TITANIUM IN THE FAMILY AUTOMOBILE: THE COST CHALLENGE

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ABSTRACT

With advances in extraction/fabrication techniques and ever increasing gasoline prices the advantage of using lightweight materials such as aluminum, magnesium and titanium in automobiles continues to increase, particularly for the first two metals. The major drawback for titanium much more so than the other light metals - high cost – is omnipresent. However innovative extraction and fabrication approaches are leading to a deceased cost. This paper discusses the present status and future potential for titanium use in the family automobile.

INTRODUCTION

In a recent JOM review of titanium use in family automobiles the basic advantages of titanium were noted as a high strength to density ratio and outstanding corrosion resistance (1). There are a number of ways for improving fuel consumption, one of which is reduced weight, Figure 1. Even beyond monolithic conventional alloy such as Ti-6Al-4V, the intermetallic TiAl-based alloy (2,3) and reinforcement concepts (4,5) offer further advantages such as higher temperature capability and enhanced stiffness/wear resistance respectively.

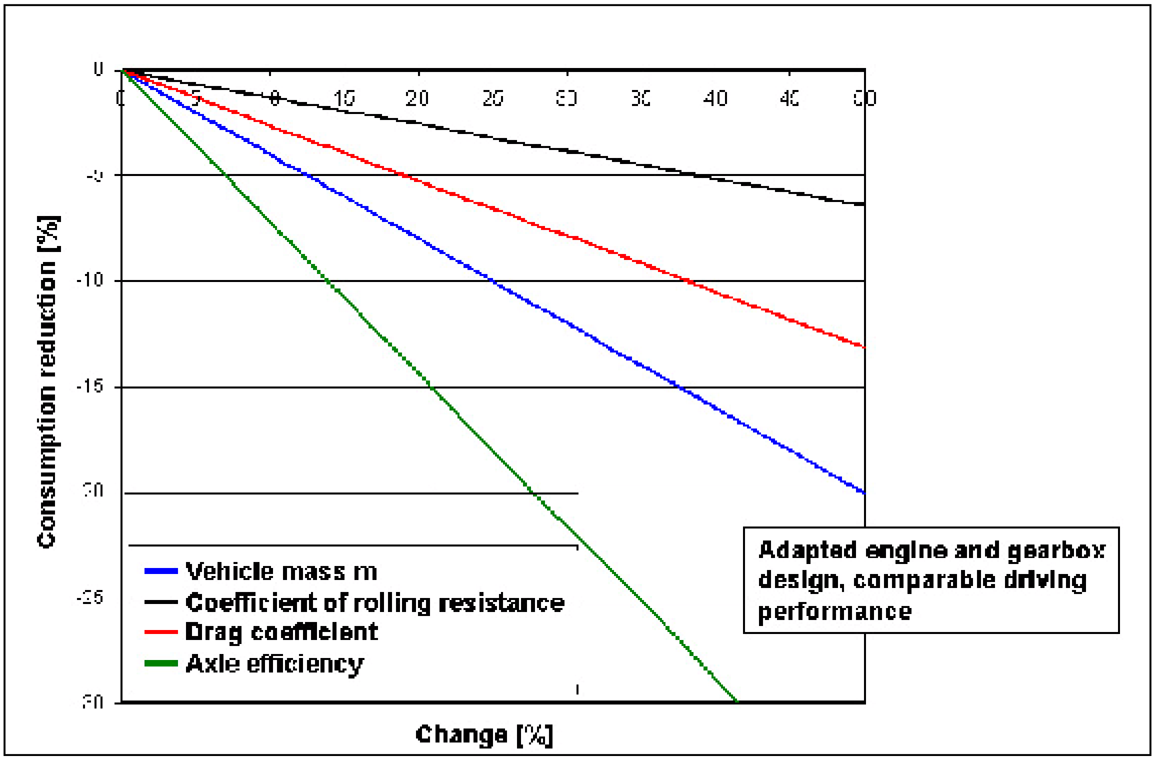


Figure 1. Parameters influencing fuel consumption.

Technical problems which are cited with titanium in automobiles include wear resistance, lower modulus than steel, and machining difficulties. However the first item can be improved with coatings/reinforcement, the second using reinforcements and the third can be minimized by using near-net shape technique and choice of appropriate machining parameters (6). The major problem is that the cost of titanium is substantially greater than competing materials such as steel and aluminum, Table I, a result of high extraction costs and decidedly more complex processing requirements for titanium (1,6,7).

Table I. Cost of Titanium Compared to Competing Automobile Materials (1,6,7).

