Structural and high-temperature resistant Ti based alloys and compounds for aero application

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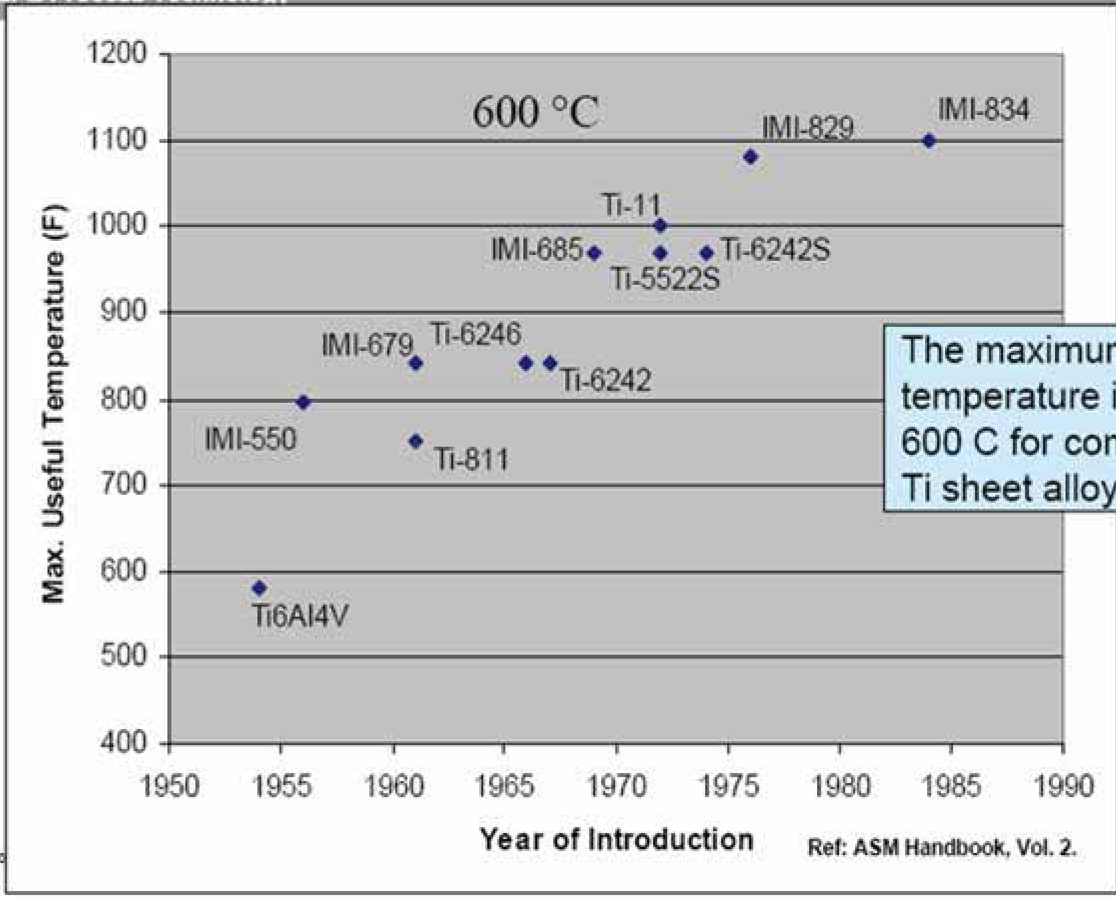
1. **Introduction. Main tendencies in elaboration of new titanium based alloys.**
2. **Ti-Si-X and Ti-B-X phase equilibrium diagrams.**
3. **Titanium "steels" and titanium "cast irons".**
4. **Some possible applications**
5. **Conclusions.**

Maximum Use Temperature for Common Titanium Alloys

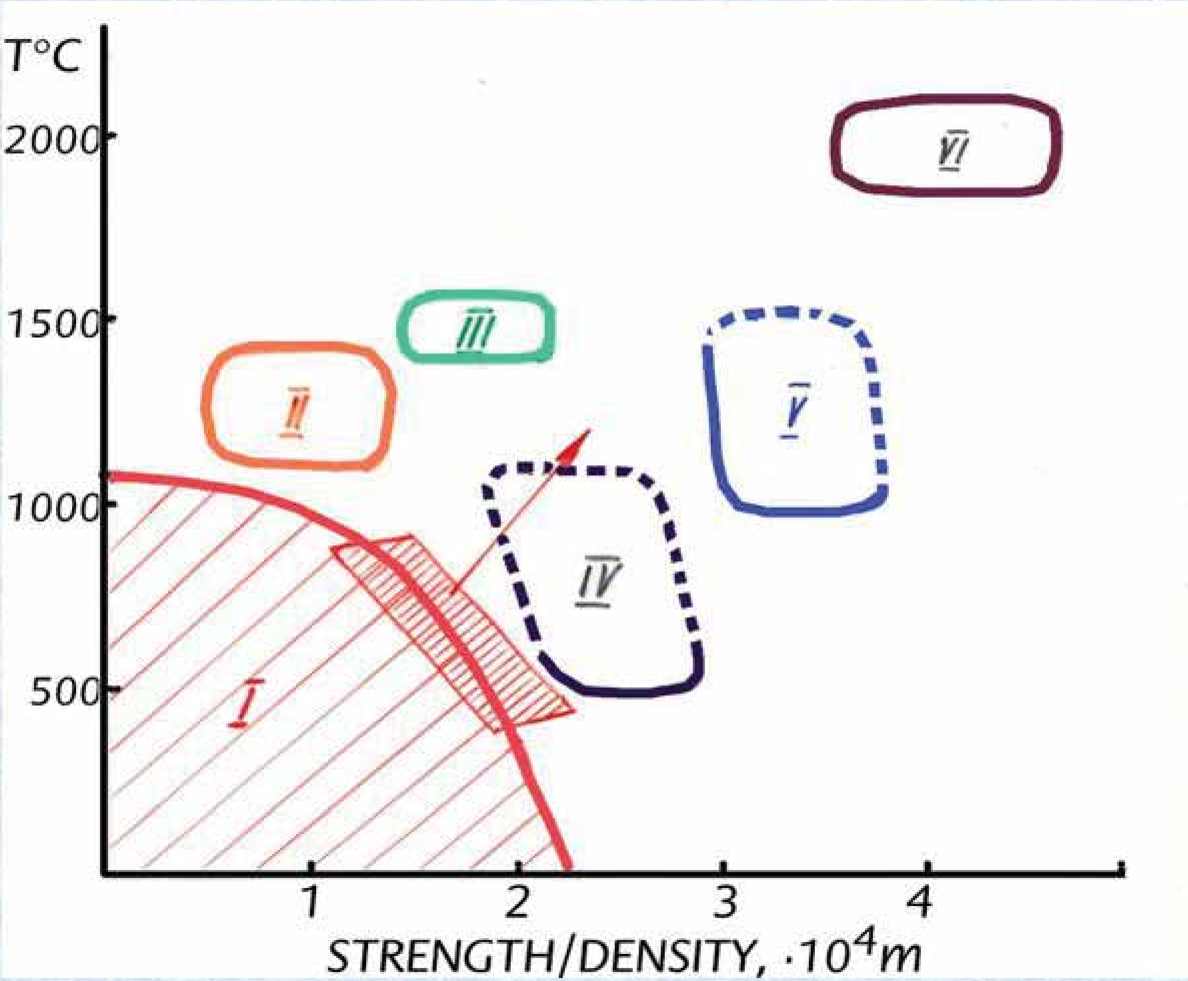
Material & Process Technology



The maximum use temperature is about 600 C for commercial Ti sheet alloys.

777 Heat Shields, Nozzle—Elevated Temperature Strength, Corrosion Resistance

Material & Process Technology



I - Conventional materials, Ti and superalloys

II – Metal matrix composites

III – Ceramics

IV – Intermetallic composites and intermetallic

V – Ceramic composites

VI – Carbon / carbon composites

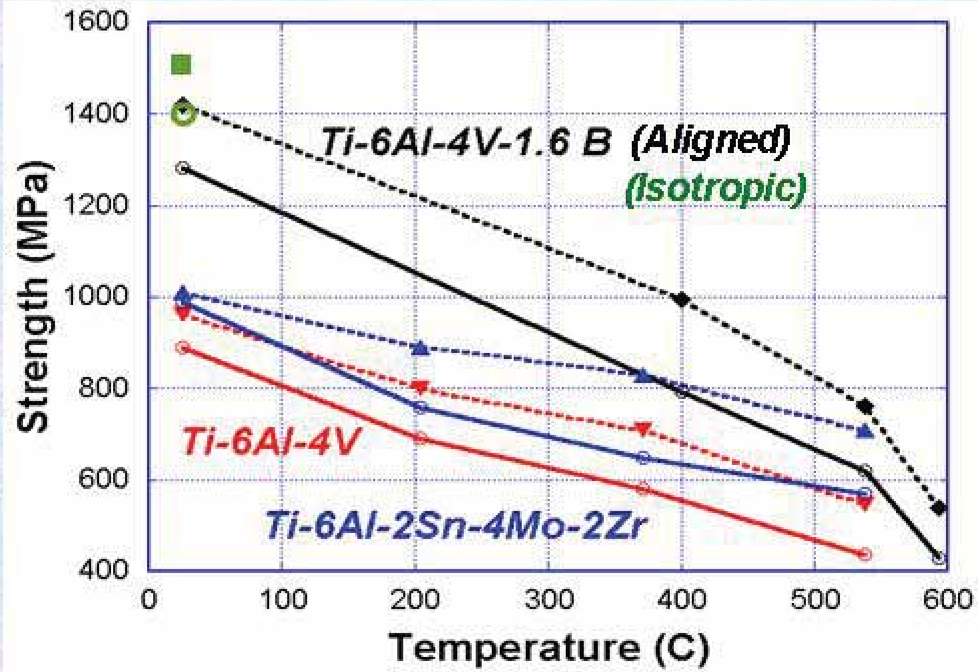
Ti-B MECHANICAL PROPERTIES

Professor Firstov S.A.

Courtesy D. Miracle (AFRL, Dayton, USA)

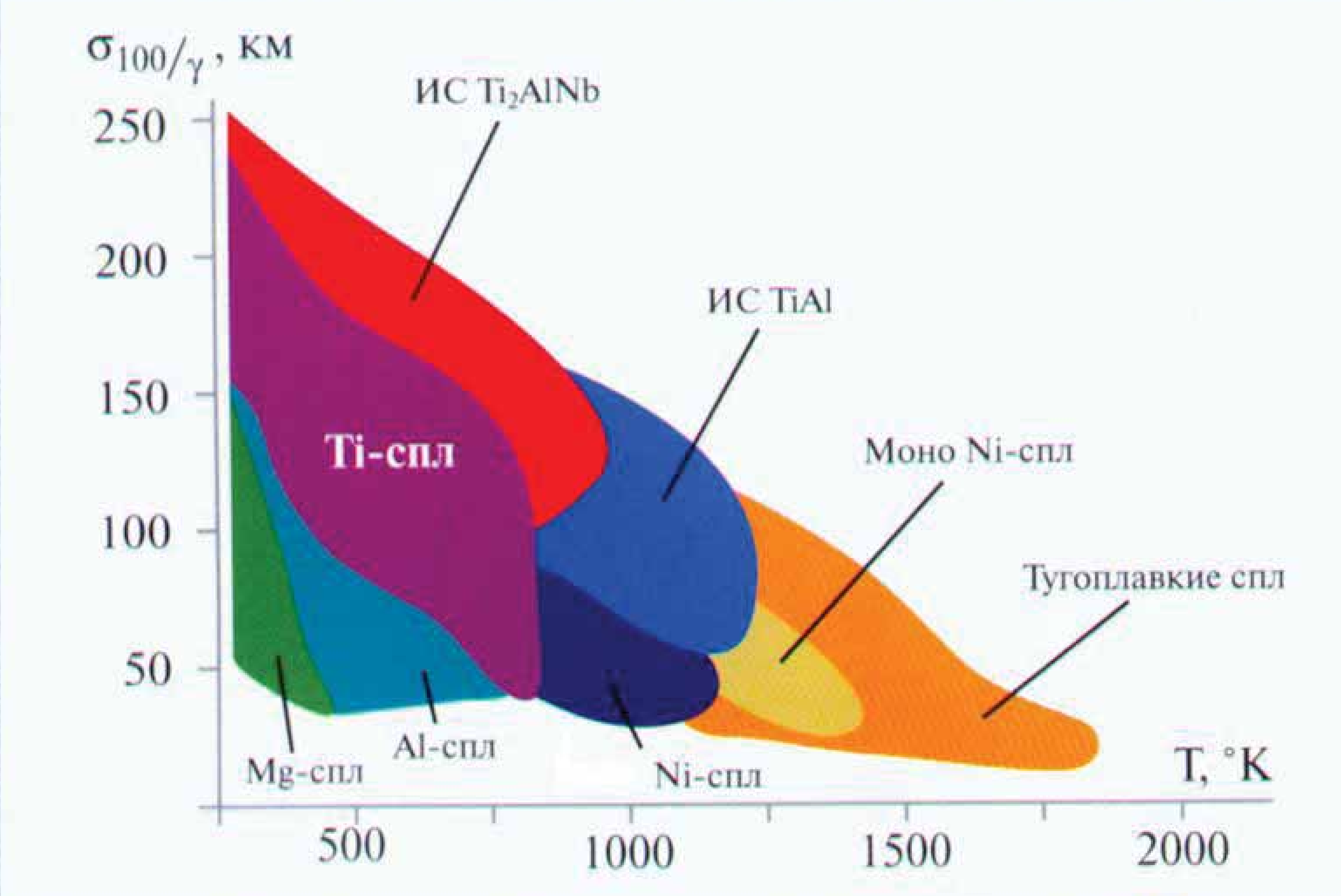
Structural and Functional

✓exceptional specific stiffness, strength
✓widely tailorable properties
✓isotropic or anisotropic properties
  →*alignment of TiB whiskers (1D) provides fiber-like properties*
  →*randomly oriented whiskers (3D) provides isotropic properties*
✓cost comparable to conventional Ti alloys
✓metallic behavior (supportable)



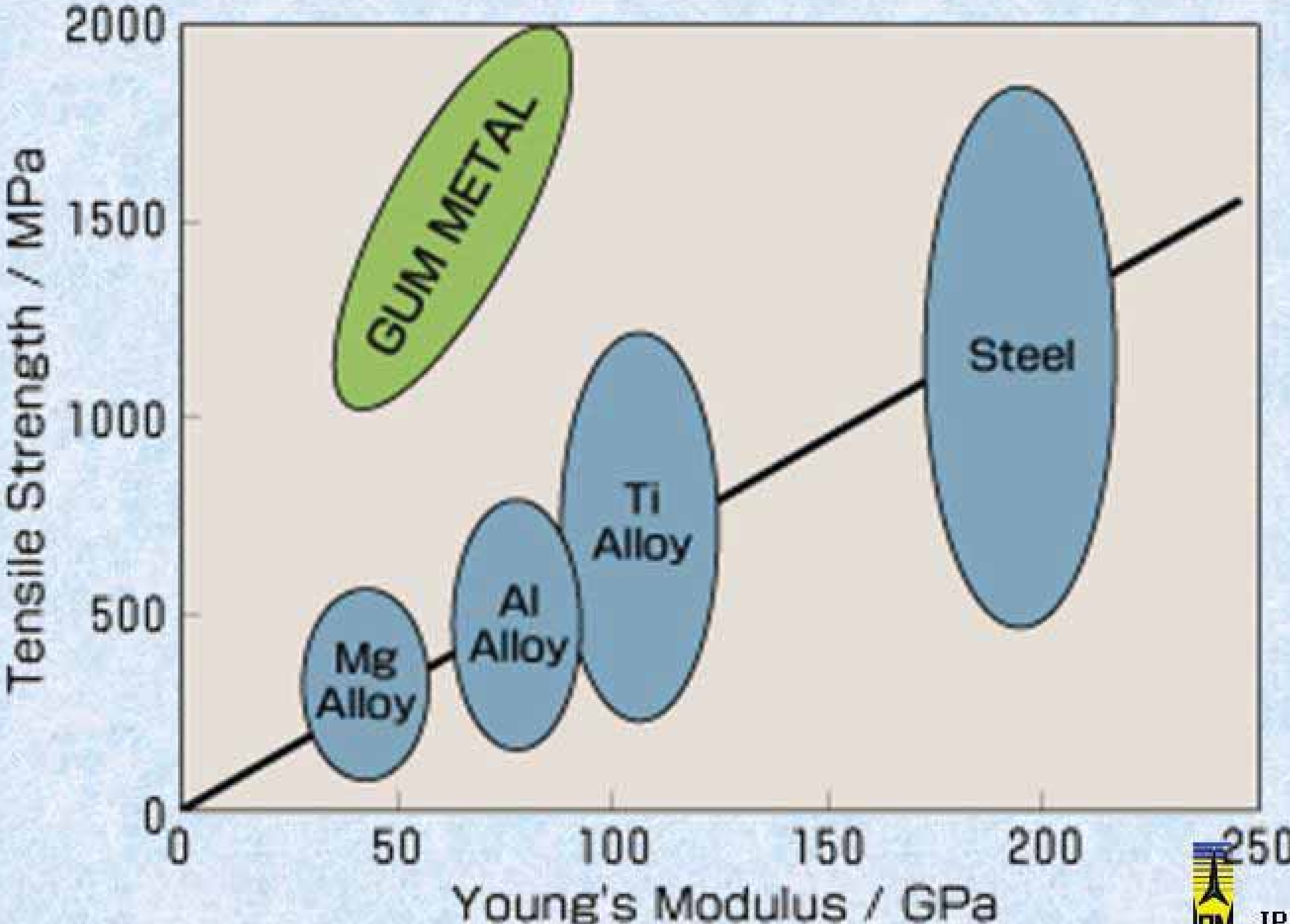
	Ti-6Al-4V	Ti-6Al-4V-0.5B (3% TiB)	Ti-6Al-4Sn-4Zr-1Nb-1Mo-0.2Si-0.8B (5% TiB)	Ti-6Al-4V-1.6B *(3D)* (10% TiB)	Ti-6Al-4V-3.0B *(1D)* (20% TiB)	GOAL
Modulus (GPa)	110-115	125	132	136	200	2X matrix
YS (MPa)	840-1070	1007	1175	1400	1250	1.5X matrix
UTS (MPa)	940-1180			1500	1350	1.5X matrix
Strain (%)	7-20%	9.5	5.0	2.4	2.6	>5%
K_{IC} (MPa.√m)	44 – 110	47		40-55		>50
Fat Str (MPa) (>10^6 cyc)	494-744		675			>1000
T_{max}	427°C/800°F					600°C/1100°F

