Development of Titanium alloy with Controlled Elastic Properties

Toyota Central R&D Labs., Inc.

T. Furuta

Outline

- Fuel-Efficient Technology of Automobile
- Why Elastic Modulus of Metal is Important? And How to Control Elastic Property
- Developed Ti-Alloys
  - TiB Reinforced Titanium MMC
  - Gum Metal
- Summary

Fuel-Efficient Technology of Automobile

Reduction of Running Resistance

- Weight Reduction of Vehicle
  - Optimal Design
  - Minimization
  - Application of lightweight with High Strength Material
    - Al, Ti, Mg・・・・
- Reduction of Air Resistance
- Reduction of Rolling Resistance

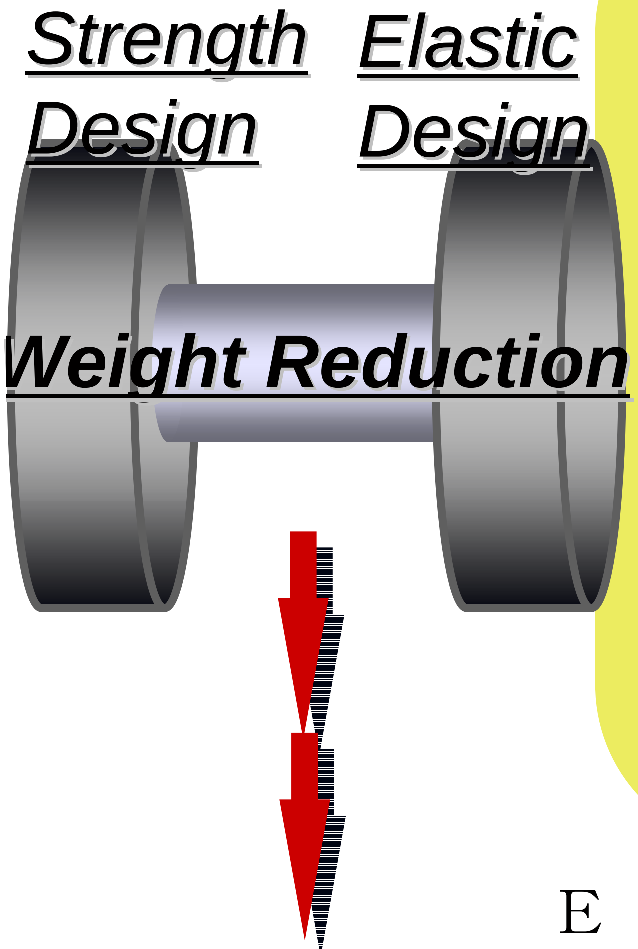
Improvement of Engine Combustion

- Direct Injection Engine
- Diesel Engine
- Hybrid Engine

Improvement of Unit Efficiency

- Reduction of Friction Loss
  - Weight Reduction of Moving Parts
- Improvement of Transmission Efficiency
  - CVT (Belt, Toroidal)

Elastic Modulus of Metal in Material Design



- *Tensile Strain :* $\varepsilon = \sigma / E$
- *Deflection in Bending :* $\delta \propto M / E \cdot Iz$

M : Bending Moment
Iz : Geometrical Moment of Inertia

- *Constant of Spring:* $K = \dfrac{Gd^4}{8D^3N}$

d : Wire Diameter
D : Coil Diameter
N : Number of turns

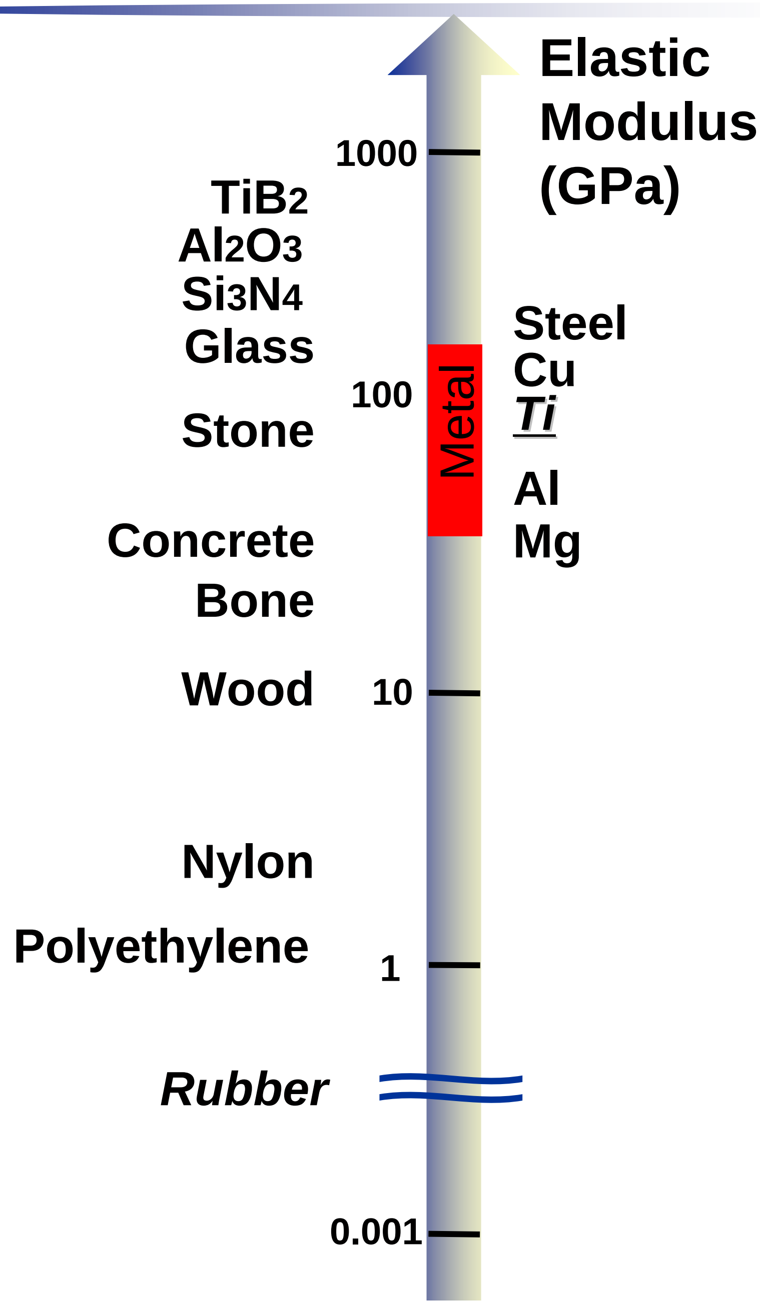
- *Resonance point* $\propto \sqrt{\dfrac{E \cdot Iz}{m}}$

m : weight of moving parts

E : Young's Modulus, G : Rigidity Modulus

Controlling Elastic properties is Key Technology

Elastic Modulus of Materials



Control by Compounding

TiB Ti-MMC

Gum Metal

Control of Binding Energy

TiB Reinforced Titanium Matrix Composite

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Adaptable of the Reinforcement for BE Titanium Alloy

Particle	*Knoop Hardness (GPa)*	*Elastic Modulus (GPa)*	*Coefficient Linear Expansion ($x10^{-1}K^{-1}$)*	*Maximum Solubility (at%) [Matrix]*	*[Particle]*	*Estimation*
TiB	*28.0*	*550*	*8.6*	*<0.001*	*1.0*	*Excellent*
TiC	24.7	460	7.4	1.2	15.0	Passable
TiN	24.0	250	9.3	22.0	26.0	Failure
SiC	25.0	420	4.3	Unstable in Ti alloy		Failure
Si_3N_4	14.7	320	3.2	Unstable in Ti alloy		Failure
TiB_2	34.0	529	6.4	Unstable in Ti alloy		Failure
B_4C	27.5	449	4.5	Unstable in Ti alloy		Failure
Al_2O_3	22.5	350	8.1	Unstable in Ti alloy		Failure

Coefficient of Linear Expansion of Ti alloy is around $9x10^{-6}$ K^{-1}

Manufacturing Process of Developed MMC

Ti Powder

TiB_2 Powder

Master Alloy Powders

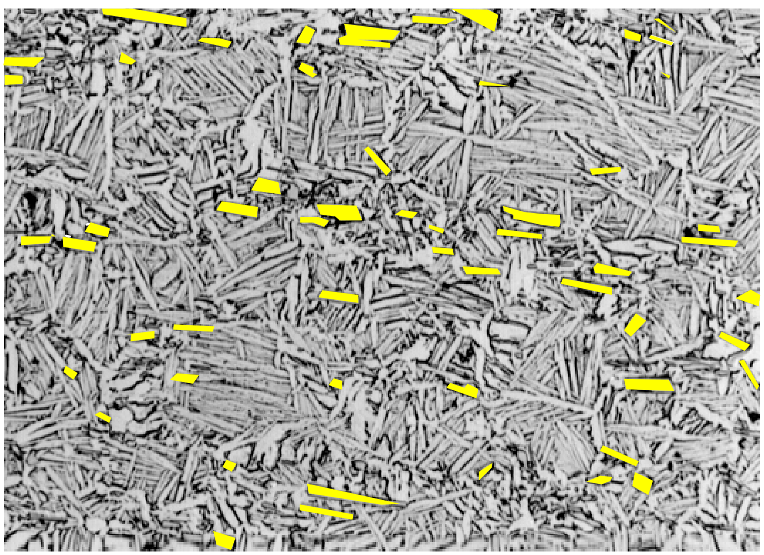
Compacting — 392MPa

Sintering — 1300℃, 4hr, 10^{-5} Torr

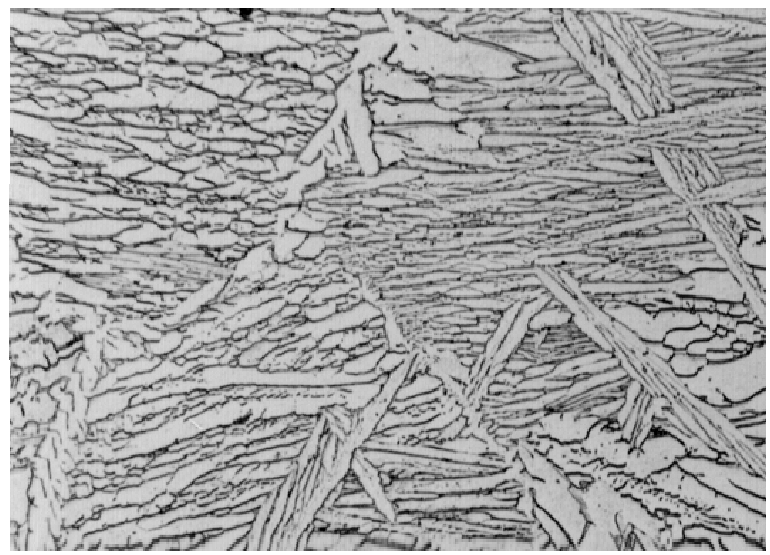
$Ti+TiB_2 \rightarrow 2TiB$

Hot Working

Heat Treatment



Developed MMC



Matrix Alloy

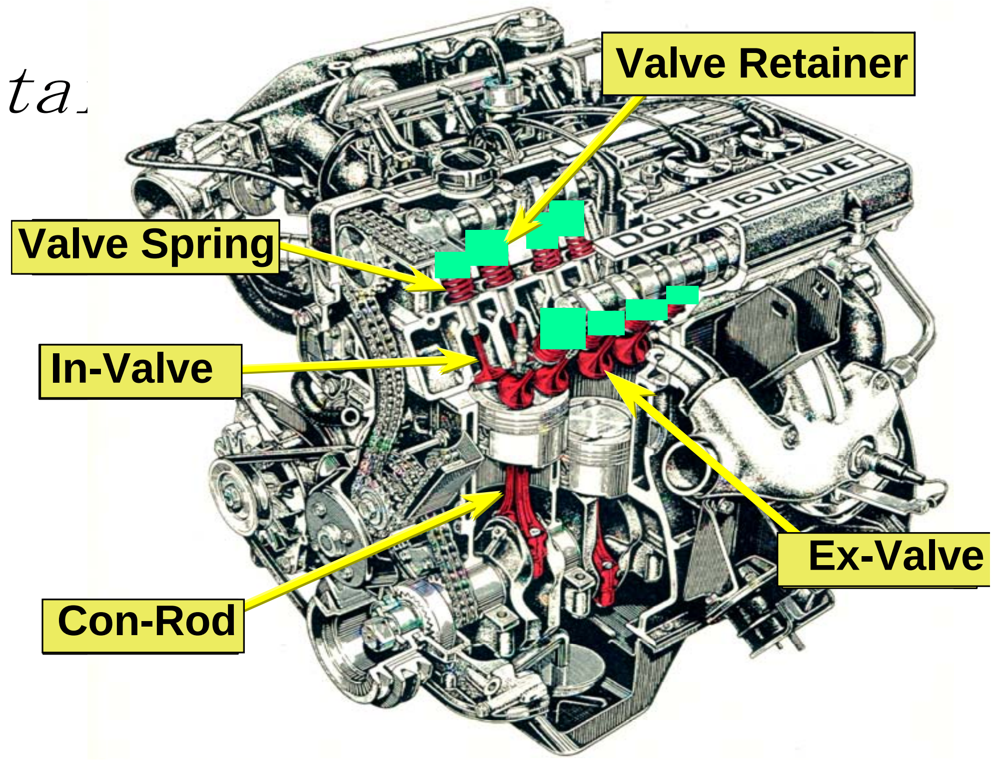
Possible Application to Automotive parts

