NATO ARW, Kyiv, Sept. 07–13 2003

The Main Tendencies in Elaboration of Materials with High Specific Strength

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Report Documentation Page

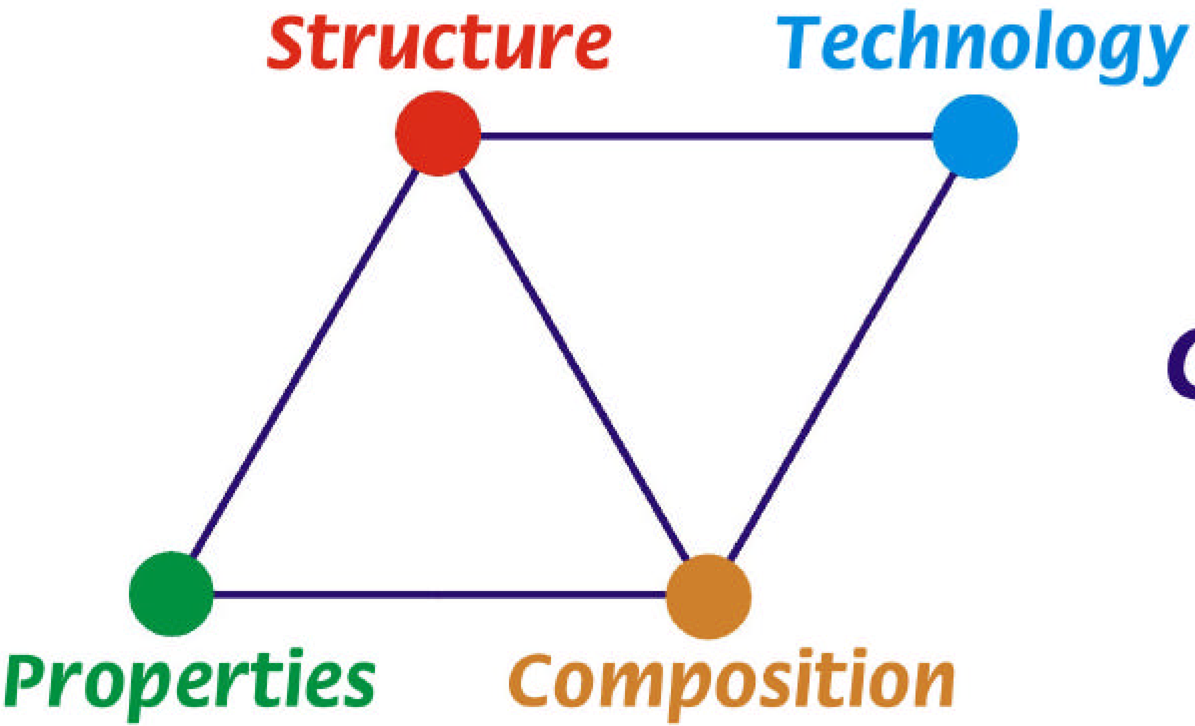
Form Approved
OMB No. 0704-0188

1. REPORT DATE **18 MAR 2004**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **The Main Tendencies in Elaboration of Materials with High Specific Strength**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **I.M. Frantcevych Institute for Problems of Materials Sciences Kyiv, Ukraine**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release, distribution unlimited**		
13. SUPPLEMENTARY NOTES **See also ADM001672., The original document contains color images.**		
14. ABSTRACT		
15. SUBJECT TERMS		

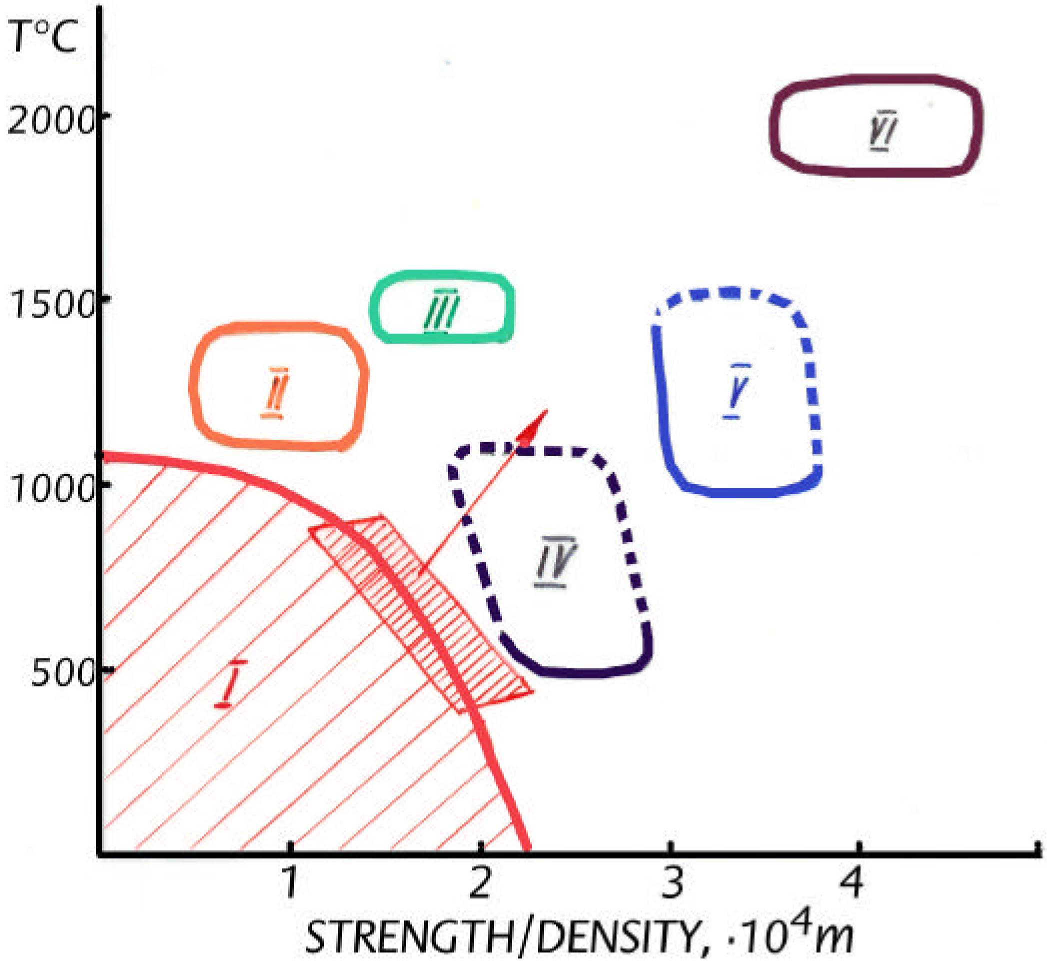
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
NATO/unclassified	**unclassified**	**unclassified**	**UU**	**40**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

