Ti-2007 Science and Technology, edited by M. Ninomi, S. Akiyama, M. Ikeda, M. Hagiwara, K. Maruyama
The Japan Institute of Metals (2007)

Status of Titanium and Titanium Alloys in Automotive Applications

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Typical potential applications of titanium and titanium alloys in automotive engineering are outlined. Generally, these are highly loaded components in the engine such as connecting rods, turbocharger wheels, pistons and piston pins as well as valve gears. Recently, titanium suspension springs as well as exhaust systems made of titanium were successfully introduced.

Keywords: *titanium connecting rods, turbo charger wheels, engine valve gears, exhaust systems, piston and piston pins, suspension springs*

1. Introduction

Since the end of the nineties of the last century, a number of new cars and motorcycles have been introduced to the market incorporating titanium applications in various components. Nowadays, titanium is definitely established in automotive constructions, at least in the niche car and motorcycle segments. Nevertheless, it has to be stated that no advancement of more cost efficient titanium production processes has been made preferable dedicated to automotive applications. Thus, recent applications focus on the high end market, mainly on super sports cars such as Porsche GT3, Corvette Z06, Koenigsegg and Bugatti Veyron.

2. Titanium Applications

2.1. Connecting rods

Connecting rods connect the pistons with the crankshaft. One of the most important properties is HCF strength to withstand the oscillating mass forces. While the low density and high strength of Ti-6Al-4V are in favor for this application, the comparatively low Young's modulus needs to be compensated for by a particular stiffness design. The first production car on the market with titanium conrods was the famous sports car NSX from Honda. It had a 3-liter DOHC V6 engine and a red-line at 8000 rpm. The conrod was made of Ti-3Al-2V with rare earth additions that offered improved machinability (Table 1).

Table 1. Application examples for connecting rods

Year	Material	Manufacturer	Model
1992	Ti-3Al-2V-RE	Honda	NSX
1994	Ti-6Al-4V	Ferrari	All 12 cyl.
1999	Ti-6Al-4V	Porsche	GT3
2002	Ti-6Al-4V	GM	Corvette Z06
2005	Ti-6Al-4V	Bugatti	Veyron 16.4
2006	Ti-6Al-4V	Koenigsegg	Koenigsegg

As seen all other titanium conrods introduced in the following years were made of Ti-6Al-4V. Recently, even γ-Ti aluminides are considered as promising candidates for connecting rods since they combine a density even lower than that of conventional titanium alloys (3.8 vs. 4.5 g/cm^3) with a significantly higher Young's modulus (170 vs. 110 GPa).

Figure 1. Connecting rods of the Corvette Z06 made from Ti-6Al-4V (courtesy of TIMET company)

(α+β) forged conrods of the Corvette Z06 are illustrated in Figure 1. The Z06 is powered by a push-rod V8 engine of 7-liter displacement. Power output of this naturally aspirated big-block engine is 512 bhp at 5300 rpm and maximum torque is 470 lb-ft (637 Nm) at 4800 rpm.
The 16 conrods made of (α+β) forged Ti-6Al-4V used in the Bugatti Veyron are shown schematically in Figure 2.

Figure 2. 16 Ti-6Al-4V connecting rods in the Bugatti Veyron's engine

The Bugatti's engine is a W16 with 8-liter displacement. Power is delivered with the help of 4 turbochargers and 2 liquid intercoolers. The maximum output is as high as 1001 bhp at 6000 rpm and maximum torque amounts to 922 lb-ft (1250 Nm) over a wide range of rpm.

2.2 Turbo charger wheels

Turbo charging is used to increase power and torque of gasoline and in particular those of diesel engines. Nowadays, almost all diesel engines in automobiles in Europe are turbocharged. Using titanium instead of the heavier Ni super-alloys as wheel material can significantly reduce the so-called turbo-lag. Typical required properties for turbo charger wheels are HCF strength (blades), LCF and creep strengths (blade root) and high resistances to oxidation and erosion.

Oxidation resistance and creep strength are becoming more and more important since exhaust temperatures reach 750°C in modern diesel engines and even 950°C in advanced gasoline engines.

While Ti-6Al-4V turbo-charger wheels can be used in diesel engines because of the lower gas temperatures, gamma titanium aluminides are used in the gasoline engines of the Mitsubishi Lancer RS (Table 2). Output from its small 2-liter 4 cylinder engine was as high as 280 bhp due to turbo-charging and this value increased to even 300 bhp in the new model.