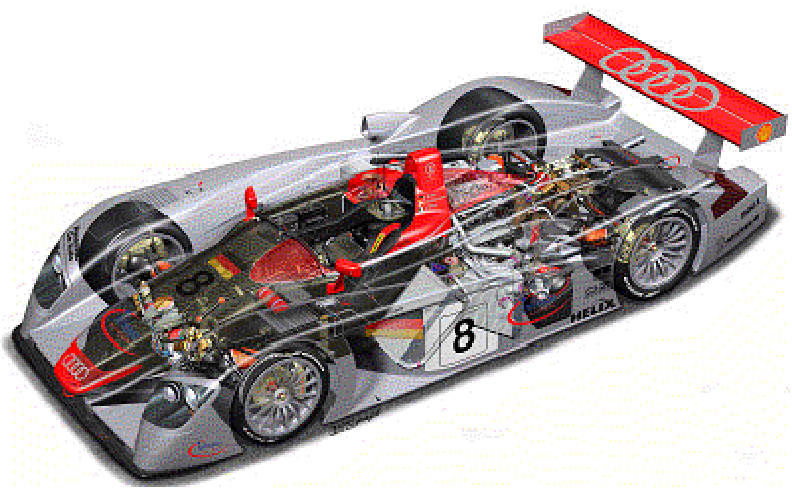
ITEM	MATERIAL ($ PER POUND CONTAINED)			
	STEEL	ALUMINUM	MAGNESIUM	TITANIUM
Ore	0.02	0.10	0.01	0.30
Metal	0.10	0.68	0.54	2.00
Ingot	0.15	0.70	0.60	4.5
Sheet	0.30-0.60	1.00-5.00	4.00-9.00*	8.00-50.00

*Mg sheet is not commonly used. Castings are $2.50-10.00 per pound.

Thus the challenge that the titanium industry has faced is to bring down the cost of titanium components by reducing the extraction and fabrication costs. However, this has not stopped use of titanium in a plethora of niche and high-end automobile components, Table II. At the same time titanium has seen significant use in racing cars where cost is no objective, winning is the name of the game, Figure 2.

Table II. Standard components manufactured from titanium.

Year	Component	Material	Manufacturer	Model
1992	Connecting rods	Ti-3Al-2V-rare earth	Honda	Acura NSX
1994	Connecting rods	Ti-6Al-4V	Ferrari	All 12-cyl.
1996	Wheel rim screws	Ti-6Al-4V	Porsche	Sport wheel option
1998	Brake pad guide pins	Ti grade 2	Daimler	S-Class
1998	Brake sealing washers	Ti grade 1s	Volkswagen	All
1998	Gearshift knob	Ti grade 1	Honda	S2000 Roadster
1999	Connecting rods	Ti-6Al-4V	Porsche	GT3
1999	Valves	Ti-6Al-4V & PM-Ti	Toyota	Altezza 6-cyl.
1999	Turbo charger wheel	Ti-6Al-4V	Daimler	Truck diesel
2000	Suspension springs	TIMETAL LCB	Volkswagen	Lupo FSI
2000	Wheel rim screws	Ti-6Al-4V	BMW	M-Techn. option
2000	Valve spring retainers	β-titanium alloys	Mitsubishi	All 1.8 l – 4-cyl.
2000	Turbo charger wheel	γ-TiAl	Mitsubishi	Lancer
2001	Exhaust system	Ti grade 2	General Motors	Corvette Z06
2001	Wheel rim screws	Ti-6Al-4V	Volkswagen	Sport package GTI
2002	Valves	Ti-6Al-4V & PM-Ti	Nissan	Infiniti Q45
2003	Suspension springs	TIMETAL LCB	Ferrari	360 Stradale



CFRP	29.48%
Steel	26.40%
Aluminum	19.92%
Magnesium	9.40%
Rubber	5.88%
Fluids	2.55%
Electrics	2.22%
Tungsten/Ni-Cd	1.98%
Titanium	**1.46%**
Plastic	0.31%

Figure 2. Distribution of titanium in the Audi R8 racing car, material's distribution.

USE OF TITANIUM IN FAMILY AUTOMOBILE COMPONENTS

The potential for use of titanium in automobile parts has been discussed in a number of publications, (1, 5-12) and is shown in summary form, Figures 3-5. The attraction of titanium use depends not only on the weight savings in a particular component, but also the effect this weight savings has on surrounding parts; the expense associated with weight savings is easier to accommodate at the front and upper portions of the automobiles (6).

Figure 3. Potential automotive applications for titanium.