1. ***α+β based MMC***

   TiB / Ti-6Al-4V, TiB / Ti-6Al-4V-1Fe-2Mo

   Well balance

   In - Valve, Valve reta



2. ***β based MMC***

   TiB / Ti-4.3Fe-7Mo-1.4Al-1.4V

   High-strength

   Connecting-Rod

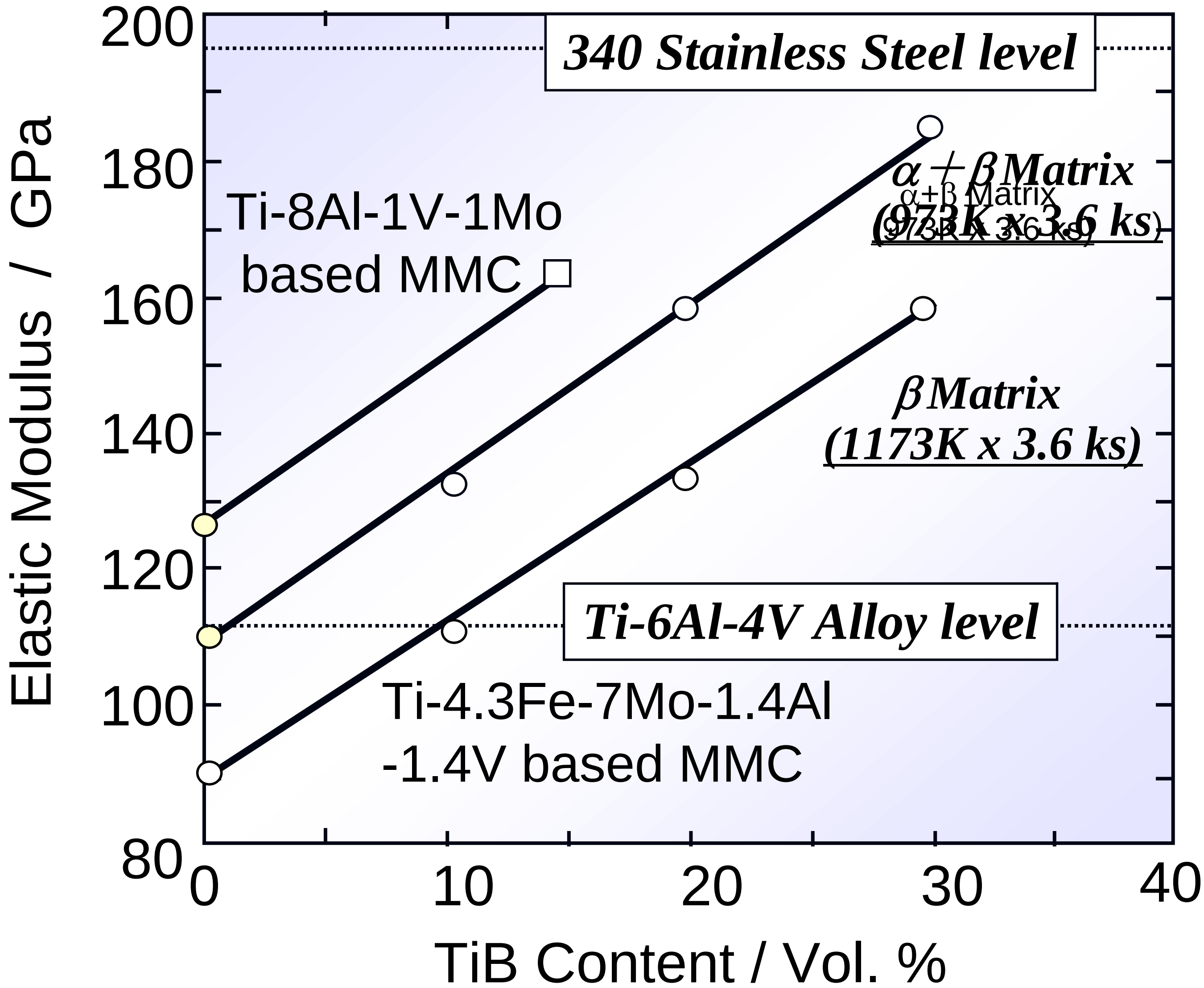
3. ***Near α based MMC***

   TiB / Ti-6Al-4Sn-4Zr-1Mo-1Nb-0.2Si

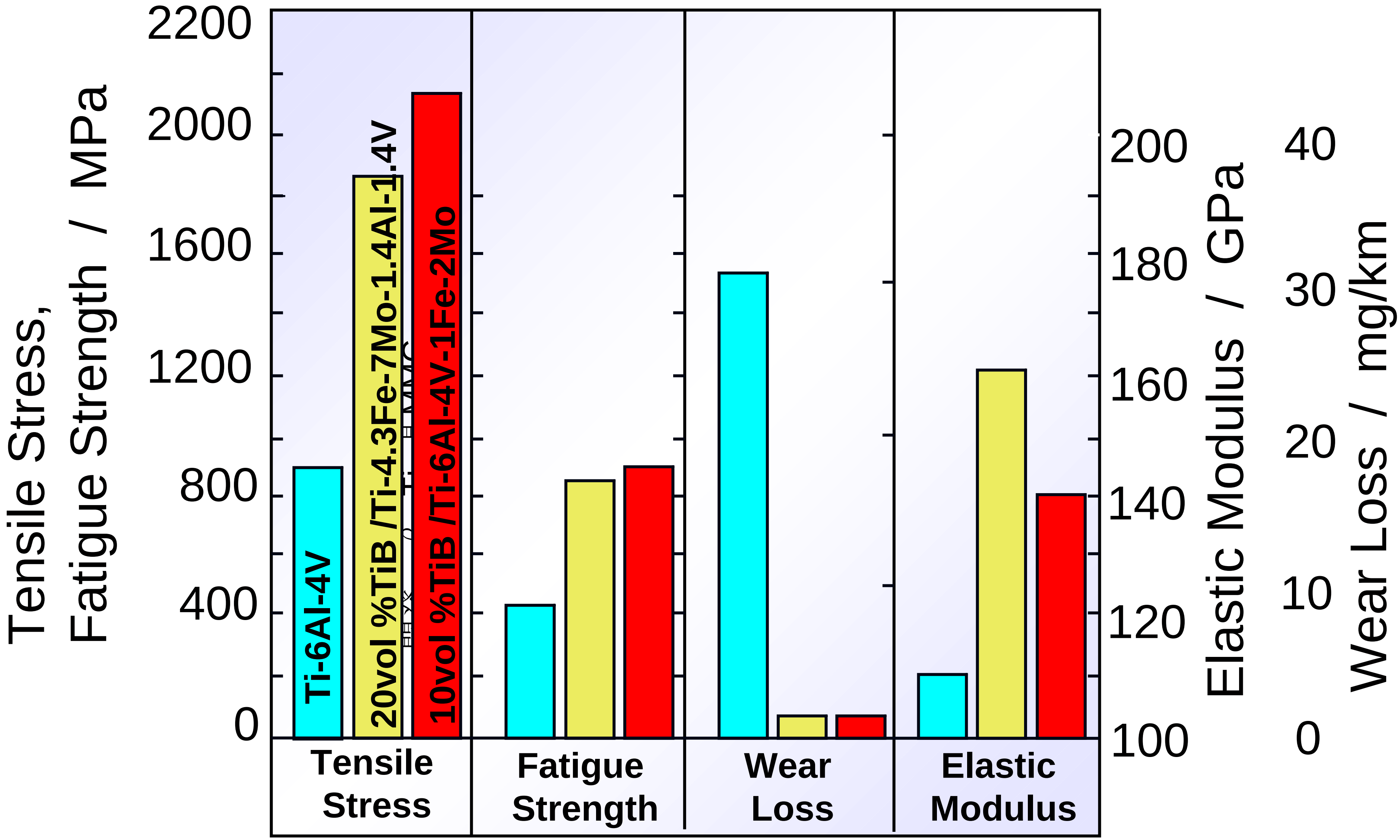
   Heat resistance

   Ex-Valve

Elastic Modulus vs TiB Content



Mechanical Properties of Developed MMC



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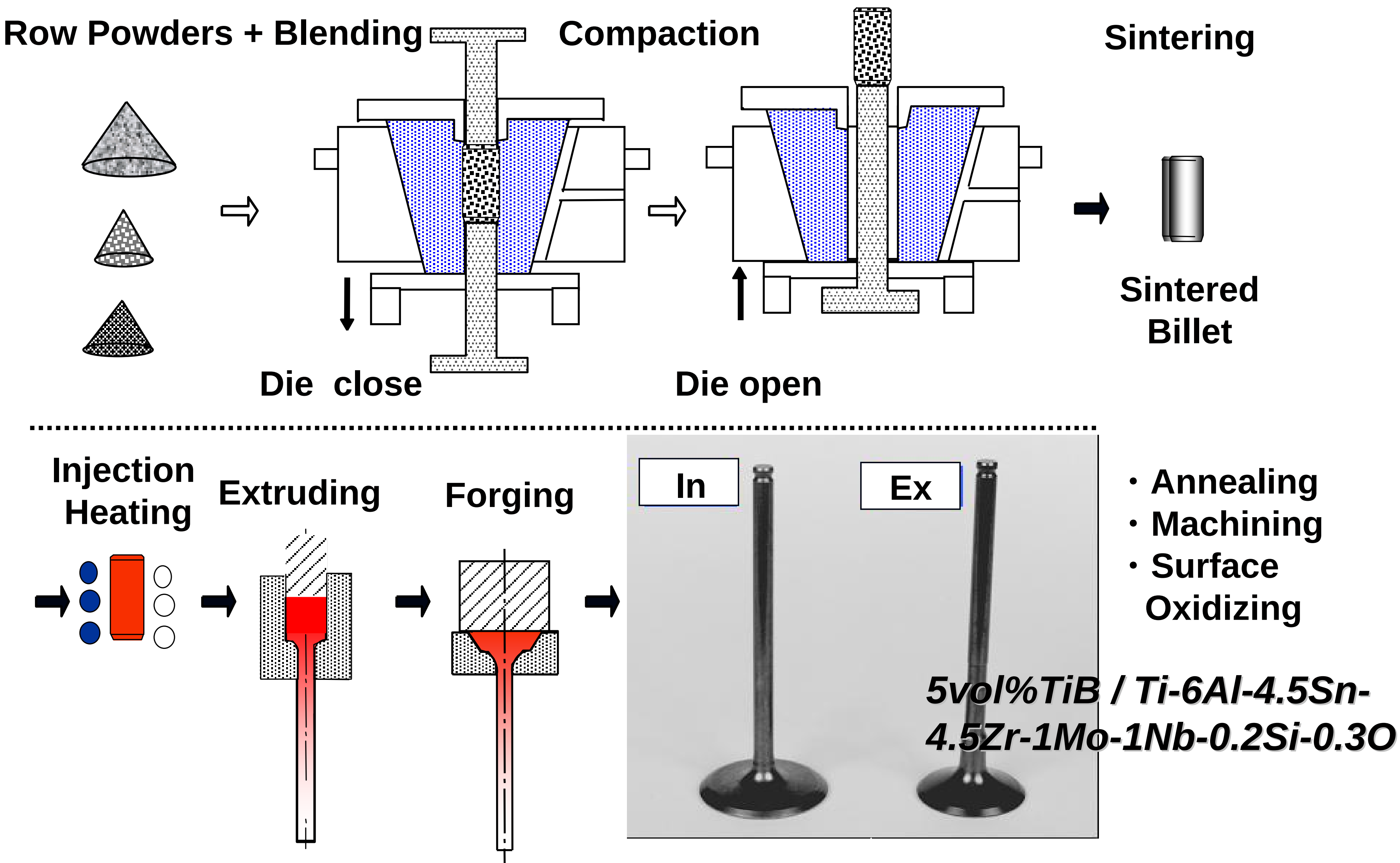
The First Family Automobile in the world Installed Titanium In and Ex Valves.