Application temperature interval of some structural and heat resistant materials

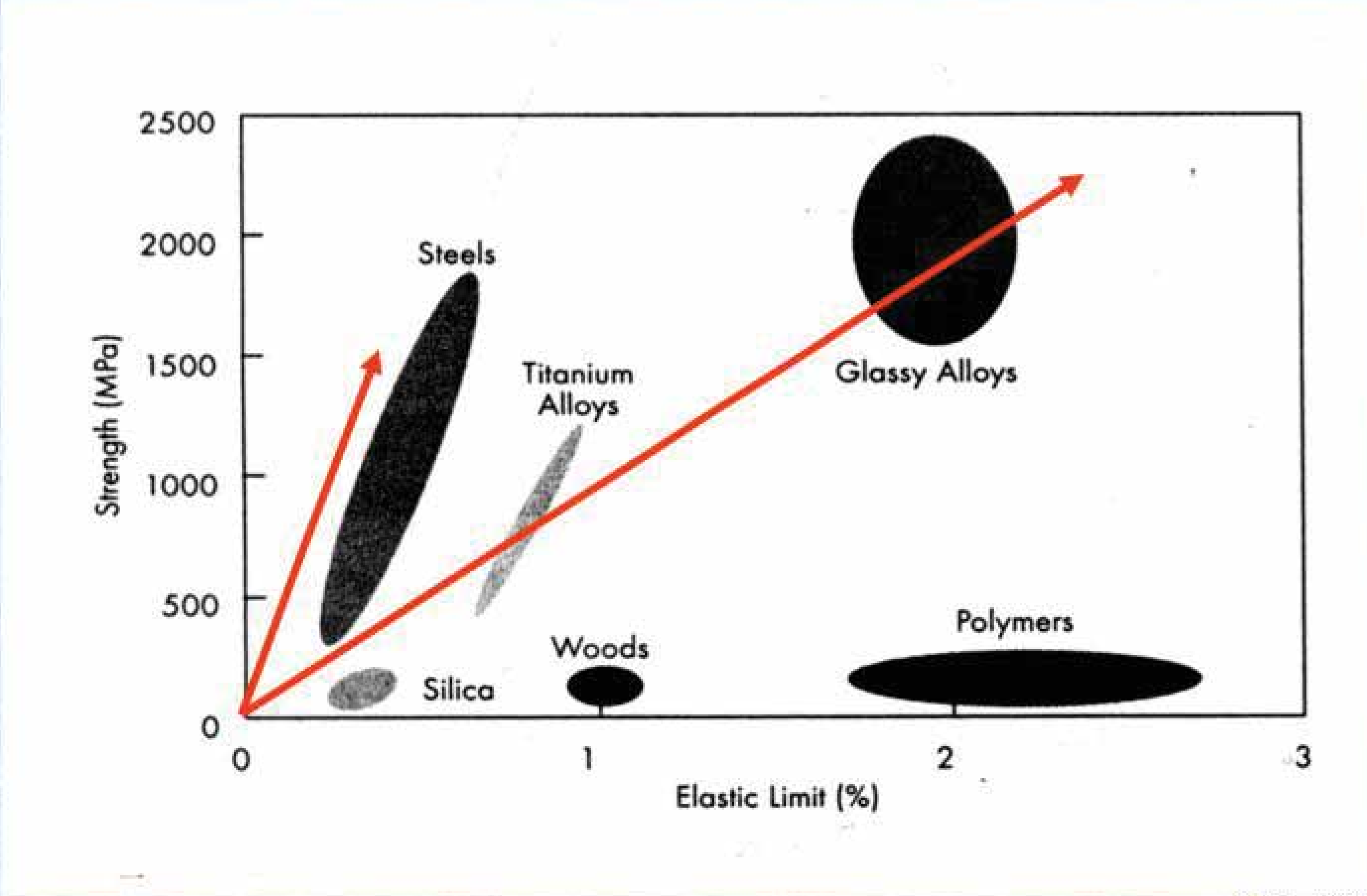


"GUM METAL", Saito,T., et al. 2003

【Fig.1】Position of Young's Modulus and Strength of GUM METAL



Metallic glasses – good combination of strength and stiffness (R.Woodman)



The tendencies in an elaboration Ti –alloys

1. Increased heat resistance and oxidation resistance
2. Increased (and decreased !) stiffness
3. Good RT plasticity and fracture toughness

- **Ti-Si-X, Ti-B-X, Ti-B-Si-X aloys**

  a) Ti "cast irons" (natural composites, eutectics, nanoeutectics)

  b) Ti "steels", thermal and themomechanical treatments

- **Nanostructures, ultimate strength, H/E, H^2/E^3**

B and Si as alloying elements

- Usually content of boron and silicon in Ti-alloys does not exceed 0.1 – 0.4 wt%At such concentrations both element provides a structure modification. Si improves the oxidation resistance.
- High content of Si and B leads to in situ composites produced via eutectic crystallization.

Phase equilibriums

- **Phase and structural compositions of the Ti-Si-X and Ti-B-X systems, where X are Al, Zr, Nb, V, Mo, Ge, Sn etc., which are the base of development of new class of**

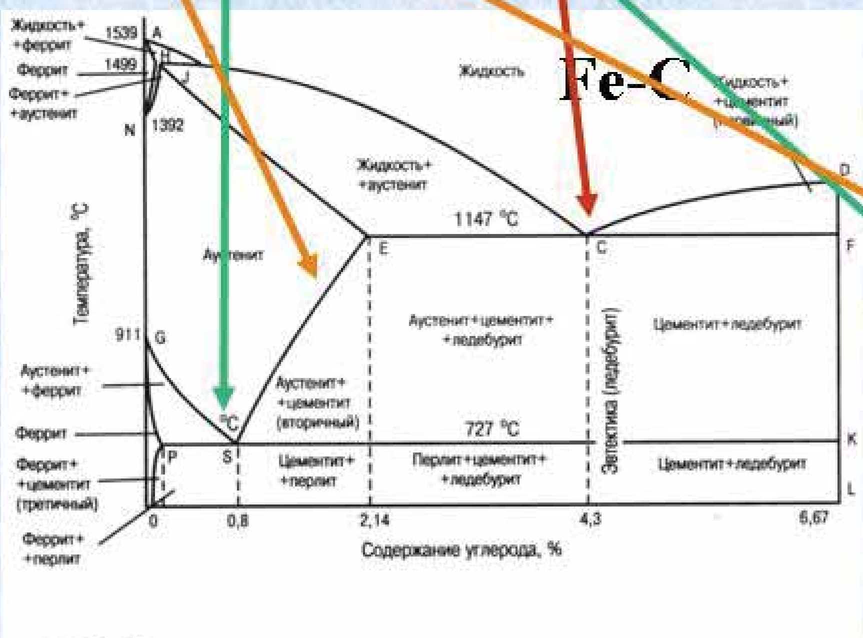
  ***in-situ* composites based on titanium, are studied.**

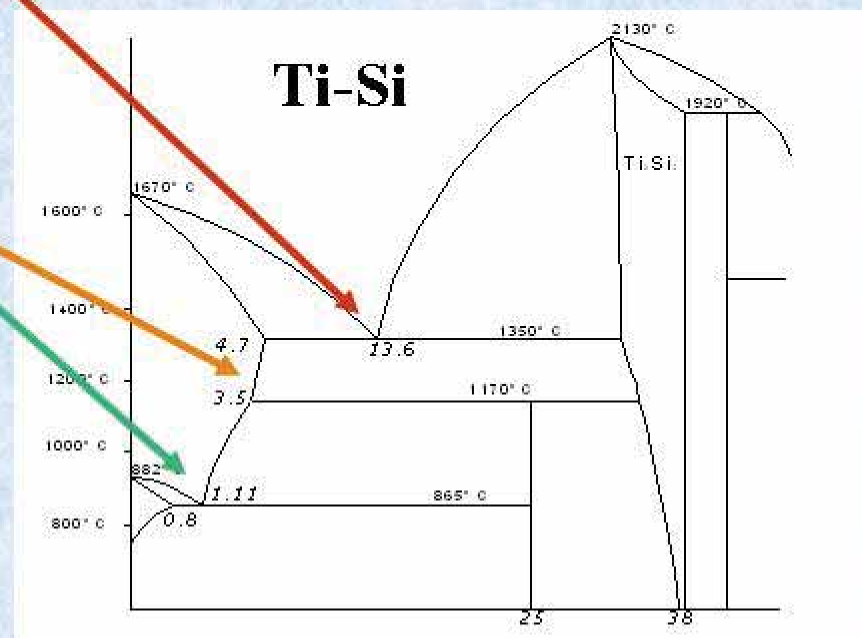
Ti "steels" and Ti "cast irons"

Eutectic

and eutectoid transformations,
martensitic transformations,
limited solubility

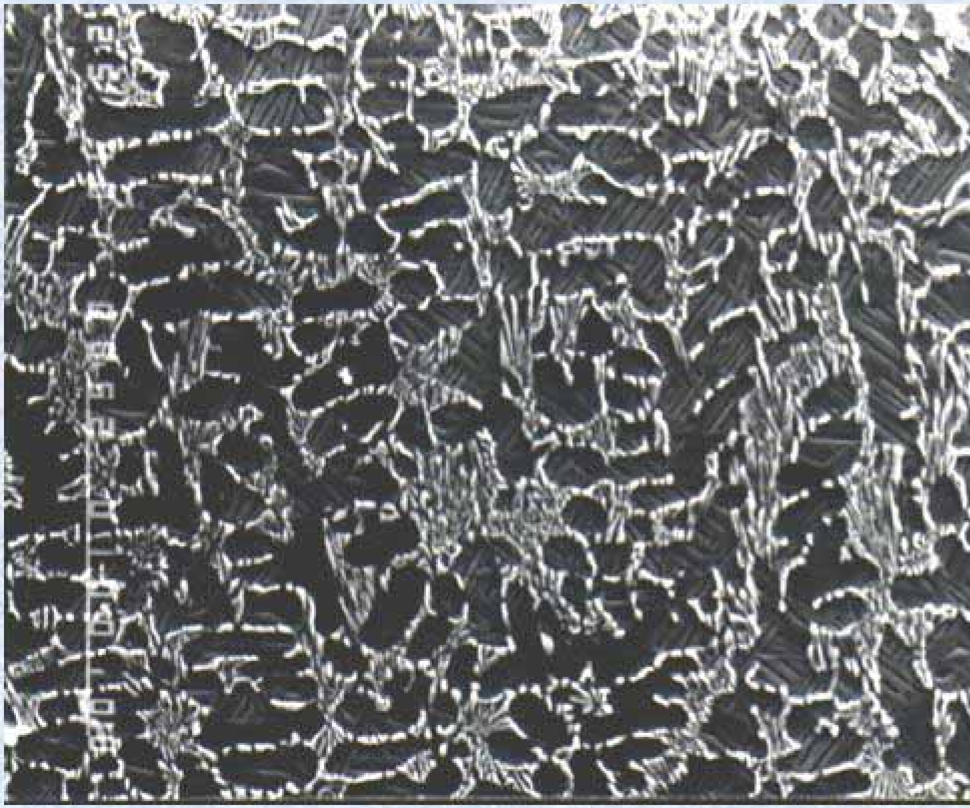
Similarity of Fe-C and Ti-Si diagrams





- “in situ” composites,
- eutectics,
- nanoeutectics

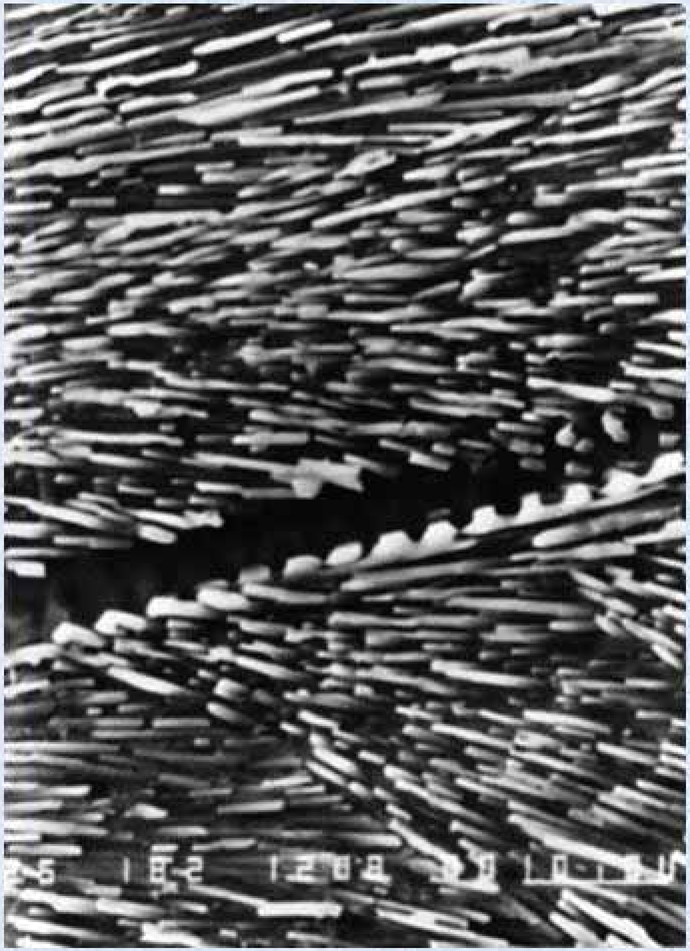
Novel natural metallic composites

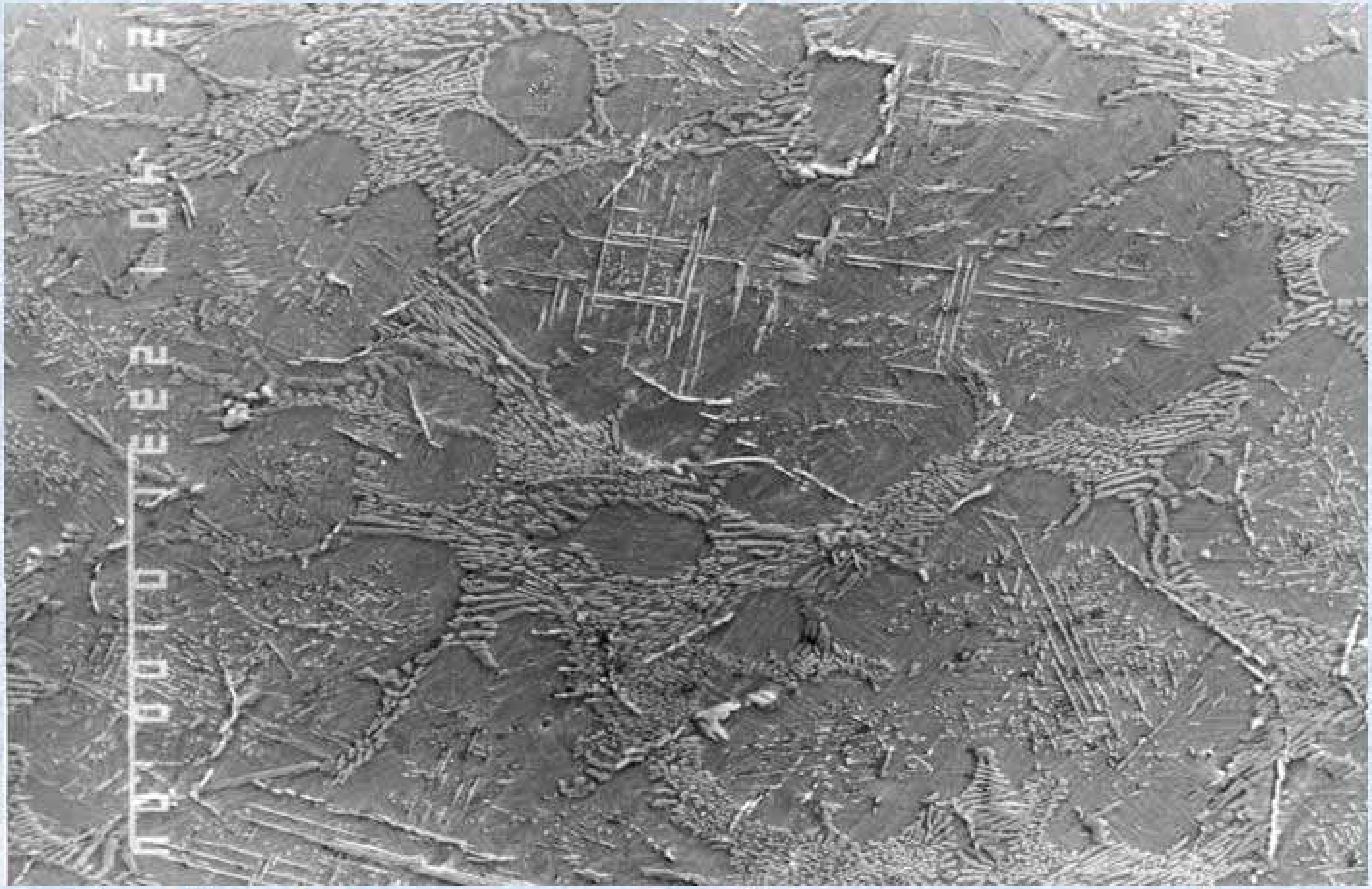


A revolutionary step forward to 700-800°C working temperature (!) in contrast to the best high temperature titanium alloys useful to a maximum of 600°C.