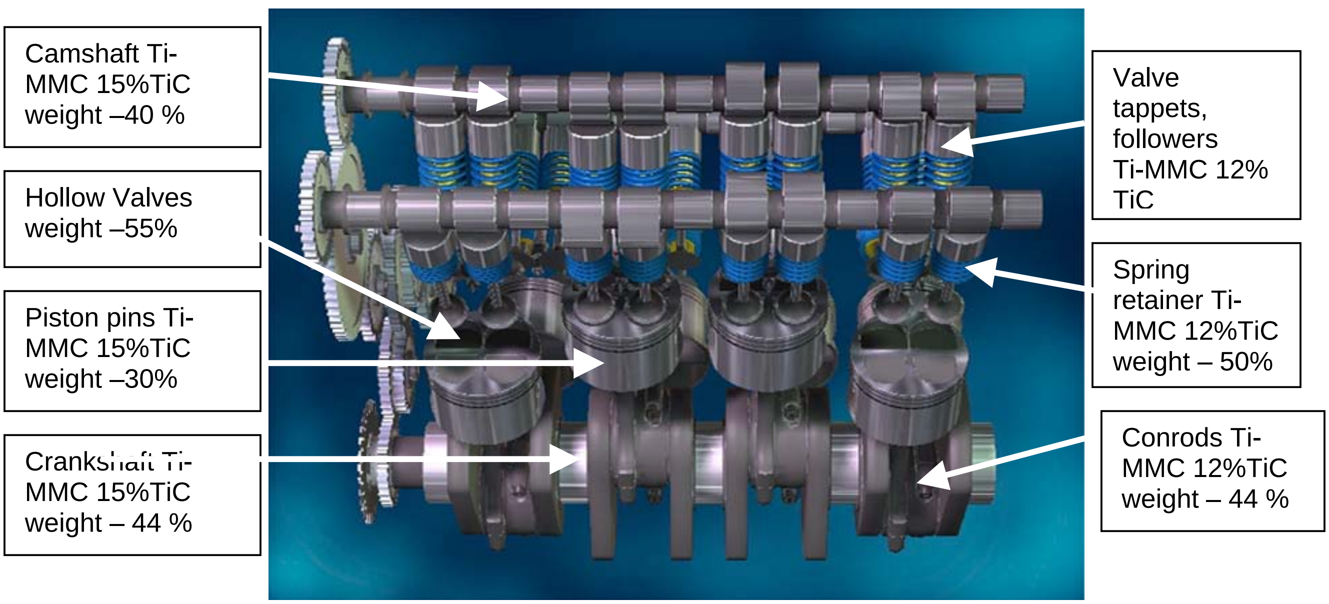


Figure 4. Application of Titanium-MMC-alloys for engine components.

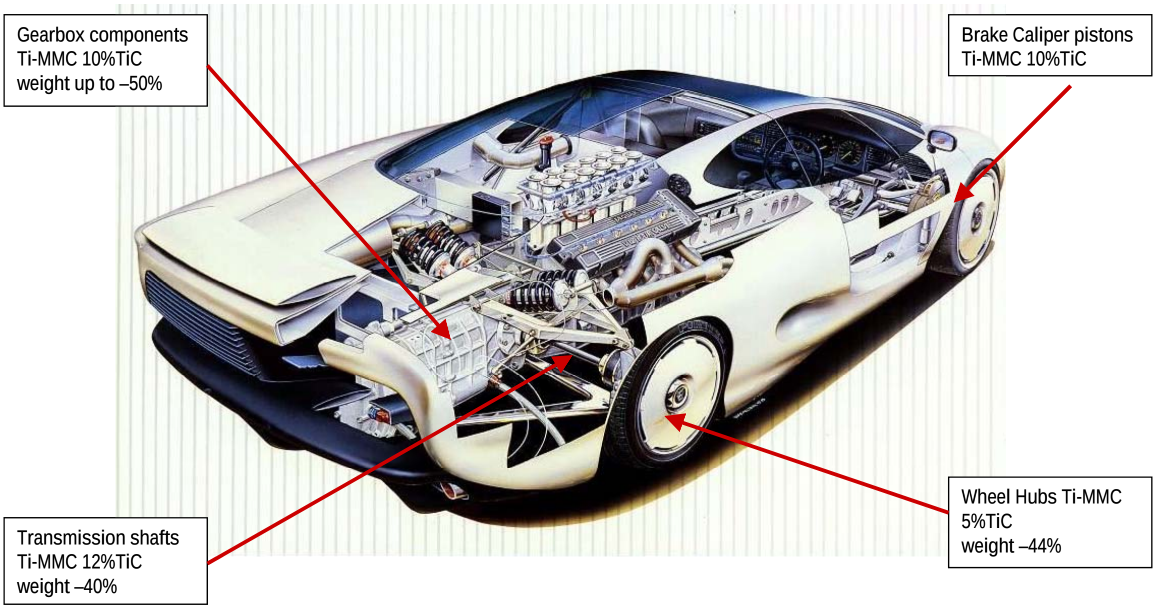


Figure 5. Potential application of titanium-MMC alloys for chassis components

Engines

The reciprocating and rotating mass components can significantly effect fuel economy and fuel emission, Figure 6 (8).

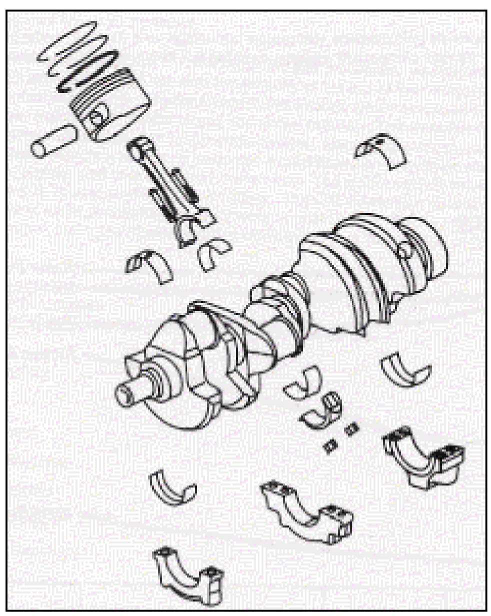


Figure 6. The major reciprocating and rotating mass components affecting fuel economy and emission (8).

