materials for 21-2N is around \$0.70 and for those of TiA1 is \$6.30. Even on a volume basis it is \$0.7 vs \$3.11. Processing costs for TiAl are also higher, so its use must generate a big benefit in engine performance to be cost effective. On a volume basis it is much lower in cost than nickel base superalloys such as INCO 751, and processing costs are comparable. Thus, there is no question that, from a cost standpoint, TiAl is a viable candidate for valve applications requiring nickel alloys or sodium filled valves. For normal passenger cars, a careful trade off analysis must be done to determine the economics of TiAl. Even with optimization of design and the processes described it would be expected the price of finished TiAl valves would be in the range of \$3.50-4.50 per valve.

REFERENCES

[1] *Development of a high performance TiAl Engine valve,* Maki et al, SAE 1996.

[2] *Titanium aluminider machining,* Schmite-Cincinnati Millicron - February 12, 1995 Symposium.

[3] *Development of titanium aluminide turbocharger rotors*, Nishiyama et al, TMS/ASM, Indianapolis-IN, October 5, 1989.

SUMMARY

Titanium aluminide is still very much an experimental material for use in automotive. The very first production of TiAl parts is for turbocharger wheels for a low volume application in Japan. The wheels are being made by Daido Steel Co. Ltd. TiAl poppet valves have been run in at least five engines and have performed well, even under stoichiometric operation. The big problem is the high cost of the material, which will preclude its wide use for the forseeable future. It currently can compete cost wise with sodium cooled and solid nickel alloys valves, however.

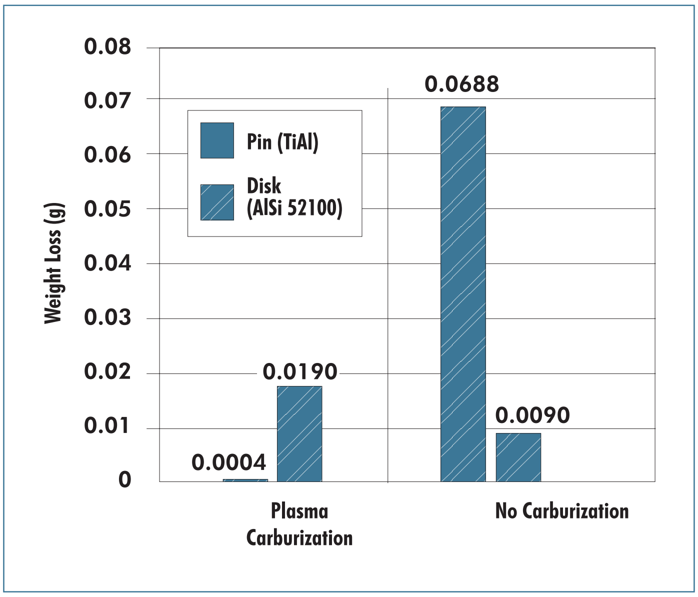

Fig. 4: Wear test results for the plasma carburization which has proven to be more than adequate for most engines.