Table 2. Application examples for titanium turbo-charger wheels

Year	Material	Manufacturer	Model
1999	Ti-6Al-4V	Daimler-Benz	Truck Diesel
2000	γ-TiAl	Mitsubishi	Lancer RS

2.3 Engine Valve Gears

Engine valves are subject to high cyclic stresses. Exhaust valves also see high temperatures. Required properties are high-temperature HCF strength, creep resistance, thermo-shock resistance as well as high resistances to oxidation and wear. Because of the elevated temperature loading, near-α titanium alloys such as Ti-6242, TIMETAL 1100 or TIMETAL 834, particle-reinforced (α+β) titanium alloys or even γ-Ti aluminides are applied. As opposed to exhaust valve application, for intake valves in automobile engines, elevated temperature properties of Ti-6Al-4V are mostly sufficient.

Valve springs and valve retainers made of titanium would reduce the weight of the entire titanium valve gear by up to 70%, maximum engine rpm could be increased by roughly 10%. The first car with titanium valves on the market was the Toyota Altezza (Table 3).

Table 3. Application examples for titanium valve gear

Year	Components	Material	Manufacturer	Model
1998	Valves	Ti-6Al-4V	Toyota	Altezza 6-Cyl.
2002	Valves	Ti-6Al-4V	Nissan	Infinity Q45
2003	Valve Spring Retainers	β-alloy	Mitsubishi	All 1.8 l-4 Cyl.
2005	Valves	Ti-6Al-4V	GM	Corvette Z06

This car was intended to challenge the 3-series of BMW. The Altezza's inline 6 cylinder engine delivered 210 bhp at 7600 rpm and a maximum torque of 160 lb-ft (217 Nm) at 6400 rpm. Other manufacturers followed: Nissan introduced the Infiniti Q45 with Ti-6Al-4V valves in 2002. Mitsubishi used valve spring retainers made of a β-titanium alloy on all 1.8-liter 4 cylinder engines. Ti-6Al-4V valves also operate in the engine of the Corvette Z06.

Motorcycle engine valves are shown in Figure 3. The Yamaha YZ 450Z has a 4-stroke single cylinder engine with 450 ccm displacement and 5 titanium valves, namely 2 intake and 3 exhaust valves.

The Kawasaki Ninja ZX10R is a racing bike with an inline 4 cylinder engine of 1-liter displacement. It delivers 175 bhp at almost 12000 rpm.

Figure 3. Examples for Motorcycle Engine Valves (courtesy of TIMET company)

Compared to valves in car engines, valves in motorcycles usually operate at much higher rpm. Due to the smaller stem diameter, wear resistance becomes important. Nippon Steel has developed a special oxidizing treatment in which β-annealed Ti-6Al-4V intake valves are heated in air at 670°C to form a hard wear-resistant surface layer. The superior wear resistance could be combined with a HCF strength as high as in the as-received equiaxed microstructure. A typical alloy for exhaust valves in motorcycles is the near-α alloy TIMETAL 1100.

2.4 Exhaust Systems

Required properties for exhaust systems are cold formability, deep drawability, weldability, oxidation resistance and elevated temperature HCF strength. In addition, the acoustic performance of an exhaust system plays an increasing role, particularly, in sports cars.

The deep drawability β_{max} of cp-Ti as evaluated in cup drawing tests has been shown to be as good as that of AISI 304 while both deep drawing depths and loads in the Erichsson tests were somewhat lower. Forming limit curves indicate that stretch forming should be avoided by good lubrication (MoS_2, Graphite, PE drawing fluids). Using cp-Ti Grade 2 instead of stainless steel, 50% weight savings can be achieved. For application at moderately high gas temperatures (diesel engines), the oxidation resistance of cp-Ti is sufficiently high. However, for longtime application at temperatures above 700°C, cp-Ti needs to be coated or new alloys be developed.

The Corvette Z06 was the first car equipped with a titanium exhaust made of cp-Ti grade 2 (Table 4). Others followed such as the Fair Lady Z (in the US or Europe better known as the 350Z), the Subaru Impreza and the Bugatti Veyron 16.4. The Bugatti's cp-Ti exhaust system is partially Al-plated as will be shown below.

Latest example for applying titanium as exhaust material is that of the super-sports car Koenigsegg from Sweden. The Koenigsegg's CCX twin supercharged modified Ford V8 delivers maximum values in power and torque of 817 bhp and 920 Nm, respectively.