Connecting rods require strength, fatigue performance, stiffness (particularly the big end) and wear resistance. The strength and fatigue performance of titanium are more than sufficient for this component, however stiffness and wear resistance need enhancement via reinforcement particles and coating (6, 10). Novel concepts such as bimetallic steel (lower part of the big end) – titanium components allow a shifting of the connecting rod's center of gravity towards the crankshaft, giving a positive effect on piston guidance (6, 13). Reduced weight connecting rods, in combination with lighter weight pistons and wrist pins lead to significantly reduced NVH (noise, vibration and harshness) and improved engine performance including fuel economy (10).

Piston assemblies (piston, piston pin and the connecting rods discussed above) account for a large amount of the friction losses in an engine over the full speed range (8). Reduced mass here leads to improved fuel economy and reduced emissions. Titanium use in these components could increase as the operating temperatures in the engine exceeds the capabilities of aluminum alloys (14). For piston pins where strength, wear resistance, high stiffness and high temperature capabilities are required the titanium aluminides appear to be a good choice (6).

Valve gears could see increased use of titanium with a trend towards higher speed engines (6); here creep resistance and oxidation resistance are required. Composite concepts and TiAl-compositions (demonstration components have performed successfully in the Corvette) look attractive especially for the exhaust valve, while Ti-6Al-4V may have adequate mechanical properties for the lower temperature intake valves. The Toyota Altezza has featured titanium valves for the part five years, Figure 7.

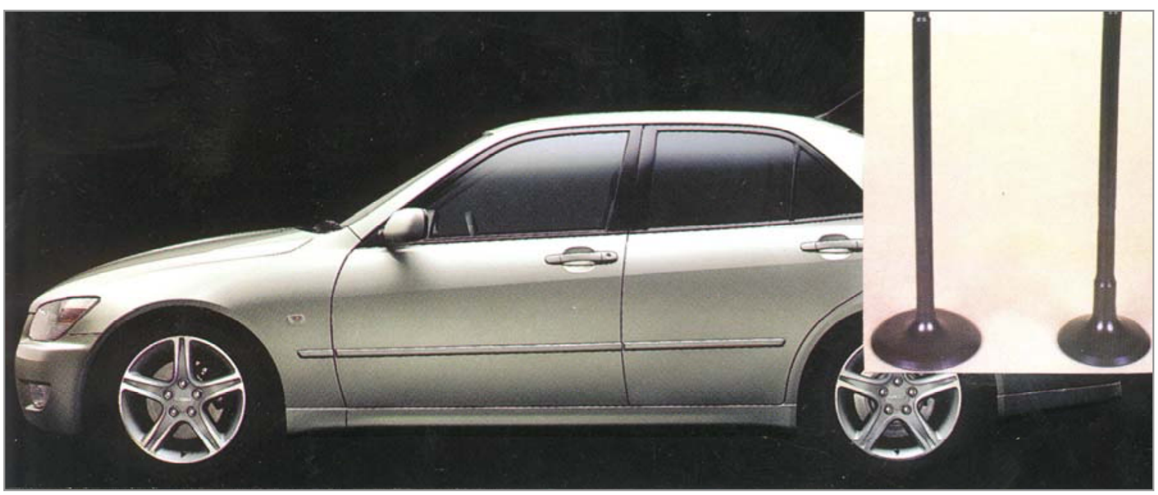


Figure 7. The Toyota Altezza, 1998 Japanese Car of the Year, the first family automobile in the world to feature titanium valves. Ti-6Al-4V intake valve (left) and TiB/Ti-Al-Zr-Sn-Nb-Mo-Si exhaust valve (right). (Courtesy Toyota Central R & D Labs, Inc.).

Titanium valve springs reduce mass due to the low modulus and density of titanium, with the higher cost beta alloys being favored here (1, 6). The use of γ-TiAl in particular for valves leads to a pronounced reduction in mass. This allows the maximum engine speed to be increased by approximately 10%. Additionally, the light-weight γ-TiAl valves reduce valve chattering at high engine speeds, Figure 8.