Manufacturing Process of Ti-MMC Valve



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Benefits of Developed Engine Valve

	Current Weight	Titanium Weight	Weight Redaction
IN-Valve	44.6g	27g	40%
EX-Valve	40g	24g	40%
Spring	43g	36g	16%

Maximum Revolution : 700 r.p.m. Improve
Engine Noise : 30% Reduction

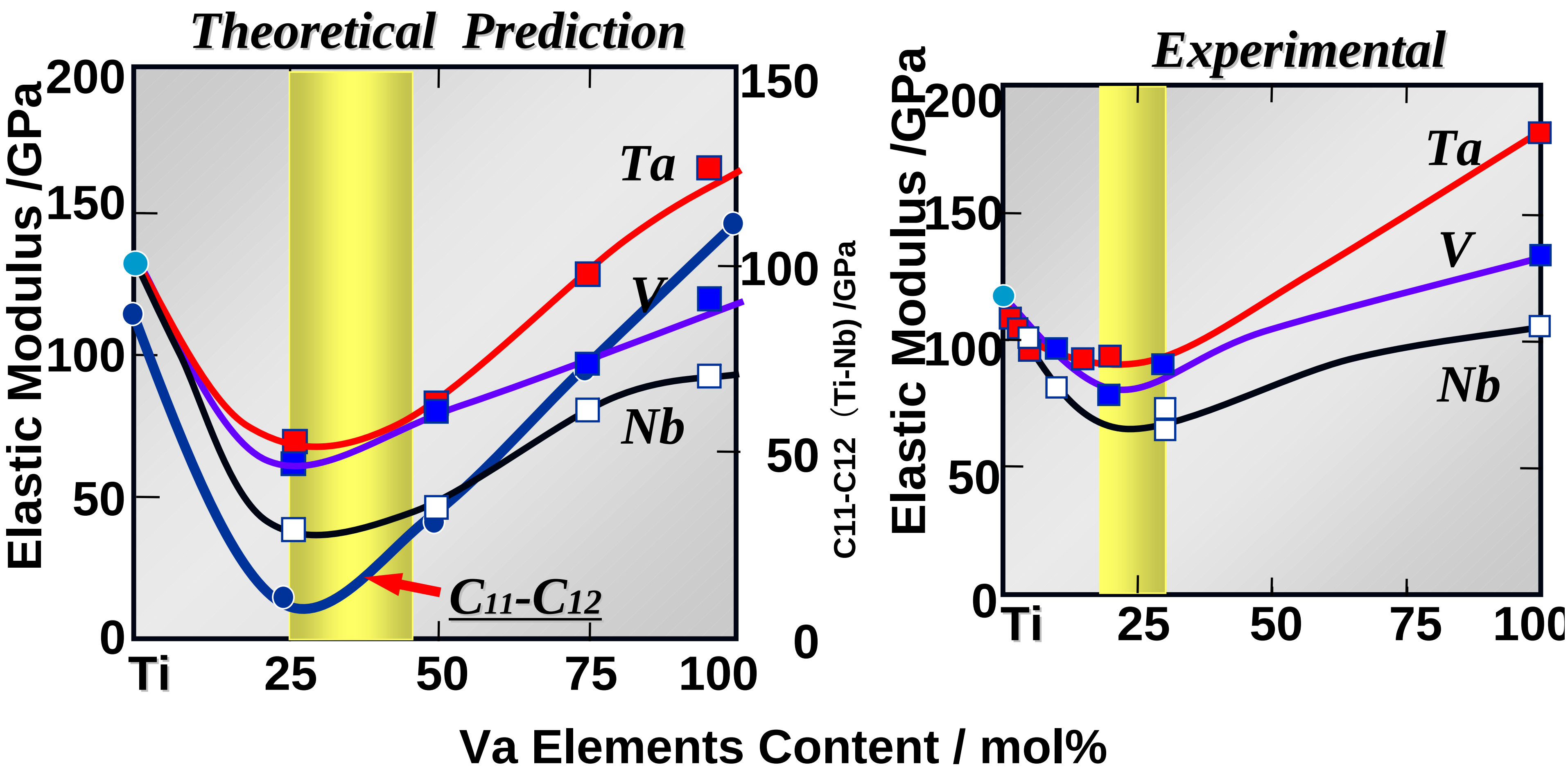
Gum Metal

- **1. Multifunctional Ti Alloy (Gum Metal)**
- low modulus, high strength, …

T. Saito, et al.,

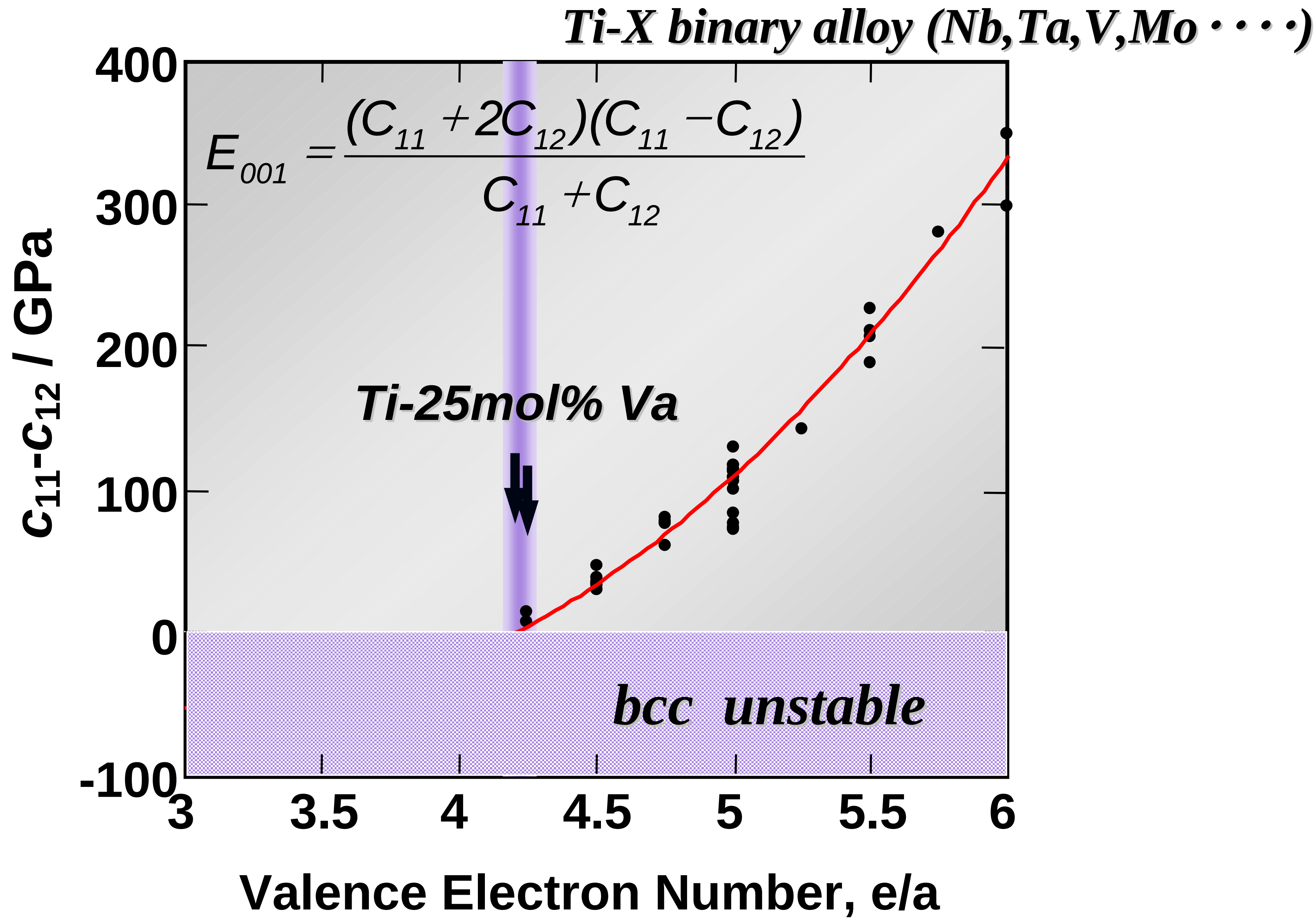
***Science*, 300 (2003), 464. Multifunctional Alloys Obtained via a Dislocation-Free Plastic Deformation Mechanism**

Elastic Modulus of Ti-X Binary Alloy System



Calculation of a parameter; C_{11}-C_{12}, which is related to elastic modulus of bcc structure and bcc phase stability

Relationship between C_{11}-C_{12} and e/a



Manufacturing Process of Gum Metal

Ti Powder | ***Nb,Ta,V,Zr,Hf Powder***

Mixing

392MPa — ***Compacting***

1573K×16hr
10^{-3}Pa — ***Vacuum Sintering***

1073K～1273K — ***Hot Working***

Cold Working

Ultrasonic Measurement of Young's Modulus

Alloy design of Gum Metal

Over a hundred of Ti-Nb-Ta-V-Zr-O (O: 1at%) alloys were prepared.

Relations between Young's Modulus and alloy composition were studied experimentally.

