

Status of Titanium and Titanium Alloys in Auto Applications

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ABSTRACT

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 introduced.

INTRODUCTION

Since the end of the nineties, a number of new cars 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 segment. 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.

TITANIUM APPLICATIONS

Connecting rods

Connecting rods connect the crankshaft with the pistons. 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 sportscar NSX from Honda. It had a 3-liter DOHC V6 engine and a red-line at 8000 rpm. The conrod was made of Ti-3-2 with rare earth additions that offered improved machinability (Table 1). 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 with a significantly higher Young's modulus.

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



Ti-64 for Connecting Rods

Corvette Z06



Figure 1: Connecting rods of the Corvette Z06

Ti-6Al-4V ($\alpha+\beta$) 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 is 512 bhp and maximum torque is 470 lb-ft.

16 Ti-6Al-4V ($\alpha+\beta$) forged conrods (Figure 2) with a duplex microstructure are used in the Bugatti Veyron 16.4.

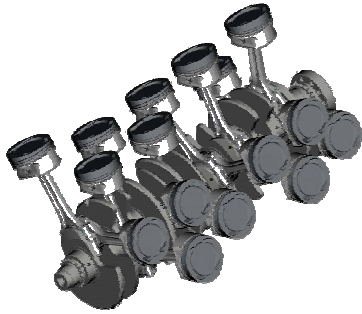


Figure 2: Titanium Connecting Rods in the Bugatti Veyron 16.4

The 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 over a wide range of rpm.

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 280 bhp due to turbo-charging and this value increased to 300 bhp in the latest model.

Table 2: Application examples for titanium turbo-charger wheels

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

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 ($\alpha+\beta$) 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 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). 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 at 6400 rpm. Other manufacturers followed: Nissan introduced the Infiniti Q45 with 6-4 valves in 2002. Mitsubishi used valve spring retainers made of a β -titanium alloy on all 1.8-liter 4 cylinder engines. 6-4 valves also operate in the Corvette Z06 engine.

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	Infiniti Q45
2003	Valve Spring Retainers	β -alloy	Mitsubishi	All 1.8 I-4 Cyl.
2005	Valves	Ti-6Al-4V	GM	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, 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

Exhaust Systems

Required properties for exhaust systems are cold formability, deep drawability, weldability, oxidation resistance and elevated temperature HCF strength. 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 long-time application at temperatures above 700°C, cp-Ti needs to be coated or new alloys be developed.

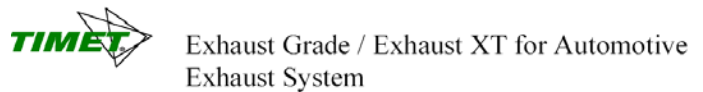
The Corvette Z06 was the first car equipped with a titanium exhaust made of cp-Ti grade 2 (Table 4). Others followed such as the Fair Lady Z (in the US or Europe better known as the 350Z), the Subaru Impreza and the Bugatti Veyron. The Bugatti's cp-Ti exhaust system is partially Al-plated as will be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



Chevrolet Corvette Z06 (2002~)



Figure 4: Exhaust system of the Corvette Z06

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

As already mentioned, long-time applications at very high temperatures require coating of cp-Ti. If cp-Ti is aluminum plated, there is almost no material loss even after long-time exposure at 860°C. This is due to a titanium aluminate oxidation barrier that is formed at high temperature (Figure 6).

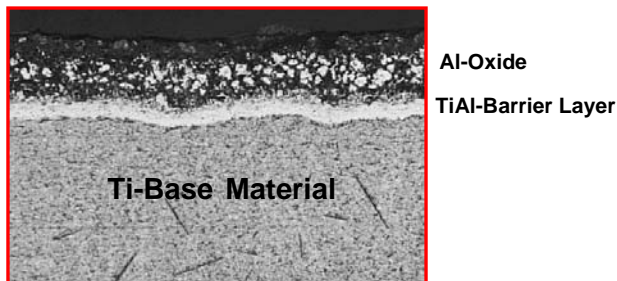


Figure 6: Near-surface cross-section of an Al-plated cp-Ti muffler

Pistons and Piston Pins

For this application, materials with high strength and low density 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.

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. Since suspension springs are cyclically loaded, required properties are high HCF strength.