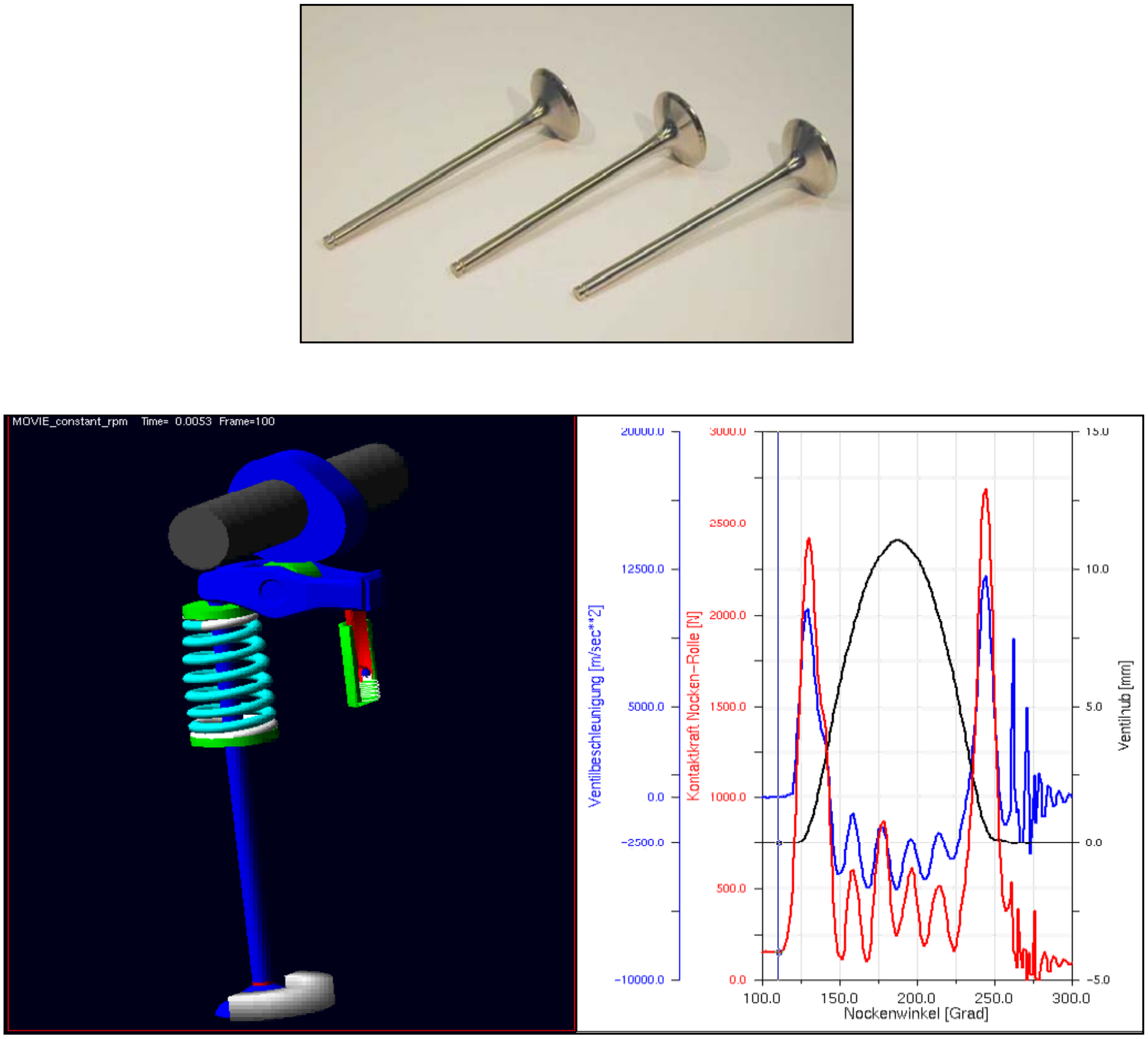


Figure 8. γ-TiAl for high engine speeds and reduced valve chattering.

Brake Systems

The low thermal conductivity and poor wear resistance of titanium negates use of titanium in brake rotors (15). However titanium's excellent corrosion resistance has led to some use in sealing rings in the brake line connection flange and in brake pad guide pins. Titanium's low thermal conductivity acts to protect the brake fluid (6).

Chassis

A reduction in the unsprung weight in an automobile leads to a more comfortable ride (6). However for parts such as pivot bearings, wheel carriers, steering linkage and axle stubs the cost of titanium has prevented use, despite it's excellent corrosion resistance.

Exhaust Systems

Titanium exhaust systems have already been shown to be an excellent choice for motorcycles (16) and are offered as an option on the Corvette Z06 (1). In the latter application the titanium components last for the lifetime of the car (12-14 years), while a stainless steel part must be replaced after 7 years; making the titanium part cost-effective when cost of ownership is considered. Tests with titanium exhaust systems were successfully conducted on the VW Golf 4motion, Figure 9. For this application titanium grades 1 or 2, which have adequate forming characteristics, were used. This specific use of titanium is at the rear of the exhaust system where weight reduction is not particularly effective. The use of titanium in the forward parts of the exhaust system would be more effective but this requires new alloys and coating developments.

Figure 9. Exhaust system for the Golf 4motion, CP titanium, approximately 50% weight reduction compared to a steel component.

Springs

The low density and modulus of titanium make it an excellent choice for spring applications; and since 2000 the rear axle in the VW Lupo FSI has featured uncoated beta titanium (Timetal Low Cost Beta) springs, Figure 10.