Table 4. Application examples for titanium exhaust systems

Year	Material	Manufacturer	Model
2001	cp-Ti Grade 2	GM	Corvette Z06
2003	cp-Ti Grade 2	Nissan	Fair Lady Z
2003	cp-Ti Grade 2	Subaru	Impreza
2005	cp-Ti Grade 1 Al-plated	Bugatti	Veyron 16.4
2006	cp-Ti Grade 2	Koenigsegg	Koenigsegg

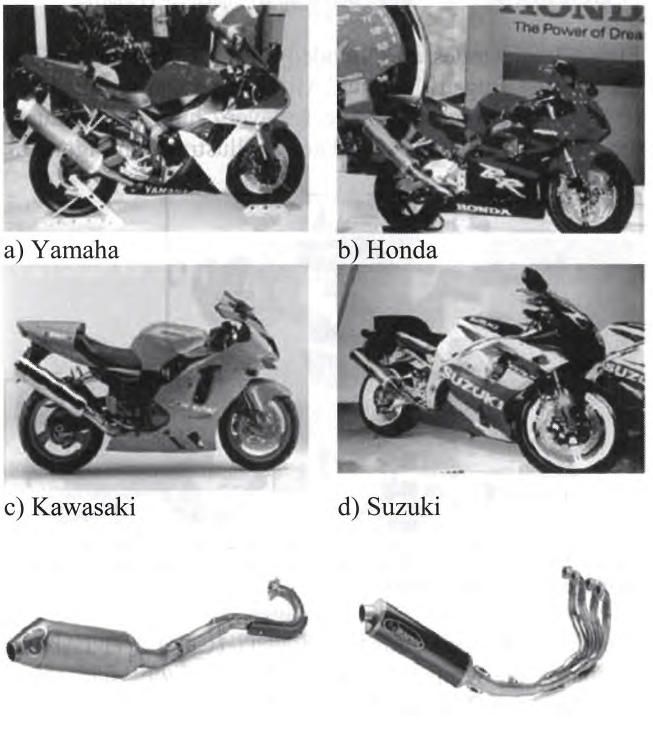
Figure 4 illustrates the Z06 Corvette's exhaust system made of cp-Ti grade 2. This system comes with a lifetime warrantee. From a materials standpoint, a stainless steel exhaust system could also last forever. However, there can be problems regarding stress corrosion cracking after welding stainless steel. This is not an issue with titanium.

Figure 4. Exhaust system of the Corvette Z06 (courtesy of TIMET company)

The Fair Lady Z (350Z) and the Subaru Impreza together with their titanium exhaust systems are shown in Figure 5.

Figure 5. Application examples of titanium exhaust systems in Japanese passenger cars (courtesy of Toshihiko Saiki)

Titanium exhaust systems are produced for all leading Japanese motorcycle companies, namely Yamaha, Honda, Kawasaki and Suzuki (Figure 6).



a) Yamaha b) Honda

c) Kawasaki d) Suzuki

Figure 6. Application examples of titanium exhaust systems in Japanese motorcycles (courtesy of Toshihiko Saiki)

Titanium exhaust systems in racing motorbikes offer weight savings typically of the order of 30-40% which together with a power increase of roughly 5% lead to markedly improved performance.
As already stated above, long-time applications at very high temperatures require coating of cp-Ti. At very high temperatures, e.g., at 860°C, the unplated cp-Ti exhibits a large-sized scale and suffers from marked material losses as indicated in Figure 7.

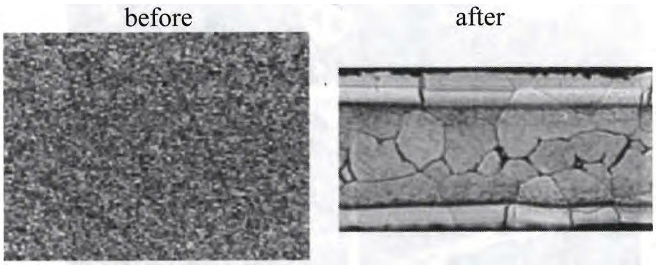


Figure 7. Cross sections of cp-Ti sheets before and after thermal exposure at 860°C for 100 hours

If cp-Ti is aluminum plated, there is almost no material loss under the same long time high-temperature exposure. This was shown to be due to a titanium aluminide oxidation barrier that is formed at high temperatures (Figure 8)

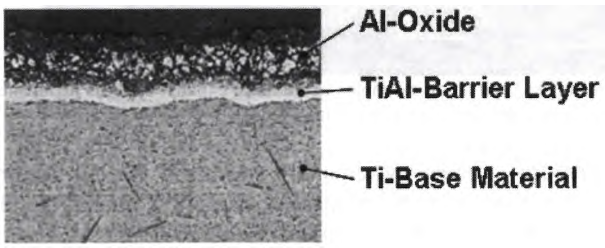


Figure 8. Near-surface cross-section of an Al-plated cp-Ti muffler

Figure 9 illustrates an exploded view of the rear muffler used in the Bugatti Veyron. All parts shown are made of cp-Ti. Parts which are subject to very high temperatures are additionally aluminum plated as illustrated in Figure 9.