Characteristic of Gum Metal

Ti-24mol%(Ta+Nb+V）-（Zr, Hf）- O

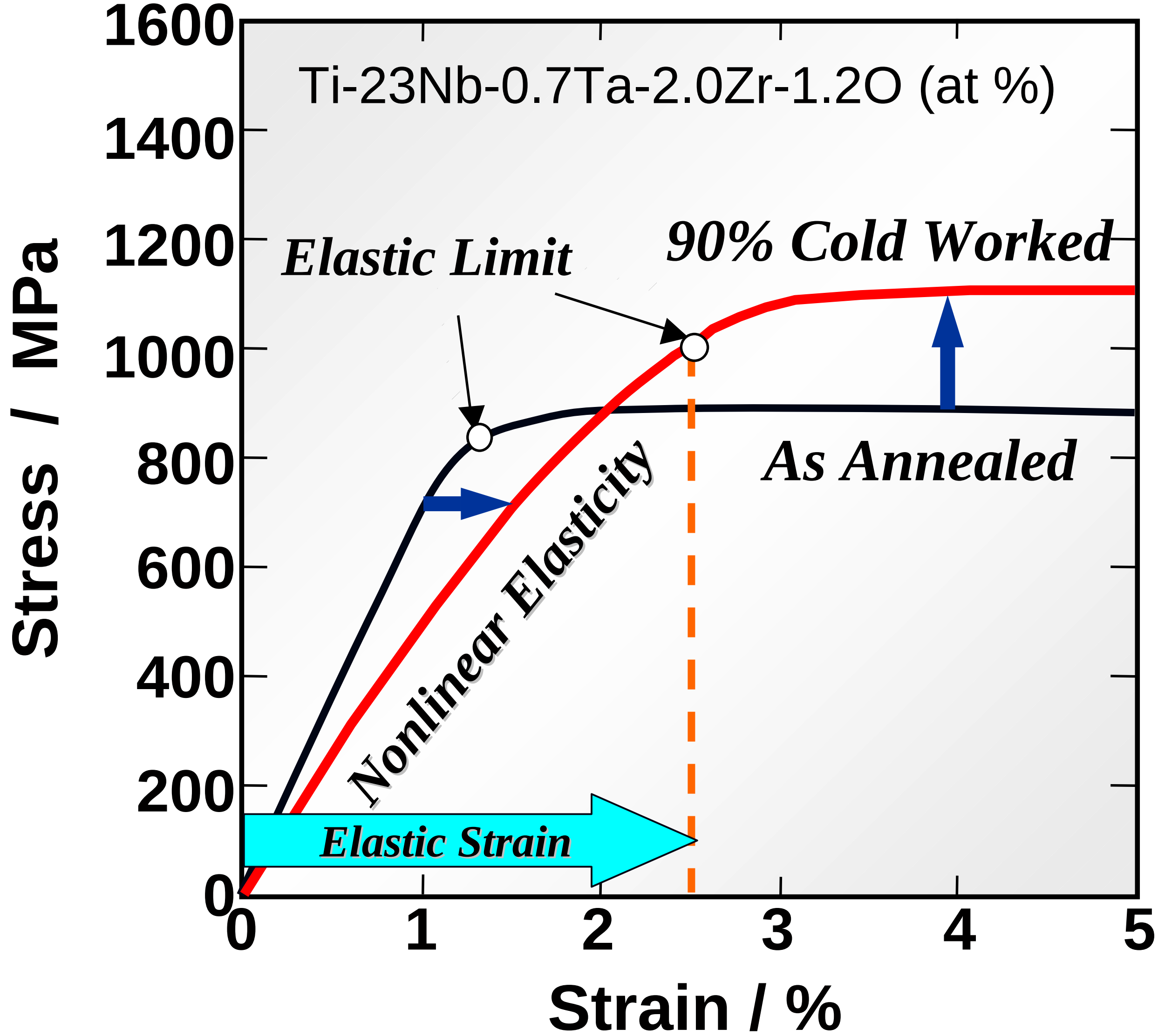
【e/a ≒4.24，Md ≒2.45，Bo ≒2.87 】

＋

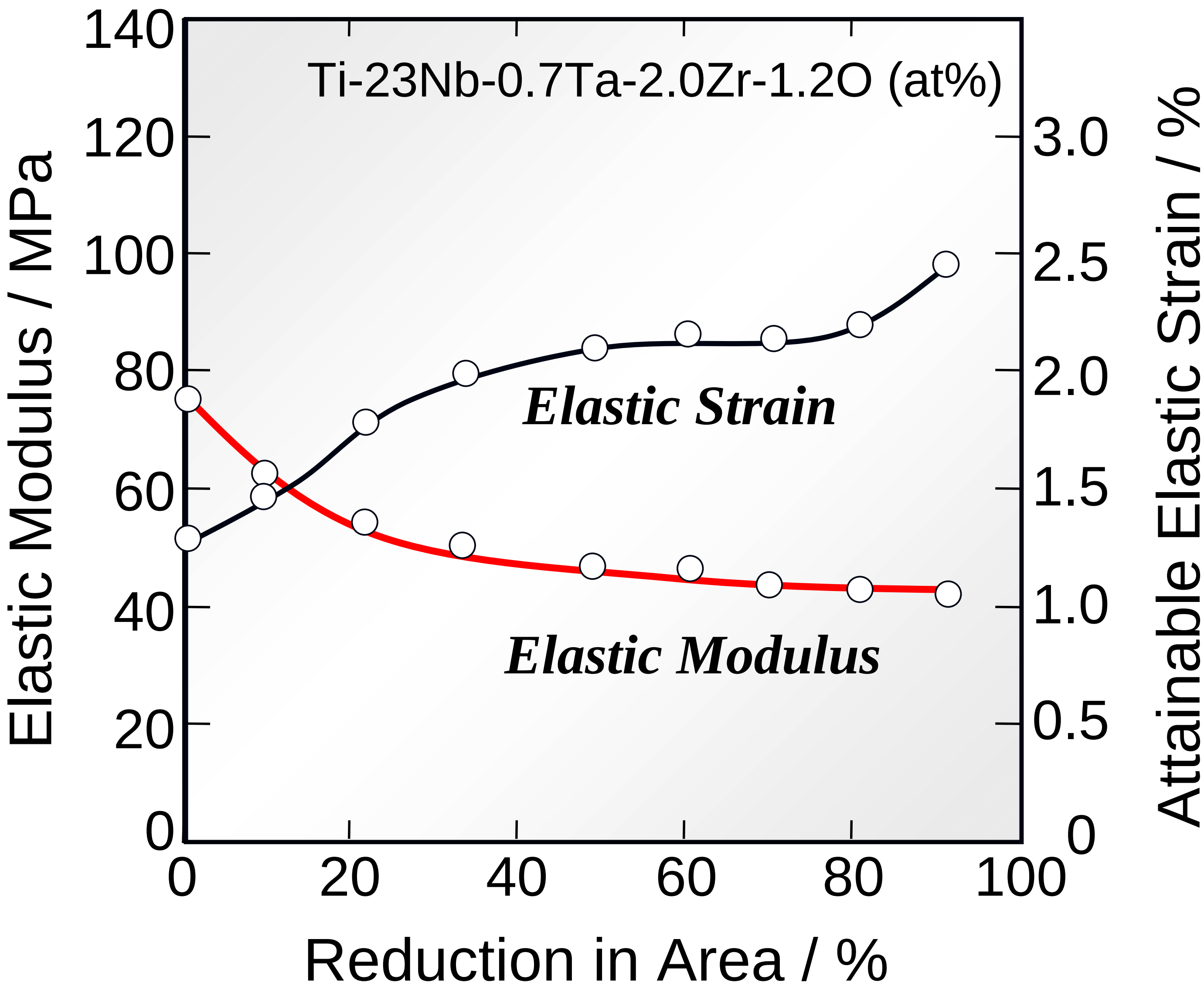
Cold Working

- a) Low Modulus (40GPa) with High Strength (1100MPa)
- b) Ultrahigh elastic deformability (2.5%)
- c) Nonlinear elasticity without any hysteresis
- d) Super ductility without work hardening
- e) Invar and Elinvar properties

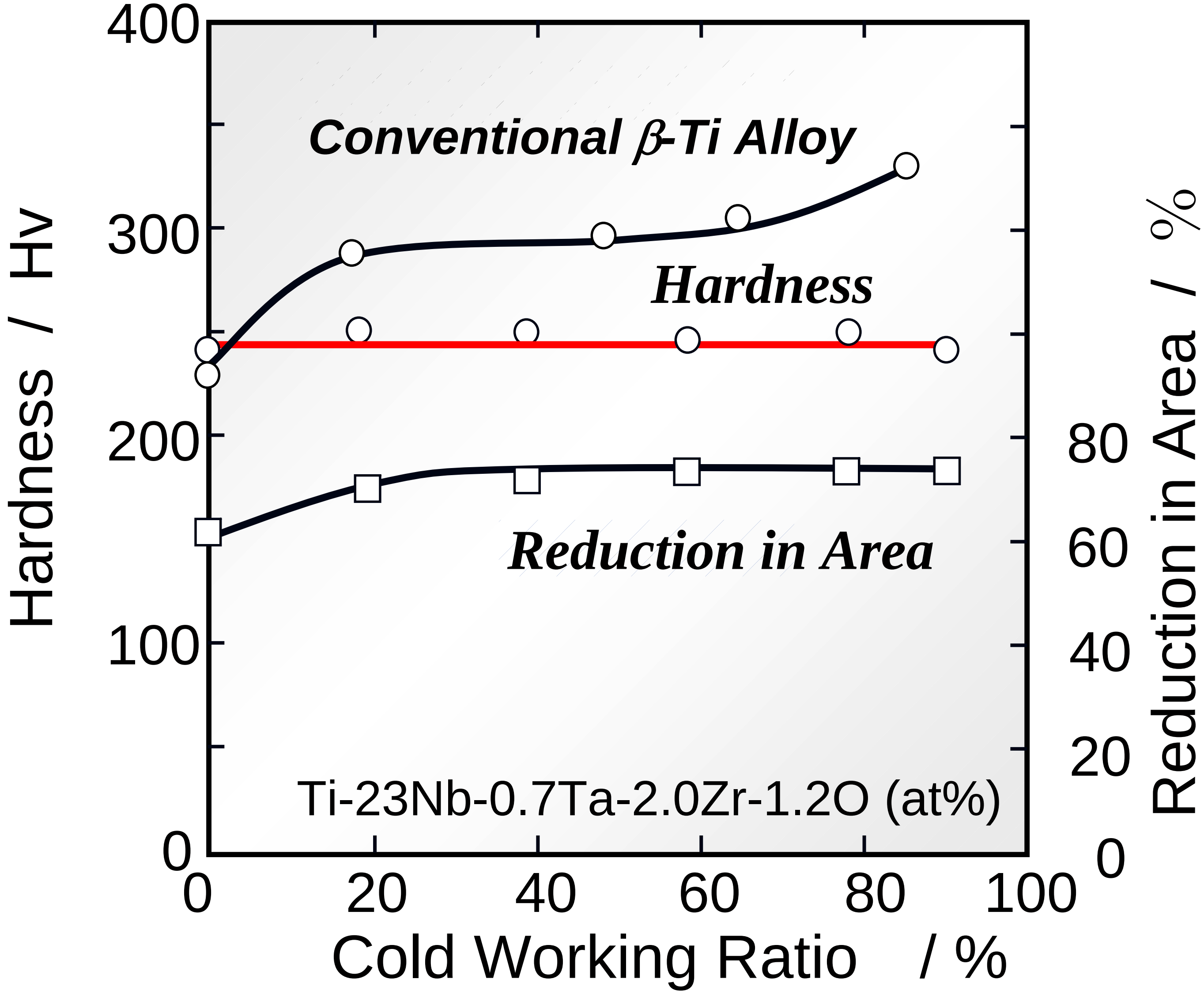
Change in Stress-strain Curve with Cold working



Effect of Cold working



Hardness, Reduction in Area vs Cold working



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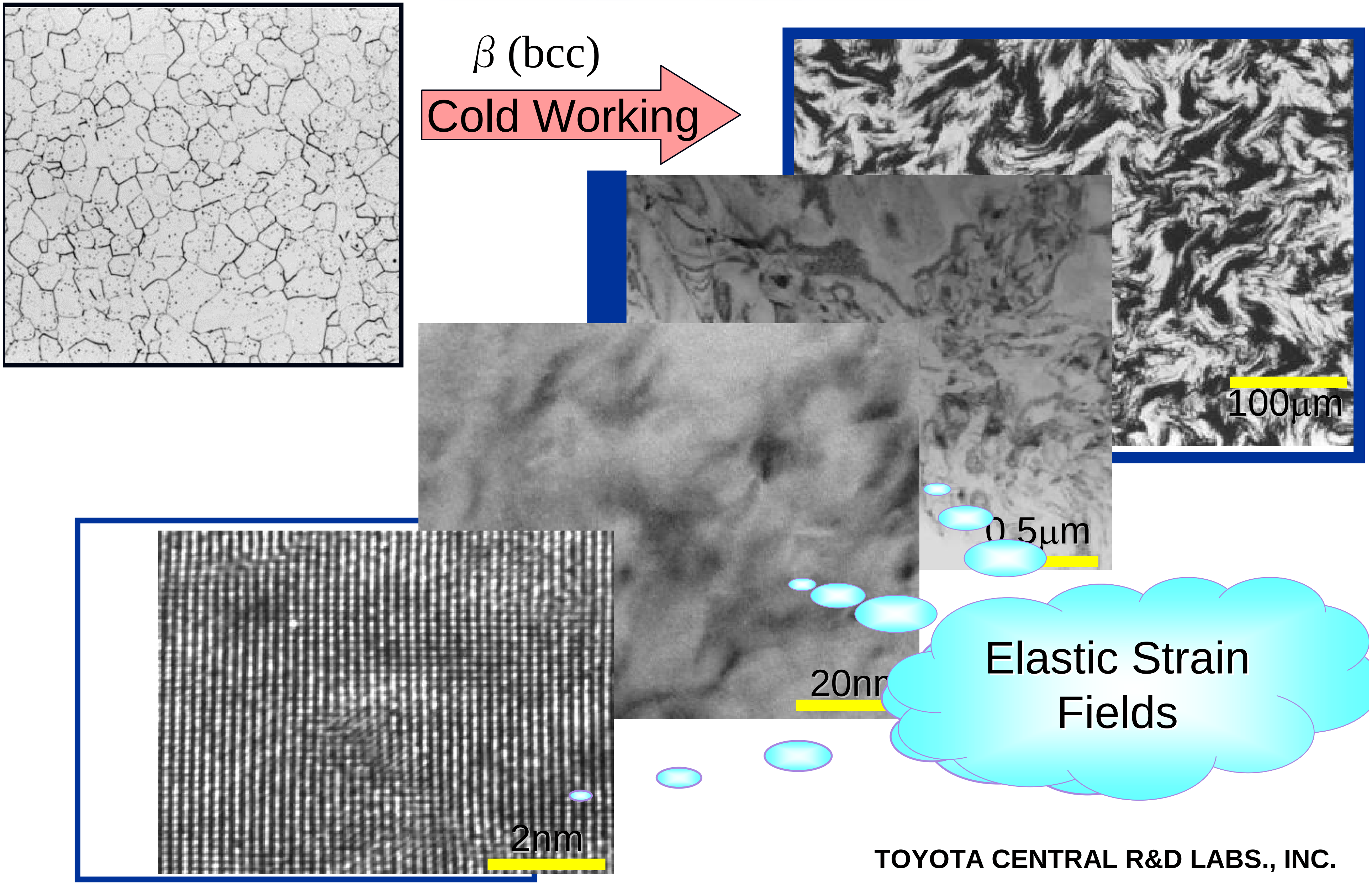
Fractal like microstructure induced by cold working