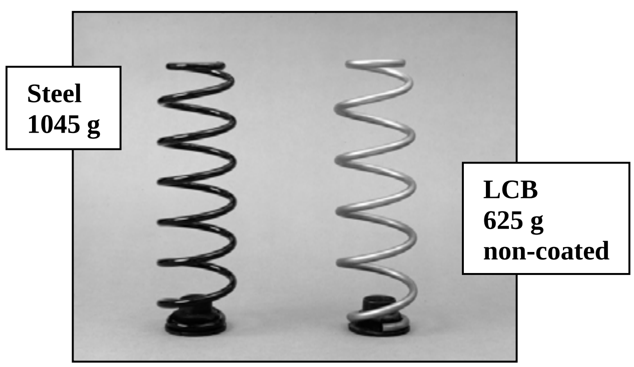


Figure 10. VW Lupo FSI rear axle springs

Bolts and Fasteners

Significant weight savings can result from replacing steel bolts and fasteners with titanium parts. This type of titanium component can be fabricated at relatively low cost by powder metallurgy (P/M) techniques, Figure 11. However surface coatings may be required to achieve necessary bolt pre-load forces (6), both initially and if replaced later (e.g. a wheel replaced by an automobile owner).

Figure 11. Ti-6Al-4V fasteners produced using the BE P/M technique suitable for automotive use (Courtesy ADMA Products).

Thus there is significant potential for use of titanium in the family automobile- but only if COST can be reduced and this is addressed in the next section of this paper.

COST-AFFORDABLE TITANIUM

As noted in the introduction titanium is significantly more expensive than aluminum or steel. This results from the cost of extraction (basically the energy required to separate titanium and oxygen atoms) and the cost of fabricating titanium (which conventionally involves relatively "cold" processing, relatively expensive conditioning; that is removal of surface regions which are brittle due to oxygen enrichment and contain cracks or surface tears). A number of emerging techniques offer good opportunities to reduce both cost factors. The goal for extensive use in the family automobile - $2.7 to 4.5 per pound ($6 to $10 per kg) (6).

Extraction

For fifty years titanium sponge has been produced commercially using the two step reduction of TiO_2 to the intermediate product $TiCl_4$ followed by reduction by Na (Hunter process) or Mg (Kroll process); with the latter approach dominating. This despite evaluation of many alternate approaches (17). In the past few years a number of innovative extraction techniques have been developed in the research base, a number of which were presented at the 10th World Titanium Conference, Hamburg, Germany, July 2003 (18). These techniques include the semi-continuous Kroll Process (International Titanium Powder, Armstrong process), the Plasma Quench approach, the Fray-Farthing-Chen (FFC) reverse electrolysis method (18), mechanochemical processing (19) and other as yet unrevealed processes. The FFC approach has received by far the most hype culminating in a $12.3M DARPA contract award to a team led by Timet to scale up the process in the USA over the next three to four years. The cost of the titanium produced by this process has been quoted at an exciting $1 per pound (20) compared to Kroll sponge at $3.50 per pound. However an independent cost analysis suggests that there may be a little if any cost advantage to the FFC approach (21). Time will tell. So there's a lot of activity in the extraction arena, with hopefully a breakthrough pending.

Fabrication

In the fabrication arena lower cost approaches are being incorporated into the conventional ingot metallurgy (I/M) method including single cold hearth melting, near-net shape extractions and lower cost chemistries (basically replacing expensive vanadium in alloys such as Ti-6Al-4V with less expensive Fe). Still to come are "non-aerospace", higher tramp element grades, of titanium from less expensive (less pure) ores.

Potentially most interesting are near net shape (NNS) casting (permanent metal mold) and powder metallurgy (P/M) techniques (18). Of these the P/M method appears to offer the greatest opportunity for real cost reductions.

As noted earlier in this article, Saito has led the way in getting titanium P/M components into the family automobile: valves on the Toyota Altezza. There are now techniques available allowing use of single press-and-sinter of low cost blended elemental (BE) powders to produce close to fully dense Ti-6Al-4V automobile components, without additional compacting steps (e.g. hot isostatic pressing) adding to the cost, Figures 12 and 13.

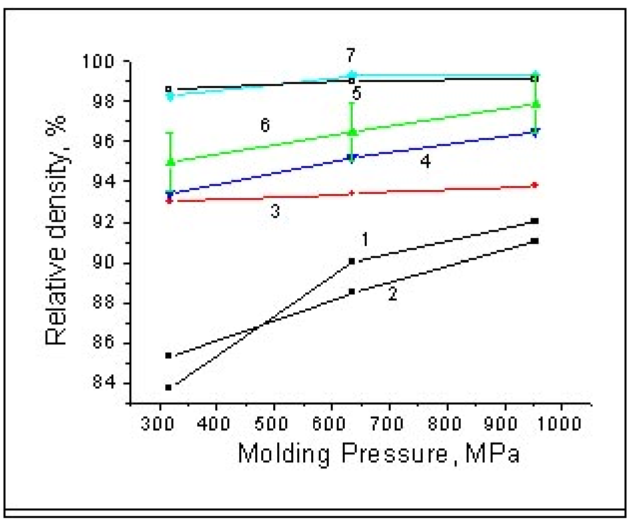


Figure 12. Density of Ti-6Al-4V compacts after sintering. Conditions 5 and 7 use hydrided powder and exhibit by far the highest and most uniform densities after sintering. The uniformity of density with molding pressure is extremely important for the fabrication of complex parts.