Sam Froes

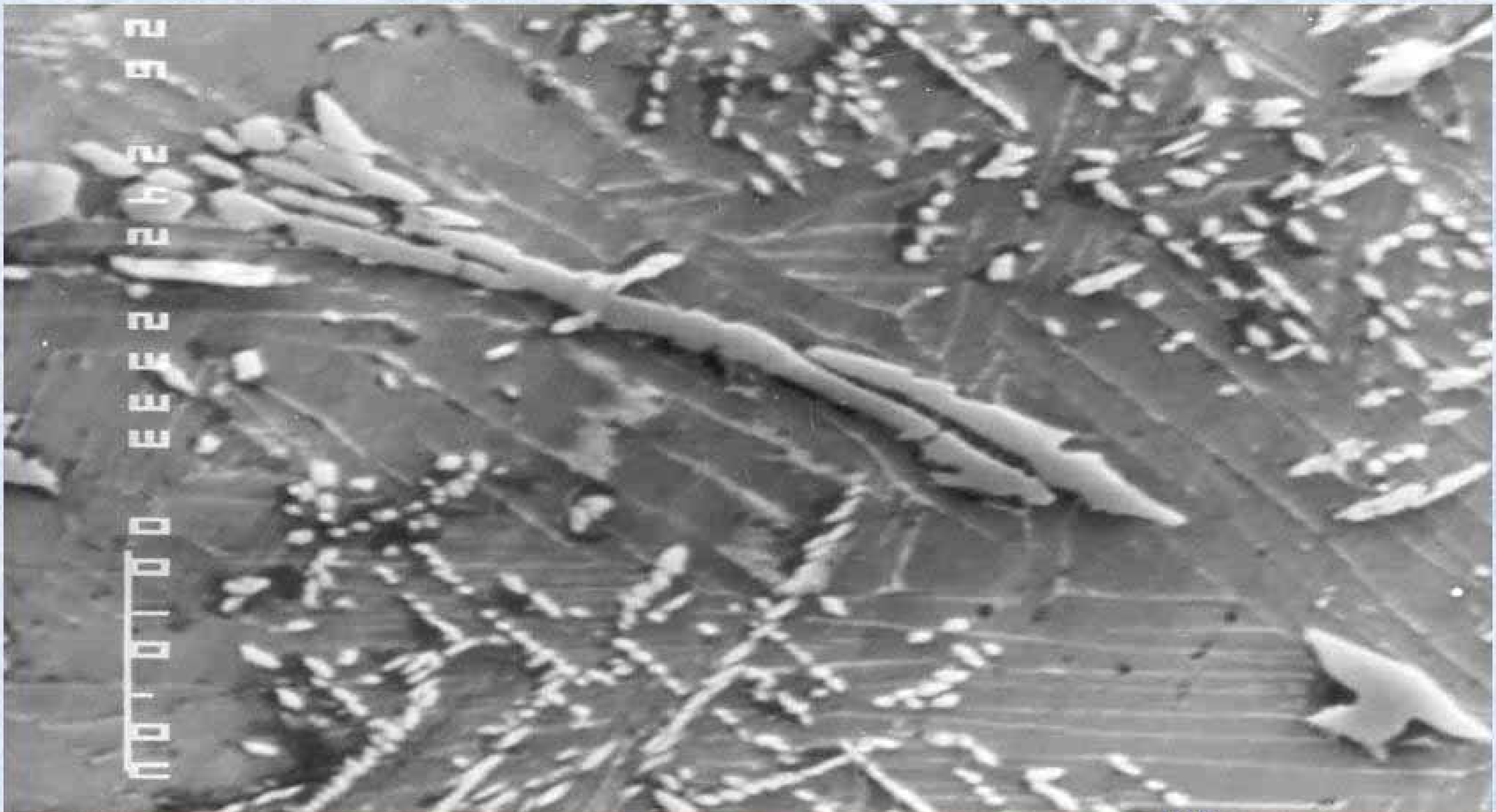
Ti -8,5 Si (wt. %), deep etching



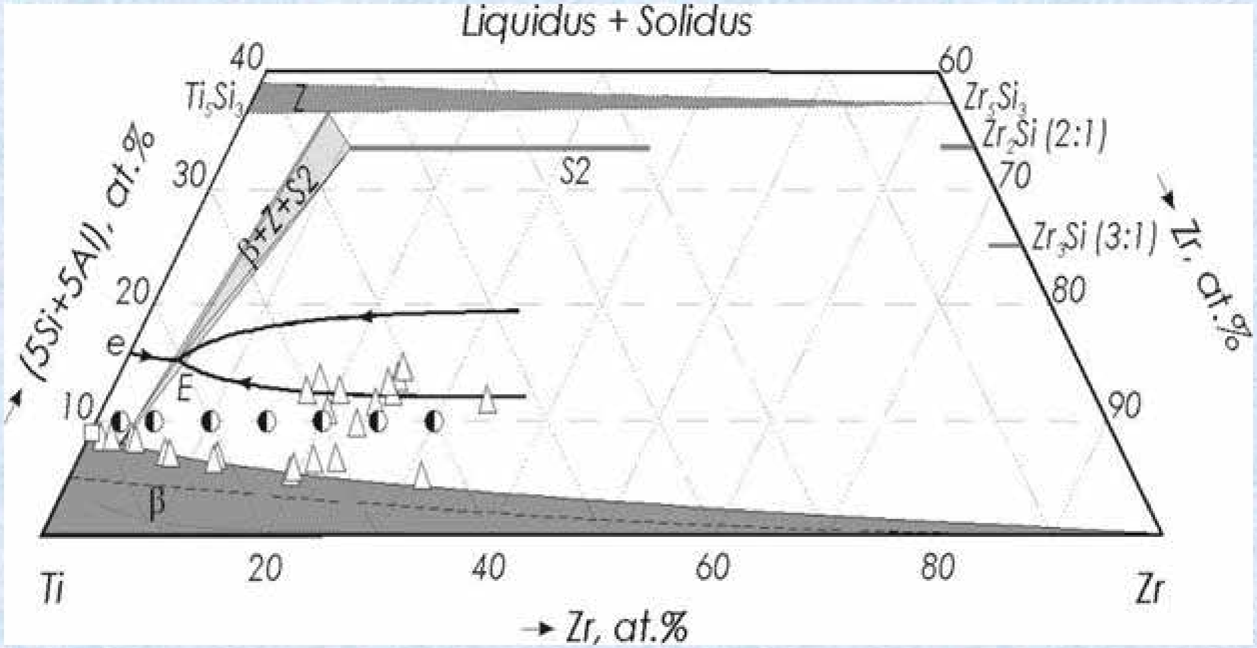


Typical structure of hypoeutectic Ti-Si-X-alloys (O.Senkov)

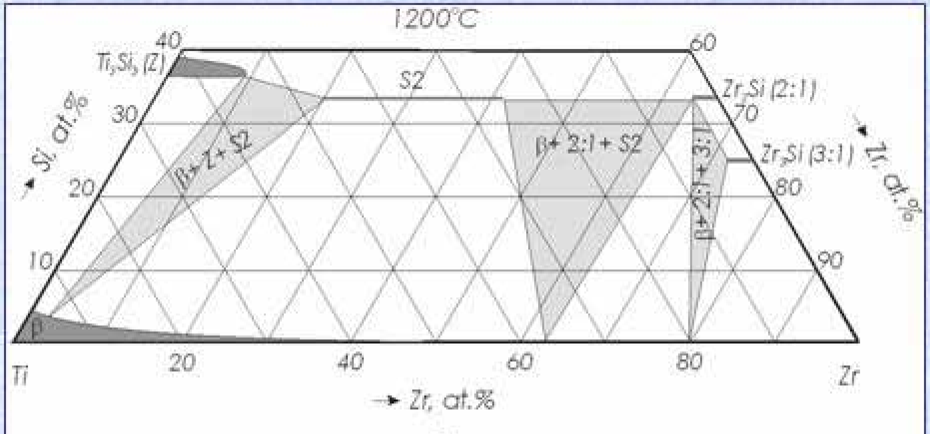
Typical structure of hypoeutectic Ti-Si-X-alloys



Phase equilibriums in Ti-Si-Zr-Al system

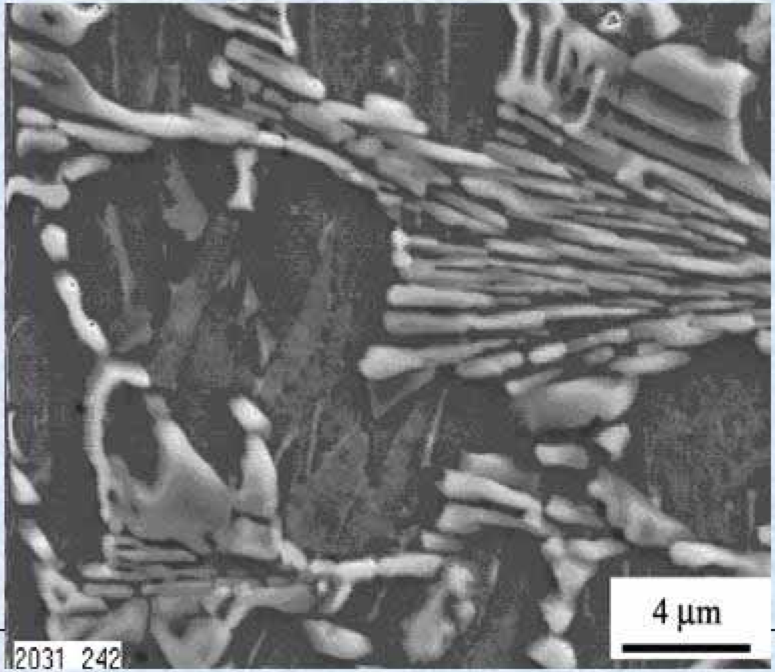


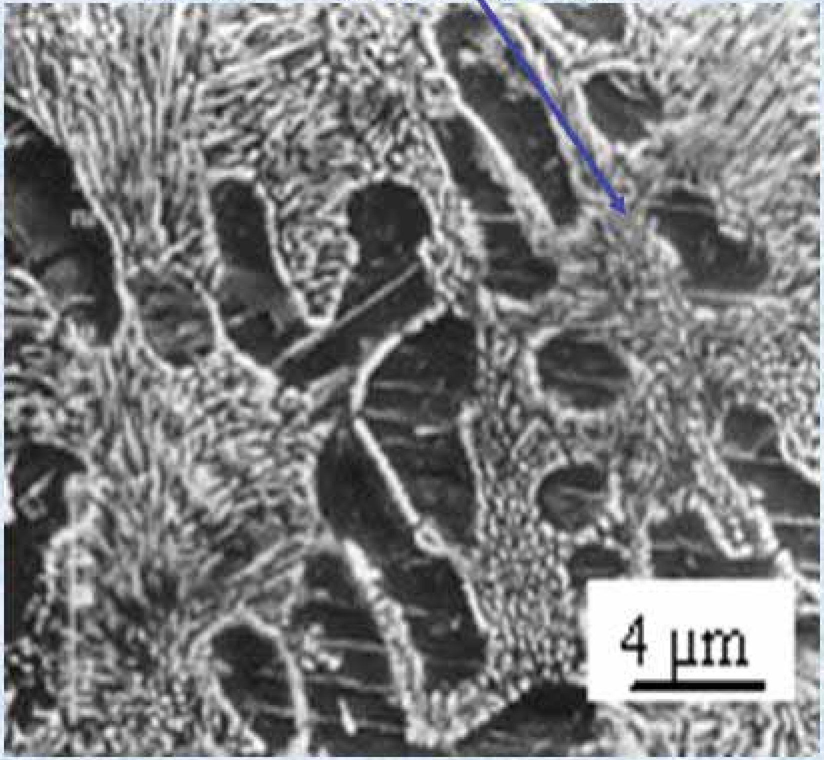
Eutectic alloys Ti-Si-Zr and Ti-Si-Zr-Al,



Salpadoru N.H., Flower H.M., 1995

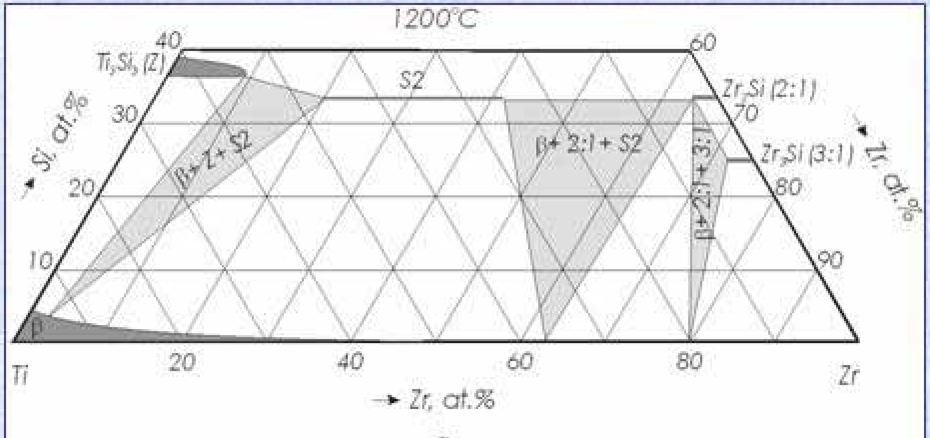
α-Ti + (Ti, Zr)$_2$Si





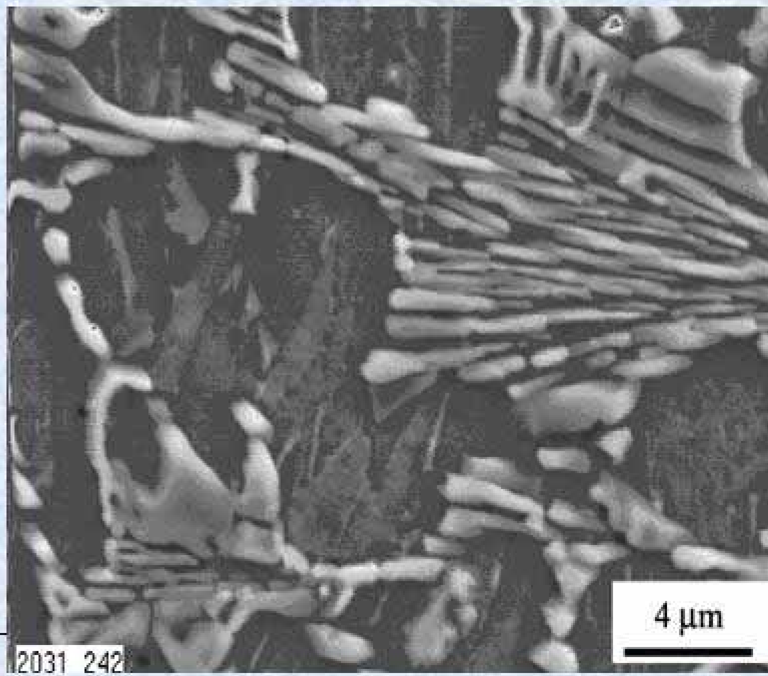
Eutectic alloys Ti-Si-Zr and Ti-Si-Zr-Al,

Professor Firstov S.A.