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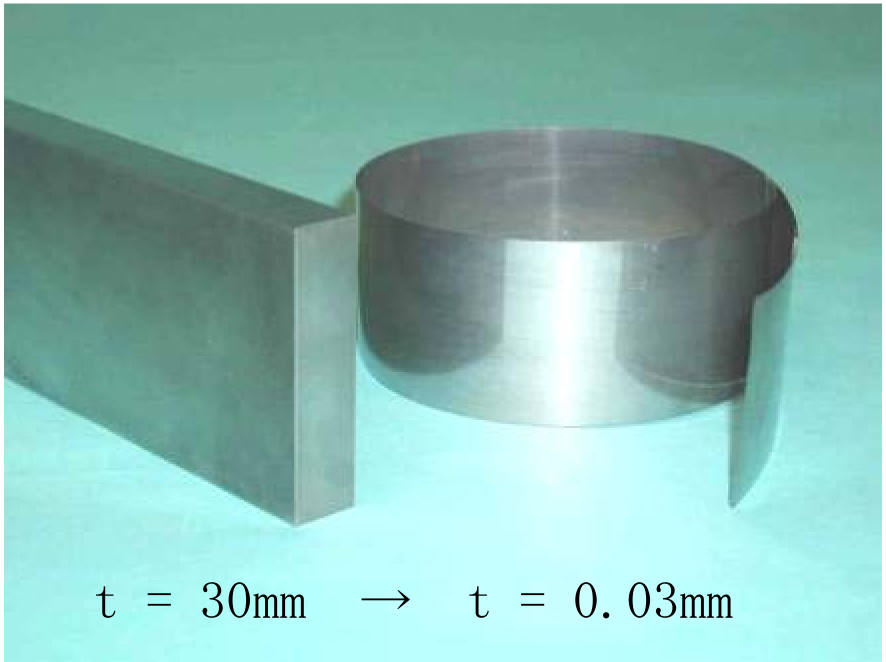
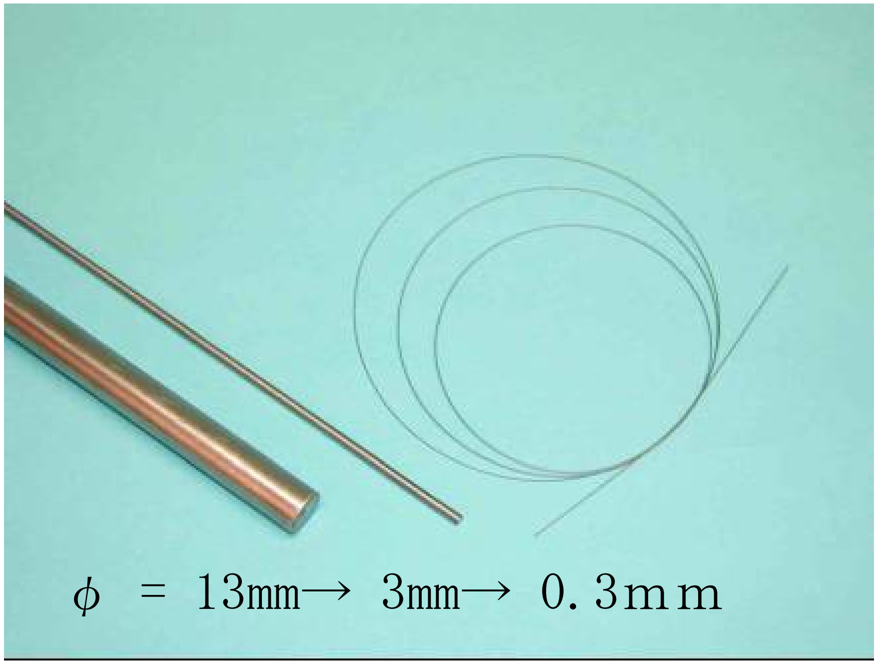
Cold Worked Samples

Cold Rolling

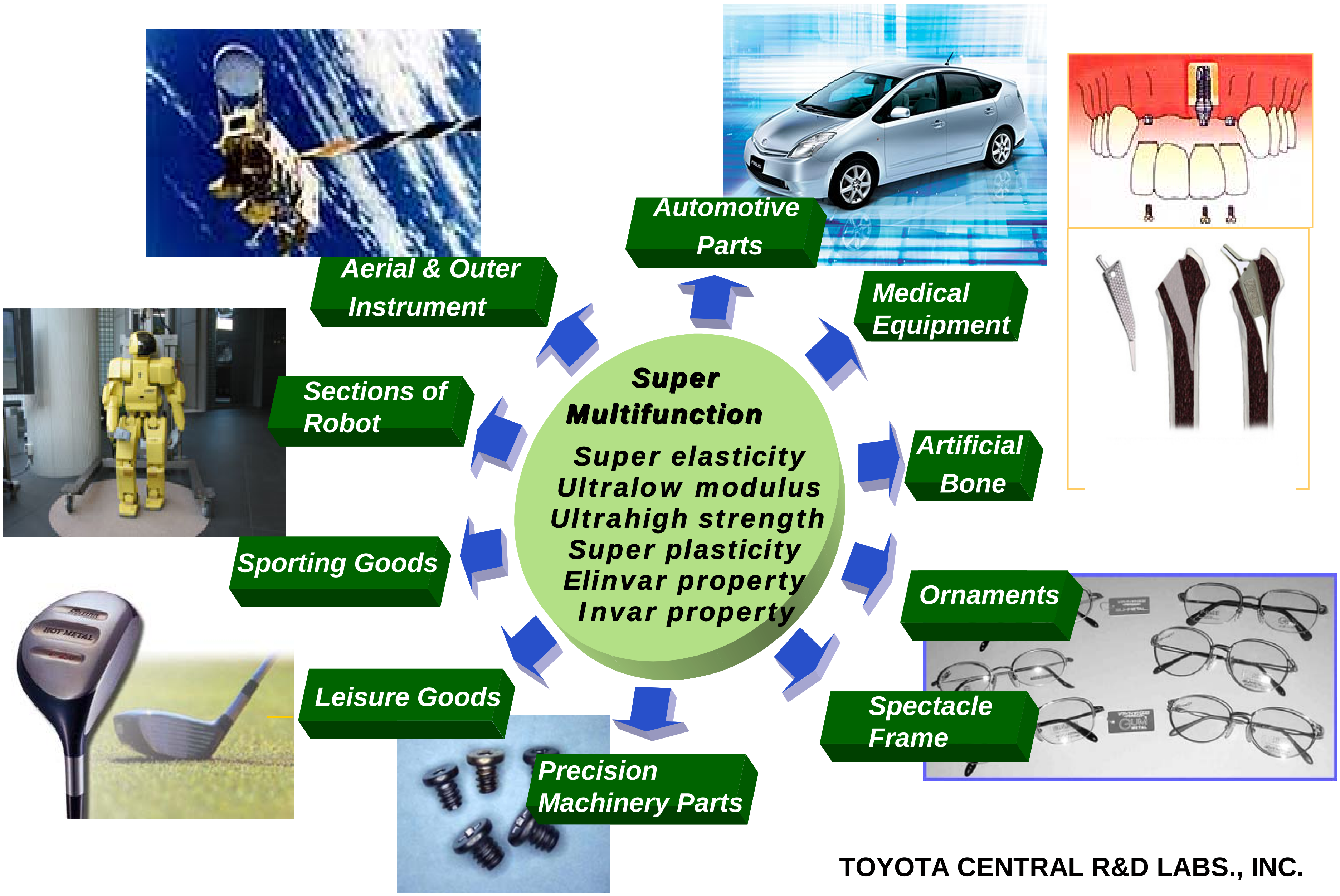


Cold Drawing



99% workable without annealing at R.T.
⇒Super ductility without work hardening

Possible Applications



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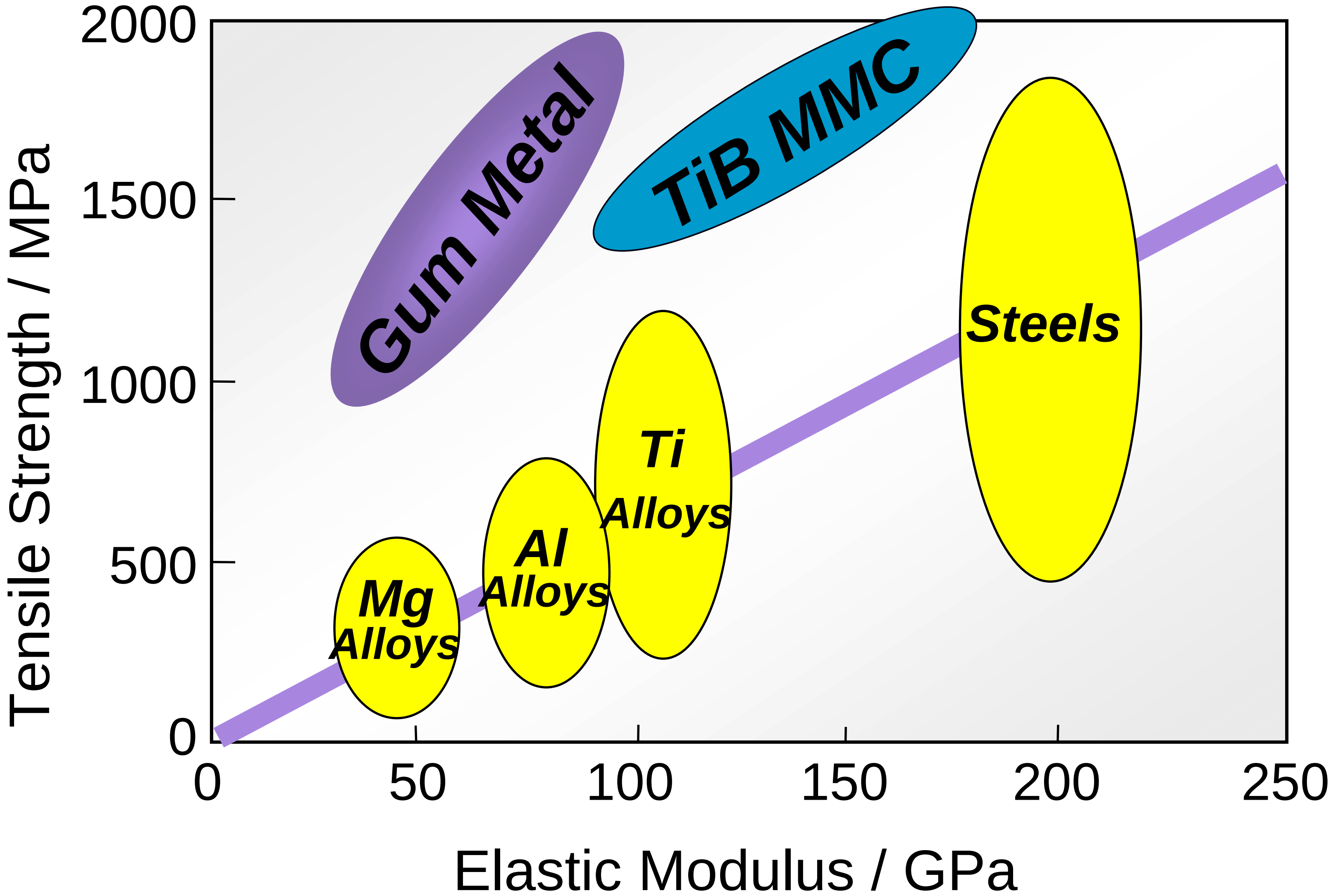
Summary


2000
1500
1000
500
0
Tensile Strength / MPa
0
50
100
150
200
250
Elastic Modulus / GPa
Gum Metal
TiB MMC
Steels
Ti
Alloys
Al
Alloys
Mg
Alloys

Thank you for your Attention!

