Technical Issues of Titanium and Aluminum Alloys for Transportation Vehicles Applications in Korea

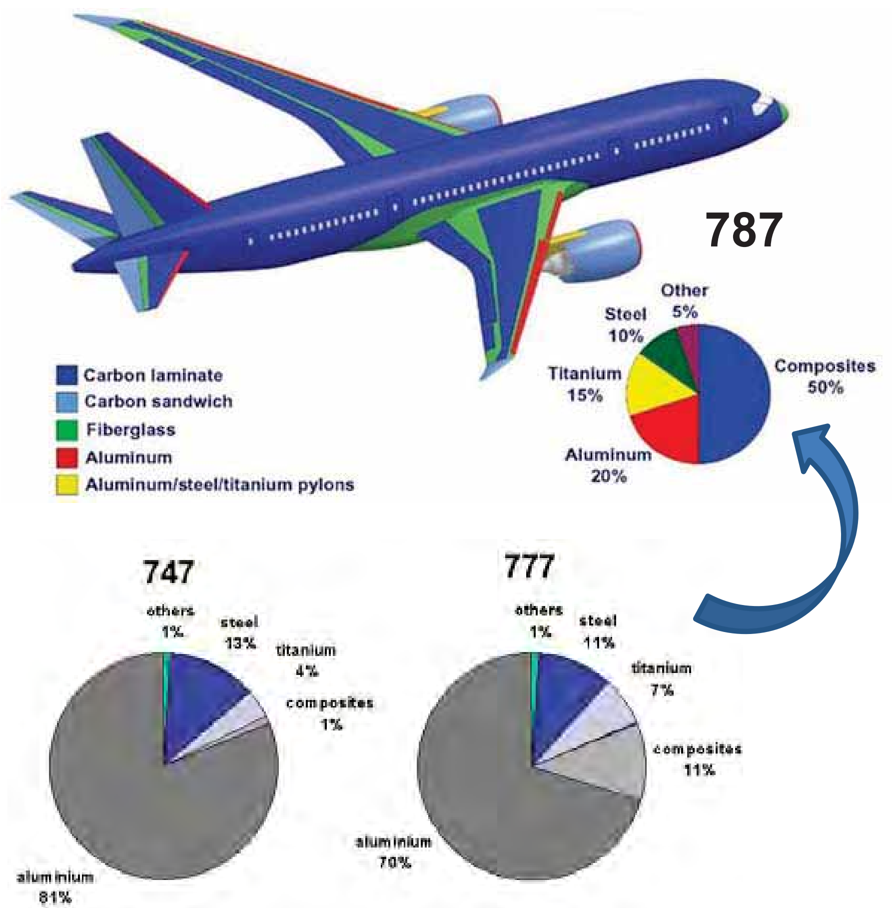
2018. 11. 10 (Saturday)

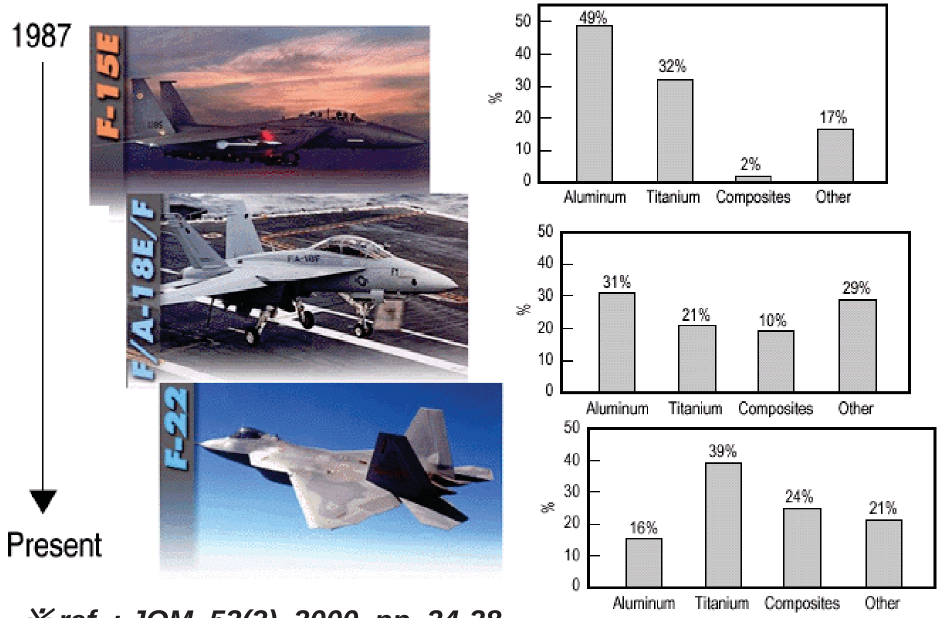
Jong-Taek Yeom

Titanium Department, Korea Institute of Materials Science(KIMS)

KIMS Korea Institute of Materials Science

- **Change trend in civilian aircraft and military aircraft materials(Example)**





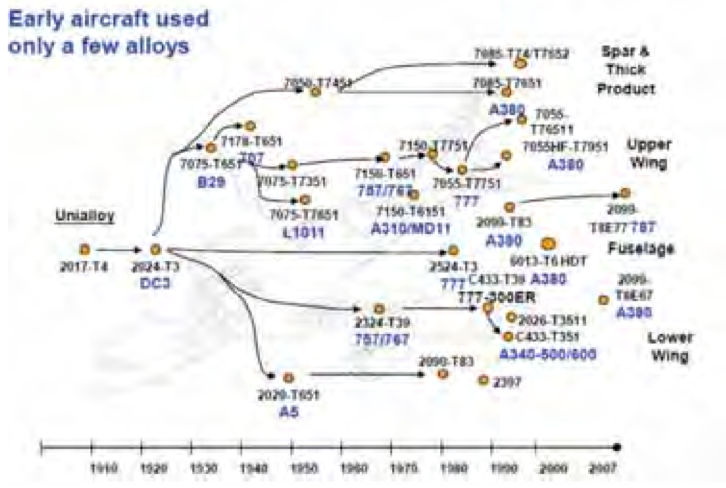
※ *ref. : JOM, 52(3), 2000, pp. 24-28.*

- Reduction of Al alloy usage
- A large increase in Ti alloy and composites usage

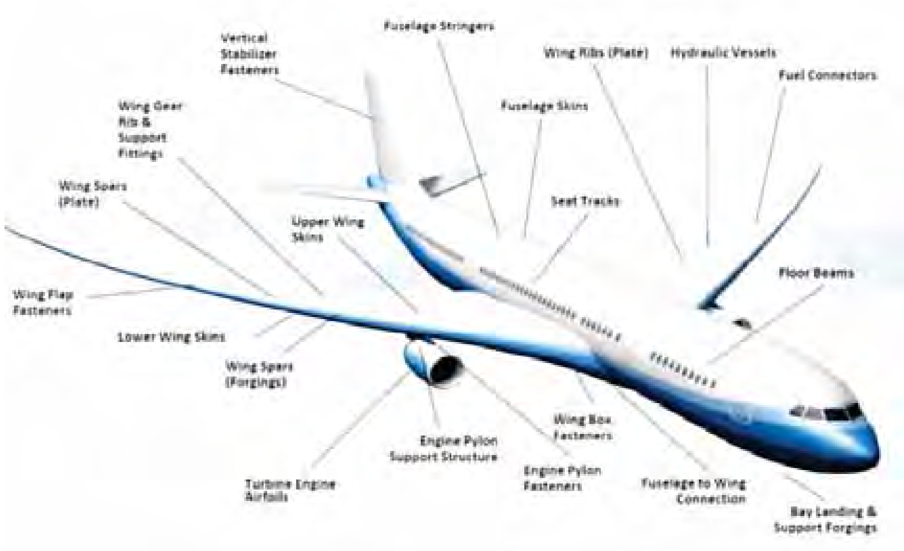
- ✓ **(Civilian) Boeing 777, Al(70%), Ti(7%), composites(11%) → Boeing 787, Al(20%), Ti(15%), composites(50%)**
- ✓ **(Military) F-18E, Al(31%), Ti(21%), composites(10%) → F-22, Al(16%), Ti(39%), composites(24%)**

Aluminum Industry Trend for Aviation

- **Al alloys → Structures that must support a certain load such as aircraft fuselage and wing (2XXX, 7XXX, Al-Li alloy)**
- **Developing a variety of Al alloys from A2024 and A7075 to high strength A7085 and A2099(Al-Li alloy) for aircraft structure**