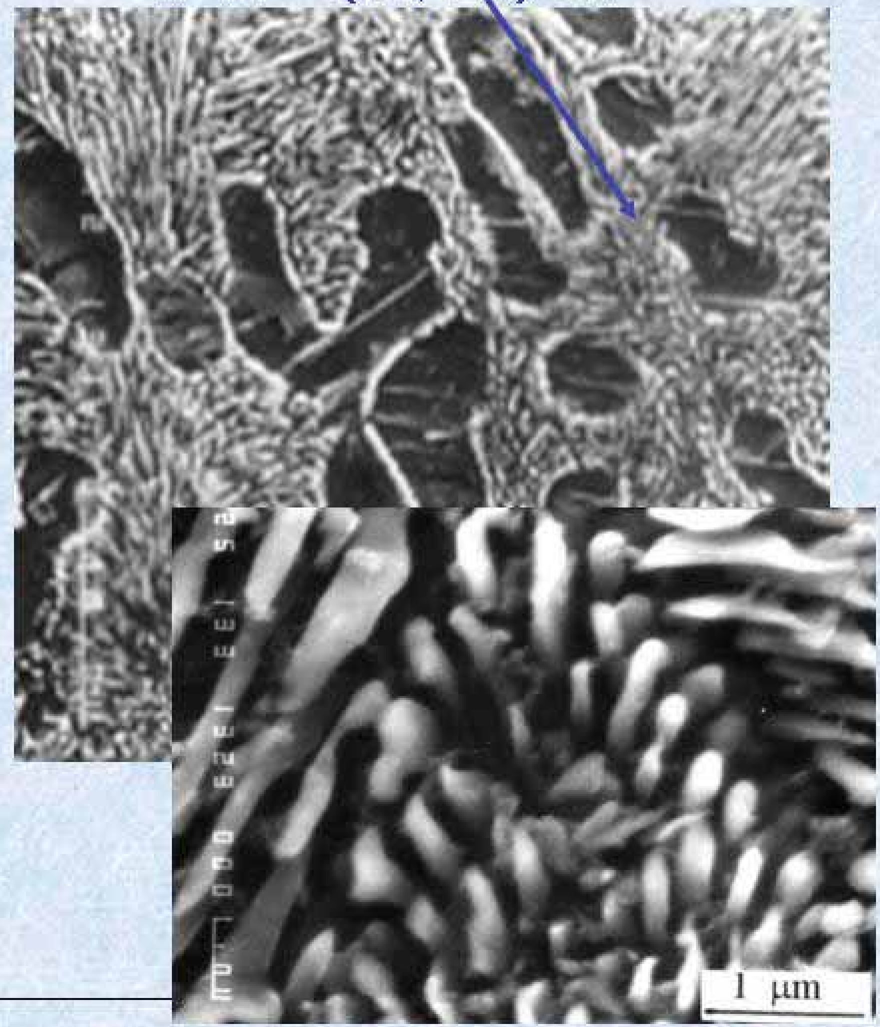


a

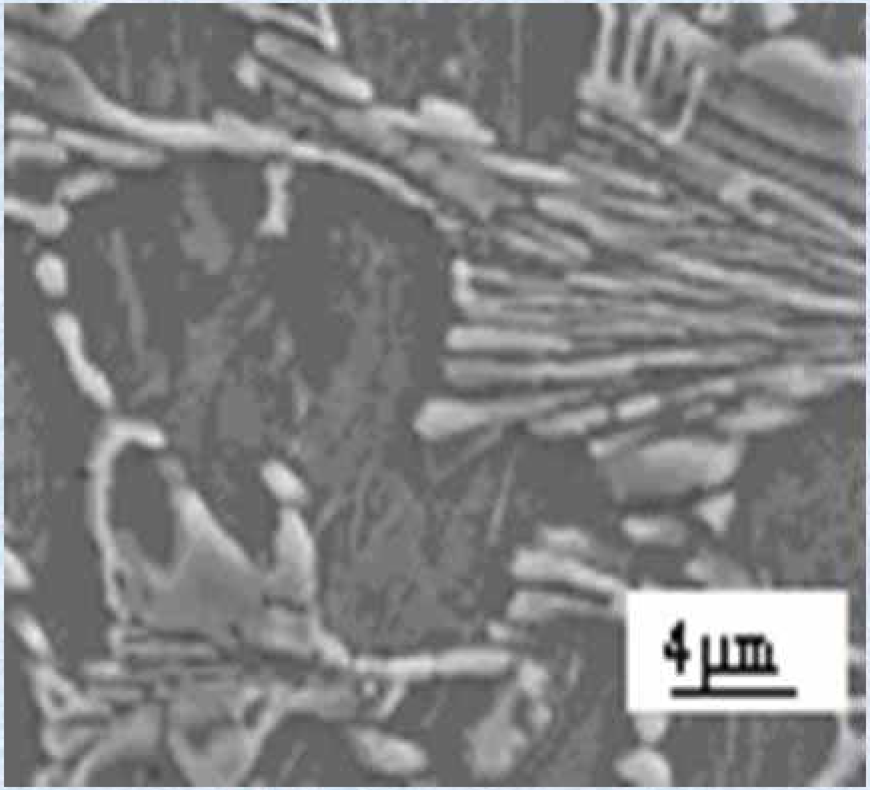
Salpadoru N.H., Flower H.M., 1995

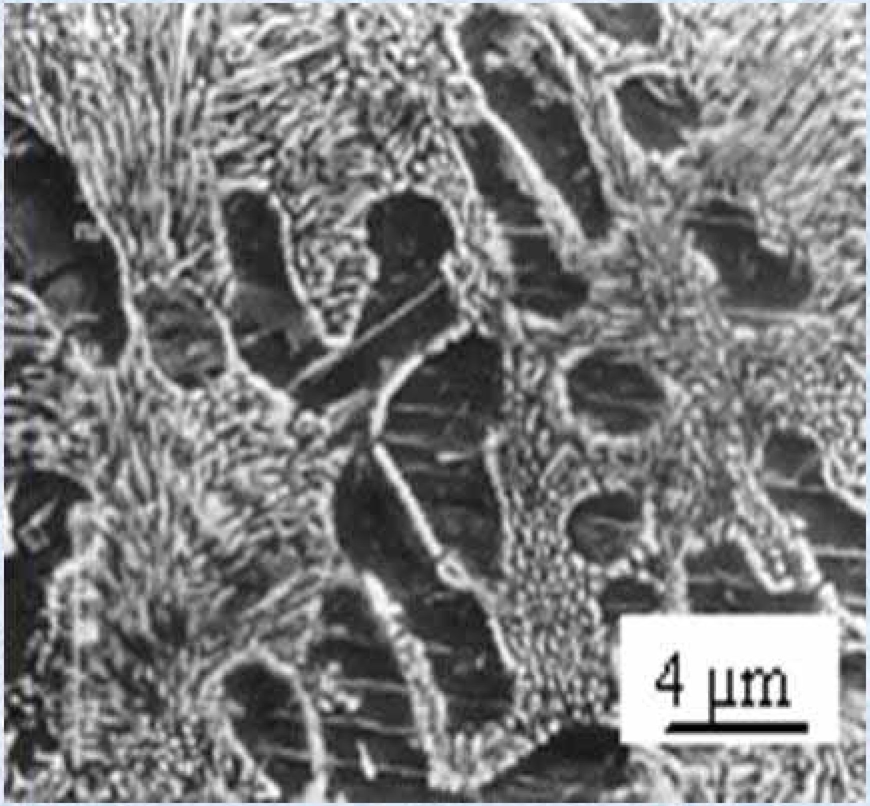


α-Ti + (Ti, Zr)$_2$Si



Ti-3Al-6Si-5Zr , Ti-3Al-6Si-18Zr

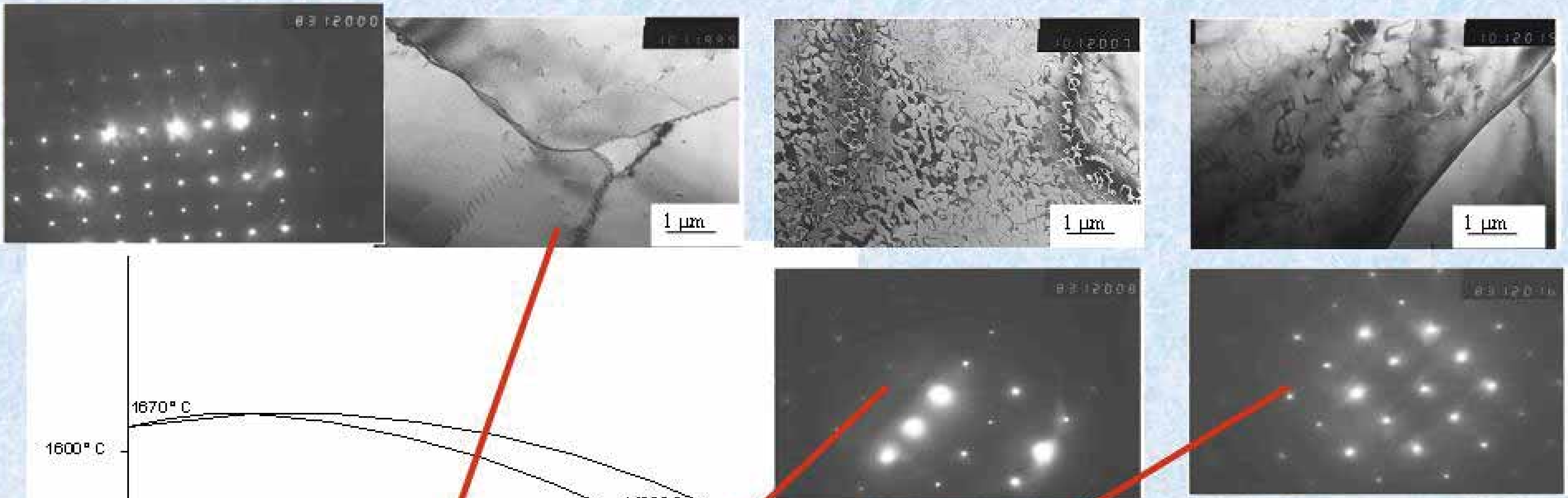


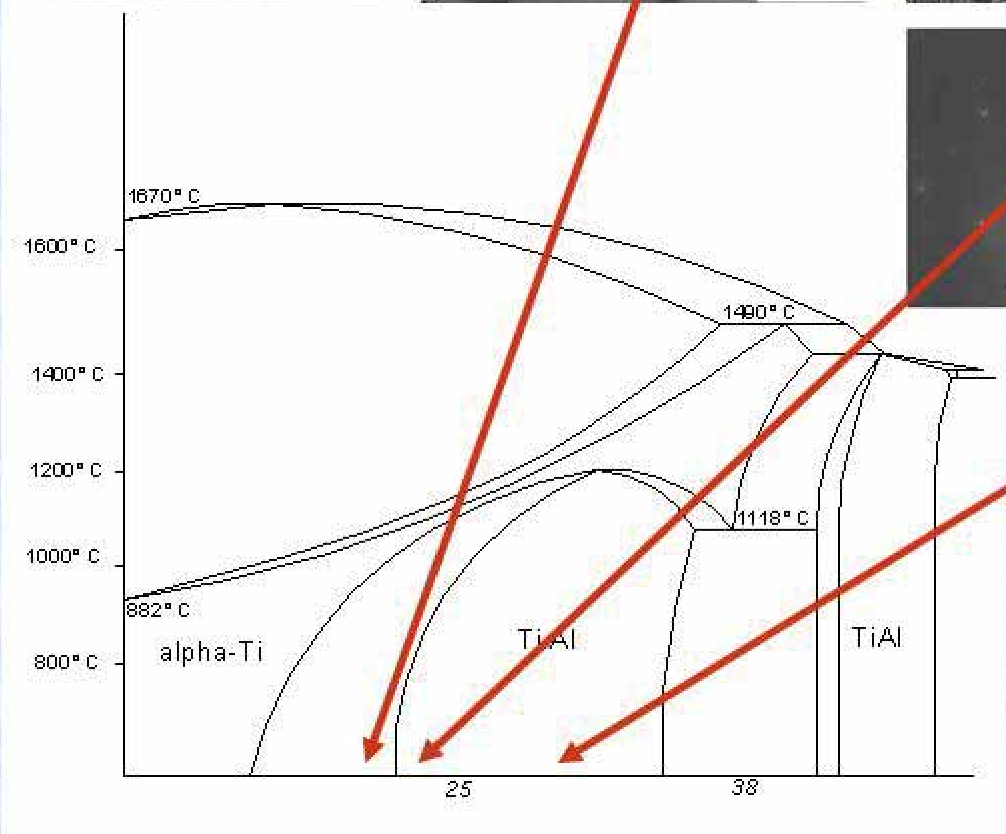


Good heat resistance of Ti-Si-X as cast alloys

Ti-6Al-5.5Zr-2.5Sn-1Mo-1Nb-6Si has at 800 °C strength of 336 MPa. Alloys with $\alpha+\alpha_2$–matrixes are looking perspective at increased content of Al (up to 12-14 %).

Ti corner of Ti-Al diagram





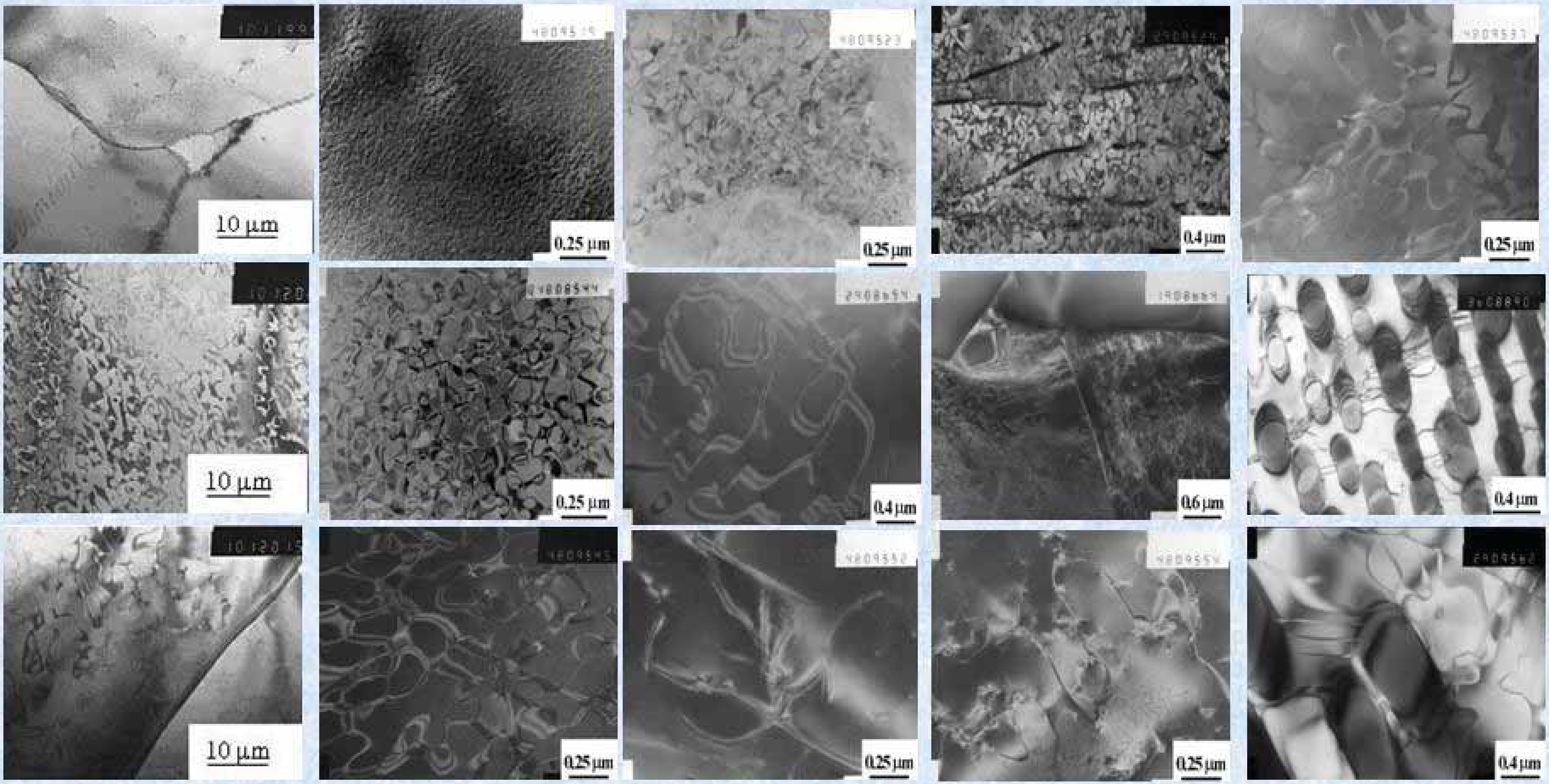
α_2-phase (Ti_3Al)

TEM micrographs of structure of as-cast Ti-Al-Si alloys (wt.%)

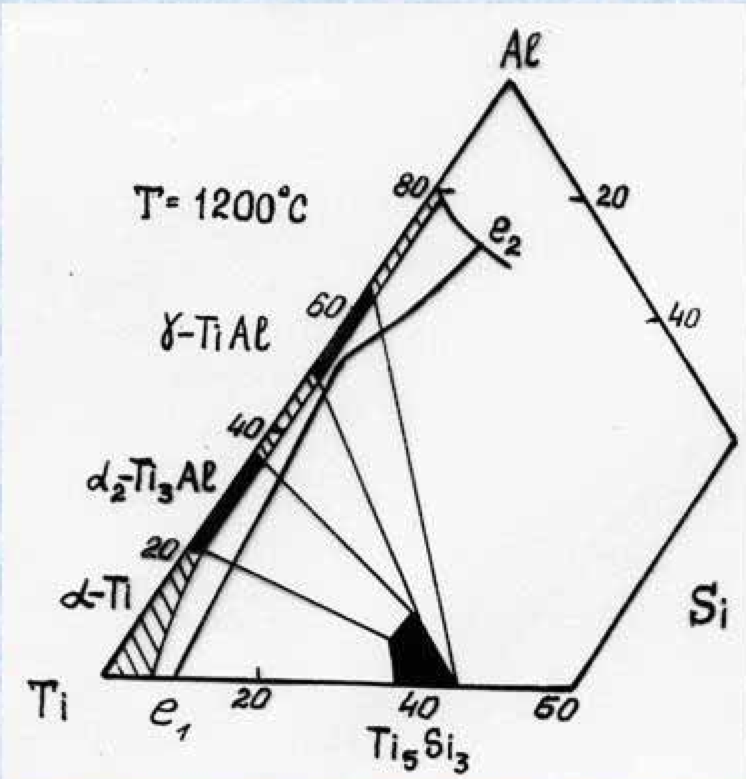
11 Al

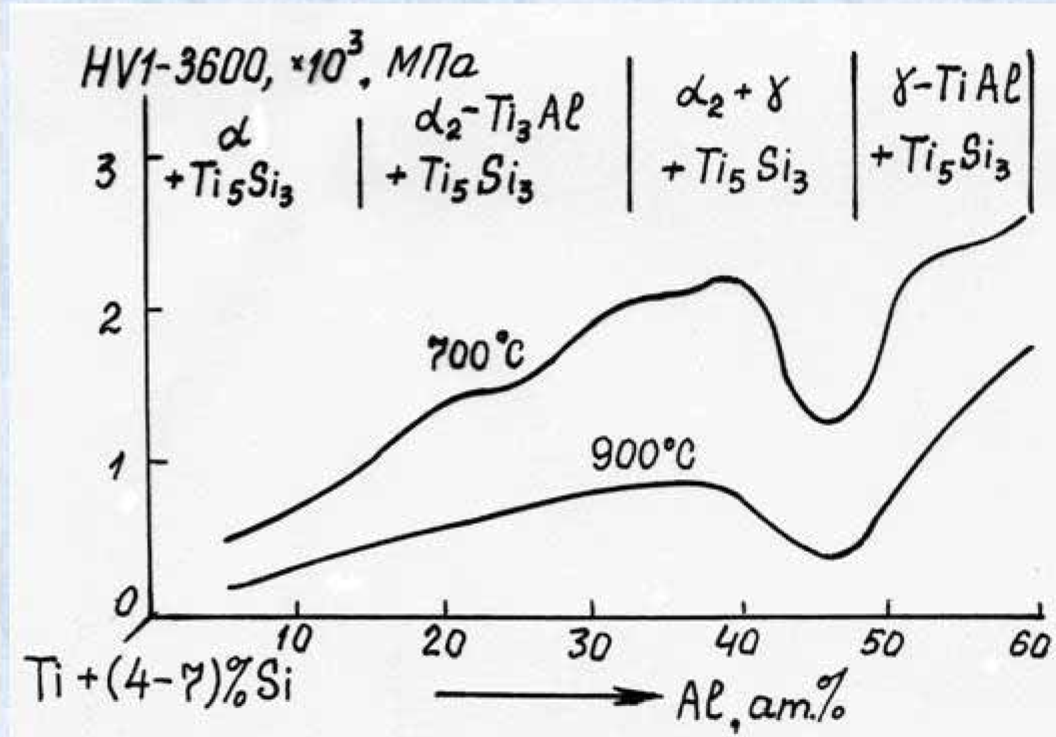
14 Al

17 Al

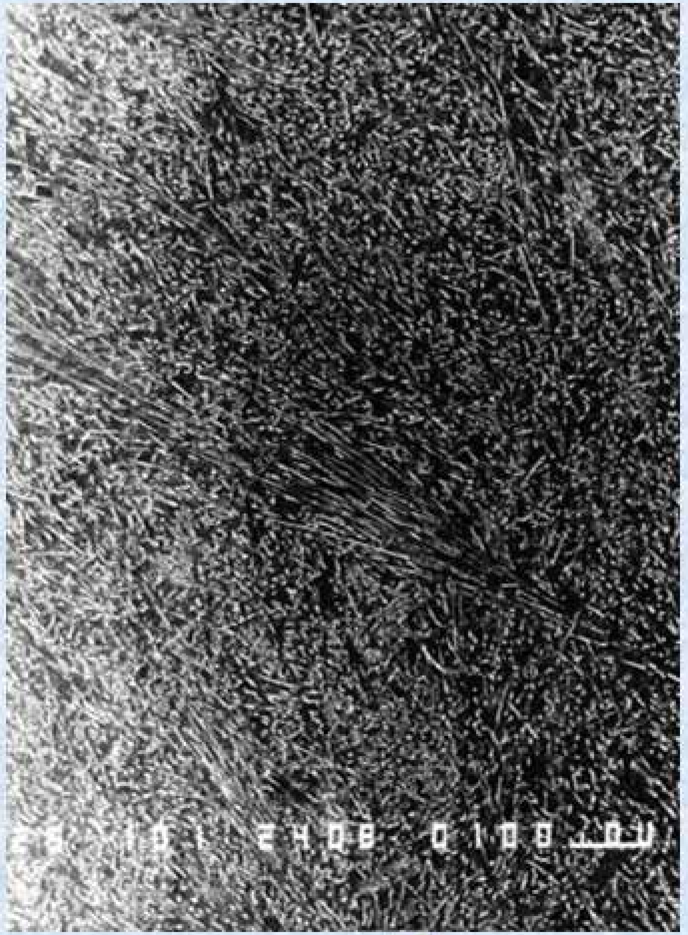


0 Si 1 Si 2 Si 4 Si 6 Si

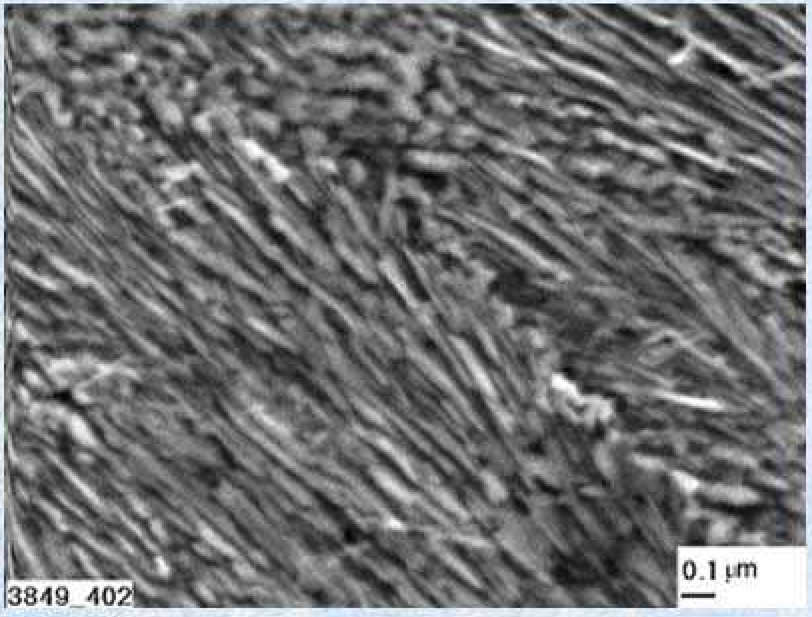

Al
T= 1200°C
80
20
e2
60
γ-TiAl
40
40
α2-Ti3Al
20
α-Ti
Si
Ti
e1
20
40
60
Ti5Si3

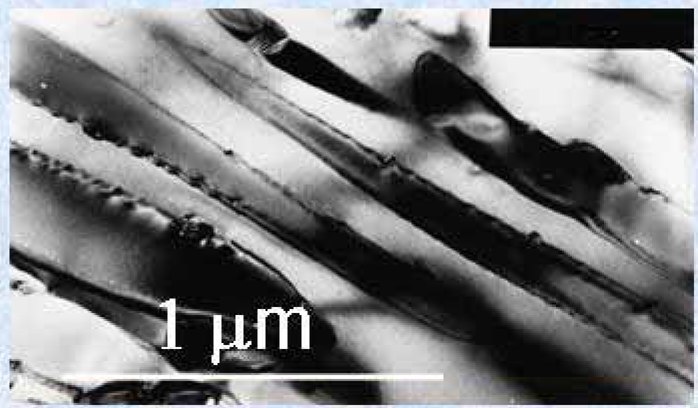

HV1-3600, ×10³, МПа
α
+Ti5Si3
α2-Ti3Al
+Ti5Si3
α2+γ
+Ti5Si3
γ-TiAl
+Ti5Si3
3
2
1
0
700°C
900°C
10
20
30
40
50
60
Ti+(4-7)%Si
Al, am.%

Ti – 2.0 B (wt. %), As cast.