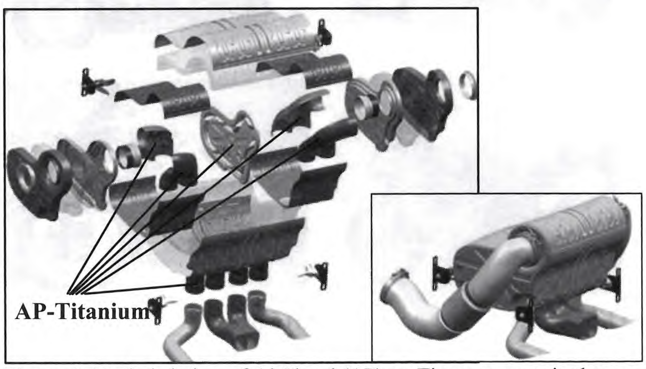


Figure 9. Exploded view of Al-Plated (AP) cp-Ti components in the rear muffler of the Bugatti Veyron

Nippon steel tested alloys such as Ti-1Cu and Ti-1Al and compared the temperature dependence of the yield stress with that of cp-Ti grade 2 (Figure 10).

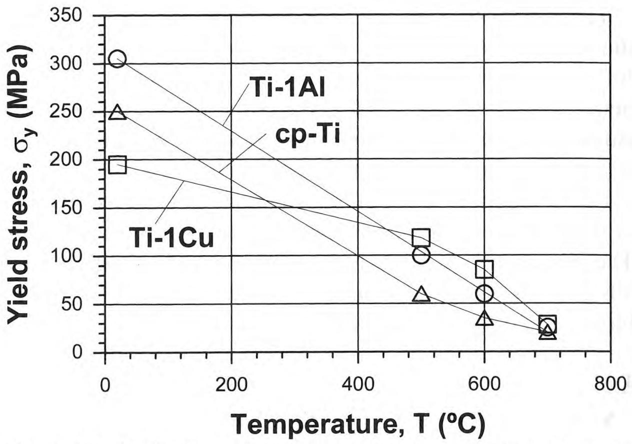


Figure 10. Yield stress dependence of various titanium alloys on temperature (courtesy of Nippon Steel)

While the yield stress of Ti-1Al was higher than that of cp-Ti grade 2 at all tested temperatures, the results on Ti-1Cu were most promising because its yield stress at room temperature where the forming is done is lower than that of cp-Ti but significantly higher at the high application temperature.
Oxidation tests at Nippon Steel (Figure 11) showed scale depths in Ti-1Cu somewhat smaller than in cp-Ti. Best results were obtained on an alloy with the addition of 0.5% Nb.

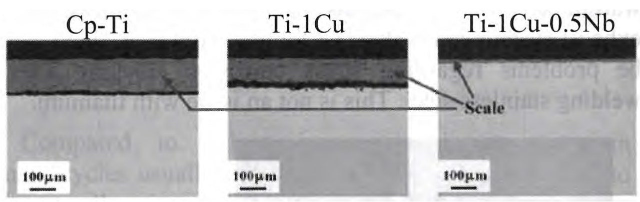


Figure 11. Scale sizes on the various materials after exposure in air at 800°C for 100hours (courtesy of Nippon Steel)

As illustrated in fatigue tests performed in fully reversed plane bending at 700°C at 20 Hz, the high temperature fatigue performance of Ti-1Cu is clearly superior to that of cp-Ti grade 2. Using Ti-1Cu instead of cp-Ti, the lifetime increases by an order of magnitude while the HCF strength at 10^7 cycles is doubled.

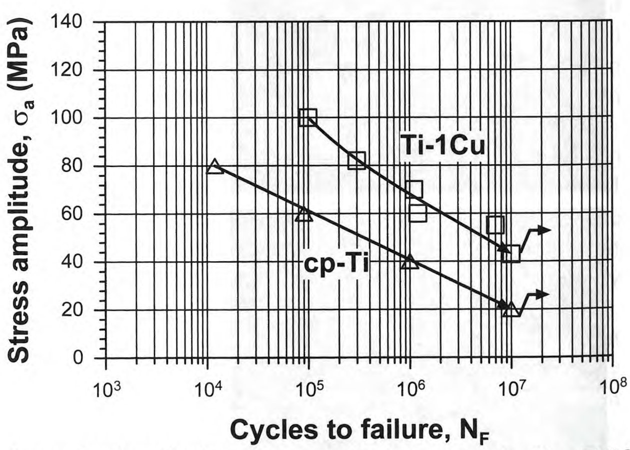


Figure 12. Plane bending fatigue results, R = -1, 20 Hz, T = 700°C (courtesy of Nippon Steel)

Research at Kobe Steel Titanium has focussed on the system Ti-Al. Compared to cp-Ti grade 2, the alloy Ti-1.5Al shows a fatigue performance at 700°C in tension-tension loading much superior to cp-Ti (Figure 13). Further improvements were observed for an alloy modified with Si and Nb at a reduced Al content.