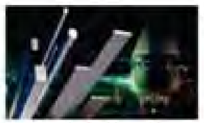


<Parts using Al Alloys>



(ref.) ALCOA

<Al Alloys Parts>



Extruded parts

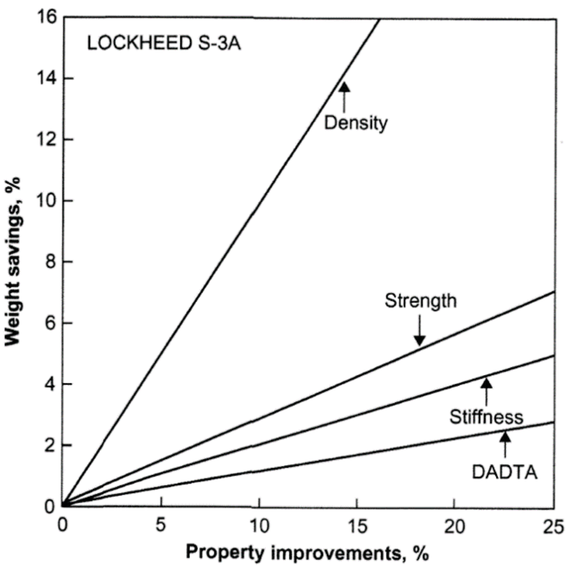
Forgings

Sheet

Aluminum Market Trend for Aviation

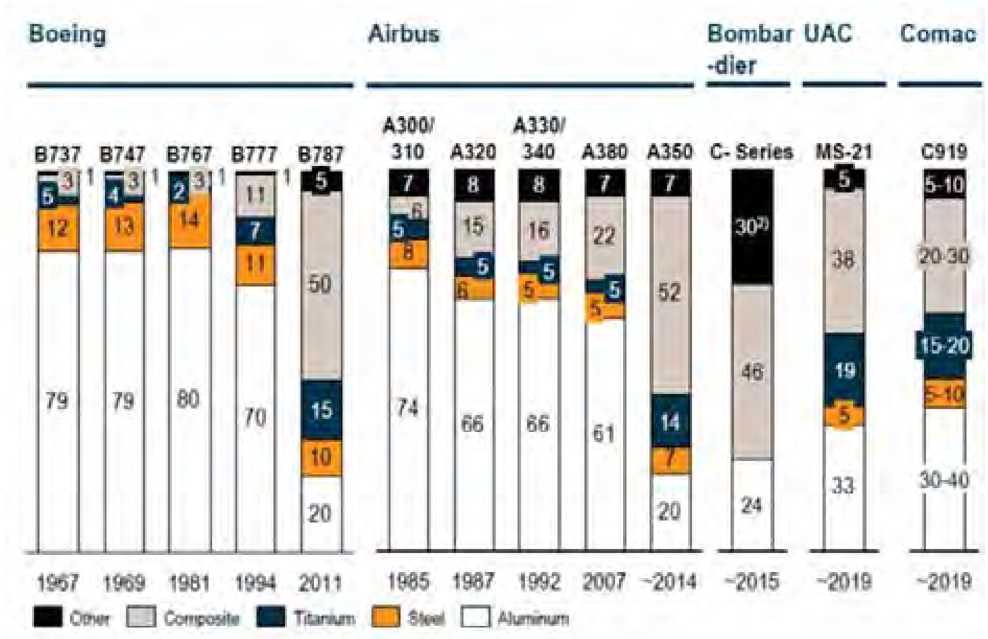
- **In the aviation fields, aluminum alloys have been used aggressively since long ago, as the need for light weighting is much higher than the cost increase.**
- **In Korea, annual aluminum alloy market for aerospace applications is estimated at about 30 million dollars and the global market is estimated at about one billion dollars.**

<Effect weight savings to material properties of aircraft >



출처: N. E. Prasad, A. A. Gokhale, and R. J. H. Wanhill, "Aluminum-Lithium Alloys, Processing, Properties, and Applications", Elsevier (2014)

<Usage rate of structural material for aircraft>

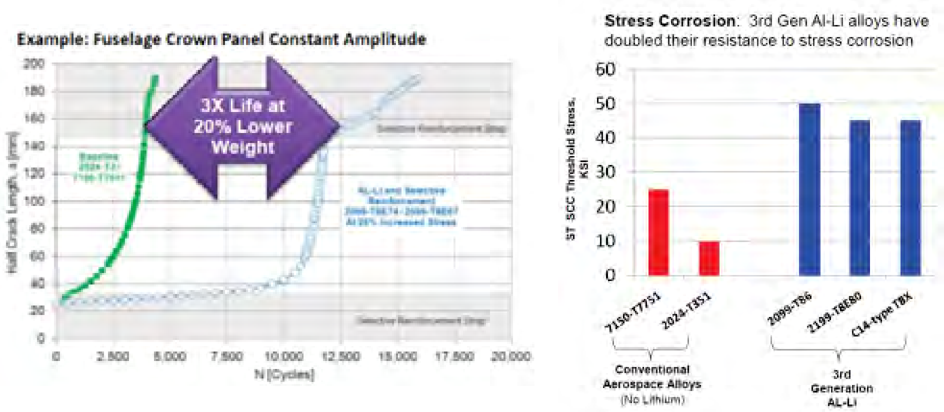


(ref.) ALCOA

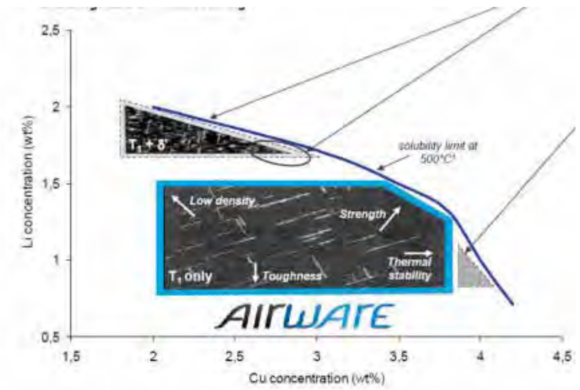
Characteristics of Al in Aviation Industry

- **Aluminum alloy for aviation occupies a unique position in leading large companies such as Alcoa and Constellium.**
- **Because aviation materials require high-quality control, it is necessary to commercialize raw materials through development of performance improvement based on impurity control. In addition, aviation materials tend to utilize only proven materials.**
- **It is difficult to transfer core technologies between countries, and some materials such as Al-Li alloy are difficult to import it because of export control items.**

<Alcoa's Al-Li alloy for aviation>



<Constellium's 7000-series Al alloy for aviation>



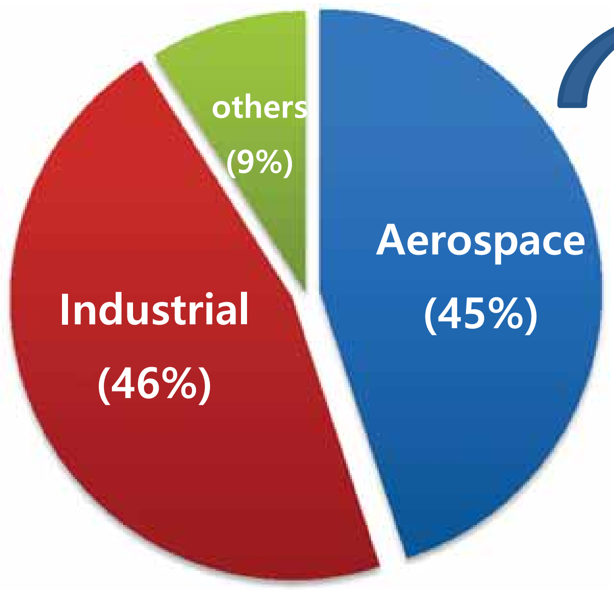
Characteristics of Ti in Aviation Industry

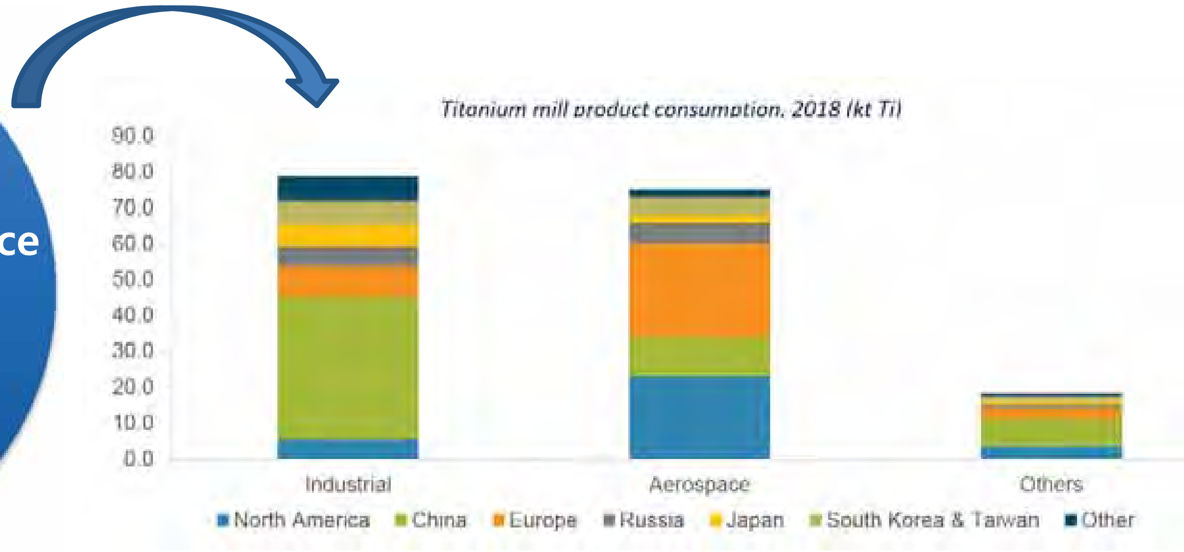
- **References :**

1)Titanium Metal: Global Industry, Markets and Outlook to 2026, Roskill 7th edition
2) Roskill, titanium metal – what will the next decade bring?, Titanium USA 2018, Las Vegas, USA, 2018

Estimated Consumption of Titanium Mill Products

2016 (Total: 149,670ton)