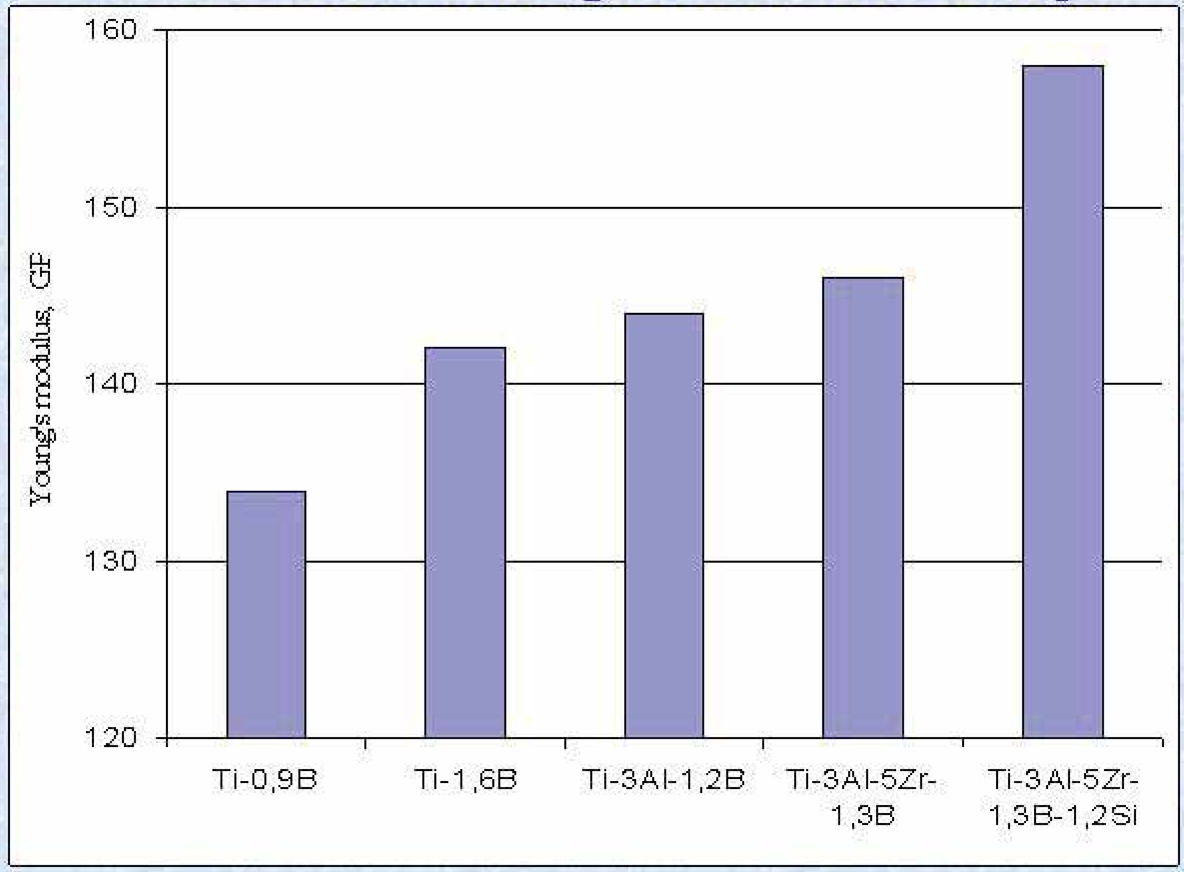
Ti – Si – B





Nanoeutectic based on Ti_6Si_2B

. Typical data on Young's modulus of different boron containing deformed alloys



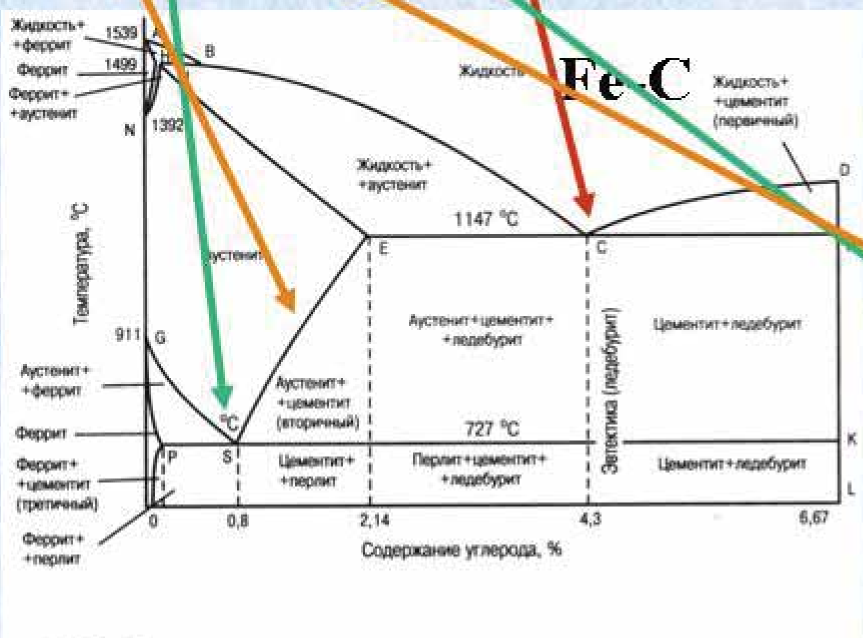
Ti "steels" and Ti "cast irons"