The first application of TIMETAL LCB suspension springs in mass production was in the Volkswagen Lupo FSI with the direct injection gasoline engine (Table 5).

Table 5: 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 7 illustrates the weight savings by using LCB as opposed to conventional steel springs made of spring steels. The weight saving is roughly 40%.



Figure 7: TIMETAL LCB Springs in the Volkswagen LUPO FSI

The application of TIMETAL LCB springs in the Ferrari Challenge Stradale is shown in Figure 8.



LCB for Springs

Ferrari Challenge Stradale (2004)



Figure 8: Ferrari with LCB springs

This Italian sportscar has a 3.6-liter V8 with 425 bhp. Other components made of titanium are parts of the exhaust system and the wheel bolts.

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.

No other production vehicle uses as much titanium as the Bugatti Veyron 16.4 being the pride of German Automotive Engineering and Technology (Fig. 9).



Figure 9: Introducing the Bugatti Veyron 16.4

100 kg titanium is used per vehicle. 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 the Bugatti 16.4 is just breath-taking: It takes only 2.5 sec. from zero to 60 mph, the quarter mile is passed after 10 sec. and the top speed is over 250 mph.

The following components are made from titanium: Bolts and threaded joints for axle suspension (Ti-6-4 with PVD-MoS₂-coating), bolts, studs and inserts in the CFRP-monocoque (Ti-6-4), conrods (Ti-6-4), 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-6-4), brake pistons and brake bells (Ti-6-4), crash-clamps (Ti-6-4), suspension springs (TIMETAL LCB), meshed metal baffles (cp-Ti grade 2).

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Titanium in Automotive Applications

- Connecting rods
- Turbo charger wheels
- Engine valves
- Exhaust systems
- Suspension springs

Connecting rods

Required properties are HCF strength to withstand the oscillating mass forces. Due to its low density and high strength, the fatigue strength of Ti-6-4 is sufficiently high.

The comparatively low Young's modulus needs to be compensated for by particular stiffness design.

γ -titanium aluminides are promising candidates since they combine a density even lower than that of titanium alloys (3.8 vs. 4.5 g/cm³) and a higher modulus (170 vs. 110 GPa).

Connecting rods

Table 1. Application examples for titanium 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

Connecting rods



Figure 1. Connecting rods of the Corvette Z06 (courtesy of TIMET company)
7-liter V8, 512 HP, 470 lb-ft

Connecting rods



Figure 2. Ti-6Al-4V connecting rods in the Bugatti Veyron 16.4
8-liter W16, 4 turbo chargers, 2 liquid intercoolers, 1001 HP, 922 lb-ft



Turbo charger wheels

Turbo charging is used to improve power and torque of gasoline and in particular, of diesel engines. Nowadays, almost all diesel engines in Europe are turbocharged.

Using titanium instead of the heavier Ni superalloys as wheel material can significantly reduce the so-called turbo lag. Thus, the engine response at low rpm (for example after up-shifting) is much faster.

Required properties for turbo charger wheels are high temperature HCF strength (blades), LCF and creep strengths (blade root), oxidation and erosion resistances.

Maximum service temperatures of turbo charger wheels in diesel engines can reach 750°C and up to 950°C in gasoline engines.



Turbo charger wheels

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

Engine valve gears

Engine valves are subjected to high cyclic stresses. Exhaust valves also see high temperatures. Thus, required properties for exhaust valves are high temperature HCF strength, creep resistance, thermo-shock resistance, oxidation and wear resistances.

Near- α alloys such as Ti-6242 or TIMETAL 1100 and γ -TiAl are good choices.

For intake valves, properties of Ti-6Al-4V are often sufficient.

Valve springs and valve retainers made of titanium would reduce the weight of the entire valve gear by up to 70%, maximum engine rpm could be increased by roughly 10%.

Engine Valve Gears

Table 3. Application examples for titanium valve gears

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



Engine Valves



Yamaha YZ450F

4-stroke 450 ccm
single cyl. engine
5 titanium valves



Kawasaki Ninja ZX10R

inline 1-liter
4 cyl. engine
175 HP

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

Exhaust systems

Required properties are cold formability, deep drawability, weldability, oxidation resistance, HCF strength at elevated temperatures and also acoustic performance (the sound should be right).

Typical materials are cp-Ti grade 1 and grade 2. They offer a weight saving of about 50% compared to stainless steel.