Figure 13. Ti-6Al-4V parts produced using a press-and-sinter approach and titanium hydride. 1) Connecting rod with big end cap; 2) Saddles of inlet and exhaust valves; 3) Valve spring plate; 4) Distribution shaft driving pulley; 5) Strap tension gear roller; 6) Screw nut; 7) Fuel pump filter; and 8) Embedding filter.

Paralleling this P/M work on monolithic alloys one of the authors of the present paper has developed reinforced (TiB_2 or TiC) titanium alloys with increased stiffness and wear resistance. Figures 14-16 (5).

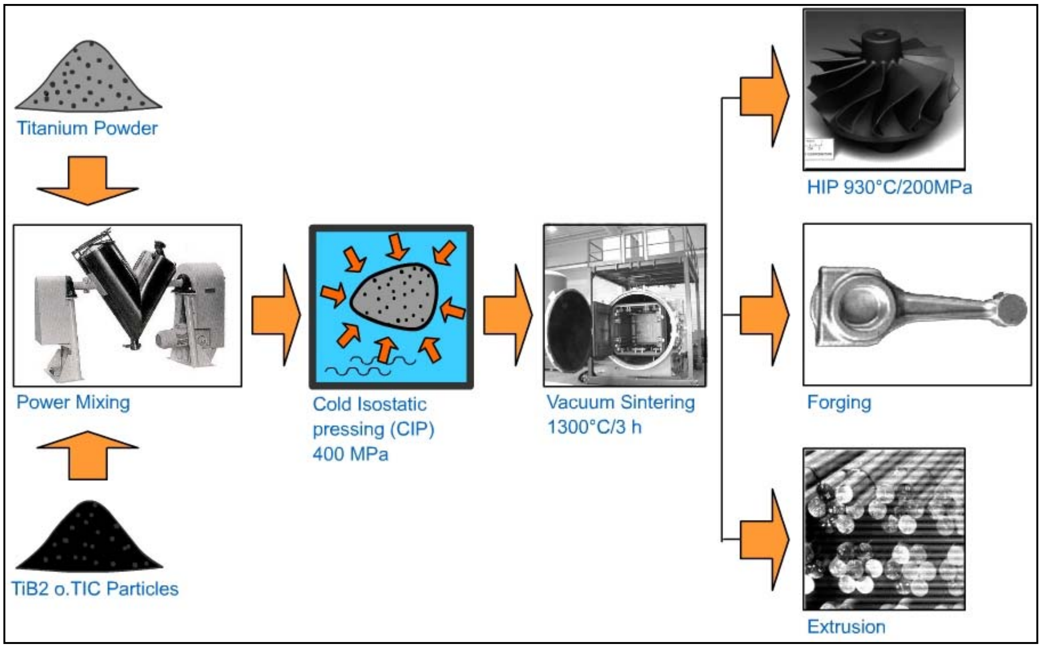


Figure 14. Processing route for Titanium-MMC alloys.