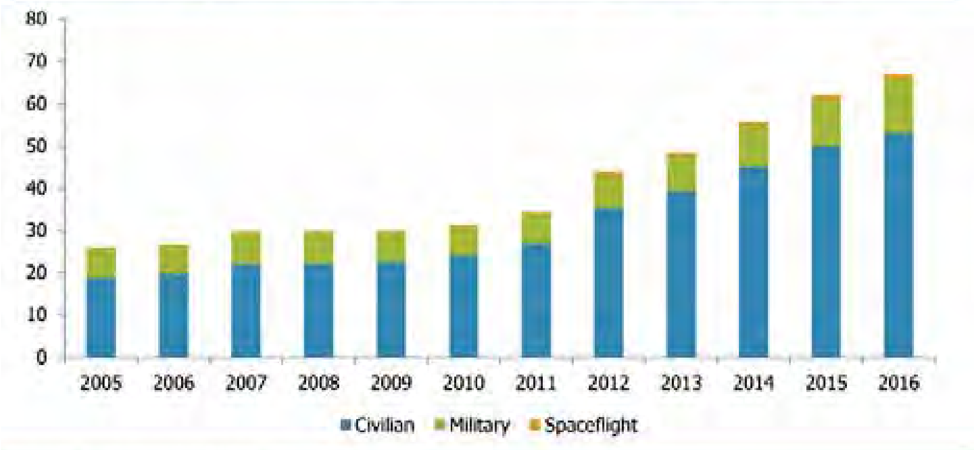


- **Global Titanium Industries : Aerospace(45%)+Industrial(46%)+other(9%)**
  - **Aerospace : The United States(32%) and Europe(35%) account for a large portion.**
  - **Industrial : Exclusive of China(51%)**

Ti Industry and Market Trend for Aviation

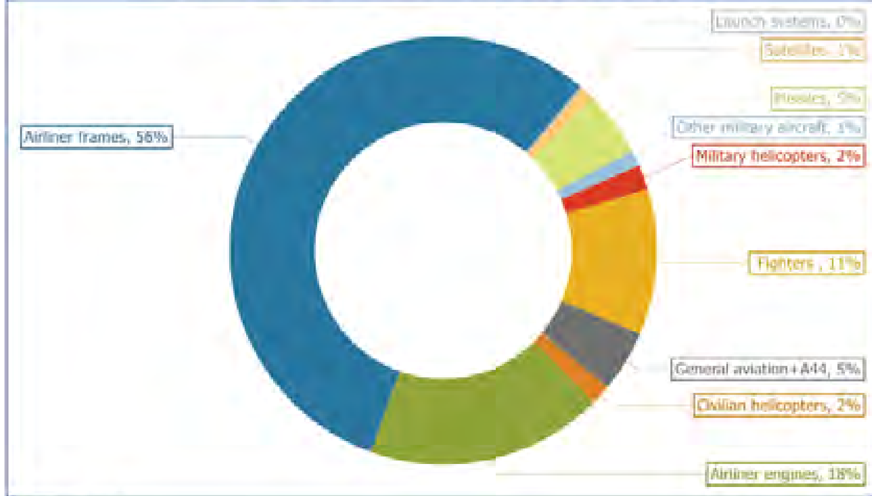
*** ref. : Titanium Metal: Global Industry, Markets and Outlook to 2026, Roskill 7th edition***

Figure A14: Titanium use in aerospace by sector, 2005-2016 (kt)



Source: Roskill aerospace database

Figure A15: Titanium use in aerospace by application, 2016



Source: Roskill

- **Used for aerospace parts over 60,000 tons by 2016**

  → Increase of application amount with increasing aircraft size and carbon composite materials usage

- **In particular, since 2012, demand for Boeing 787, Airbus A380 and A350 has led to a sharp increase in consumption of titanium.**

- **However, the major producers are very few such as VSMPO(RU), ATI(USA), TIMET(USA), RTI(USA)**

Technical Issue of Al and Ti in Aerospace

Aluminum Alloy

- Development of new Al alloy to compete with carbon composite materials (2xxx and 7xxx-series Al alloy are in use.)
  - Development of new alloy and property improvement technology by controlling additive elements such as Li and Sc. (Al-Li alloy)
  - Manufacturing technology of billet and slab by continuous casting process and TMP(thermo-mechanical process) technology

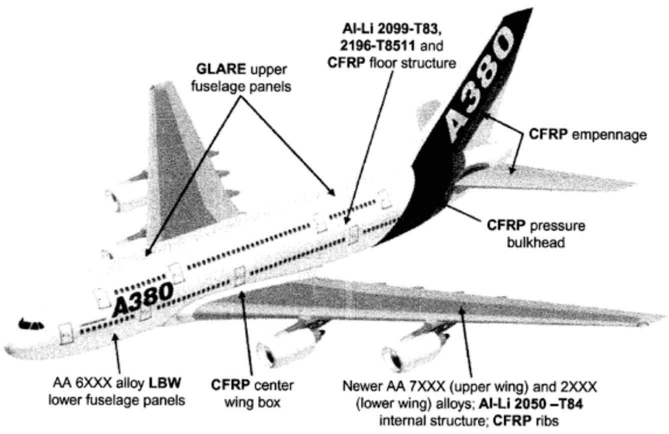
Titanium Alloy

- Activation of Domestic market and reinforcement of export of Ti alloy materials for aircraft
  - Fostering global aviation parts manufacturers by securing manufacturing commercialization technology of Ti alloys aviation parts
  - Manufacturing Technology of High-quality and low cost Ti alloy aviation parts

Al-Li Alloy

- **Al-Li alloys are increasingly used as aircraft materials despite their high price due to their excellent lightweight properties.**
- **Al-Li alloy is a typical metal material that can compete with carbon composites in the future.**
- **Global advanced Al companies have been developing new Al-Li alloys and manufacturing processes for aircraft, and new alloys such as 2099 and 2199 have been reported since 2000.**

<AL alloy applications in A380 >



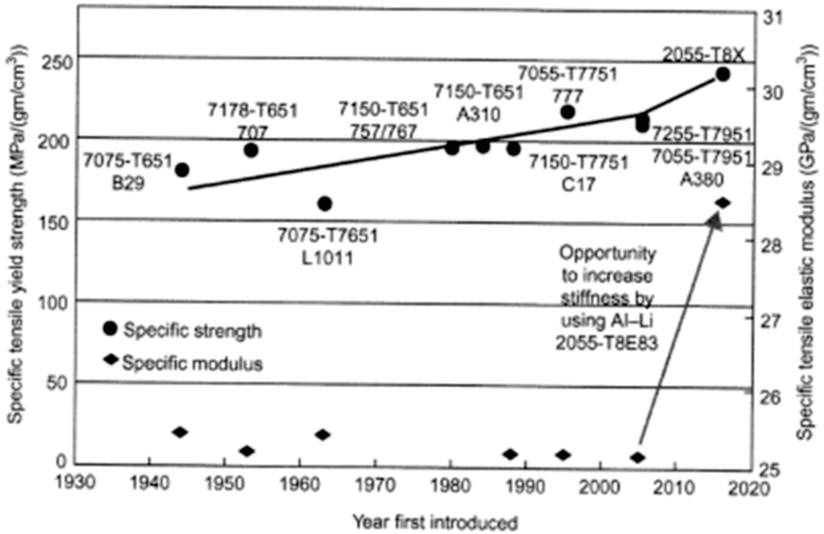
<Aerospace applications of Al alloys>

Company	Applications	Model	Alloy	Application parts
Boeing	warplane	A-5 Vigilante	2020	Wings and horizontal stabalizer
AgustaWestland NV (Westland Helicopters)	warplane	EH-101	8090	Airframe
NASA	Spaceship	Ares I	2195, 2050	Crew launch vehicle - upper stage
Bombardier	Aircraft	CSeries	AirWare I-Form	fuselage
Space X	Launch vehicle	Falcon 9	2198	Second stage rocket
Airbus	Aircraft	A350-XWB	AirWare I-Gauge	Inner wing structure
Airbus	Aircraft	A380-800	2050-T84	Lower wing

Ref.: N. E. Prasad, A. A. Gokhale, and R. J. H. Wanhill, "Aluminum-Lithium Alloys, Processing, Properties, and Applications", Elsevier (2014)

- Due to the reactivity of Li in Al-Li alloy, it is necessary to acquire the specialized melting and casting technologies for Al-Li alloy, and develop the Al-Li alloy and manufacturing method applicable into domestic industrial infrastructure.
- In the future, competition with carbon composites is expected to be even more intense. Therefore, it is necessary to develop the termo-mechanical processing for strength improvement and the ultra-low density alloys.