Exhaust systems

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
2007	cp-Ti Grade 2	Porsche	GT 2

Exhaust Systems

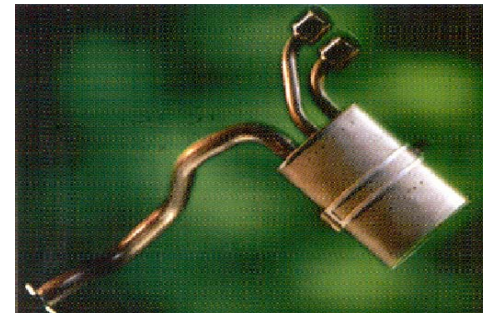


Figure 4. Exhaust system of the Corvette Z06 (courtesy of TIMET company)

Exhaust systems

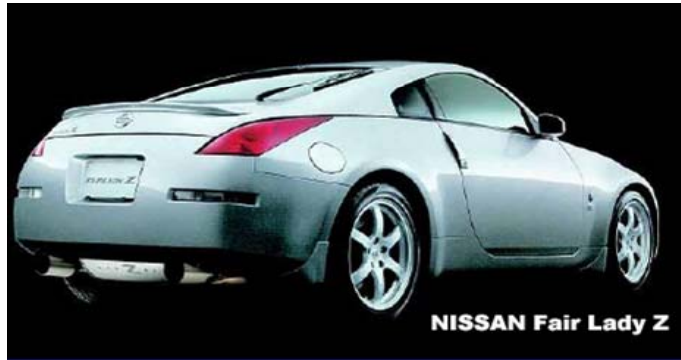


Figure 5. Application examples of titanium exhaust systems in Japanese passenger cars (courtesy of Toshihiko Saiki)

Exhaust systems

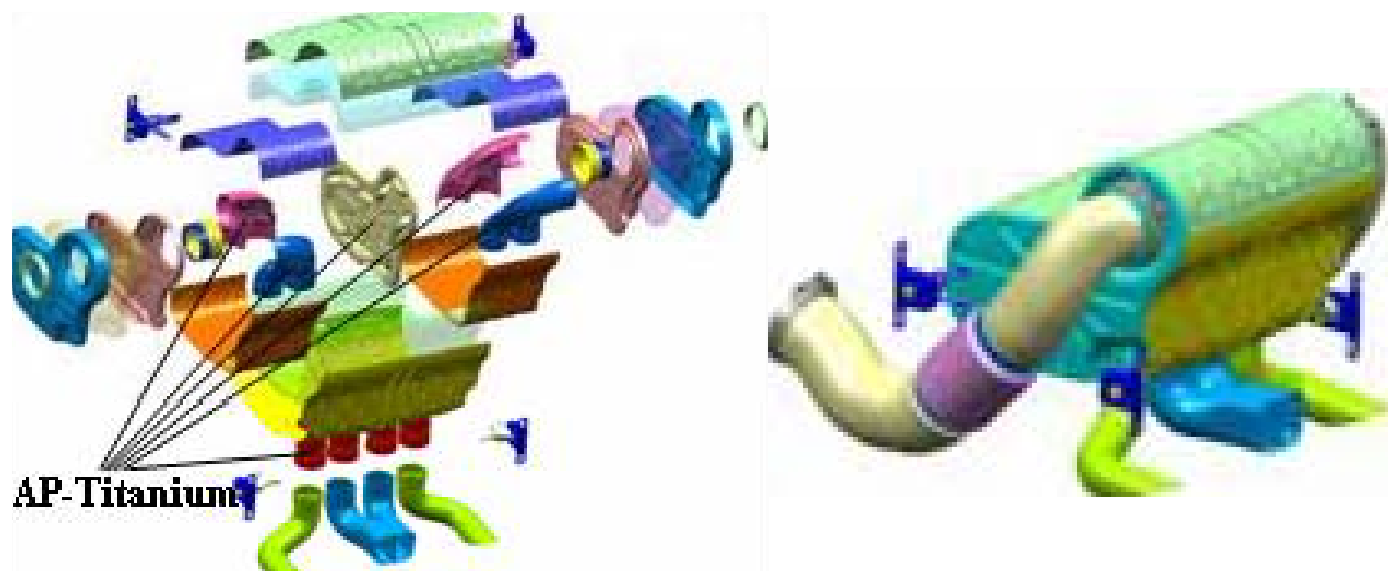


Figure 6. Exploded view of Al-Plated (AP) cp-Ti components in the rear muffler of the Bugatti Veyron