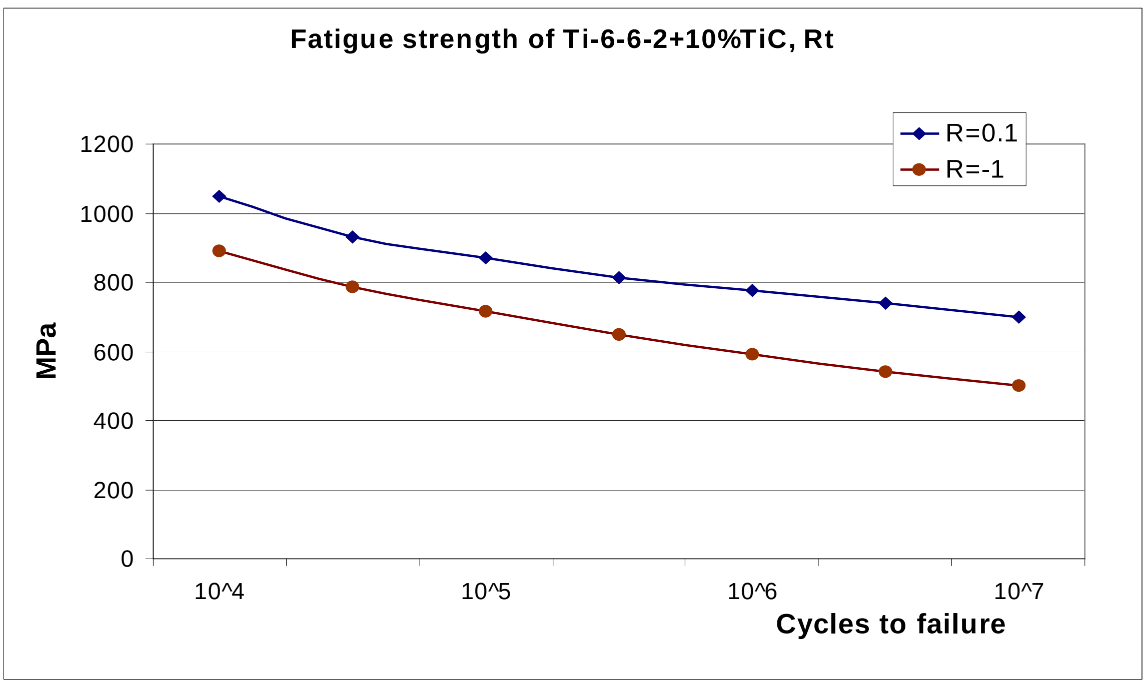


Figure 15. Fatigue strength of titanium-MMC alloys.

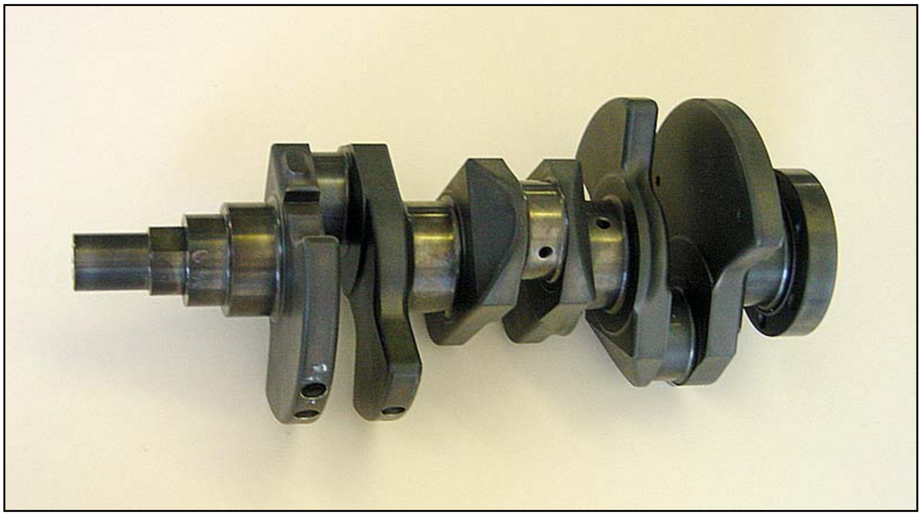


Figure 16. A demonstration titanium – MMC crankshaft weighing 5 kg.

In this latter work powder costs were $1.80 per pound ($4 per kg), but are projected to go to $0.82 per pound ($1.80 per kg) (5). Auto applications for titanium MMC's can include con rods, valves and piston rings. Weight reductions of up to 44% are possible at 12% loading with TiC reinforcement.

WHAT LIGHTWEIGHT MATERIALS CAN ACHIEVE

The Volkswagen CCO diesel (one 300 cc cylinder engine) weighing a spritely 640 pounds (290 kg), is shown in Figure 17. This automobile utilizes a mix of lightweight materials including aluminum, magnesium, titanium and polymeric composites to give an amazing 250 mpg(100 km per liter) fuel consumption. Titanium use includes engine, gearbox and chassis components: a MMC titanium connecting rod, a titanium exhaust system and bolts in the gearbox fabricated from titanium. Other titanium components include wheel hubs and wheel bearings, the steering rack and pinion, and tie rods for a total titanium use of about 3% (6).

Figure 17. Volkswagen CC0 “one-liter car”, ultra-low consumption car.

CONCLUDING REMARKS

Titanium can clearly play a role in the future fuel efficient lightweight automobile. However the cost must be reduced; and there appear to be approaches to achieve this goal. With 50 million cars and light trucks produced per year world-wide, the impact of just a few kg per automobile would be dramatic with the current world-wide titanium market running at about 50,000 mtons.

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SIDE BAR

The Environmental Issue

By 2015 the European Union will require that 95% of an automobile be recyclable. A challenge especially for components such as tires.

And how about the energy consumed in producing the automobile, a separate issue from the fuel consumption during use? A recent paper by E.D. Williams in Environmental Science and Technology 36 (2002) 24 compared the fossil fuel use in producing a 2 gm 2MB DRAM chip (such as those found in PC's) with that required to manufacture a 3,000 pound automobile. The chip requires 1700 gms while the automobile uses up 1500-3000 kg. Much more for the car – but hold it! If we look at the fuel consumption to weight ratio it's 2:1 for the auto but a massive 630:1 for the microchip. Compounding that ratio for the chip is that over an 8-10 year period perhaps 5 computer up-grades will occur, and at the high price of automobiles one car. The net result being that over the ten year period the total energy use in producing device(s) and the automobile are probably not that different.