<Development direction of Al alloy for aircraft>



<Core technologies of Al-Li alloy for aircraft>

Core technologies	◎ New alloy design ◎ Strength improvement technology ◎ Ultra-low density alloy design ◎ Melting and casting technology ◎ Application evaluation of aviation parts

Low cost strategy of Ti alloy

- ✓ **Titanium alloys are being utilized in a limited manner despite their excellent properties.**
- ✓ **Strong affinity with oxygen → very difficult to extract Ti from minerals.**
- ✓ **Poor workability → considerably higher processing costs than other materials**

ITEM	Materials ($/Kg)		
	Steel	Al	α+β Ti
Ore	0.04	0.20	0.44
Metal	0.20	2.20	10.88
Ingot	0.30	2.30	18.14
Sheet / Rod	0.60-1.20	2.00-10.00	30.00-100.00
Part (Aerospace)	- (cold forming)	- (cold forming)	250.00-1000.00 (Hot forming)

Hot working: 1st price rise

Hot working: 2nd price rise

- **Extraction, melting, forming and parts manufacturing processes**
  → Development of high-quality and low-cost process technology

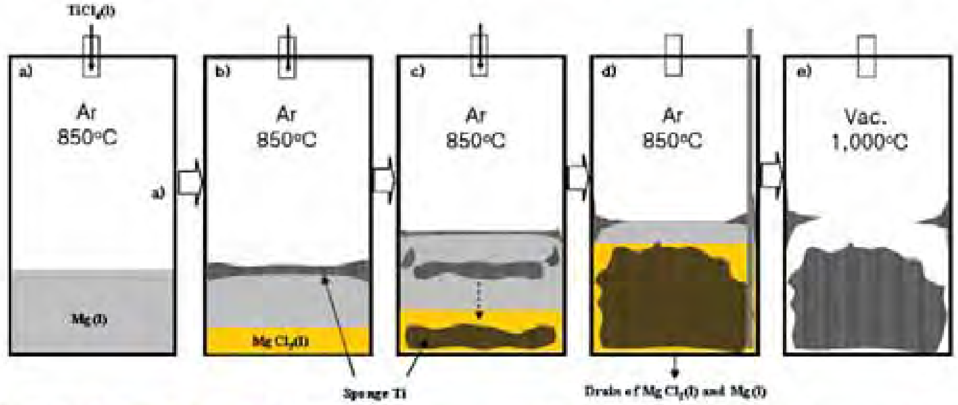
New Extraction Process of Metallic Titanium

Improvement of existing titanium extraction process (Kroll process) and development of new processes

- Mg thermal(Magnesiothermic) reduction of $TiCl_4$

  TiO_2 ore → $TiCl_4 + 2Mg$ → $Ti + 2MgCl_2$

- Hazardous and expensive extraction process (RUS, USA, JPN after 2nd world war)



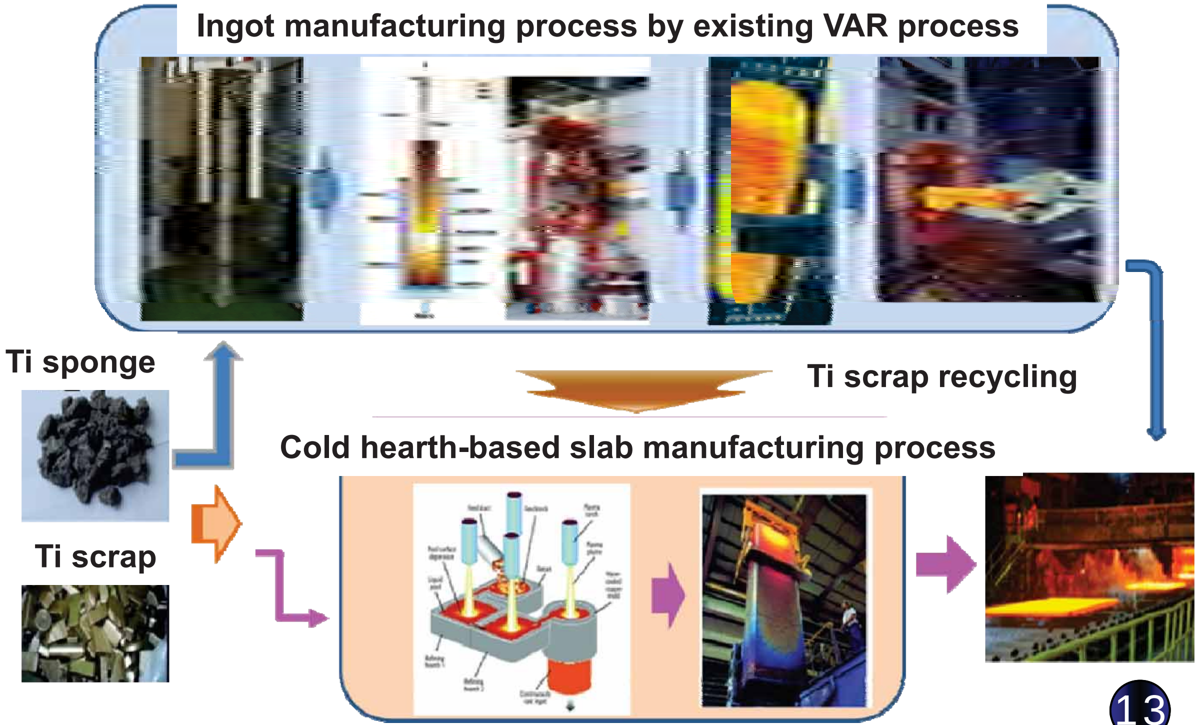
- **New extraction process of metallic titanium**
  → **(Leading country) Developing more than 20 new technologies including Armstrong method.**
  → **(Korea) A low-cost continuous process to replace the Kroll's process**

Development of Ti materials Melting Processes

Ti alloy melting processes (AMS 2380F)

- Grade 1 : Double Consumable Electrode Vacuum Arc Re-melted (VAR)
- Grade 2 : Triple Consumable Electrode Vacuum Arc Re-melted (VAR)
- Grade 3 : Electron Beam Cold Hearth Refined(EBCHR) + Single VAR
- Grade 4 : Plasma Arc Melted Cold Hearth Refined(PAMCHR)+Single VAR

- **VAR melting enterprise**
  (Global) VSMPO(RU), TIMET(US), ATI(US), RTI(US)
  (Domestic) KPCM, HVM, HANSCO
- Currently, cold hearth process for making low-cost and high-quality ingots using titanium scrap is increasing worldwide.
- **EBCHR, PAMCHR**
  (Global) ATI(US)
  (Domestic) HVM



New Ti Alloys Design

Ti Alloys Used for Aviation

- Titanium alloys → airframe, engine parts

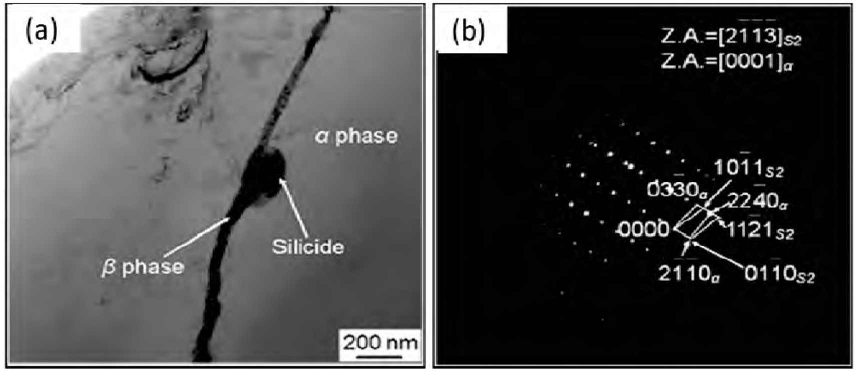
Main Materials	Example of application
Ti-6Al-4V	Cockpit window frame, Wing box, Fastener
Ti-3Al-2.5V	Hydraulic pipe
Ti-10V-2Fe-3Al	Landing gear, Track beam
Ti-6Al-2Sn-4Zr-2Mo	Exhaust, Tail cone
Ti-15V-3Cr-3Sn-3Al	Duct

* Ti-6Al-2Sn-4Zr-6Mo, Beta C, Beta-21S etc.

Development Status of New Ti Alloys

- Currently, the direction of the Ti alloy design for aviation is focused on two categories.
- High temperature Ti alloys: (Previous) Ti-1100(USA), IMI834(UK), TiAl intermetallics
- High Strength Ti alloys:
  - ✓ New Ti alloys design and strengthening of commercial titanium alloys by grain refinement
    → Easy super plastic forming, materials substitution and expansion of applicable parts

Materials : High temperature Ti alloys (KIMS)



$(TiZr)_6 Si_3$ (Ternary elliptical silicide)

database

Alloy development - Composition

➢ *Basic criterion* [1,2]

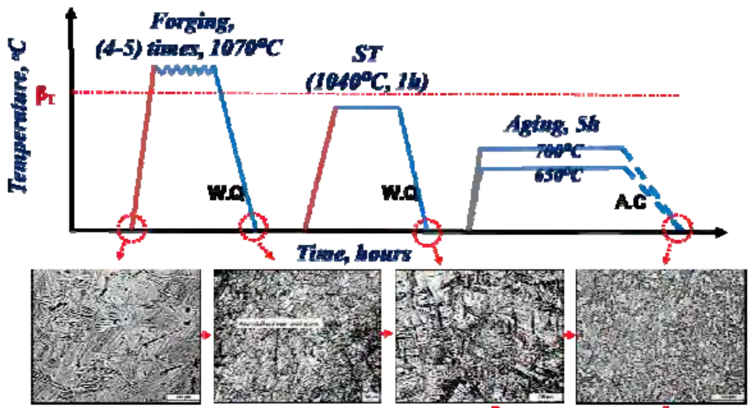
- $[Al]_{eq} = [Al] + 1/6[Zr] + 1/3[Sn] + 10[O] \leq 9$ (Rosenberg Formula)
- $[Mo]_{eq} = [Mo] + 1/5[Ta] + 1/3.6[Nb] + 1/2.5[W] + 1/1.5[V] - 1.25[Cr] + 1.25[Ni] + 1.6[Mn] + 1.7[Co] - 2.5[Fe]$