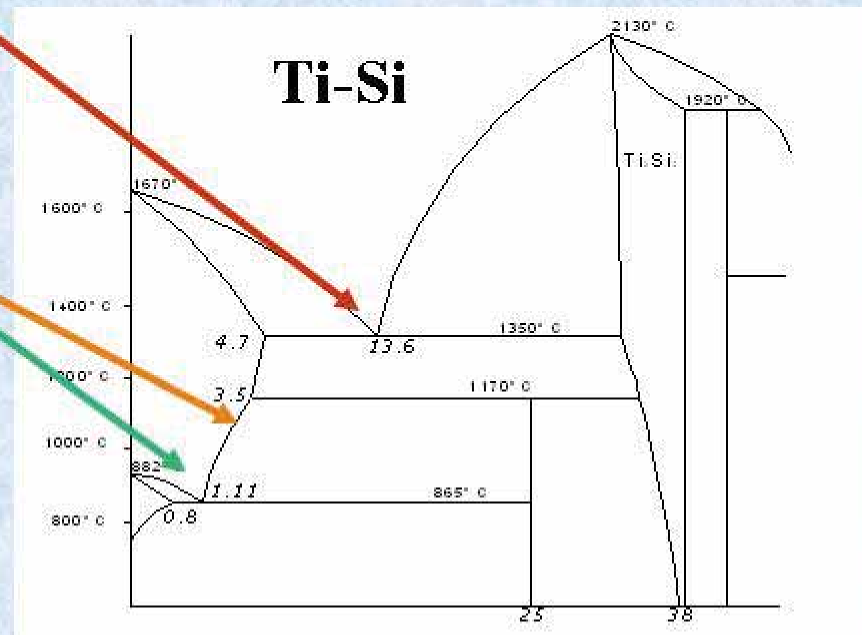
Eutectic

и and eutectoid transformations,

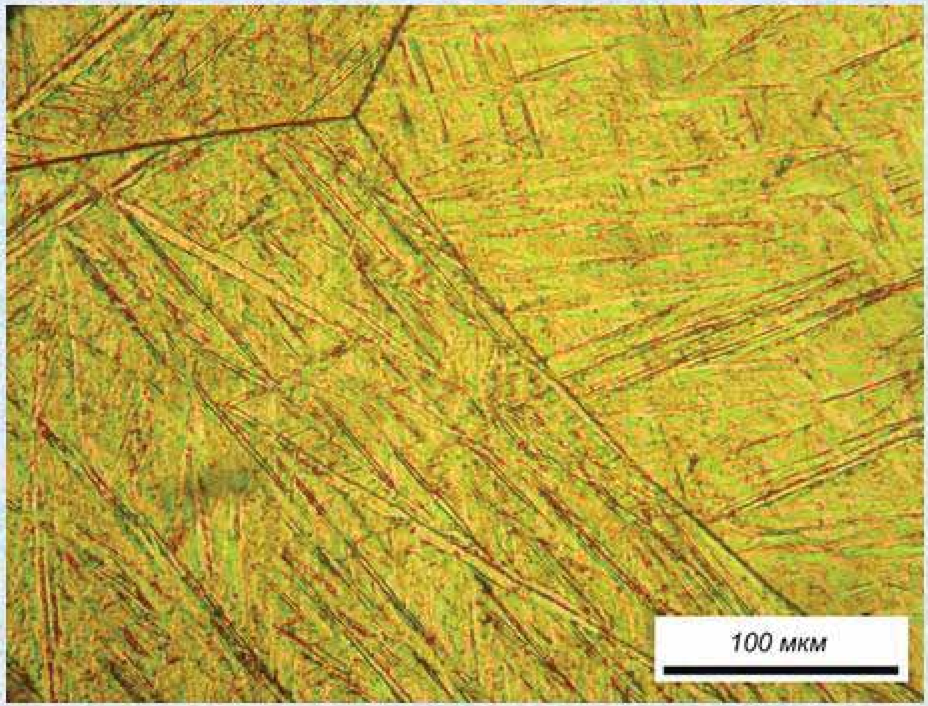
martensitic transformatione,

olimited solubility

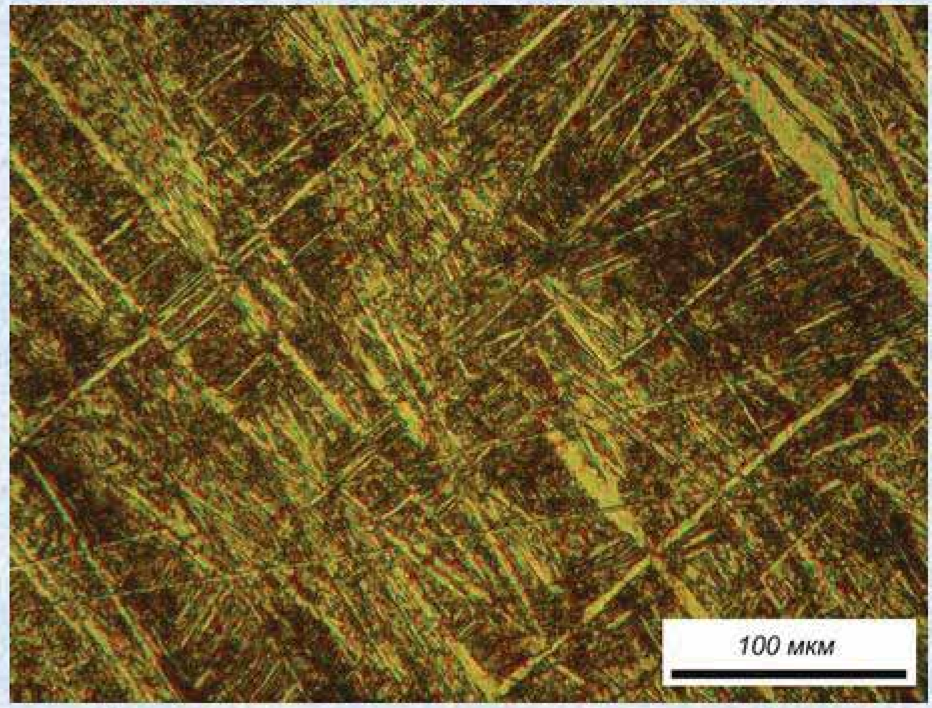




Microstructure of Ti-Si alloys after quenching



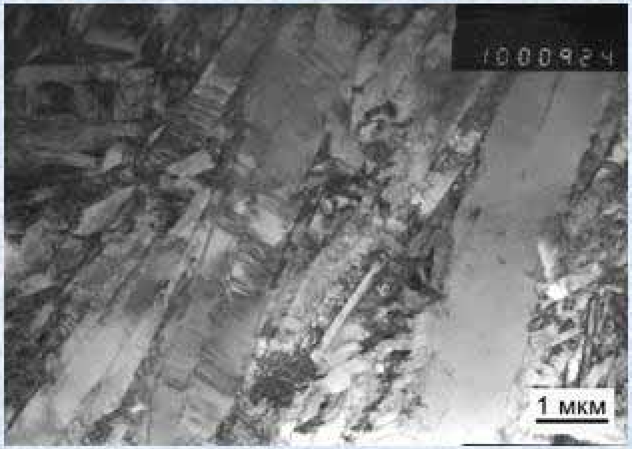
a



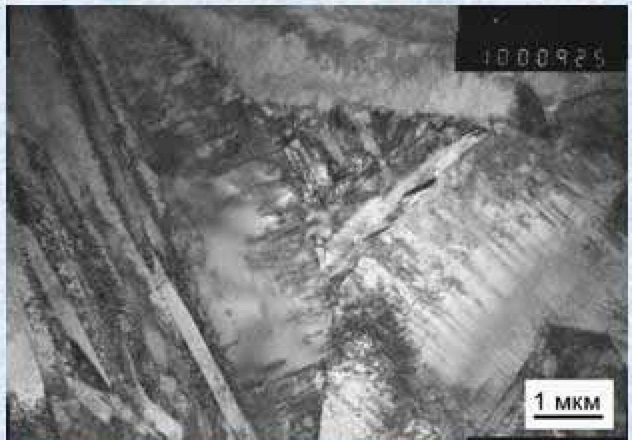
b

a - Ti-2.4Si; b - Ti-2.3Si-7.5Zr

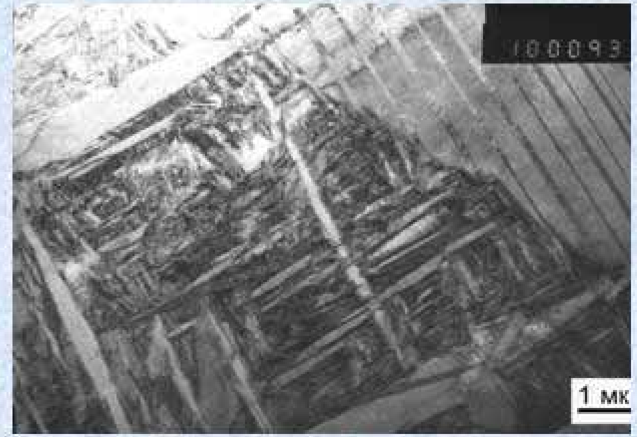
Quenched Ti-Si-X alloys



a



c



e

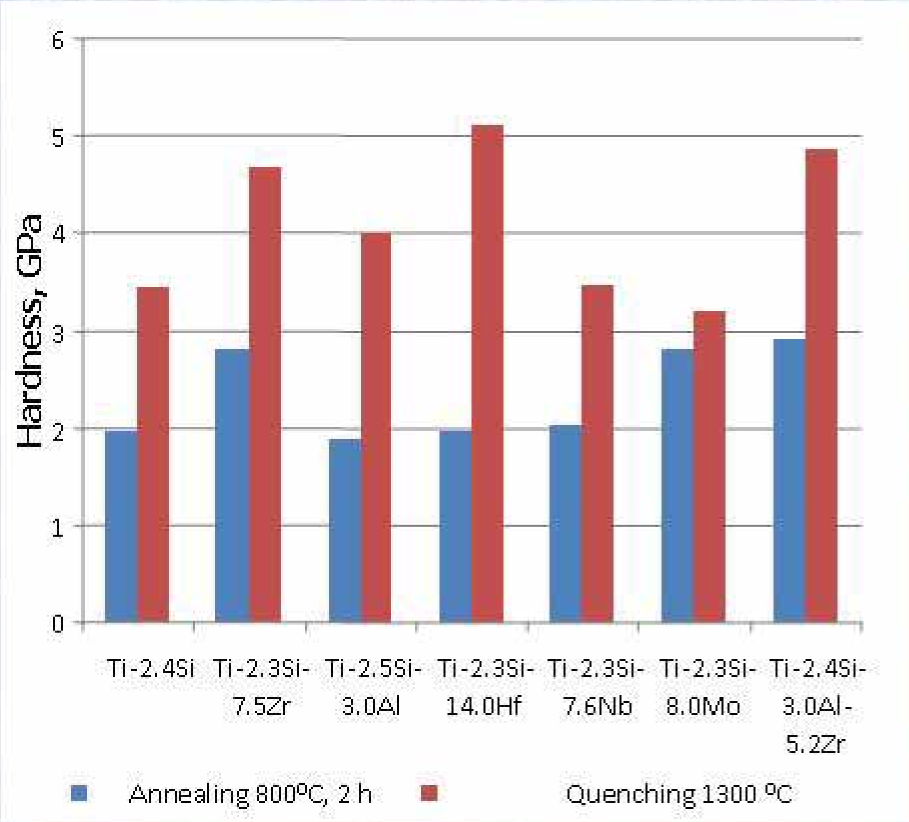
b

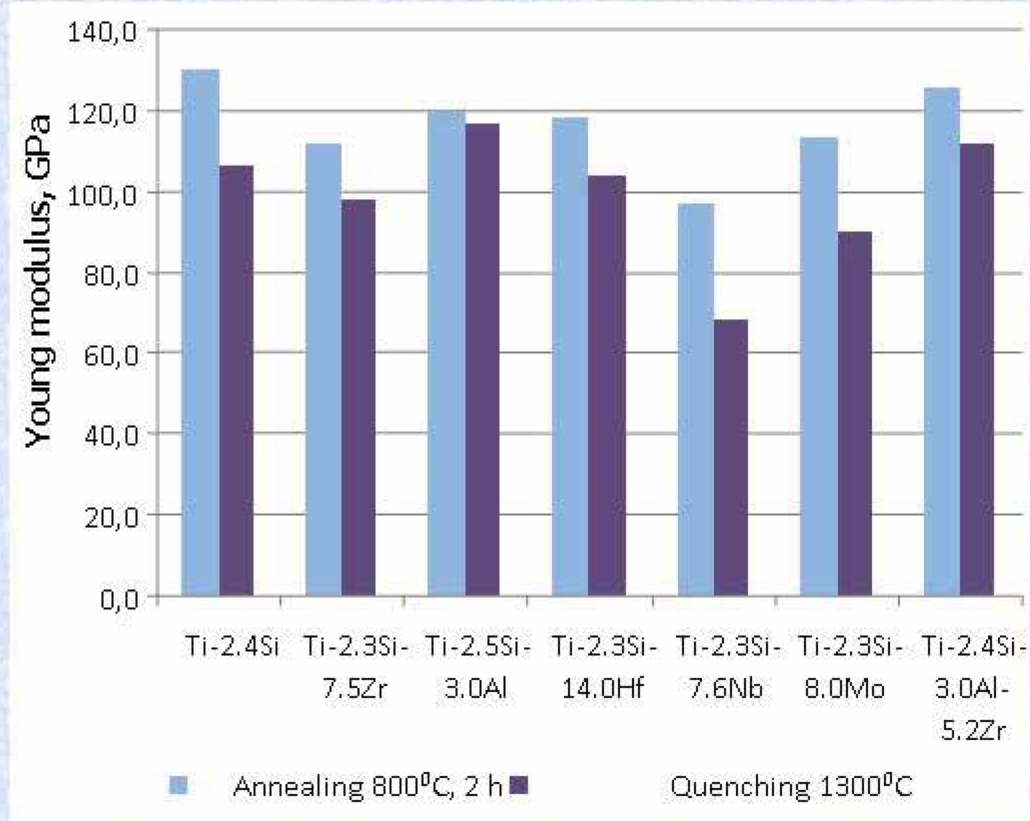
d

f

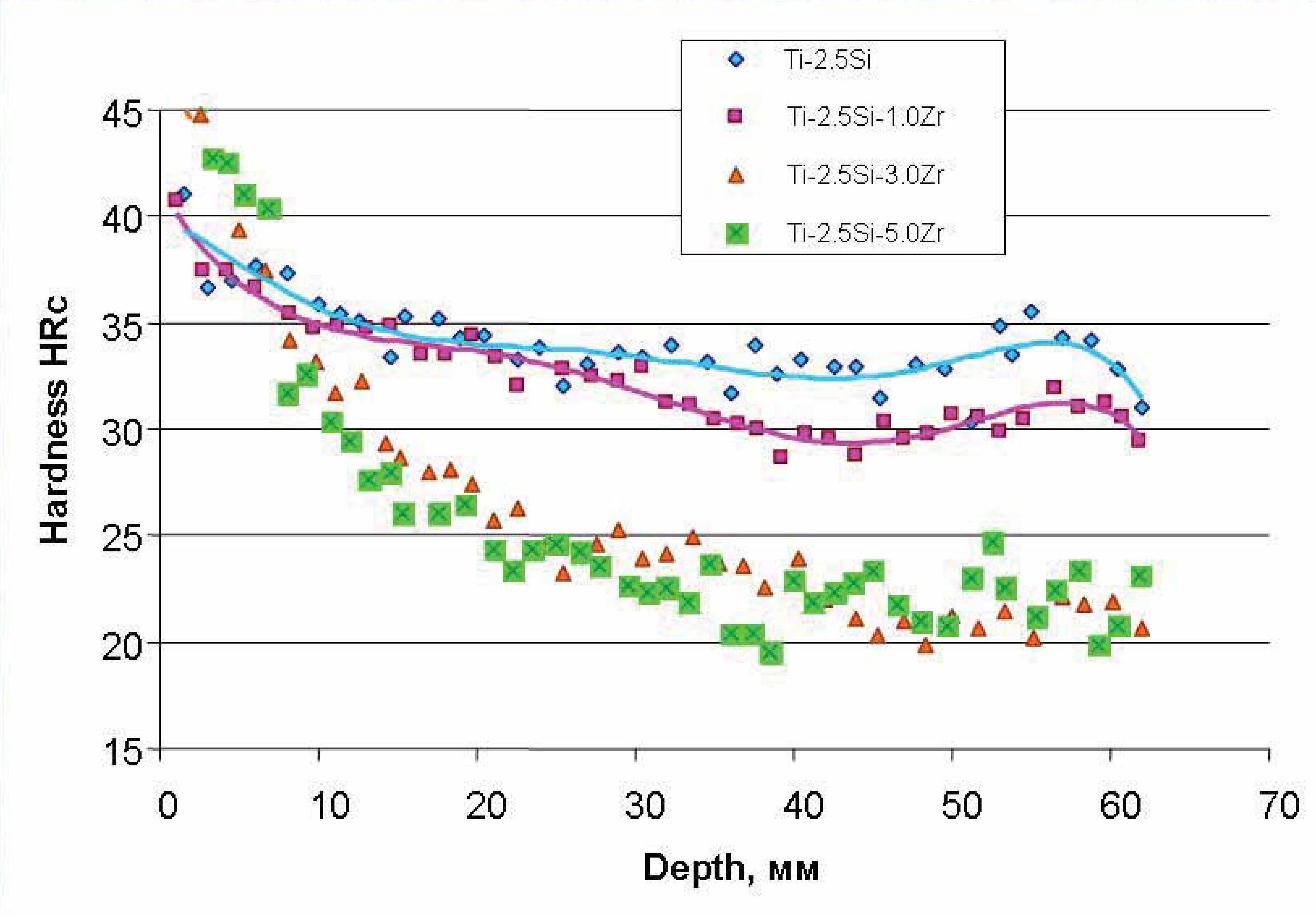
a - Ti-2.4Si, b- Ti-2.4Si, dark field c,d - Ti-2.5Si-3.0Al; e – Ti-2.3Si-7.5Zr; f- Ti-2.3Si-3.0Al-5.2Zr

Hardness and Stiffness of some Ti-"steels" after quenching and annealing

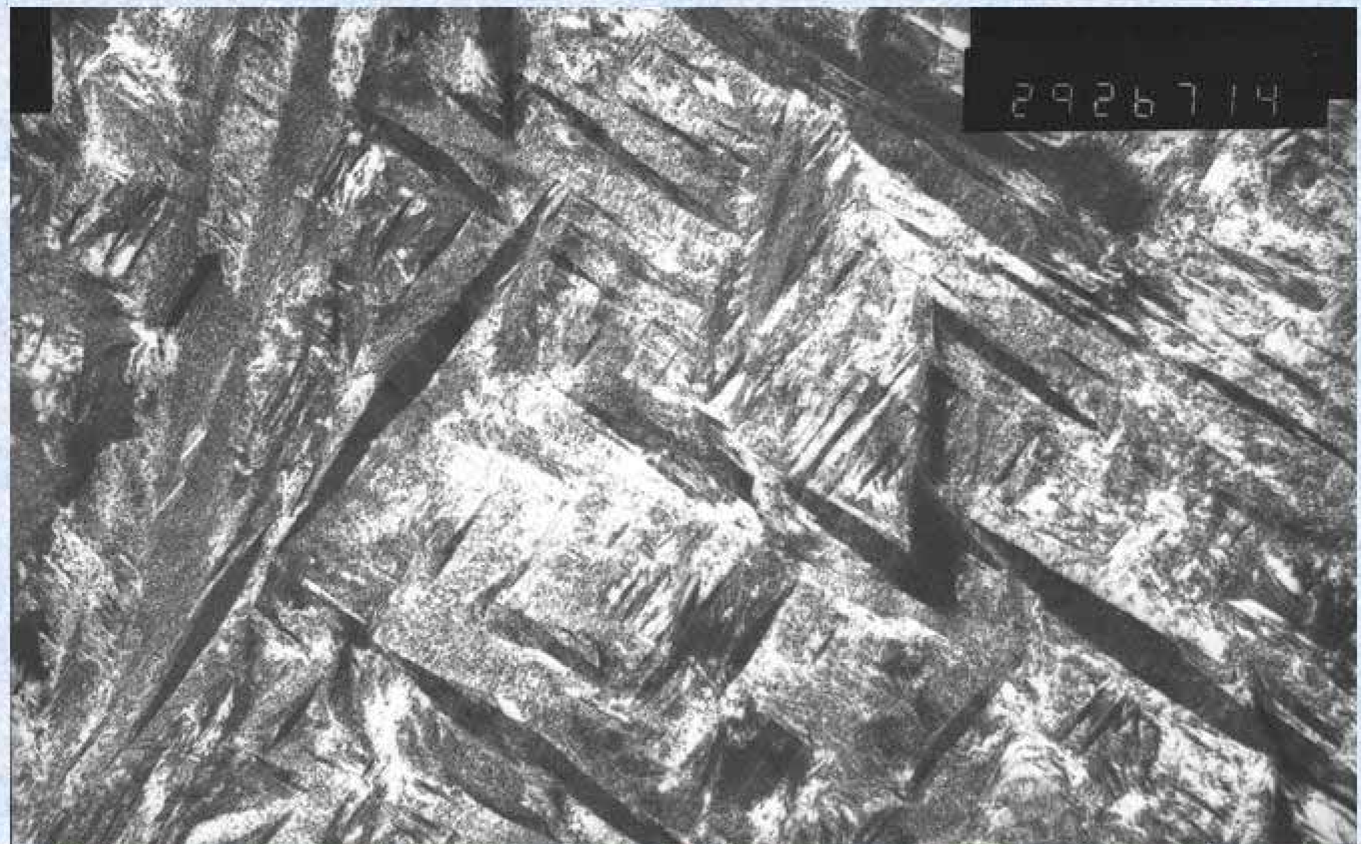




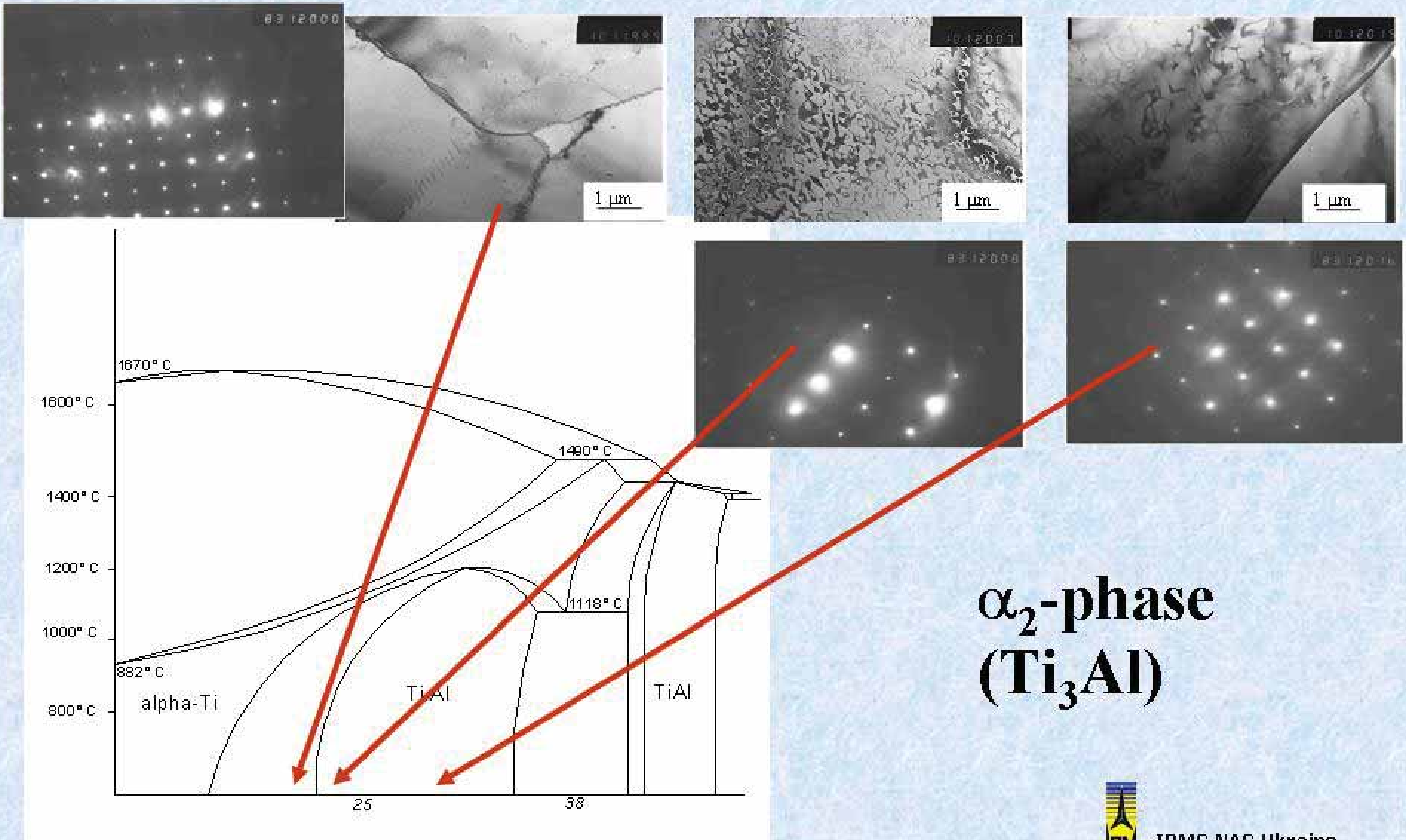
Hardenability of Ti-Si-Zr alloys



Ti-2,5Si-5Zr, Distance to surface 1mm



Ti corner of Ti-Al diagram



α_2-phase (Ti_3Al)

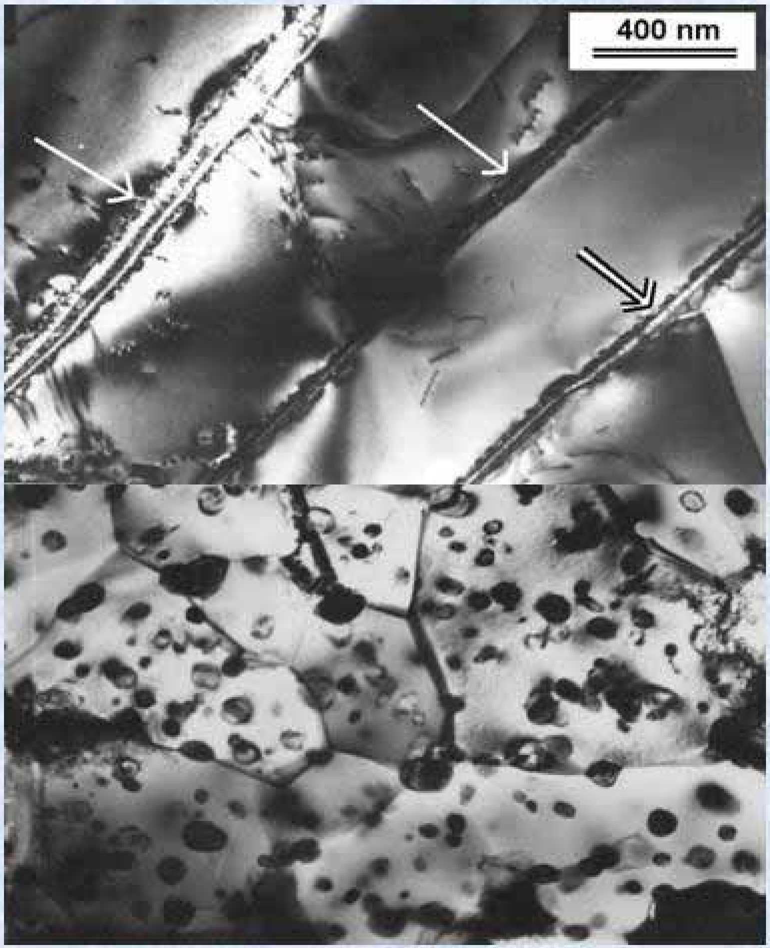
Al-rich Ti-"steel"

Deformability of Ti-5Al-1,9Si-4Zr

Rolling without thermal treatment

Rolling after preliminary quenching

Substructure evolution in Ti- «steels»