Exhaust systems

before



after

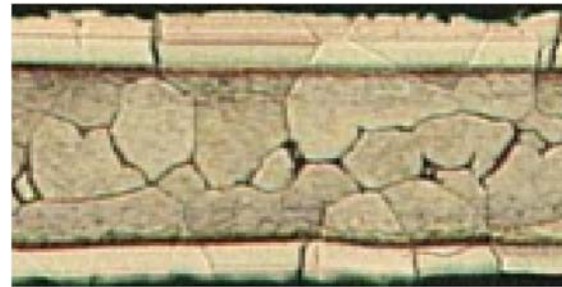


Figure 7. Cross sections of cp-Ti sheets before and after thermal exposure at 800°C for 100 hours (material loss, scale formation, grain growth)

Exhaust systems

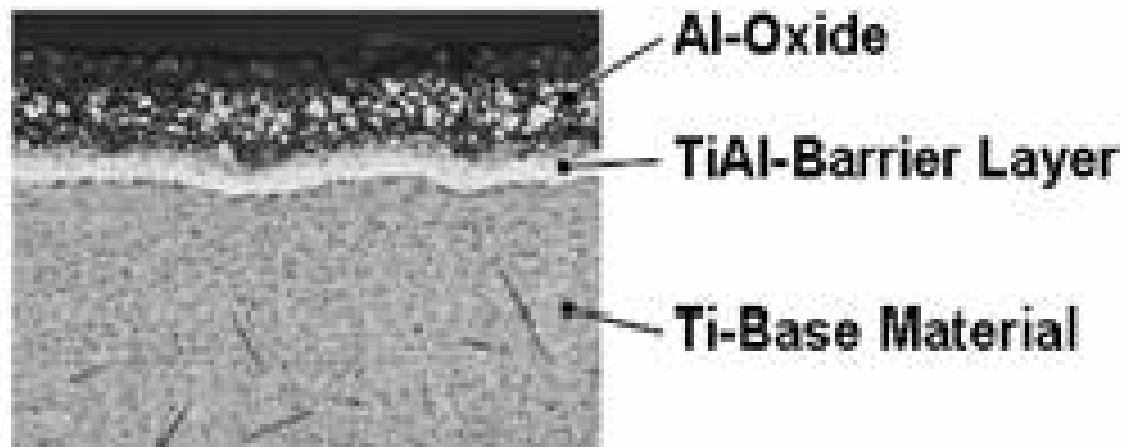


Figure 8. Near-surface cross-section of an Al-plated cp-Ti muffler

Exhaust systems

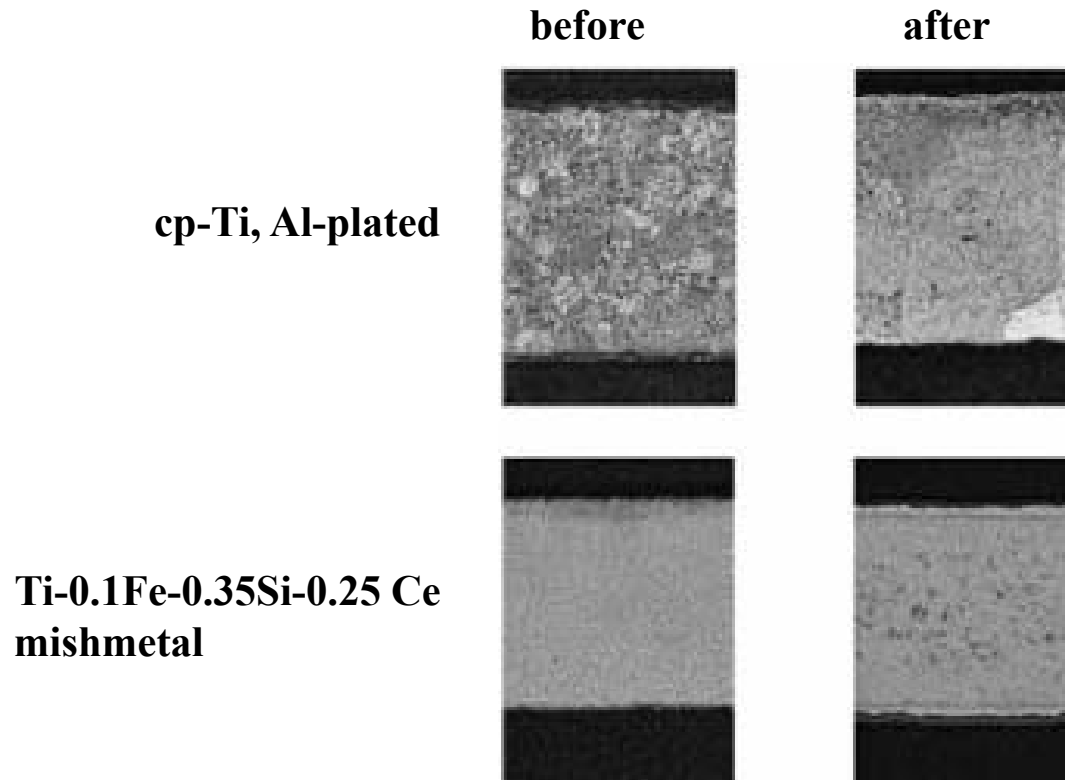


Figure 9. Grain growth and scale formation due to exposure at 860°C for 100 hours (courtesy of ThyssenKrupp Titanium)

Suspension springs

Springs are used to store elastic energy ($\sigma^2/2E$).

Suspension springs are subject to high cyclic loading.

Desired properties are:

- Cold (preferred) formability
- high HCF strength
- low modulus

Suspension springs

Table 5: Spring steel vs. TIMETAL LCB (Ti-6.8Mo-4.5Fe-1.5Al)