➢ *Present Alloy*

Al	Sn	Hf	Nb	Mo	Si	B
6.5	3.0	4.0	0.2	0.4	0.4	0.1

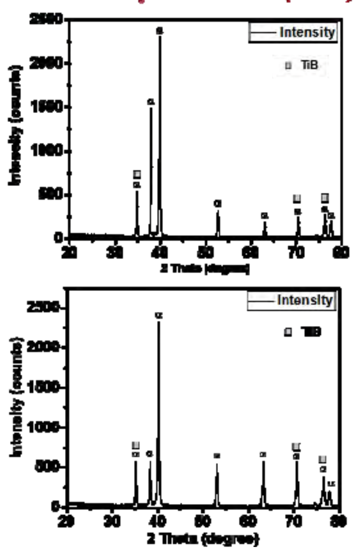
$[Al]_{eq}$: 7.5 *$[Mo]_{eq}$: 0.45*

$(TiZr)_6Si_3$ ➡ ➢ Strength ➢ Ductility

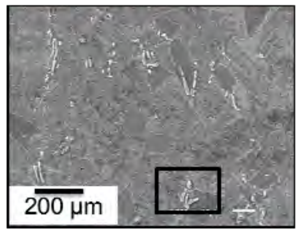


- Grain refinement.
- recrystallized equi-axed grains.
- Duplex microstructures
- Low volume fraction of equi-axed primary α

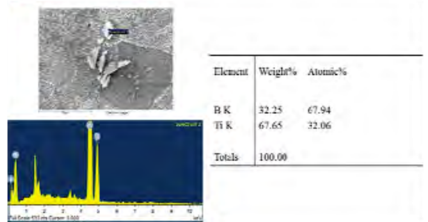
- X-ray diffraction (XRD)



- Scanning electron microscopy (SEM)



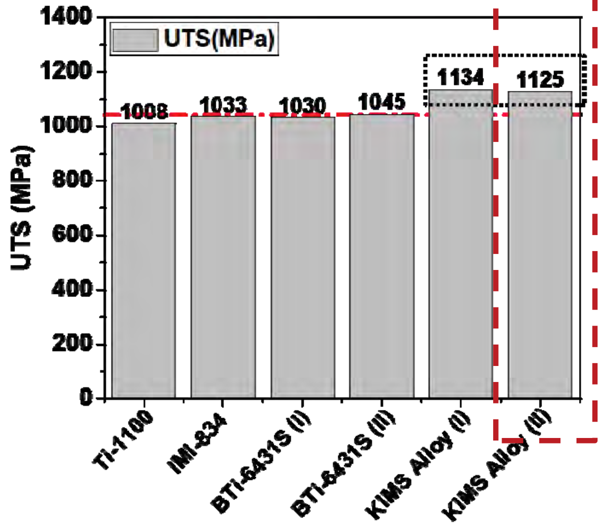
- Energy dispersive spectroscopy (SEM-EDS)



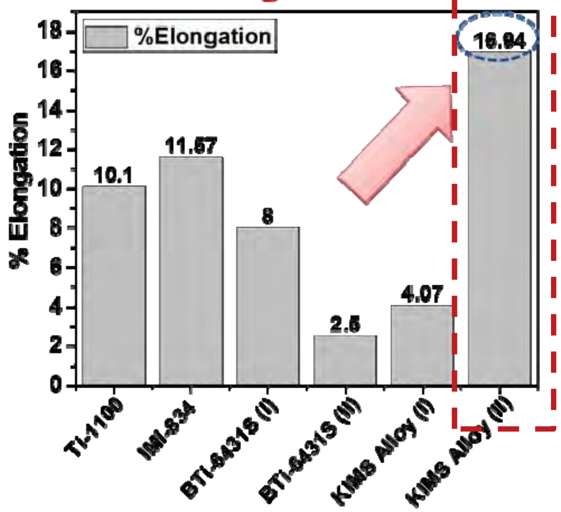
Materials : High temperature Ti alloys

- Room Temperature

➢ UTS

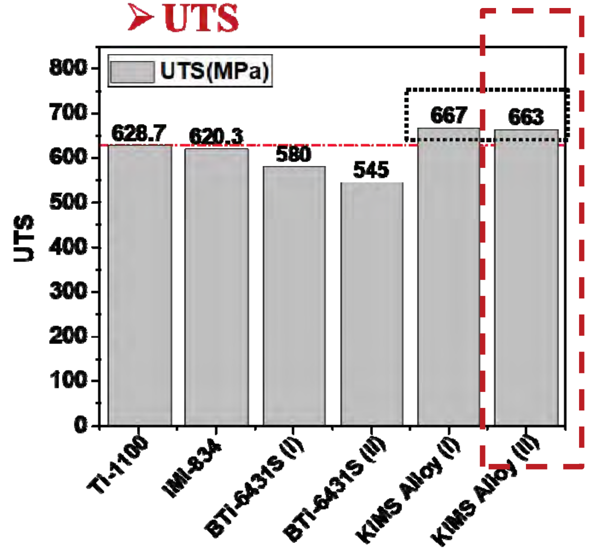


➢ % Elongation

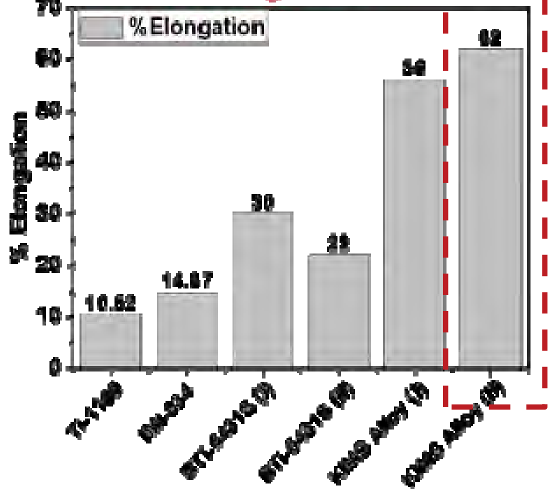


- high Temperature (650°C)

➢ UTS



➢ % Elongation



Materials : Gamma TiAl Intermetallic Alloys(KIMS)

Relatively good RT ductility, Excellent high-temperature oxidation resistance, strength and castability

Ti-44Al-6Nb-2Cr-0.3Si-0.1C (#13) ⟹ Ti-46Al-6Nb-0.5W-0.5Cr-0.3Si-0.1C (#16)

➔ KIMS alloy having excellent oxidation resistance up to 950°C

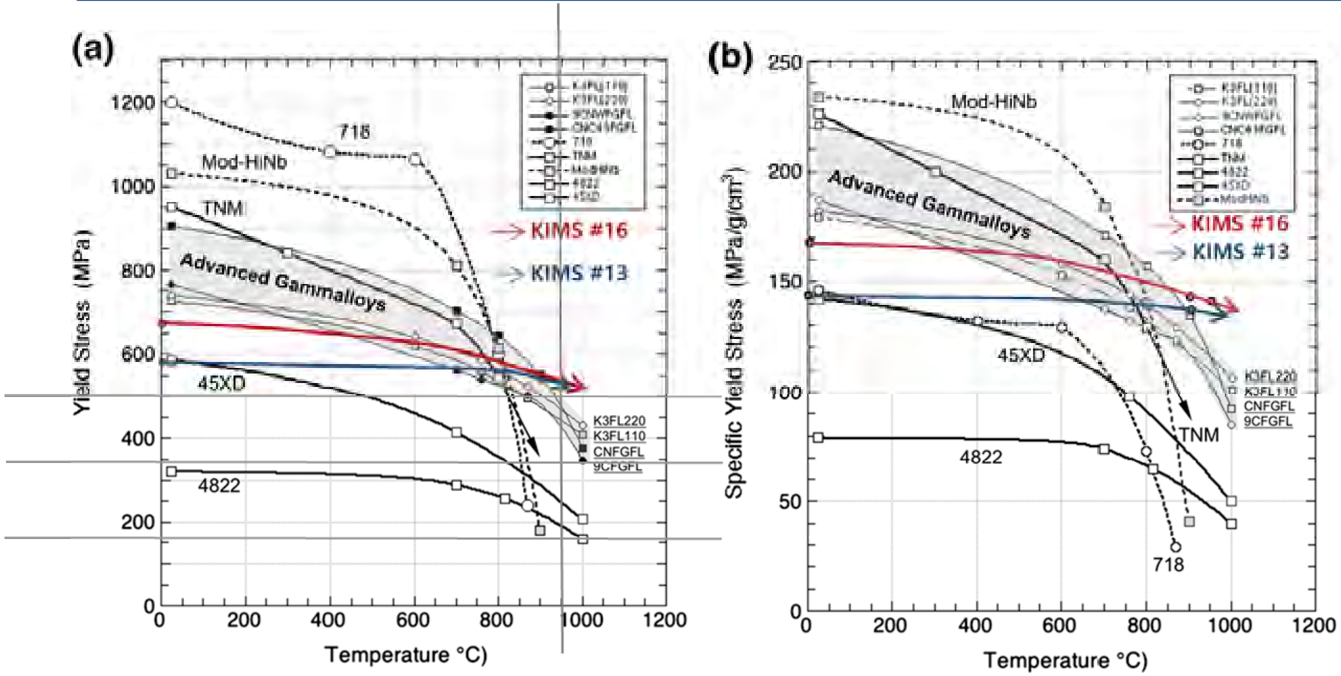
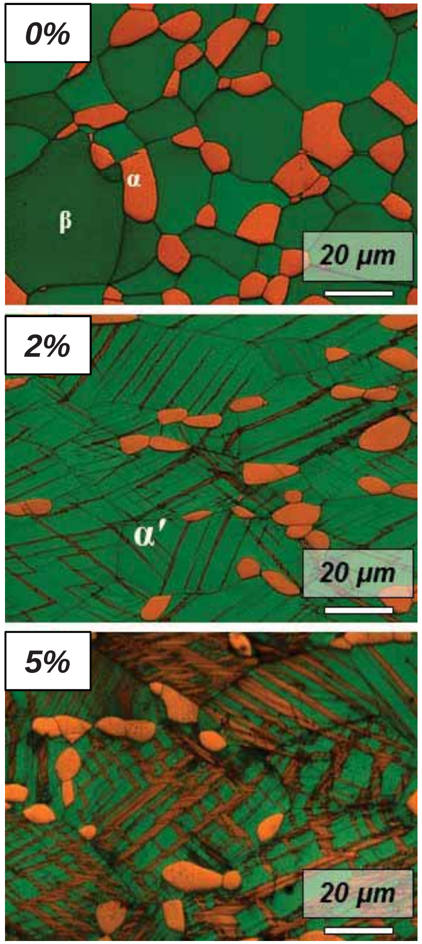