- **Rolled in β - region, T=1050^{0}C**
- **Rolled in α- region, T=970^{0}C**

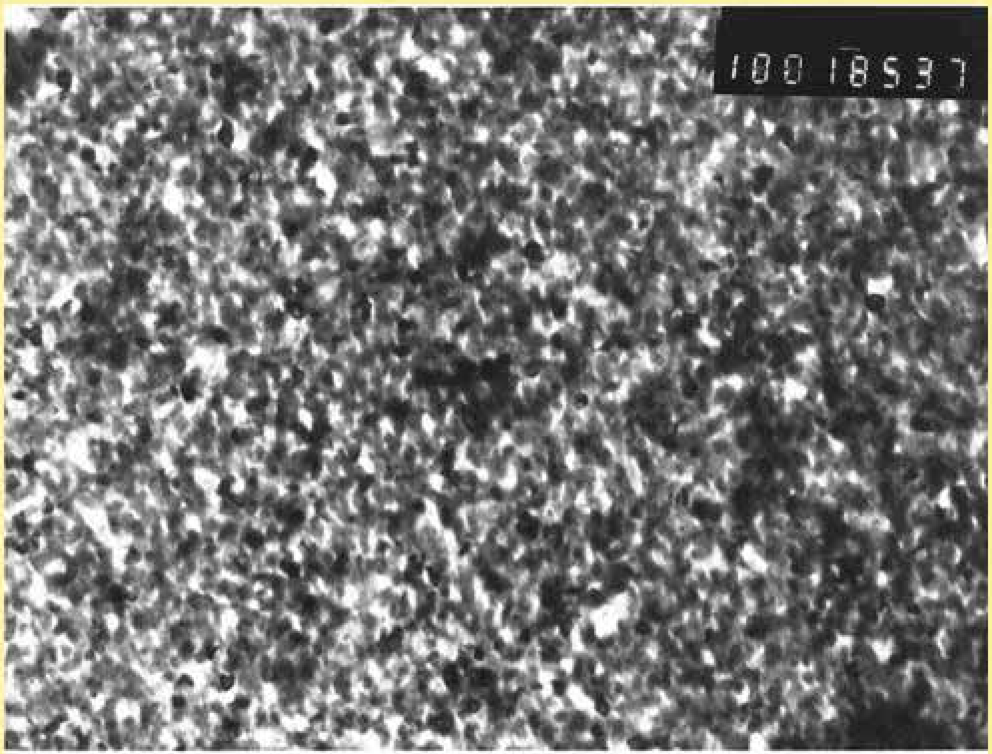
Influence of the processing on the properties Ti-8Al-2.2Zr-1.4Si alloy

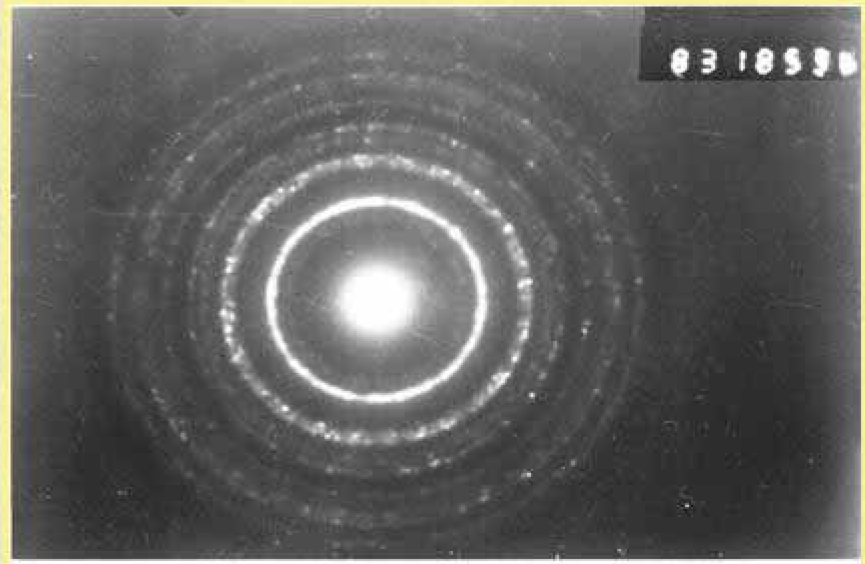
Property	Forging in β-region	Rolling in β-region	Rolling in α-region
RT strength, MPA	1300	1182	1234
600 C strength,MPa	-	923	608
700 C strength,MPa	632	653	409
RT elongation,%	1.83	2.1	6.1
RT Fracture toughness, MPa√m	-	19.2	51.1
Fracture mode	ductile	ductile	ductile

Silicon improves the oxidation resistance

Alloys	Properties before oxidation		Oxidation temperature	Properties after oxidation	
	σ, MPa	δ,%		σ, MPa	δ%
Ti-7.1Al-2.5M0-3.1Nb-3.7W-1Zr-0.5Si	1059	2.6	700	766	0
Ti-8.5Al-1Si-3.1Zr	1316	7.8	700	1320	8.1

Structure of cast alloy Ti-Zr-Sn-Bi obtained under cooling rate of 1000 °C^{-1}

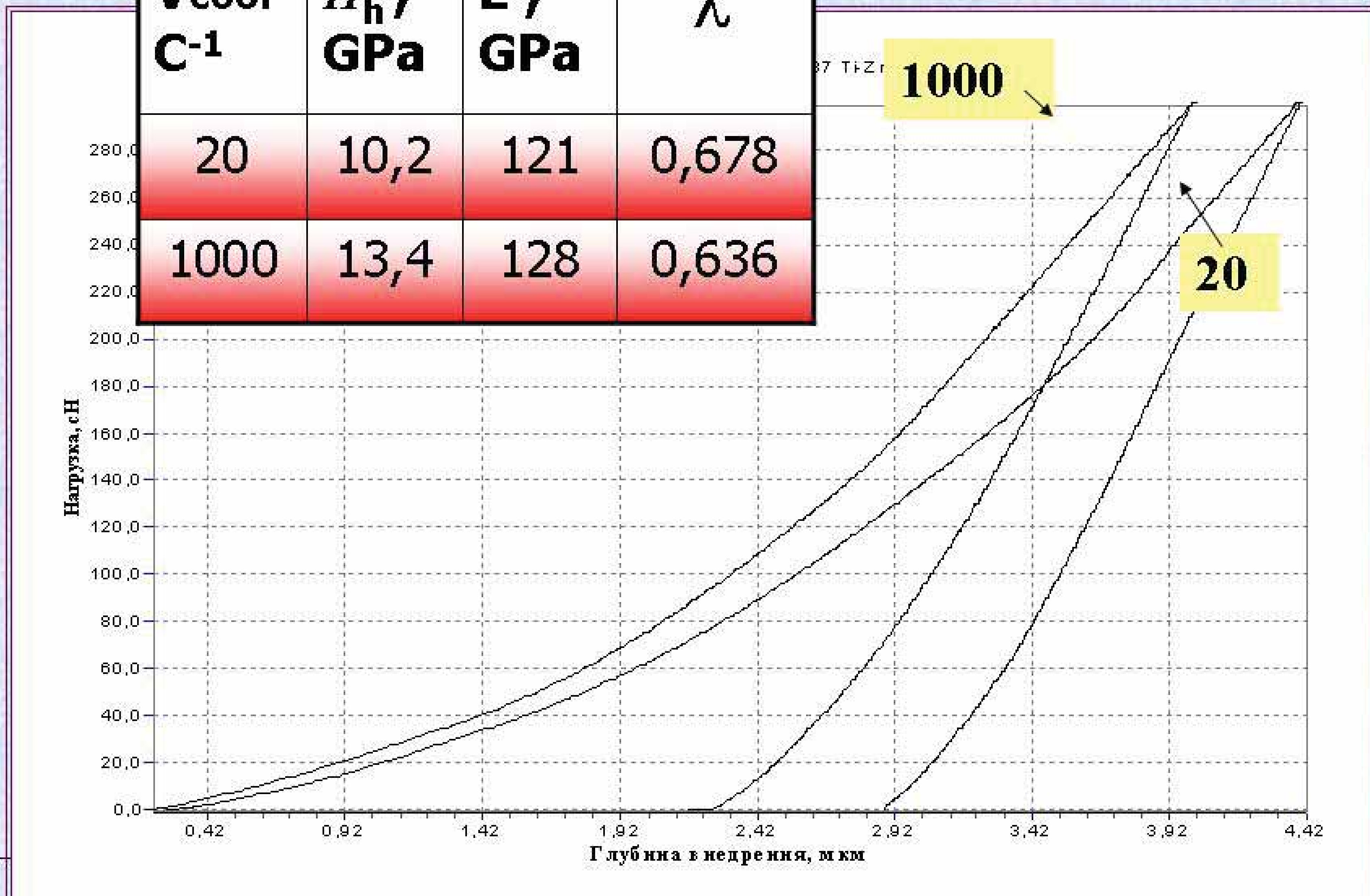




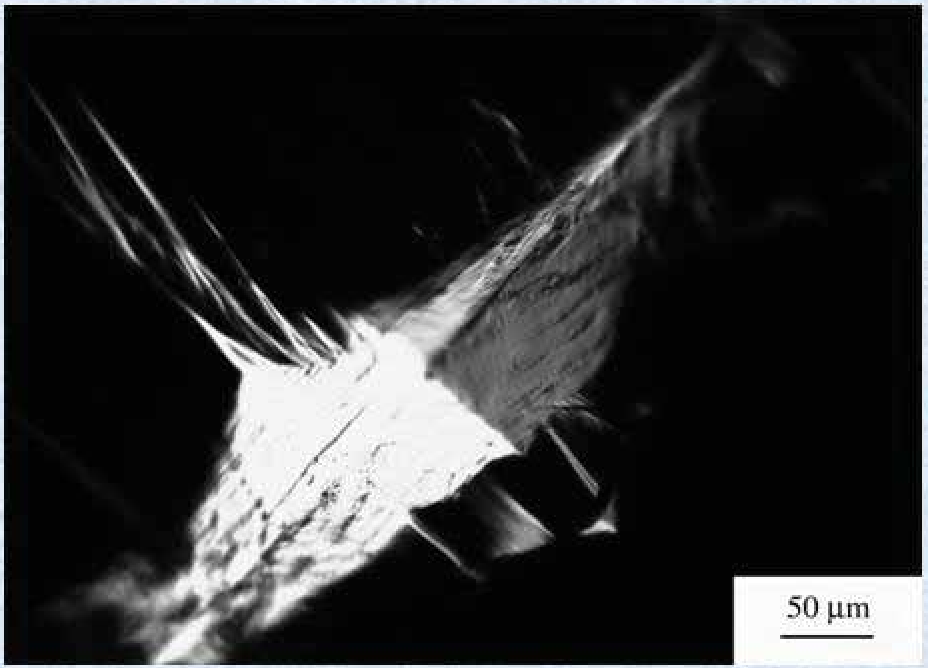
Diameter of ingot is 10 mm

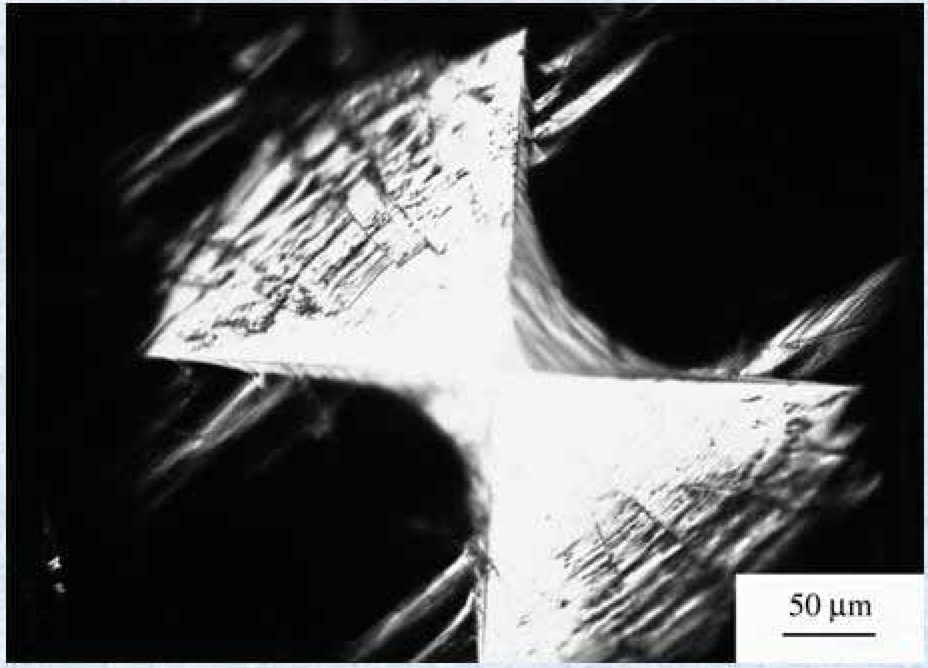
Effect of cooling rate on properties of cast alloy Ti-Zr-Sn-Bi

Vcool° C⁻¹	H_h, GPa	E, GPa	λ
20	10,2	121	0,678
1000	13,4	128	0,636



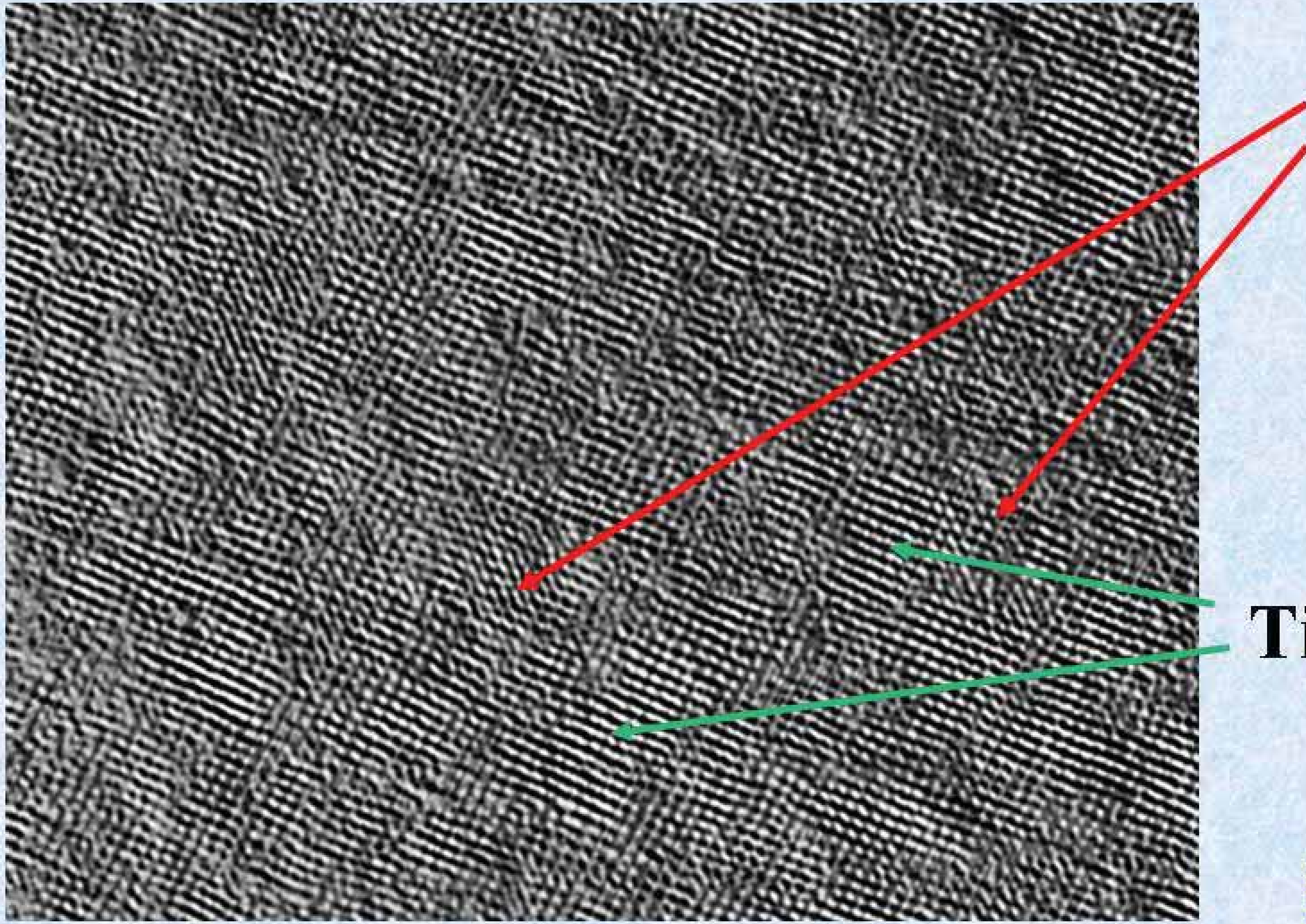
"GUM" behavior of Ti_3Sn (Bulanova, Podrezov)



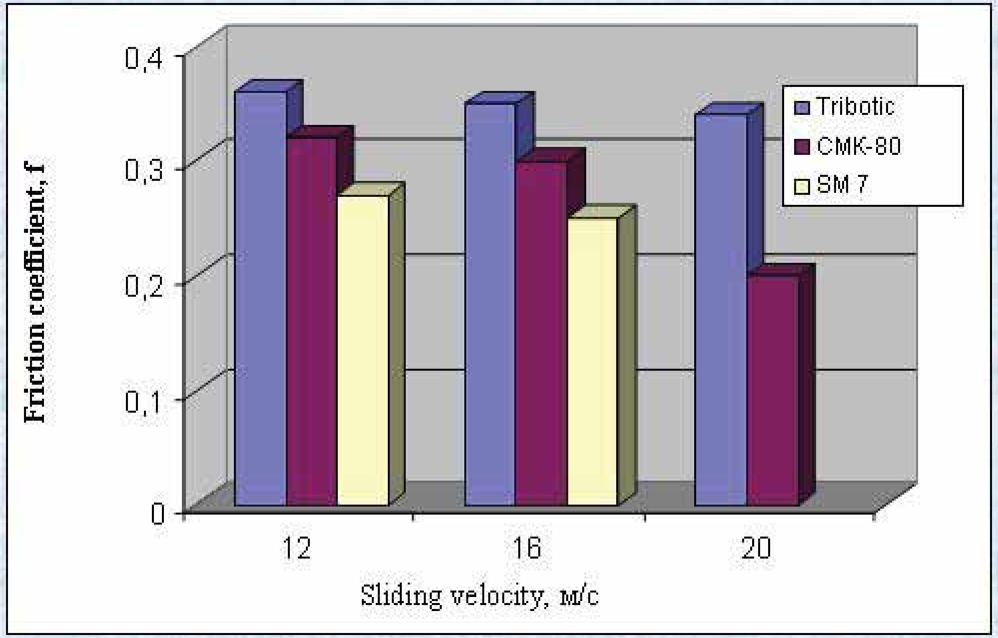


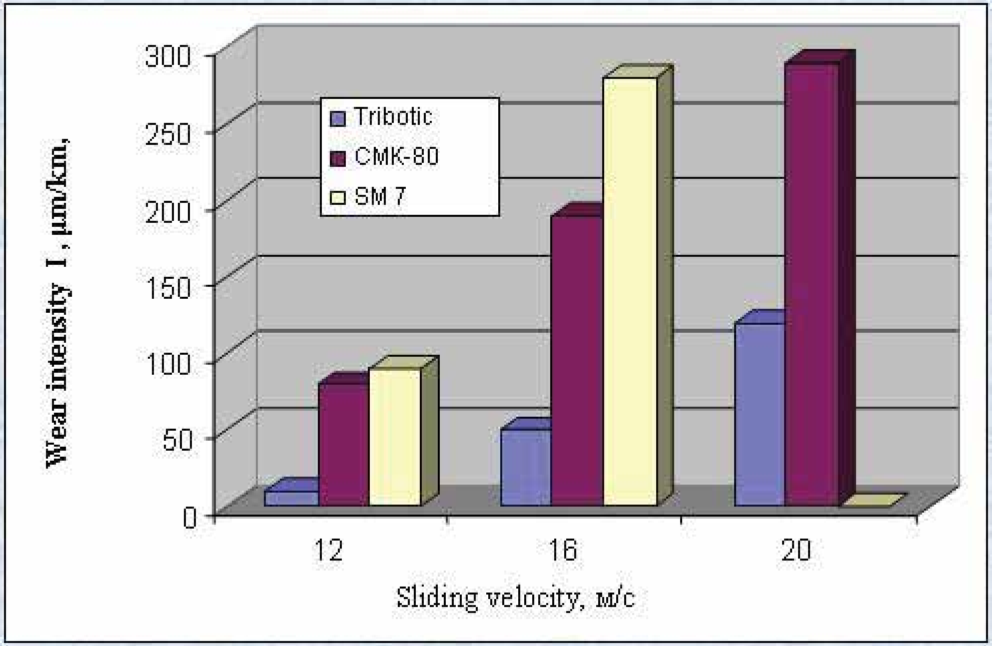
E less than 20 GPa

Ti_3Sn, HR-image



The comparative tribotechnical characteristics of traditional frictional materials (Fe-based CMK-80 and Cu-based SM-7 «Ferodo Ltd», England) as compared to *Tribotic composite*