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

Table 6: Spring steel vs. TIMETAL LCB (normalized by density)

Normalized Property	Spring Steel	LCB
Modulus, E/ ρ	26 GPacm ³ g ⁻¹	26 GPacm ³ g ⁻¹
Yield stress, σ_Y/ρ	230 MPacm ³ g ⁻¹	360 MPacm ³ g ⁻¹
Work done, w_{el}/ρ	2.4 Jg ⁻¹	5.7 Jg ⁻¹

Suspension springs

Table 7. Application examples of titanium suspension springs in automobiles

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

In contrast to steel springs, these LCB springs do not need any coating because of the excellent corrosion resistance of the titanium alloy.



Suspension springs

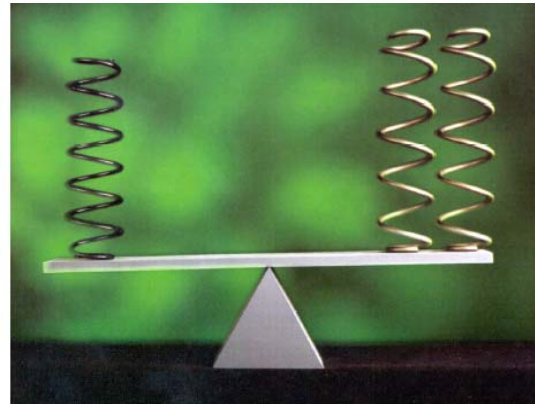


Figure 10. Volkswagen Lupo FSI with TIMETAL LCB suspension springs

Suspension springs



Figure 11. Ferrari Stradale 360 with LCB springs (courtesy of TIMET company)
3.6-liter V8, 425 HP