TITANIUM 2005 21st Annual ITA Conference & Exhibition Scottsdale, Arizona

Development of Titanium Alloys with Controlled Elastic Properties

T. Furuta

Toyota Central Research and Development Laboratories Inc., Nagakute, Aichi, Japan

Abstract

In this paper, the work of Toyota Central R & D Labs., Inc. regarding titanium alloys with controlled elastic properties is introduced. These alloys are (1) a TiB reinforced titanium metal matrix composite obtained via a cost-effective powder metallurgy process for automotive engine parts. We found that the TiB particle is the only ideal reinforcement which has a high rigidly, strength and thermodynamic stability in titanium alloy, and (2) Gum Metal, a new multifunctional β titanium alloy, Ti-24at%(Ta+Nb+V)-(Zr +Hf)-O, which exhibits a low elastic modulus, high strength, high elastic deformability, superior cold formability without work hardening, and both Invar and Elinvar properties over a wide temperature range. The multifunctional properties of Gum Metal must offer a wide range of applications in the emerging markets.

1 Introduction

It is well known that titanium alloys are extremely attractive materials for aeronautical, aerospace, automobile and marine applications, because they have excellent properties such as specific strength and corrosion resistance. Nowadays, applications include not only transport components but also a wide range of uses in artificial bone, implants, medical equipment, sporting goods and so on. Therefore, the development of titanium alloy with new functionality has been conducted. In particular, control of the elastic modulus is required for developing new functional and designed components. However, it is very difficult to control the elastic modulus of metals. This is because the elastic modulus of metals is related to the binding energy, and conventional metallurgical processes have no significant effects on the physical properties of metals. The reason for this is that changes that can be effected by plastic working and heat treatment occur at the microstructural level and do not extend to inter-atomic bonds or electronic states. However, we have recently discovered new titanium alloys exhibiting multiple "super properties", by using a blended elemental (BE) method. The BE process is potentially the lowest cost titanium components manufacturing process, and furthermore it enables the production of complex materials that are difficult to make via ingot metallurgy. Metal matrix composites (MMC) and high-alloyed materials containing elements which easily segregate are typical examples.

In this article, the newly developed titanium alloys from Toyota Central R & D Labs are introduced These are (1) a TiB reinforced titanium metal matrix composite obtained via a cost-effective powder metallurgy process for automotive engine parts.[1-9] We found that the TiB particle is the only ideal reinforcement which has a high rigidly, strength and thermodynamic stability in titanium alloy.[2] The developed Ti-MMC has potential that has not been considered in conventional titanium alloys, and (2) Gum Metal, a new multifunctional β titanium alloy group, Ti-24at%(Ta+Nb+V)-(Zr+Hf)-O, which exhibits significant changes in physical and mechanical properties after cold working.[10-12] The developed β titanium alloys simultaneously show a low elastic modulus, high strength, high elastic deformability, superior cold formability without work hardening, and both Invar and Elinvar properties over a wide temperature range.[11]

2 Titanium Metal Matrix Composite (Ti-MMC)

2.1 Selection of an ideal reinforcement for Ti-MMC

While the specific strength of titanium alloy exceeds that of maraging steel, the elastic modulus of titanium alloy is approximately half that of steel. Therefore, weight savings from the use of titanium parts are not as great as expected from the difference in specific gravities between titanium alloy and steel. Additionally, further reductions in the size and weight of automotive components require elastic designing as well as conventional strength designing. In order to overcome this essential problem of titanium alloys, we attempted the development of a totally new type of high performance Ti-MMC. The first major decision for the alloy design was to select an ideal reinforcement. To use the BE method, the requirements for ideal reinforcing compounds are; (1) thermodynamic stability in titanium alloy from approximately 1600 K to room temperature, (2) high rigidity and strength, hardness and heat resistance, (3) mutual insolubility, and (4) minimal difference in thermal expansion between the matrix and reinforcing compounds. We finally decided on titanium monoboride (TiB) as the ideal reinforcement for titanium alloy. This is because TiB has a thermodynamic stability superior to that of current reinforcing compounds such as TiC, SiC, TiN, Si_3N_4 and TiB_2. **Table 1** compares the properties of reinforcing compounds for titanium alloys. TiB has outstanding mechanical properties which are desirable for an ideal reinforcement, and the linear

Table. 1 Adaptable of the reinforcement for BE titanium alloy.

Particle	*Knoop Hardness (GPa)*	*Elastic Modulus (GPa)*	*Coefficient Linear Expansion ($x10^{-1}K^{-1}$)*	*Maximum Solubility [Matrix] (at%)*	*Maximum Solubility [Particle] (at%)*	*Estimation*
TiB	28.0	550	8.6	$<$0.001	1.0	Excellent
TiC	24.7	460	7.4	1.2	15.0	Passable
TiN	24.0	250	9.3	22.0	26.0	Failure
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TiB_2	34.0	529	6.4	Unstable in Ti alloy		Failure
B_4C	27.5	449	4.5	Unstable in Ti alloy		Failure
Al_2O_3	22.5	350	8.1	Unstable in Ti alloy		Failure

Coefficient of Linear Expansion of Ti alloy is around $9x10^{-6}$ K^{-1}

coefficient of thermal expansion of TiB is nearly equal to that of titanium. Therefore, we selected TiB as the reinforcing compound for the titanium matrix composite.

While TiB is stable in titanium alloys, it is unstable by itself and can not be obtained in powder form. We use a boron powder or several boride powders as raw materials for forming TiB particles. During the sintering, the blended boron powder or boride powders react with titanium powder and are completely transformed to thermodynamically stable TiB particles in the titanium matrix. Due to the thermodynamic stability of the TiB, no reaction occurs around a TiB / titanium matrix boundary. A crystallographic relation is verified by electron diffraction analysis to be; (010) TiB // (001) β, <001) TiB // <110> β and the habit planes of the TiB particle are (100), (101) and (010).This result suggests that excellent crystallographic coherency is maintained at the boundary.[3] The matrix alloy can be changed and is carefully selected for the required properties of the component parts as listed in **Table 2** with the master alloy powders used.[3]

Table. 2 Matrix alloy composition and master-alloy powders.

Matrix Alloy (mass%)	*Master Alloy Powders*
Ti-6Al-4V	Al-40V
Ti-6Al-4V-1Mo-0.2B	Al-40V + MoB + pure B
Ti-8Al-1Mo-1V	Al-38Ti +Al-40V + pure Mo
Ti-6Al-2Sn-4Zr-2Mo-0.2Si	Al-14Sn-28Zr-14Mo-1.4Si
Ti-6.5Al-4.5Sn-4.5Zr-1Nb-1Mo-0.35Si	Al-25Sn-25Zr-5.6Nb-5.6Mo-1.9Si
Ti-5Al-12Cr-3.3V	Al-40V + pure Cr
Ti-10V-2Fe-3Al	Al-40V + Fe-80V (ferro-V)
Ti-4.3Fe-7.0Mo-1.4Al-1.4V	Al-50V + Fe-62Mo (ferro-Mo)
Ti-33.5Al	Al-38Ti

2.2 Performance of the developed Ti-MMC

The elastic moduli of the developed Ti-MMC can be controlled by changing the TiB content and the matrix alloy, for example α, α+β or β-Ti alloy. **Figure 1** shows changes in

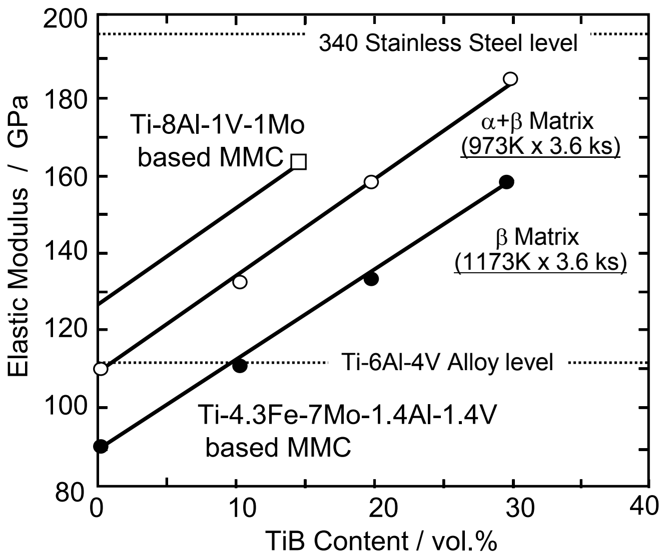

Figure. 1 Change in Elastic modulus for the developed MMCs with TiB content.

the elastic modulus at room temperature for the developed Ti-MMCs with different types of matrix alloy with the TiB particle content. In each case, the elastic modulus increases linearly with increasing TiB content. It exceeds 180 GPa for 30 vol.% TiB in the β Ti matrix alloy, which is almost the same as that of stainless steel. The result is in excellent agreement with the topological transformation and mean field theory by A.P. Miodownic calculated from the elastic modulus and Poisson ratio of titanium alloys (115 GPa and 0.27, respectively) and TiB (550 GPa and 0.19, respectively).[13] **Figure 2** summarizes the tensile and fatigue strengths and wear resistance of the developed high-strength Ti-MMCs, such as 10 vol.% TiB / Ti-6Al-4V-1Mo-2Fe MMC [8] and 20 vol.% TiB / Ti-4.3Mo-7Fe-1.4Al-1.4Fe MMC [6] under the post-forged-annealing condition, compared with IM β annealed Ti-6Al-4V. All of the properties of the developed Ti-MMC are far superior to those of Ti-6Al-4V alloy. The anomalous strength with the high elastic modulus means that the Ti-MMC has greater potential for weight reduction in

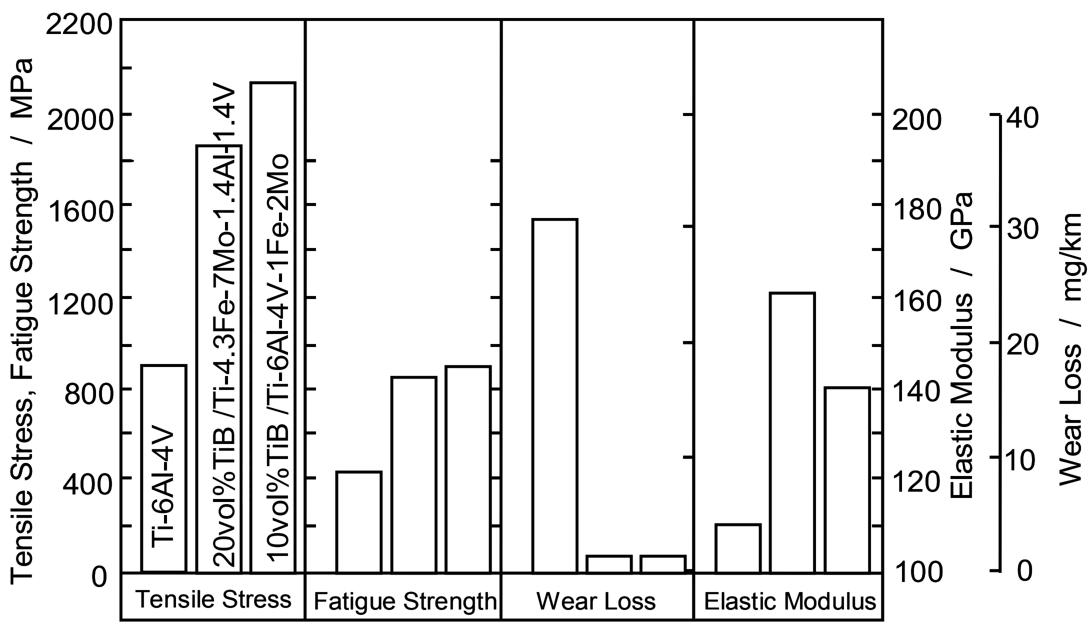

Figure. 2 Comparison of mechanical properties of high strength developed MMCs with wrought Ti-6Al-4V alloy

automotive parts than conventional titanium alloys, and the excellent wear resistance allows elimination of expensive surface treatment.