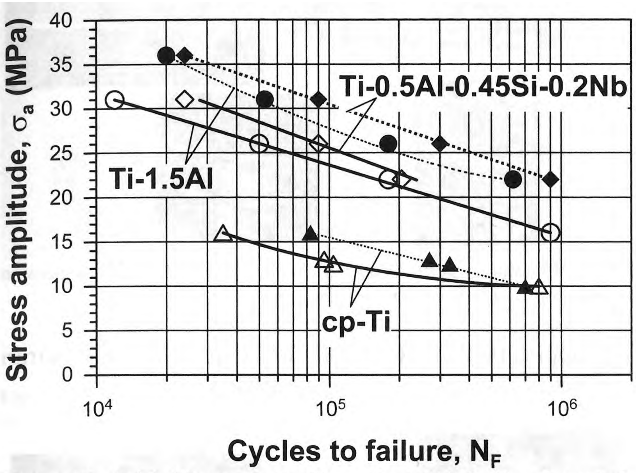


Figure 13. Axial fatigue results (R = 0) at 700°C (closed symbols indicate prior exposure at 700°C for 200 hours) (courtesy of Kobe Steel Titanium)

Apparently, fatigue strength values of all alloys are improved after prior exposure at 700°C for 200h. This indicates surface strengthening by oxygen diffusion into the surface of the materials.

Suzuki's superbike GSX-R1000 with a Ti-1.5Al exhaust is illustrated in Figure 14. The GSX-R1000 has a 16 valve DOC 1 liter inline 4 cylinder engine delivering a maximum output of 178 HP at 11000 rpm.

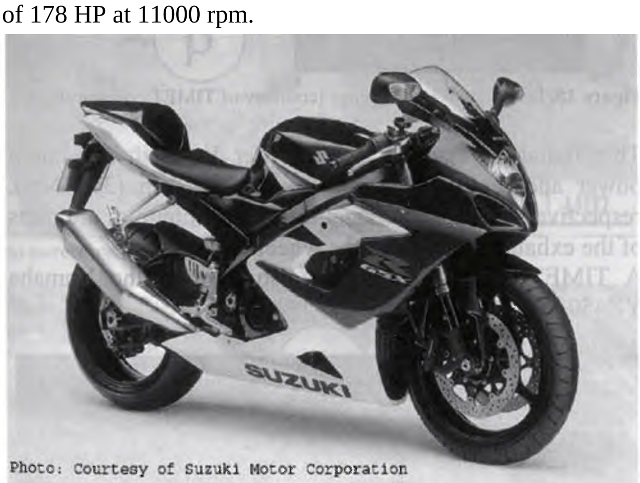


Figure 14. Suzuki GSX-R1000 featuring a Ti-1.5Al exhaust system

Oxidation studies at Kobe Steel Titanium have shown that the modified titanium alloy containing 0.5Al, 0.45Si and 0.2Nb (Ti-1.2ASNEX) has much better performance than cp-Ti and is also superior to Ti-1.5Al. As demonstrated in Figure 15, there is a marked sheet thickness reduction and grain growth in cp-Ti after an exposure at 800°C for 100 hours. While thickness reduction and grain growth are already less pronounced in Ti-1.5Al, the material loss of the advanced Ti-1.2ASNEX is almost none. In addition, hardly any grain growth occurs in this alloy during the high temperature exposure.

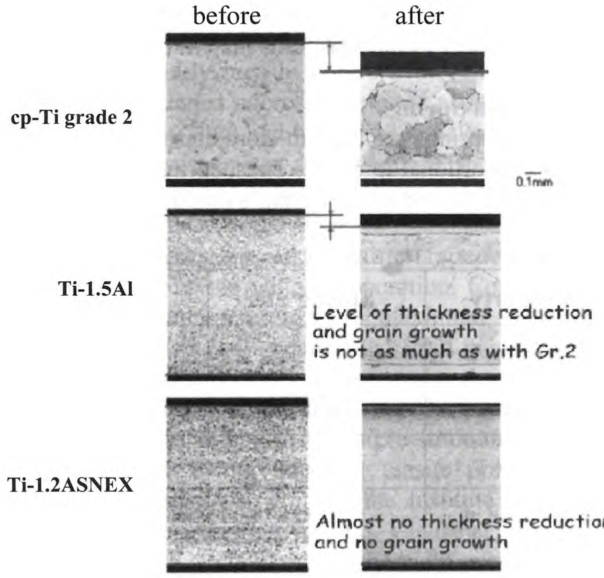


Figure 15. Cross-sections of sheets before and after thermal exposure at 800°C for 100 hours (courtesy of Kobe Steel Titanium)

Another approach to overcome the poor high-temperature performance of cp-Ti was taken by ThyssenKrupp Titanium (Figure 16). A new alloy Ti-0.1Fe-0.35Si with the addition of 0.25% cerium mishmetal was developed. This cost-efficient alloy exhibits the following mechanical properties: E = 92 GPa, YS = 305 MPa, UTS = 440 MPa, El = 22%. The alloy proved to be highly resistant not only to scale formation but to grain growth as well (Figure 16). Deep drawability of this alloy is sufficient although not as good as that of Al-plated cp-Ti. Fatigue testing has not been done yet.