Suspension springs

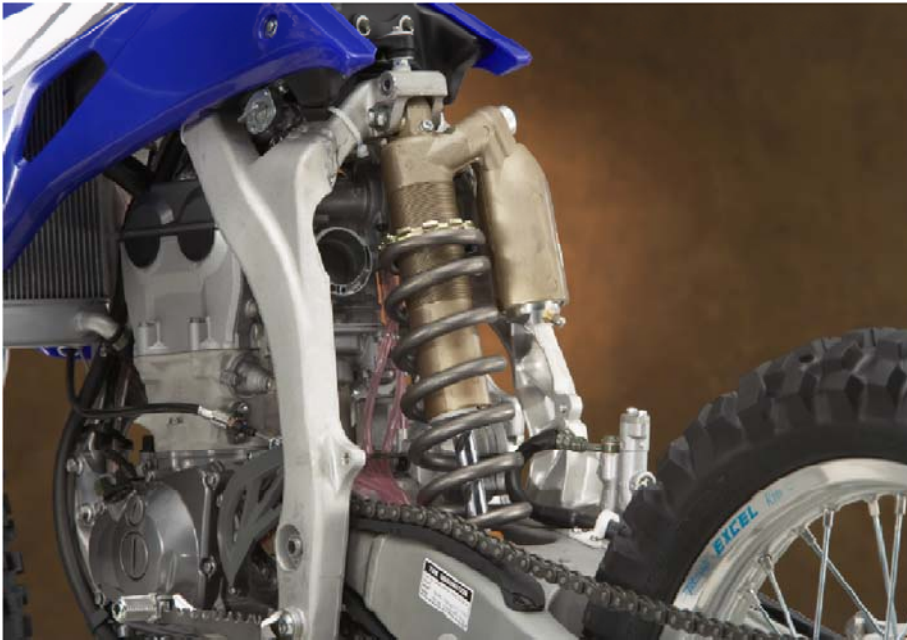


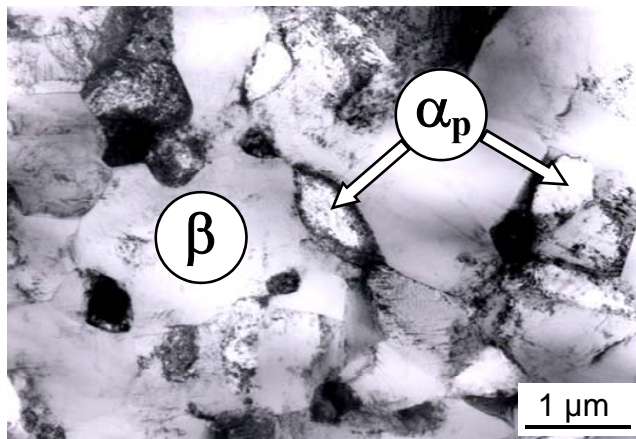
Figure 12. TIMETAL LCB suspension spring of the Yamaha YZ450F
(courtesy of TIMET company)

Suspension springs

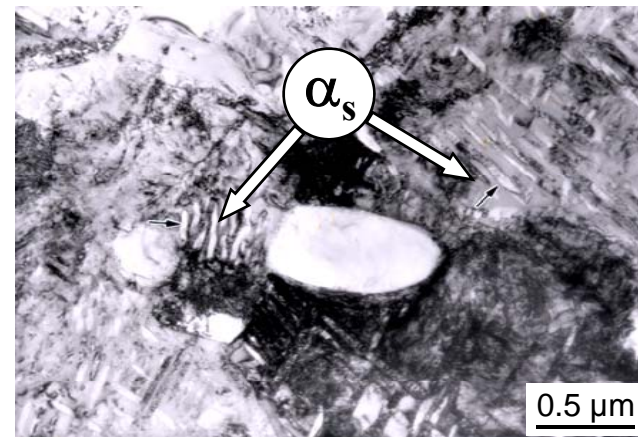


Figure 13. Large TIMETAL LCB suspension springs for heavy duty vehicles (trial)
(courtesy of TIMET company)

Suspension springs



a) as-received (YS = 1100 MPa)
1360 MPa)



b) age-hardened (YS =

Figure 14. TEM microstructures of TIMETAL LCB

Suspension springs

Table 8. Effect of plastic pre-strain (simulating coil winding) on tensile properties after aging of TIMETAL LCB

Aging temperature	Tensile pre-strain	σ_Y (MPa)	UTS (MPa)	EI (%)
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

High strength condition (10% pre-strain) at the spring surface



Figure 15. Introducing the Bugatti Veyron 16.4

100 kg titanium used per vehicle
(40 kg after machining)

Curb weight: 1880 kg

Mid-mounted engine

Four wheel drive

Acceleration: 0 – 62 mph (100
km/h) in 2.5 seconds

Quarter mile in 10 seconds at
143 mph (230 km/h)

Top speed over 250 mph (400
km/h)

Status of Titanium and Titanium Alloys in Auto Applications

R&D for potential applications of titanium and titanium alloys has made good progress.

New applications have been introduced and existing ones improved through new alloys and new manufacturing technologies.

Today, titanium is established in automotive applications, at least, in motorbikes and niche car segments such as super sports cars.

However, for mass production, more cost efficient titanium production processes are highly needed because cost is one of the most important driving forces in automotive applications.

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