The combustion temperatures of recent mass-produced engines have a tendency to be increasingly higher, due to the required emission reductions, with exhaust gas temperatures reaching 900°C and exceeding 800°C for the actuating temperature of exhaust valves. The exhaust valve materials need to have excellent creep resistance, fatigue strength, and oxidation resistance. Generally, Steel 21-4N, which is well known as heat resistant steel, is used for the exhaust valves of automotive engines. This material has excellent balanced characteristics including static strength, fatigue properties, creep resistance and oxidation resistance at room temperature and high temperatures (around 800°C) in addition to being cost-effective. **Figure 3** shows 0.2 proof strengths at 1073 K for the developed Ti-MMCs reinforced by 10 vol.% TiB and the heat-resistant materials of 21-4N and Ti-1100. It is apparent that the heat resistance of the developed Ti-MMCs is superior to that of the heat-resistant materials. **Figure 4** shows changes in the high-cycle fatigue strength at 1123 K for the developed heat-resistant Ti-MMC with the TiB particle content, which is one of the most essential properties for an exhaust valve. The high temperature fatigue strength of the heat-resistant matrix alloy is considerably improved by the dispersion of TiB particles. It is worth noting that even at a compounding of 5 vol.% TiB or so, it exceeds that of 21-4N steel. Figs. 2 and 3 indicate that careful selection of the matrix alloy system and TiB content for the developed Ti-MMC makes it possible to obtain heat resistance that is superior to that of typical heat-resistant steel at high temperatures beyond 1000 K.

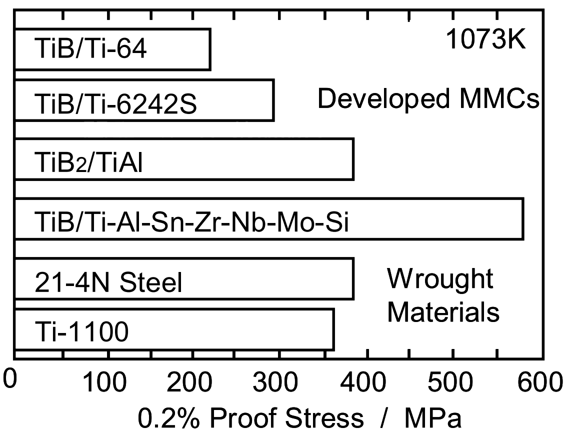

Figure. 3 Comparison of 0.2 proof high strength at 1073K for the developed MMCs with the commercial heat resistant materials.

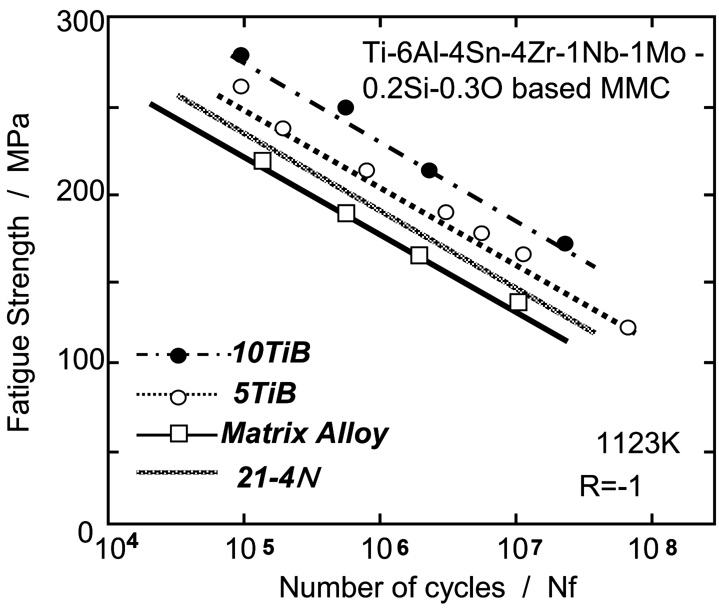

Figure. 4 Comparison of fatigue strength at 1123K for the developed MMCs with the commercial heat resistant materials.

2.3 Applications of the developed Ti-MMC

In October 1998, a new mass-produced public car using titanium engine valves (both intake and exhaust) was released by TOYOTA Motor Corporation (**Fig. 5**). Both valves were manufactured via a newly developed cost-effective P/M forging process. Furthermore, the material for the exhaust valve is a high performance Ti-MMC.[9] Synergistic effects of the heat-resistant matrix alloy and the reinforcement particles (TiB) achieve the excellent mechanical properties of the developed Ti-MMC. The ideal composition of the matrix alloy was determined to be Ti-6Al-4Sn-4Zr-1Nb-1Mo-0.2Si-0.3O, taking into consideration the high temperature creep, fatigue and oxidation resistances. In addition, taking into consideration the ductility, hot formability and machinability, which are essential to the component production in addition to the heat resistance, the ideal amount of TiB particle was determined to be 5 vol.%. A new engine installed with these valves had a valve weight that was 40% less and a valve spring that was 16% less than that for an engine installed with conventional steel valves. As a result, the maximum revolution increased by 700 rpm and the noise in the high revolution range decreased by 30%. Moreover, the reduction in friction reduced the camshaft driving torque by 20%, and high performance and low fuel consumption were achieved. Last year, in 2004, more than 250000 of the developed Ti-MMC valves were produced as automotive and motorcycle engine valves on the Japanese market (**Fig. 6**).

Figure 5. The Toyota Alltezza, 1998 Japanese Car of the Year, the first family automobile in the world to feature titanium intake and exhaust valves.

Figure 6. The developed BE titanium intake valve (left) and Ti-MMC exhaust valve (right).

3 Multi Functional Titanium Alloy

3.1 Design of low elastic modulus titanium alloy

We have recently developed a multifunctional β titanium alloy, Gum Metal,[10] that exhibits a low elastic modulus with high strength, by using the BE method and a new alloy design method. From literature and experience, the elastic modulus of titanium alloy takes a minimum value near the composition limit of the bcc phase. It is also well known that several electronic parameters, such as (i) the valence electron number (*e/a*); (ii) the bond order (*Bo* value), and (iii) the "d" electron-orbital energy level (*Md* value), [14] are strongly related to the phase stability. However, there have been few attempts to theoretically compute and predict elastic moduli of titanium-based alloys. We first calculated elastic moduli using the ultra-soft pseudo-potential method within a generalized gradient approximation to the density function theory, and found a new method for theoretical calculation.[15] This new theoretical calculation can accurately predict the elastic modulus by calculating elastic constants (c_{11}, c_{12}, c_{44}) of Ti-*X* binary alloy systems (*X*=V, Nb, Ta, Mo and W). From the calculation results, we found that (c_{11}-c_{12}) is correlated with the averaged valence electron number (*e/a*), and the value (c_{11}-c_{12}) approaches zero when an *e/a* is close to 4.24. The results also indicate that the polycrystalline elastic modulus of Ti-*X* binary alloys attains a minimum value with an *e/a* of around 4.24. So, we are quite sure that an *e/a* of around 4.24 is one of the most important requirements in the design of a low-elastic modulus titanium alloy. Next, we experimentally investigated the efficient group IVa elements, which improve the strength of the alloy without increasing the elastic modulus, allowing changes in *Bo* and *Md* while maintaining an *e/a* of 4.24. We finally reached an optimum combination of these three electronic numbers; an *e/a* of around 4.24; a *Bo* of around 2.87; and an *Md* of around 2.45. The unique properties such as low elastic modulus, high strength and cold-workability only appear when all three of these magic numbers are satisfied simultaneously, and each alloy system requires significant cold working and the presence of a certain amount of oxygen, at least 0.7 at%. The composition of the developed alloy is fundamentally expressed as Ti-24 at% (Ta+Nb+V)-(Zr, Hf)-O. Various alloy compositions are available, such as Ti-23Nb-0.7Ta-2Zr-O and Ti-12Ta-9Nb-3V-6Zr-O (in at %), wherein each alloy has a simple body-centered-cubic (bcc) crystal structure.

3.2 Mechanical properties of Gum Metal

The unique characteristics of Gum Metal are developing by cold working. **Figure 7** shows a change in tensile stress-strain curve at room temperature with cold working for a typical alloy, Ti-23Nb-0.7Ta-2Zr-1.2O. The elastic modulus drops dramatically as a result of the cold working, from 70 GPa to 55 GPa, at near-zero stress, and the yield stress increases after cold working. We can confirm non-linearity in elasticity for the cold-worked specimen, with the gradient of the stress-strain curve in the elastic region continuously decreasing with a stress increase. **Figure 8** shows changes in elastic properties, such as elastic limit strength, average elastic modulus and attainable elastic strain. Here, the average elastic modulus is the average value of the gradients during non-linear elasticity. The attainable elastic strain of the solution treatment material is about 1% and increases to 2.5% after 90% cold working. The average elastic modulus decreases with increasing cold working ratio, this downward trend is unsurpassed and decreases to below 40 GPa at 90% cold working.

It is well known that the large elastic strain obtained in "super-elastic alloys" originates from a reversible martensitic transformation, such as stress-induced α" transformation, dubbed "pseudo-elastic deformation".[16, 17] Conversely, Gum Metal shows a quite unique elastic behavior with no hysteresis in the stress-strain relation, as seen in **Fig. 7**, which is inherent in conventional super-elastic alloys. We confirmed by in-situ XRD measurement during tensile loading that all β peaks shift monotonically to higher 2θ angles with increasing tensile strain up to 2.7%. This result suggests that no phase transformation such as stress-induced α" or rearrangement of variants of α" occurs during tensile deformation, and that the true elastic deformation of β crystal proceeds in Gum Metal.[11]

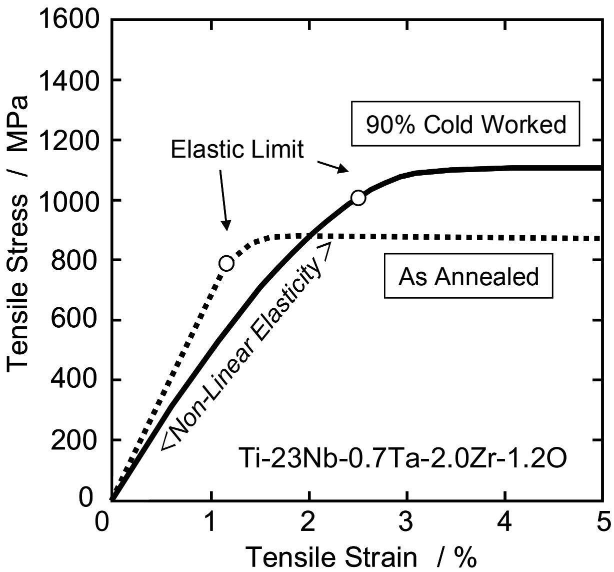

Figure. 7 Change in stress-strain curve of Ti-23Nb-0.7Ta-2.0Zr-1.2O alloy before and after cold working.