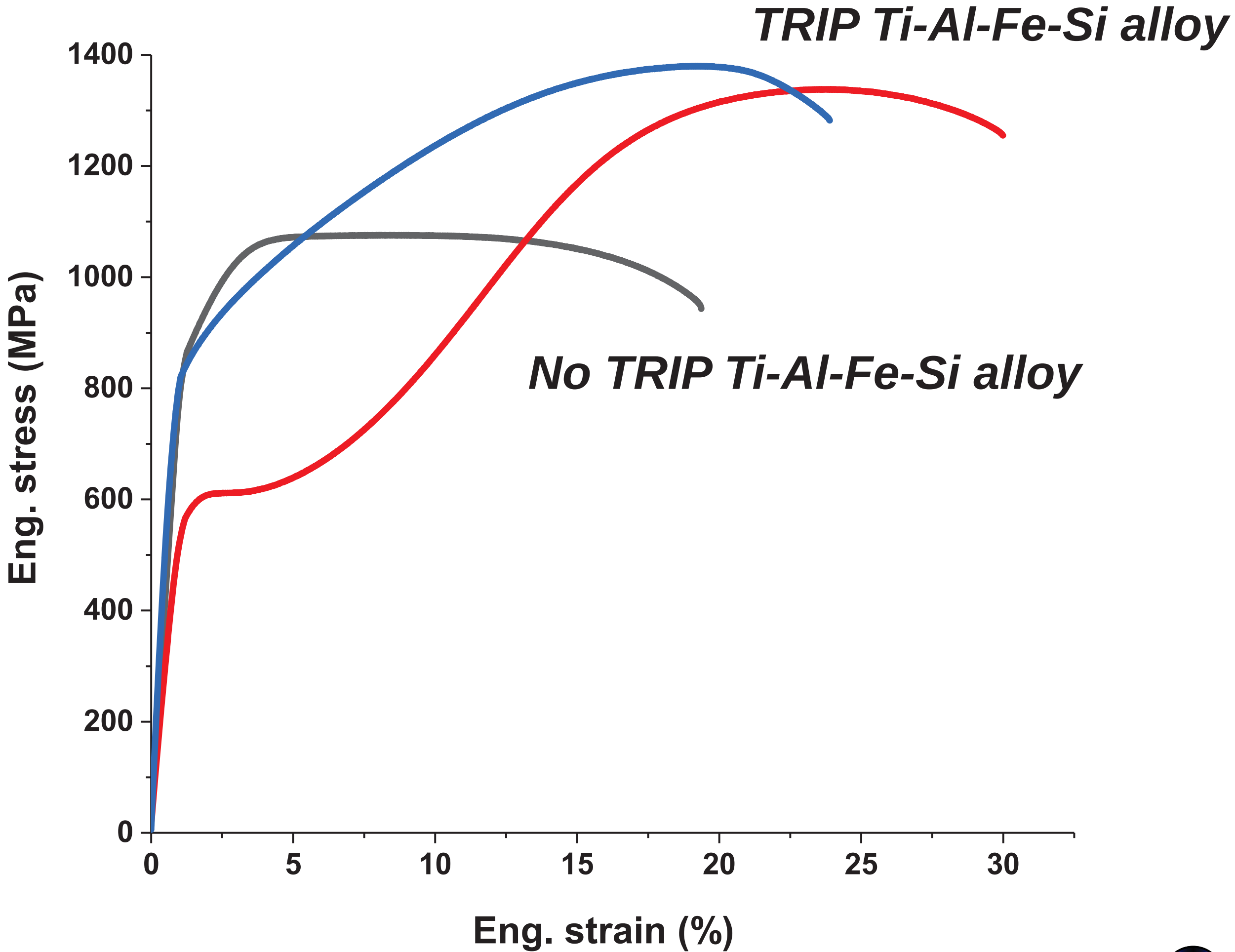
Fig. Yield stress versus temperature (a) and specific YS versus temperature (b) of two advanced alloys (CG alloy K3 and BG alloy 9C) in their specific processing-FL microstructure combinations are compared with those of current engineering **gammalloy materials**, 4822-CDP,3,28 45XDL3 and cast TNM,46 and a modulated high-Nb alloy material, 47 along with wrought superalloy 718 (Gamteck DKI Base, Y-W. Kim, 17.0910).

(ref.) Y. –W. Kim & S. –L. Kim, "Advances in Gammalloy Materials – Process-Application-Technology: Successes, Dilemmas, and Future" JOM (2018)

Materials : TRansformation Induced Plasticity(TRIP) titanium(KIMS)

- *Low cost Ti-Al-Fe-Si alloy*
- *Deformation induced α'-martesnite transformation*
- *High strength and high ductility titanium alloy*

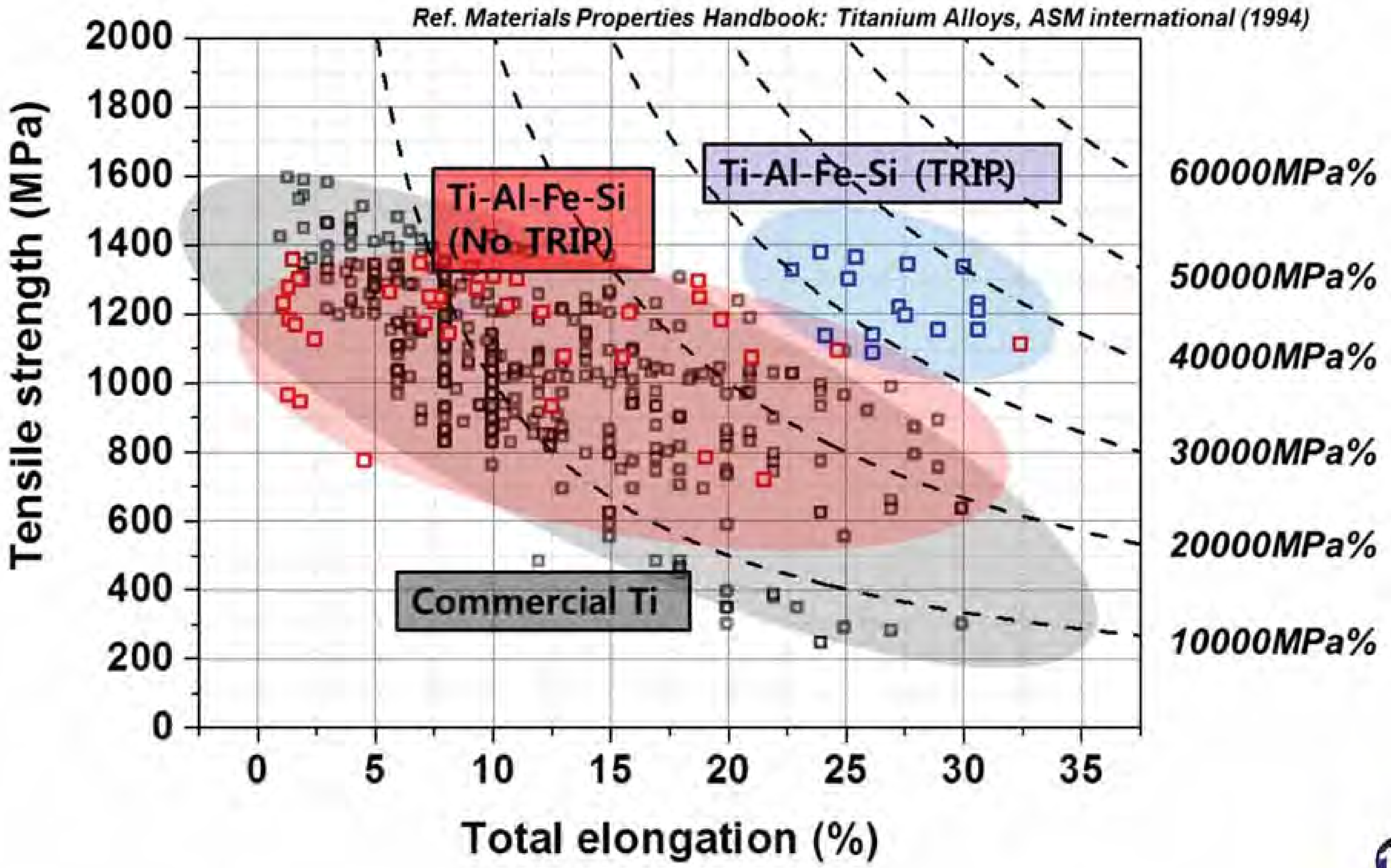




(ref.) S.W. Lee, C.H. Park, J.K. Hong, J.T. Yeom, Sci. Rep. 8(2018), pp.11914-

Materials : TRansformation Induced Plasticity(TRIP) titanium(KIMS)