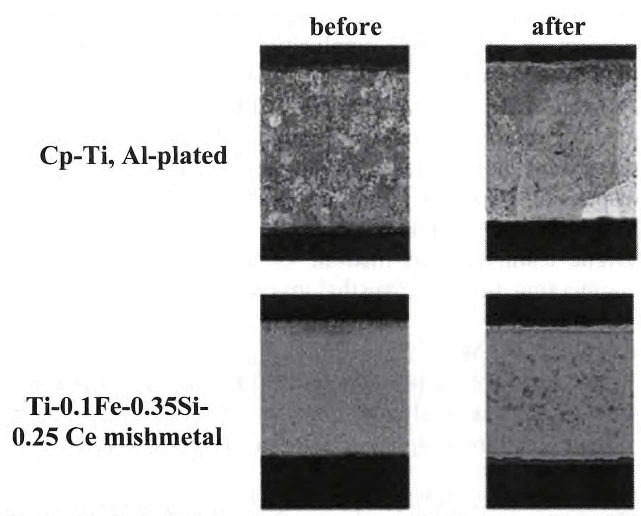


Figure 16. Scale formation and grain growth due to exposure at 800°C for 100hours (courtesy of ThyssenKrupp Titanium)

2.5 Pistons and Piston Pins

For this application, materials with low density and high strength at elevated temperatures are needed. The ever increasing combustion chamber temperatures and pressures in modern direct injected gasoline and turbo diesel engines may limit the application of Al-based pistons in the near-future. Due to its higher strength and stiffness at elevated temperatures, titanium alloys are potential candidates for pistons. Titanium pistons would increase the efficiency of engine operation. For piston pins, the even higher stiffness of γ-Ti aluminides would make this material interesting.

2.6 Suspension Springs

In general, springs are used to store elastic energy. This energy is proportional to $\sigma^2/2E$. Thus, springs should have a high yield stress and a low Young's modulus (Tabelle 5).

Table 5: Spring steel vs. TIMETAL LCB as Spring Material

Property	Spring Steel	LCB
Modulus, E	210 GPa	115 GPa
Yield stress, σ_Y	1800 MPa	1600 MPa
Density, ρ	7.8 gcm^{-3}	4.5 gcm^{-3}
Work done, w_{el}	19 Jcm^{-3}	26 Jcm^{-3}

Normalized Property	Spring Steel	LCB
Modulus, E/ρ	26 $GPa{\cdot}cm^3{\cdot}g^{-1}$	26 $GPa{\cdot}cm^3{\cdot}g^{-1}$
Yield stress, σ_Y/ρ	230 $MPa{\cdot}cm^3{\cdot}g^{-1}$	360 $MPa{\cdot}cm^3{\cdot}g^{-1}$
Work done, w_{el}/ρ	2.4 Jg^{-1}	5.7 Jg^{-1}

As seen from Table 5, the Young's modulus of TIMETAL LCB in a fully age-hardened condition is only roughly half that of a spring steel. While the yield stress of a spring steel is typically somewhat higher than that of TIMETAL LCB, the elastic work done is much higher in the titanium alloy. Since weight reduction is of high concern in automotive applications, material properties should be normalized by density as listed in the lower part of Table 5. Evidently, TIMETAL LCB springs are much superior to steel springs with regard to normalized yield stress and normalized stored energy (Table 5). Since suspension springs are cyclically loaded, required properties are high HCF strength in addition. Extensive fatigue testing at the Institute of Materials Science and Engineering of TU Clausthal has demonstrated potential HCF strength values in rotating beam loading (R = -1) of as high as 800 MPa.

The first application of TIMETAL LCB suspension springs in mass production was in the Volkswagen Lupo FSI with the direct injection gasoline engine (Table 6).

Table 6. Application examples of titanium suspension springs

Year	Material	Manufacturer	Model
2000	TIMETAL LCB	Volkswagen	Lupo FSI
2003	TIMETAL LCB	Ferrari	360 Stradale
2005	TIMETAL LCB	Bugatti	Veyron 16.4

Other manufactures followed: Ferrari used TIMETAL LCB springs in the 360 Challenge Stradale as does Bugatti in its Veyron 16.4.