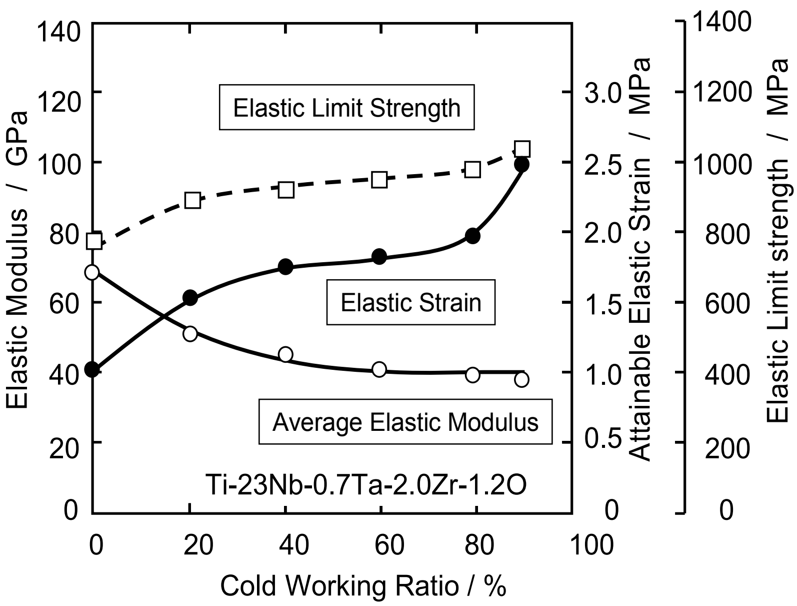

Figure. 8 Change in elastic properties and elastic limit strength with cold working ratio.

Oxygen content, as well as cold working, influences the elastic properties of multifunctional alloys. **Figure 9** shows effects of oxygen content on the attainable elastic strain and the elastic modulus of the Ti-23Nb-0.7Ta-2Zr-O

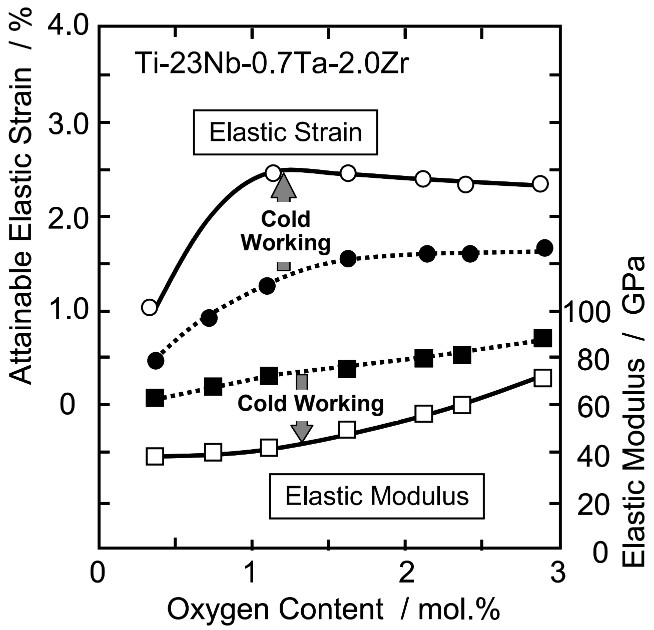

Figure. 9 Change in elastic properties oxygen content and cold working.

alloy before and after cold working with a 90% reduction in area. The attainable elastic strain increases with increasing oxygen content and is enormously accelerated by the cold working. That of the cold-worked alloy is only 1% at a lower oxygen level (0.3 mol%), but it increases to 2.5% at around 1 mol% oxygen. The elastic modulus gradually increases with increasing oxygen content. That of the cold-worked alloy at 3 mol% oxygen is about 70 GPa, which is still a small value for a titanium alloy. It can be seen from Fig. 9 that both oxygen addition and cold working are fundamental for achieving a low elastic modulus with high attainable elastic strain. Additionally, the effect of oxygen content on the tensile strength is remarkable; it reaches 1600 MPa at 3 mol% O. The strength increases to approximately 2100 MPa after the aging treatment. The ductility maintains a very high value, exceeding 40% even at 3 mol% O. Furthermore, an important point to emphasize is the fact that the heat-treated alloy maintains a reduction in area of 10 % along with an ultra-high strength of more than 2000 MPa.[11]

3.3 Applications of multifunctional titanium alloy Gum Metal

Cold-workability is an important factor for practical applications. **Figure 10** shows the effects of cold working on hardness and reduction in area. The Vickers hardness and the reduction in area of the multifunctional alloy both remain approximately constant regardless of the cold working ratio. On the other hand, the hardness of the conventional β titanium alloy gradually increases with an increasing cold working ratio. This suggests that the multifunctional alloy has super-plastic like deformability at room temperature without any work hardening. **Figure 11** shows an example of the cold-worked samples. Since the alloy does not show work hardening after cold working, continuous deformation without annealing is possible to more than 99.9% under any kind of cold working, such as formation of a round bar, wire or thin sheet. Namely, no amount of plastic deformation at room temperature causes work hardening or decreased ductility, which is a nifty property for the practical use of Gum Metal.

Gum Metal, which has various unique characteristics that set it apart from other metals, is a

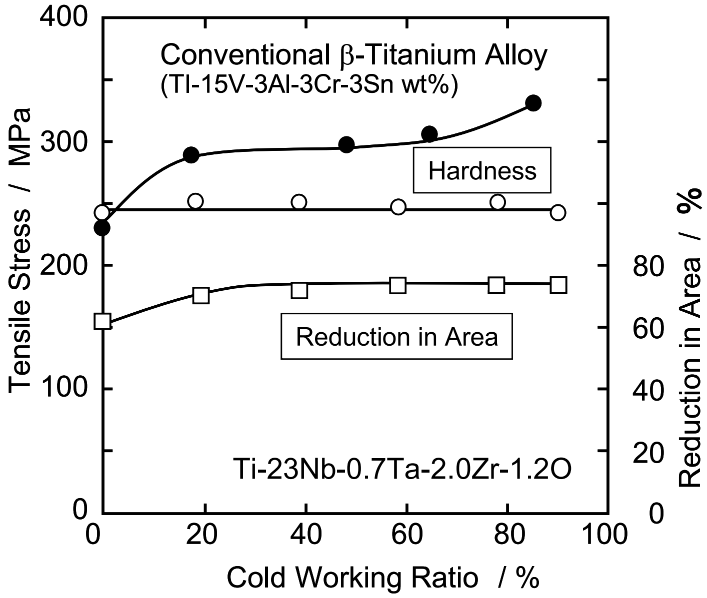

Figure. 10 effect of cold working on hardness and reduction in area.

totally new material that has infinite possibilities for practical applications. **Figure 12** shows examples of (a) a spectacle frame and (b) precision screws. The spectacle frame made from Gum Metal is very flexible, with supreme die-press formability. The material for precision screws is required to have extreme cold formability with high strength. The properties of Gum Metal are optimal for this use, and furthermore, the elastic property prevents the screws from coming loose. They are already on the market in Japan. Each function or complex function of Gum Metal will provide a wide range of applications for automotive components, artificial bone, implants, medical equipment, sporting goods, decorative materials and aerial and outer space instruments in the near future **(Figure 13)**.

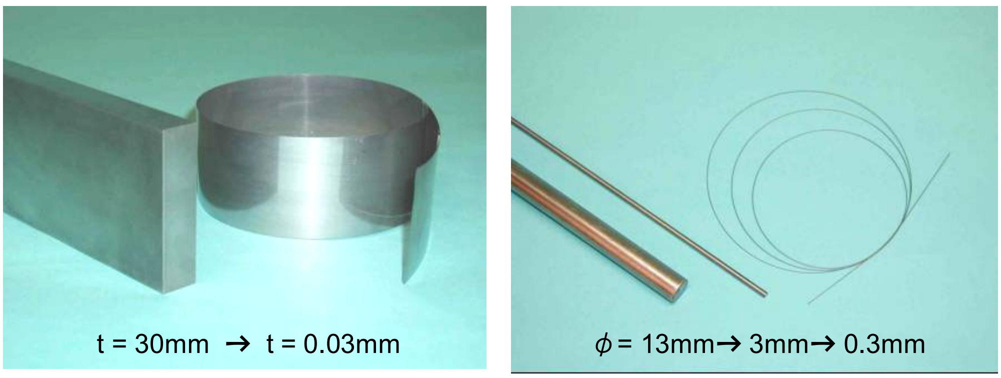

Figure 11. Example of the cold worked samples.

Figure 12. Demonstrates example of (a) a spectacle frame and (b) precision screws.

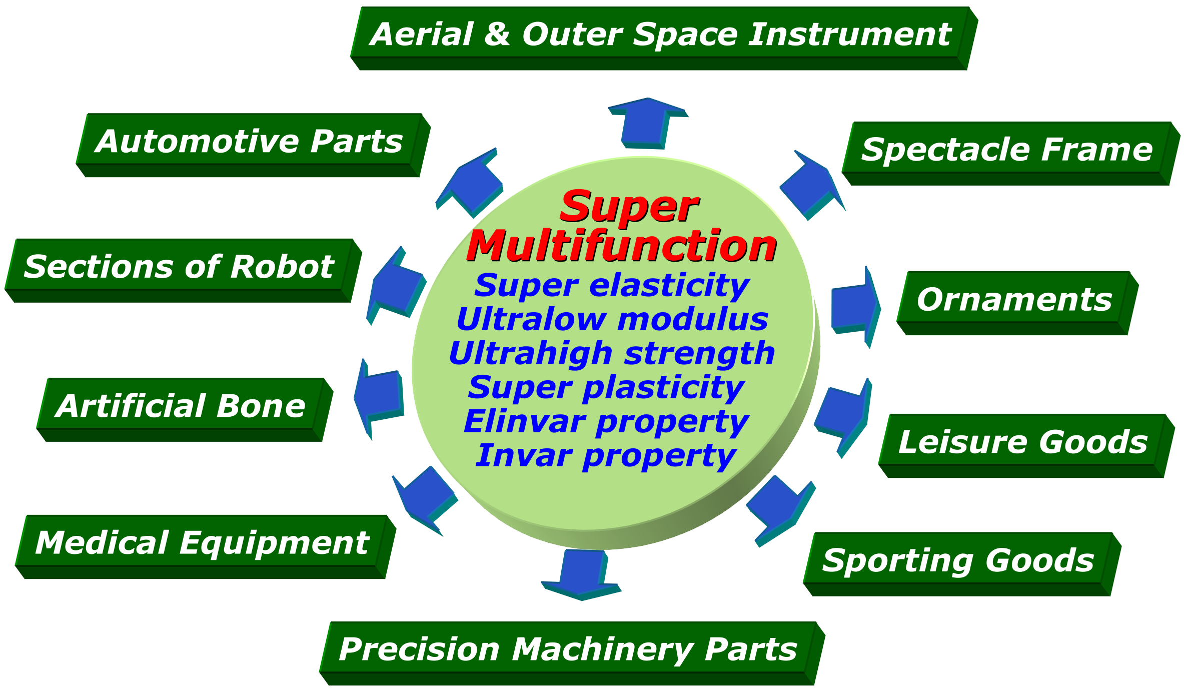

Figure 13. Possible applications of Gum Metal.

4 Summary

We have developed high performance TiB reinforced Ti-MMC and a multi functional titanium alloy, Gum Metal, by using the BE method. These materials could not be manufactured via conventional ingot metallurgy.

TiB reinforced Ti-MMC has remarkable properties such as high rigidity, high strength (both tensile and fatigue), and superior heat resistance and wear resistance. All these superior properties are attributed to the characteristics of TiB, such as thermodynamic stability in titanium alloy, and outstanding mechanical and physical properties. We found that the TiB particle is the only compound that satisfied the requirements for ideal reinforcement of titanium matrix alloy. Gum Metal simultaneously possesses multi functions such as a low elastic modulus (40 GPa), high strength (more than 1100 MPa), high elastic deformability (2.5%), super-plastic like deformability at room temperature without work hardening, and Invar and Elinvar properties.

The developed alloys bring many new possibilities to titanium technology. For example, the anomalous strength with high elastic modulus means that Ti-MMC has a greater ability for weight reduction in automotive parts than conventional titanium alloys. The multifunctional properties of Gum Metal will provide a wide range of applications for automotive components, artificial bone, implants, medical equipments, sporting goods, decorative materials and aerial and outer space instruments in the near future.

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