- *Development of next generation of High strength Titanium alloy*



Material : High strength C.P. titanium (CP-Ti) by Thermo-mechanical process

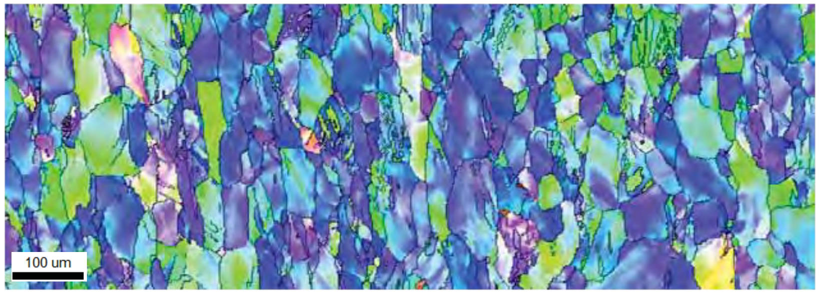
Microstructure control without severe plastic deformation(SPD) :

- ✓ **We are able to improve the strength by controlling the nanostructure of CP-titanium by only thermo-mechanical process without severe plastic deformation.**

Optimization of Twin formation and twin-aided DRV + cold working

[Microstructure of Pure Ti manufactured by TIMET]

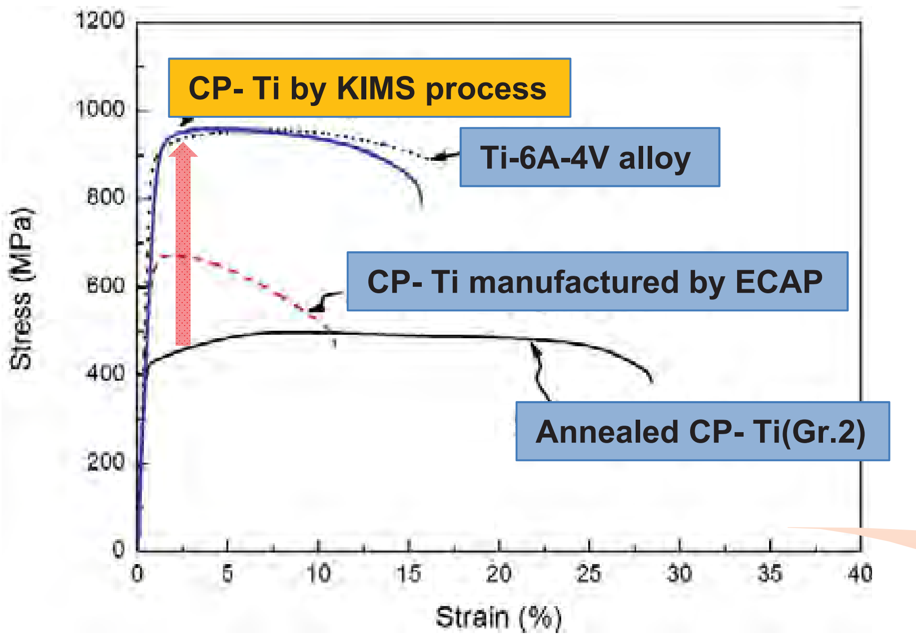
[Microstructure of Pure Ti manufactured by KIMS Process]



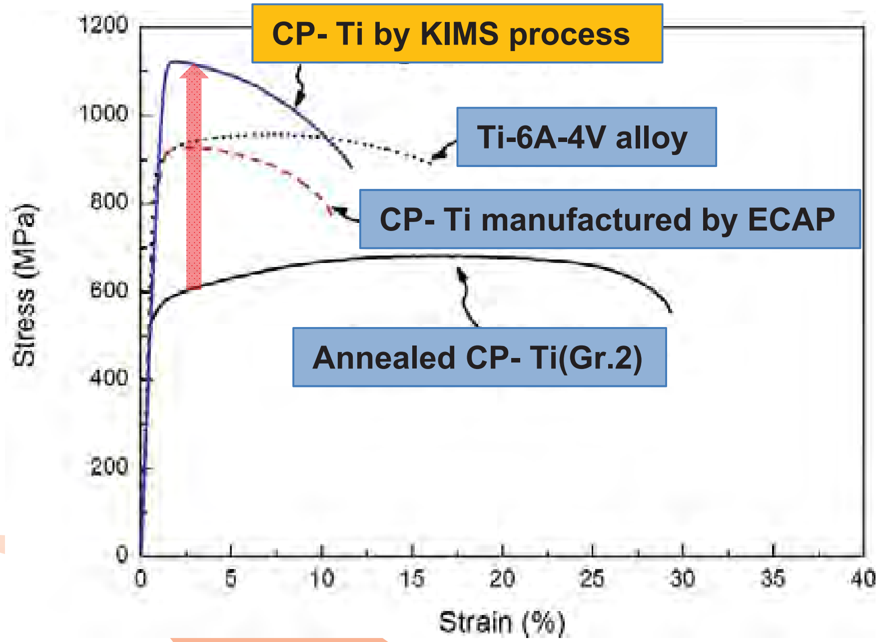
Thermo-Mechanical Processing – CP-Titanium

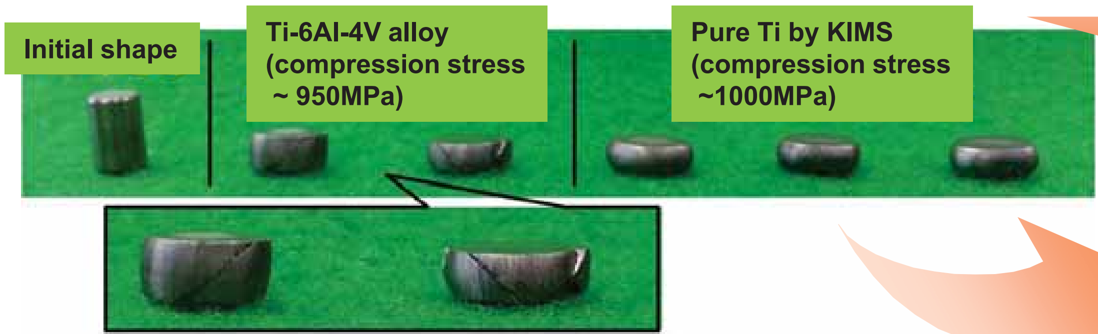
Material : High strength pure titanium (CP-Ti) by Thermo-mechanical process

Gr.2 CP-Ti



Gr.4 CP- Ti





-. Twice Strength
-. Good Formability
(above 70%)

Manufacturing – Forged Parts

Ring and Forged Products of Ti Alloys

Company	Products	Images
Wyman-Gordon, ATI, VSMPO, etc	Wide-body Door Frame (400 lbs, Ti 64), Engine Fan Disk (1,300 lbs, Ti 17), Fighter Bulkhead (5,000 lbs, Ti 64 ELI), Submarine Component (2,000 lbs, CP Ti), Helicopter Main Rotor Hub (800 lbs, Ti 64), Transport Flap Hinge (900 lbs, Ti 64), Armored Vehicle Hatch (250 lbs, Ti 64)	

Fan case forgings

Inner support forgings

- ✓ **Domestic Status : Forged products (Hanwha, KAI etc.) → Machining → Assembling parts**
- ✓ **Domestic companies(Hanwha, KAI) are making efforts to manufacture Ti forgings and ring parts**
- ✓ **Productions : (Military) pivot shaft, spar, front and real bulkhead,**

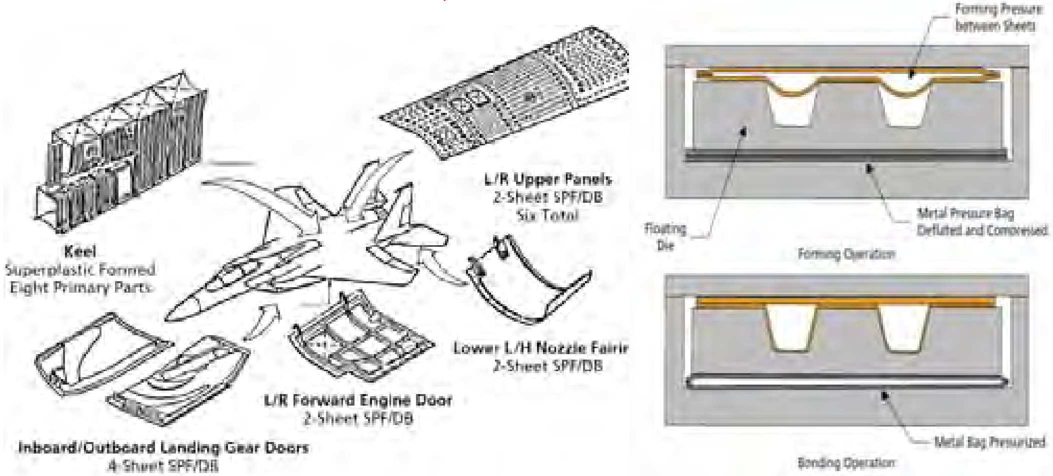
  (Aviation Engine) fan case, Inner support etc.