The comparative tribotechnical characteristics for *Tribotic* working in air without lubrication (velocity range V= 4-20 m/s, pressure 2 MPa)

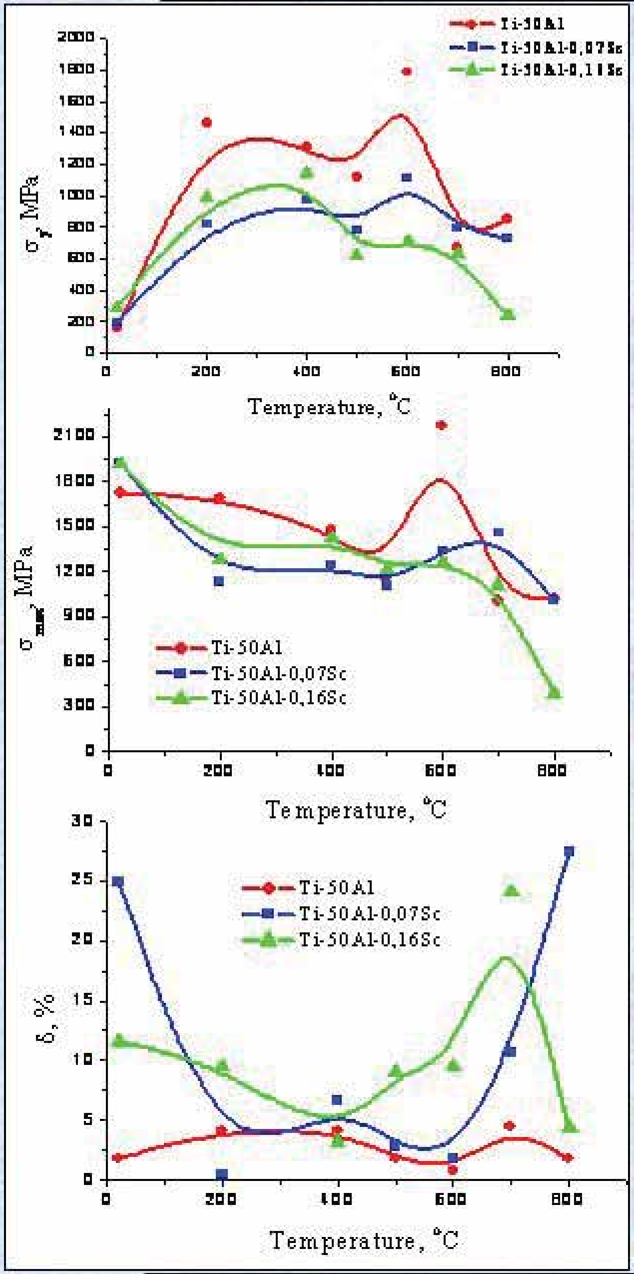
V	Titanium alloy VT-20 (Ti-6Al-2Zr-1Mo-1V)		Titanium Ti-Si-X composite *Tribotic*	
	f	I	f	I
	Steel U9 as a counterpart material			
4	0.59	10	0.60	1.5
8	0.52	150	0.58	3.5
12	-	c.w.	0.52	60
16	-	c.w.	0.51	100
20	-	c.w.	0.50	160

V- sliding rate, m/s;
f - friction coefficient;
I - wear intensity, μm/m.
c.w. – catastrophic wear

The above data testify for high capability of *Tribotic* application in friction units working at high sliding rates such as arrestic arrangements of airplanes.

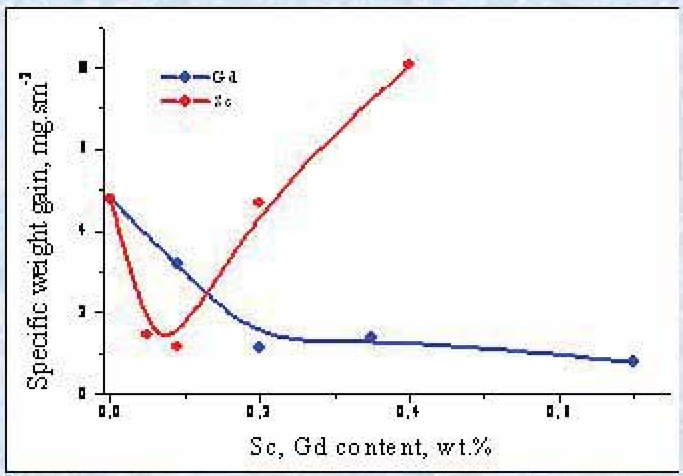
BT-6-based brake disk with *Tribotic* frictional lining

Study of γ-TiAl alloys additionally alloyed by Nb, Sc, REM with enhanced physical-mechanical properties and a development on this basis structural materials and functional vacuum arc coatings.



Specific weight gain (q, $mg\cdot sm^{-2}$) and oxidation rate (V_q, $mg\cdot sm^{-2}\cdot h^{-1}$) during oxidation of Ti-36Al-x alloys at 900 °C in air (50 h.)

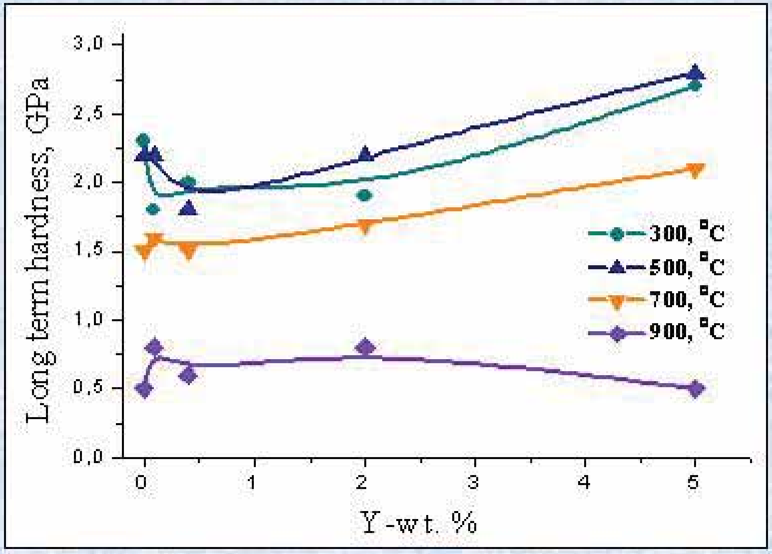
Alloy	q_5	q_{10}	V_{q10}	q_{20}	q_{50}	V_{q50}
Ti-36Al	2,7	4,8	0,48	6,1	10,6	0,21
Ti-36Al-0,09Sc	0,59	1.15	0,11	2,05	3,56	0,07
Ti-36Al-0,2Sc	1,24	2,0	0,2	2,48	4,2	0,08
Ti-36Al-0,09Gd	1,44	3,2	0,32	3,9	7,32	0,15
Ti-36Al-0,2Gd	0,9	1,25	0,11	1,96	7,2	0,14
Ti-36Al-0,09Y	1,64	1,64	0,16	1,92	8,56	0,17



It was showed a different type of Sc and Gd effect on a heat resistance of as-cast Ti-36Al alloy. Only small addition of (0,05÷0,09)Sc effectively decreased weight gain during oxidation in air at 900 °C and increased a long term hardness (high temperature strength) in a temperature interval of 700-900 °C. The Gd efficiency on heat resistivity and oxidation resistance grows with its content increasing.

Y effect on oxidation resistance (in air at 900 °C) and long term hardness of the as-cast Ti-36Al-xY alloys

Alloy	q_2	q_5	q_{10}	q_{20}	V_q, $mg/sm^2 \cdot h$.
Ti-36Al	**1,54**	**2,7**	**4,8**	**6,1**	**0,3**
Ti-36Al-0,1Y	**1,43**	**1,67**	**1,67**	**2,01**	**0,1**
Ti-36Al-0,2Y	**1,2**	**1,43**	**1,43**	**2,24**	**0,1**
Ti-36Al-0,4Y	**0,81**	**1,04**	**1,16**	**1,39**	**0,07**
Ti-36Al-0,6Y	**0,76**	**0,92**	**1,01**	**1,14**	**0,06**
Ti-36Al-5Y	**1,18**	**2,15**	**2,9**	**4,3**	**0,2**



Optimal alloying of as-cast Ti-36Al alloys with 0,4-0,6-wt. % Y provides its oxidation resistance increase; specific weight gain (q, mg·sm-2) under oxidation at 900 °C deceases in some times. Growth of Y content up to 5-wt. % decreases long term hardness of alloy at 900 °C.

As-cast cathodes based on titanium aluminides alloys for magnetron and ion-plasma spraying of coatings by PVD method.

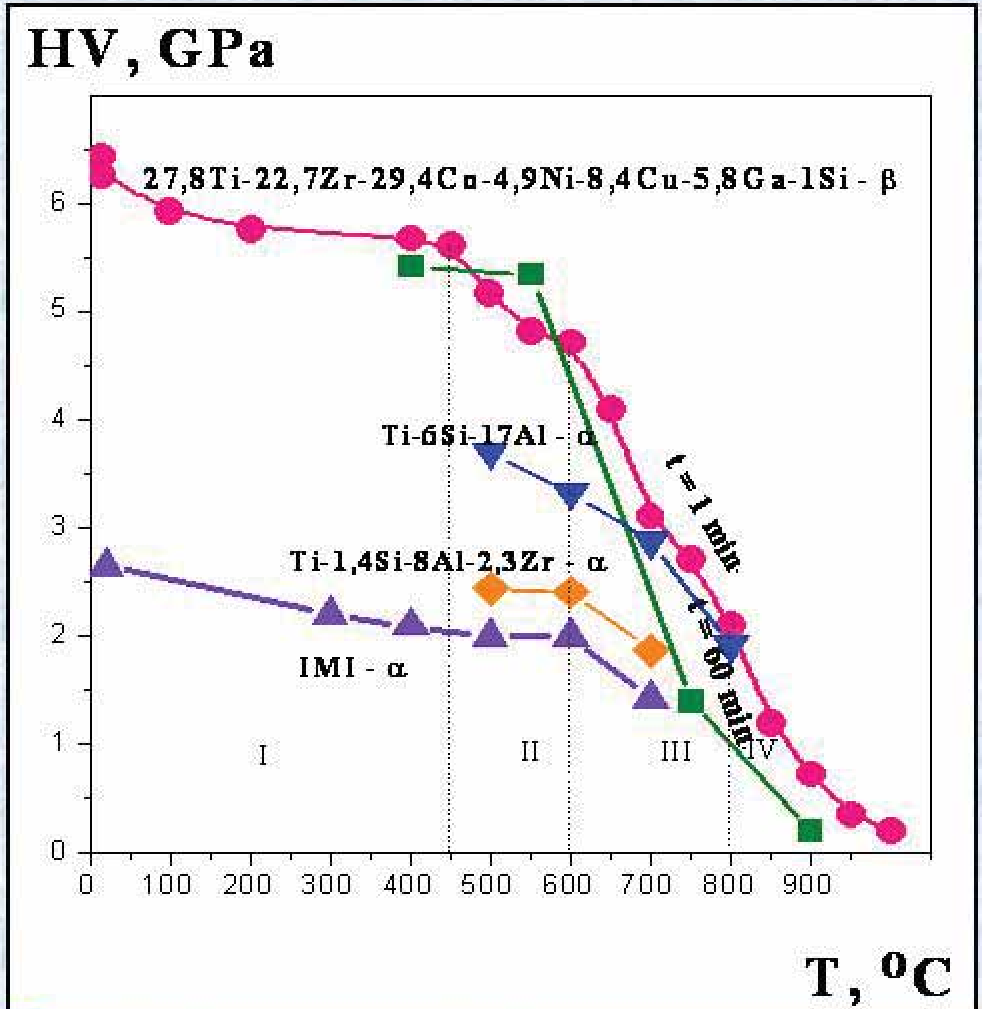
Professor Firstov S.A.

Ti-Al

Ti-Al, Ti-Al-Si,
Ti-Al-B, Ti-Al-Y

The developed TiAl alloys with optimal properties will be used as starting materials for a vacuum arc evaporation with a subsequent deposition of plasma flow onto metal substrates in order to produce these intermetallics as functional coatings. Ti-Al-N cover sprayed magnetron method from Ti-36Al alloy cathode has anomalous hardness about 40-50 GPa.

High-temperature mechanical properties



Strength and plasticity of alloy at different temperatures			
T, °C	$\sigma_{пц}$, MPa	$\sigma_{в}$, MPa	ε, %
20	3480	3480	0
700	1720	2200	5,6
750	1340	1680	25,5
900	350	400	50,0

Novel titanium composites *Tribotic* for application in modern transmissions

The unique result on increased frictional coefficient in coal oil was obtained:

- **traditional materials: *f* = 0.08;**
- ***Tribotic* composite: *f = 0.12-0.18***

Destination of Materials

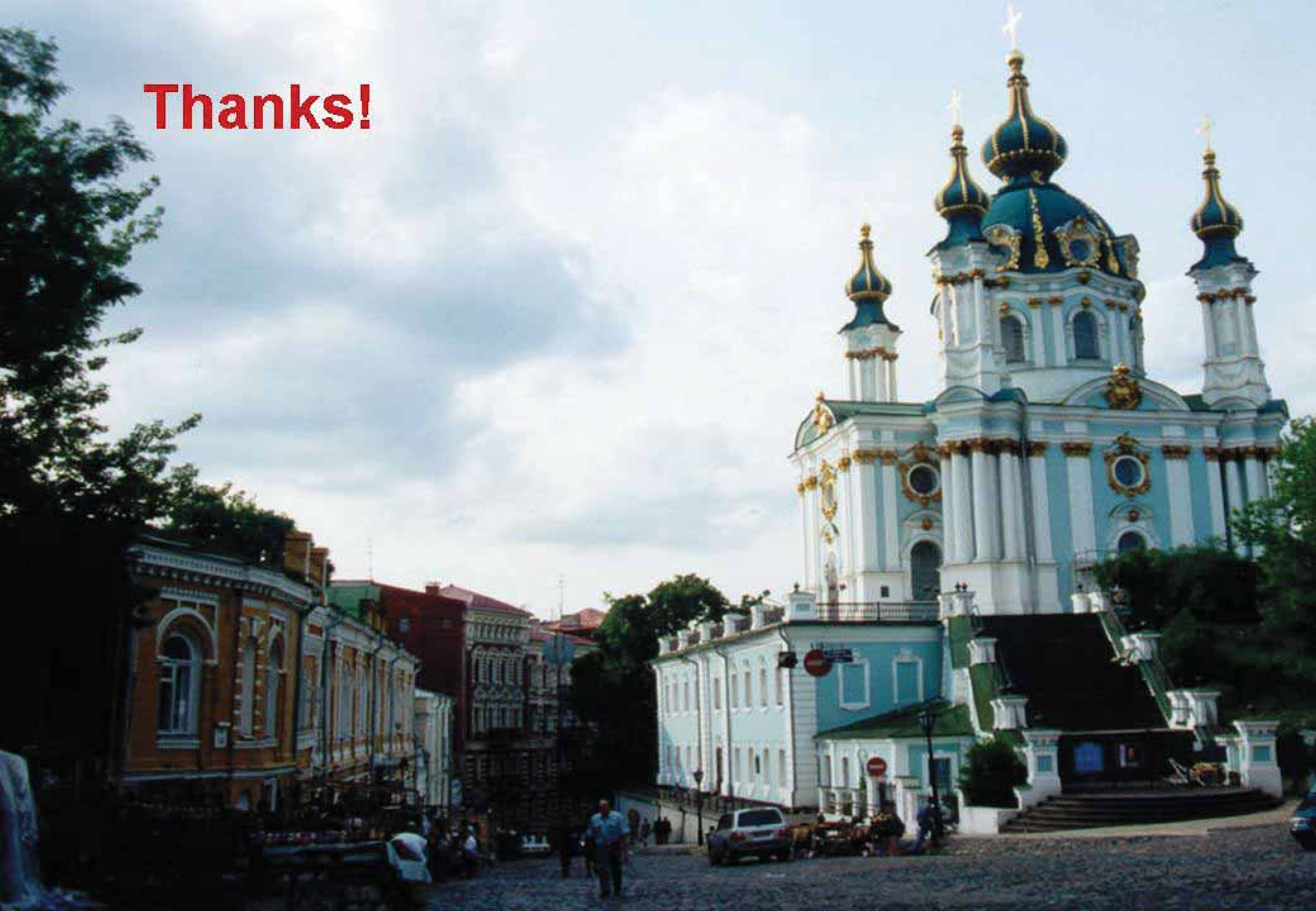
- Automotive, Aircraft & Aerospace
- Structural materials with high specific strength;
- Adiabatic diesel engine parts;
- Rotor turbo-chargers;
- Wear resistant and brake parts;
- Corrosion and abrasion resistant parts (sea water, acids, alkali's).

1. Ti-Si-X alloys are attractive for creation of heat resistant and oxidation resistant materials.
2. Ti-B-X alloys are promising for achievement of high specific stiffness.
3. Ti-B-Si-X alloys can have a good combination of all needed properties.
4. Increased and decreased (Gum behavior) stiffness can be achieved

Materials and their processing may be produced with

Casting, near shape casting, powder metallurgy, forging, rolling, stamping etc.

- **Their costs are comparable with of conventional titanium alloys.**
- **These materials are competitive with γ-TiAl-based materials and MMC reinforced with SiC fibers.**


Thanks!