Figure 17 illustrates the weight savings by using LCB as opposed to conventional steel springs made of spring steel. The weight saving is roughly 40%.

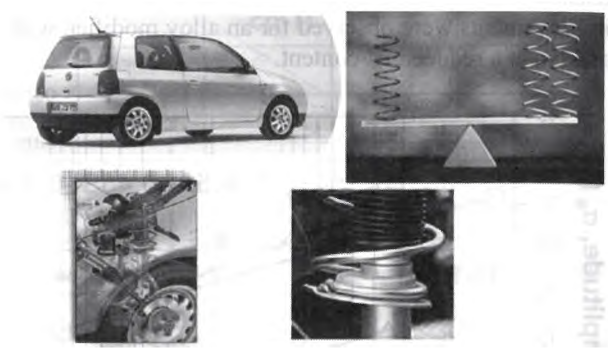


Figure 17. Volkswagen Lupo FSI with TIMETAL LCB suspension springs

The application of TIMETAL LCB springs in the Ferrari Challenge Stradale is shown in Figure 18.

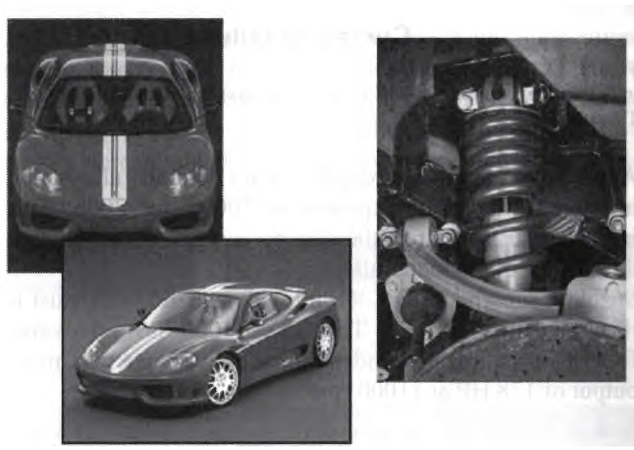


Figure 18. Ferrari with LCB springs (courtesy of TIMET company)

This Italian sportscar has a 3.6-liter V8 with maximum power and torque of 425 bhp and 275 lb-ft (373 Nm), respectively. Other components made of titanium are parts of the exhaust system and the wheel bolts.

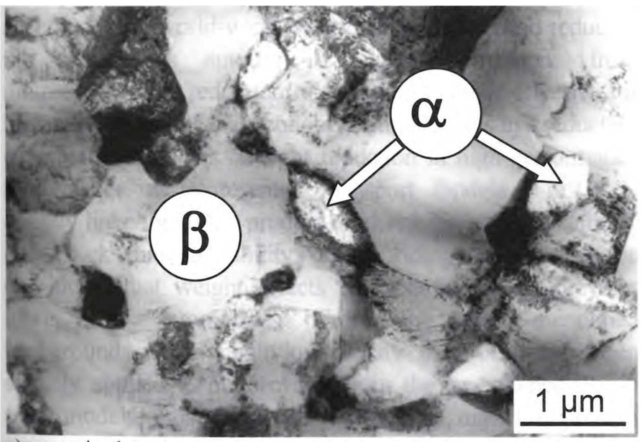
A TIMETAL LCB spring is also used in the Yamaha YZ450F (Figure 19)

Figure 19. TIMETAL LCB suspension spring of the Yamaha YZ450F (courtesy of TIMET company)

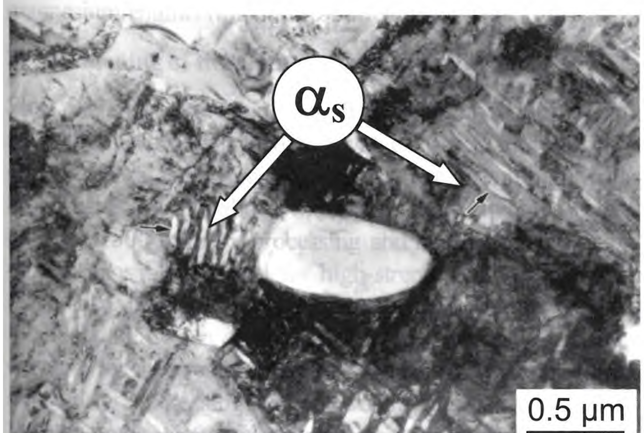
At the time of this writing, large suspension springs of TIMETAL LCB with a weight of 30 kg are being tested for heavy Duty Vehicles (Figure 20). The weight savings for the whole vehicles will be roughly 50 kg.