Manufacturing – Sheet Forming Products

Hot press forming

F-15E Super plastic forming

- Boeing (2006) – over 726 detail part and over 10,000 fasteners.



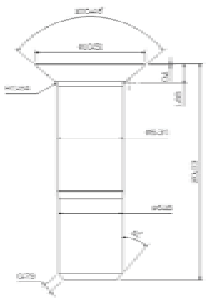
- **Hot press forming** : (Research stage) Manufacturing lines of domestic hot press forming
  - ✓ Domestic status : Imports of Ti alloys sheet products → Parts and inspection → Assembly (Korean Air, KAI etc.)
  - ✓ Aviation products: firewall, system support bracket, frames etc.

- **Super plastic forming** : (Research stage) low temperature and high speed super plastic forming
  - ✓ Domestic status : Research and development in progress
  - ✓ Aviation products: doors, nozzle fairing, panels etc.

Manufacturing – Fasteners

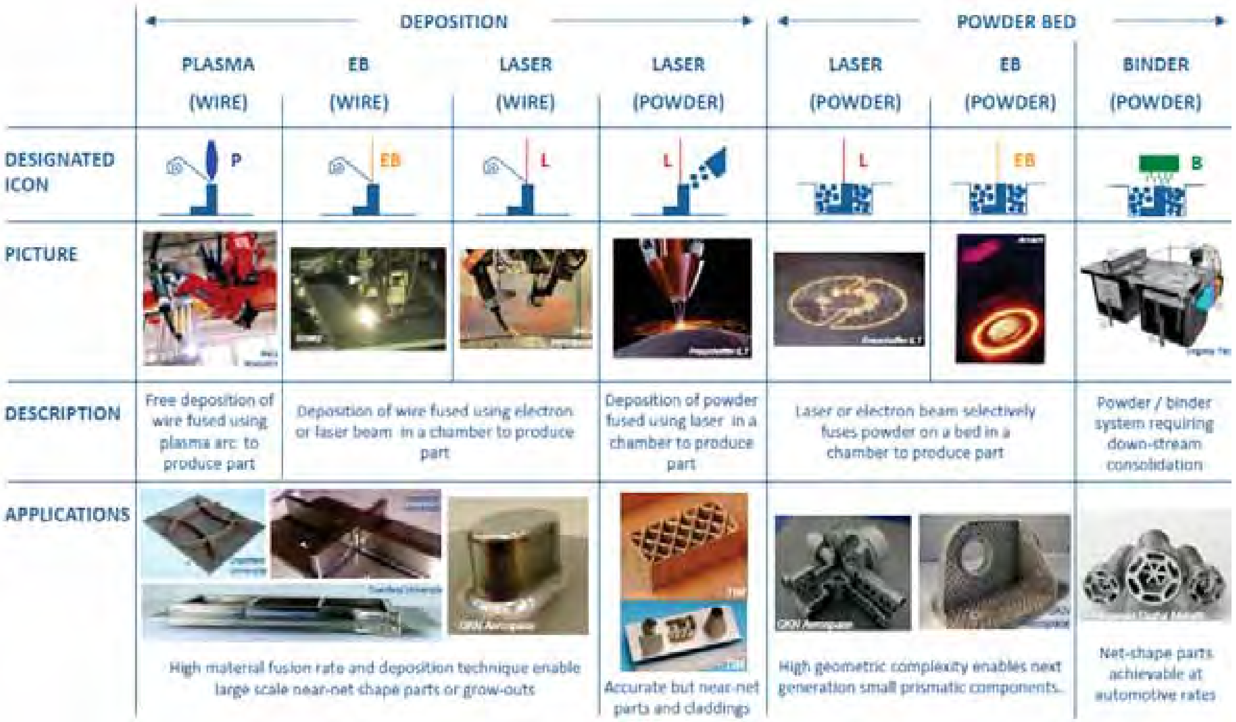
Ti alloys fasteners : Hot former and thread roller

AN Fasteners – Air Force – Navy Aeronautical			
Configuration	**AN Number**	**Description**	**Material**
	NAS 653 – NAS 656	Hex Head Bolt, Close Tolerance	Titanium
	NAS 673 – NAS 678	Hex Head Bolt, Close Tolerance Drilled Head or Drilled Shank	Titanium
	NAS 1083	100° Flush Head Bolt Phillips Recess	Titanium
	NAS 6403 – NAS 6416	Hex Head Bolt	Titanium



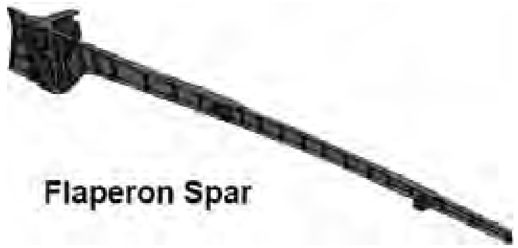
- **Manufacturing of Ti alloys fasteners** **: (Research stage) Focus on aerospace fasteners manufacturing**
  - ✓ **Domestic status : Imports of Ti alloys fasteners → Assembly (Korean Air, KAI etc.)**
  - ✓ **Key payers: Alcoa, Heartland, Precision Fasteners Inc, Precision Castparts Corp.(PCC) etc.**

Manufacturing – 3D printing Products



	DEPOSITION				POWDER BED		
	PLASMA (WIRE)	EB (WIRE)	LASER (WIRE)	LASER (POWDER)	LASER (POWDER)	EB (POWDER)	BINDER (POWDER)
DESIGNATED ICON	P	EB	L	L	L	EB	B
PICTURE							
DESCRIPTION	Free deposition of wire fused using plasma arc to produce part	Deposition of wire fused using electron or laser beam in a chamber to produce part		Deposition of powder fused using laser in a chamber to produce part	Laser or electron beam selectively fuses powder on a bed in a chamber to produce part		Powder / binder system requiring down-stream consolidation
APPLICATIONS	High material fusion rate and deposition technique enable large scale near-net shape parts or grow-outs			Accurate but near-net parts and claddings	High geometric complexity enables next generation small prismatic components.		Net-shape parts achievable at automotive rates

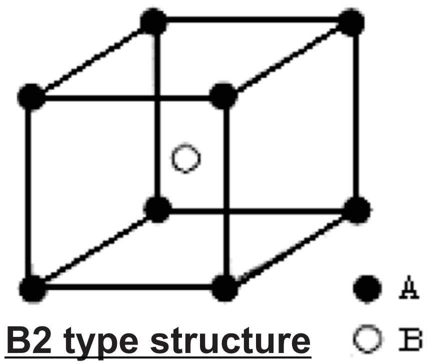
Stator vane



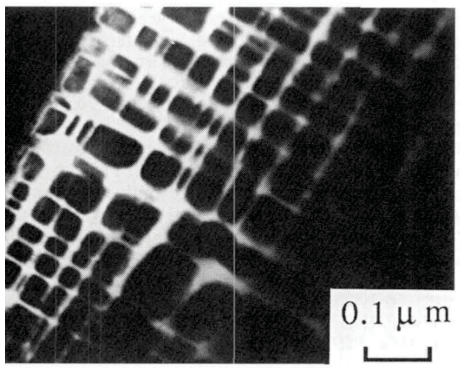
- **3D Printing : The most suitable process for the manufacture of domestic Ti alloy aviation parts**
  - ✓ (Global status) Global GE(General Electric)
    1) FAA approvals of sensor housing(T25), fuel nozzle, etc.
    2) Acquisition of concept Laser and Arcam
    3) Manufacturing of turbine blades and vanes for aviation engines by 3D printing
  - ✓ (Domestic status) Hanwha and KAI are trying to commercialize 3D printing products.
  - ✓ Aviation products : Spars, Root Rib, Stator Vane, etc.

Light-Weight Superalloy

- ✓ Ti-Al-(Mo, Nb, Cr, W, Ta and V) base ternary and quaternary alloys
- ✓ $\beta+\beta_2$ microstructure (B2 phase, $\beta_2(Ti_2AlX)$)



B2 type structure



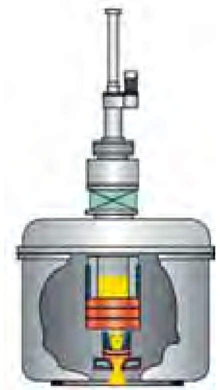
(Fig) TEM dark field image of the two-phase microstructure (B2+A2) in Ti-Ta base alloy

(ref.) S. Naka and T. Khan, Journal of Phase Equilibria Vol.18 No. 6, 1997, pp. 635-649

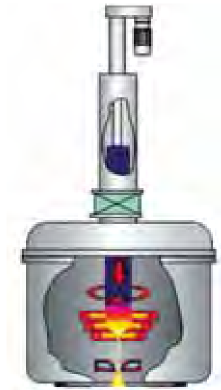
3D printing process and powder making process

- ✓ High-quality titanium alloys powder for 3D printing by VIGA-CC or EIGA
- ✓ 3D printing processes by EBM and SLM
- ✓ Microstructure and properties control
- ✓ Materials : TiAl intermetallics, High-temperature titanium alloys, CP-titanium etc.

VIGA-CC



EIGA



감사합니다

Thank you for your attention