Figure 20. Large TIMETAL LCB suspension springs for heavy duty vehicles (trial)

The TIMETAL LCB springs in the Bugatti Veyron are thermomechanically processed at subtransus temperatures as shown by the presence of primary-α (α_p) in the β-phase (Fig. 21).



a) as-received



b) age-hardened

Figure 21. TEM microstructures of TIMETAL LCB

As seen in Figure 21a, the as-received solution heat treated condition is essentially free of secondary-α (α_s). The yield stress in this very ductile ($\varepsilon_F = 0.77$) condition amounts to 1100 MPa. During aging, fine α_s particles are precipitated out from the β-matrix. These α_s platelets in the β-phase are clearly seen in Figure 21b. Tensile properties of this age-hardened microstructure are as follows: G = 46 GPa, YS = 1360 MPa and UTS = 1395 MPa. In contrast to steel springs, suspension springs made from TIMETAL LCB do not need any coating because of the excellent corrosion resistance of the alloy.

Aging of a coil spring will result in a graded material as a consequence of the winding operation. Coil winding is done at room temperature. The maximum strain at the surface of the rod can be calculated from the rod diameter and the coil diameter. For a 10 mm rod and a 100 mm coil diameter, this strain at the surface is 10%.

To determine the effect of such a pre-strain on mechanical properties after aging, uni-axial tensile pre-straining of 10% before aging was done at the Institute of Materials Science and Engineering of TU Clausthal. As seen in Table 7, this pre-strain increases the yield stress after aging at 500°C by as much as 200 MPa. With an increase in aging temperature, this differential decreases from 200 MPa at 500°C over 130 MPa at 525°C to 70 MPa at 550°C aging temperatures. Note that this pre-deformed and markedly higher strength material condition is present at the spring surface where maximum stresses occur in service due to cyclic loading in torsion.

Table 7. Effect of pre-strain (simulating coil winding) on tensile properties after aging of TIMETAL LCB

Aging temperature	Tensile pre-strain	σ_Y (MPa)	UTS (MPa)	El (%)
500°C	0%	1470	1560	8.4
	10%	1665	1680	4.6
525°C	0%	1470	1525	7.3
	10%	1600	1650	5.7
550°C	0%	1420	1475	10.0
	10%	1490	1525	7.1

No other production vehicle uses as much titanium as the Bugatti Veyron 16.4 being the pride of German Automotive Engineering and Technology (Fig. 22).

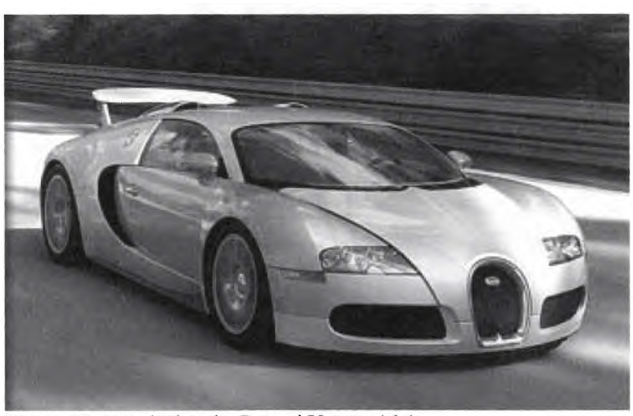


Figure 22. Introducing the Bugatti Veyron 16.4

100 kg titanium is used per vehicle (40 kg after machining). Its curb weight amounts to 1880 kg. The Bugatti Veyron carries a mid-mounted W16 engine, its

power and torque put to the road via all-wheel drive. The driving performance of this super sports car is just breath-taking: It takes only 2.5 sec. from zero to 60 mph, the quarter mile is passed after 10 sec. at a speed of 143 mph (230 km/h) and the top speed is over 250 mph (400 km/h) making it the fastest production car in the world.
The following components used in the Bugatti Veyron 16.4 are made from titanium: Bolts and threaded joints for axle suspension (Ti-6Al-4V with PVD-MoS_2-coating), bolts, studs and inserts in the CFRP-monocoque (Ti-6Al-4V), conrods (Ti-6Al-4V), outer shell of the muffler (cp-Ti grade 1), inner shell of the muffler (Al-plated cp-Ti grade 1), heat shields (cp-Ti grade 2), brake-heat shields (SPF Ti-6Al-4V), brake pistons and brake bells (Ti-6Al-4V), crash-clamps (Ti-6Al-4V), suspension springs (TIMETAL LCB), meshed metal baffles (cp-Ti grade 2).

Acknowledgements
The authors would like to thank Yoji Kosaka of TIMET, Henry Rack of Clemson University, Hideki Fujii and Hiroaki Otsuka of Nippon Steel, Takashi Yashiki of Kobe Steel Titanium and, H. Sibum of ThyssenKrupp Titanium for their valuable contributions during the preparation of this paper.
One of the authors (LW) likes to thank Honda Research & Development for providing him with a Honda German Initiation Grant.