- Introduction
- Nanostructured materials
- Ti-Si-X and Ti -B-X systems as the base for elaboration of new in situ composites
- Conclusions



Cost ?



I - Conventional materials, Ti and superalloys

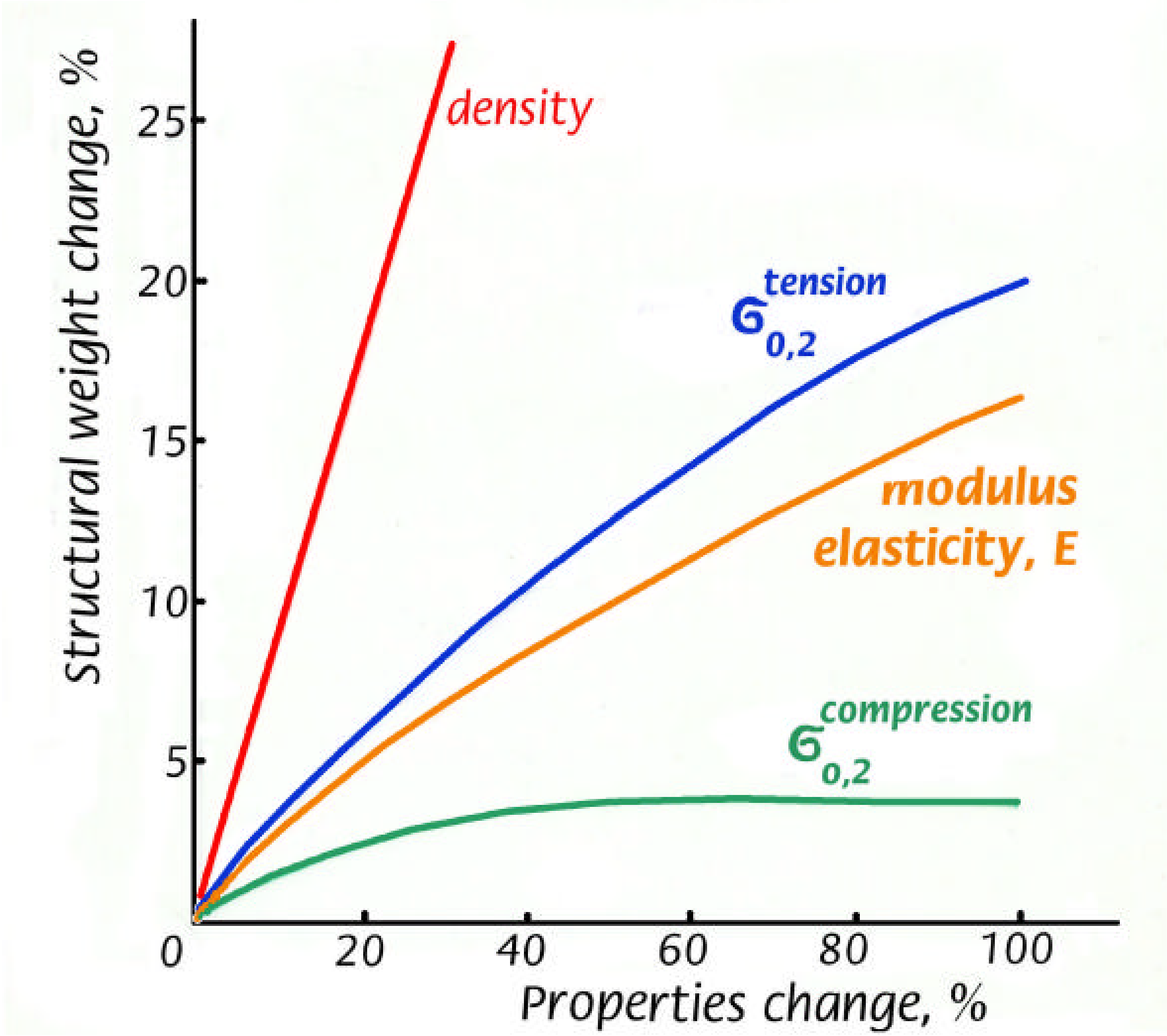
II – Metal matrix composites

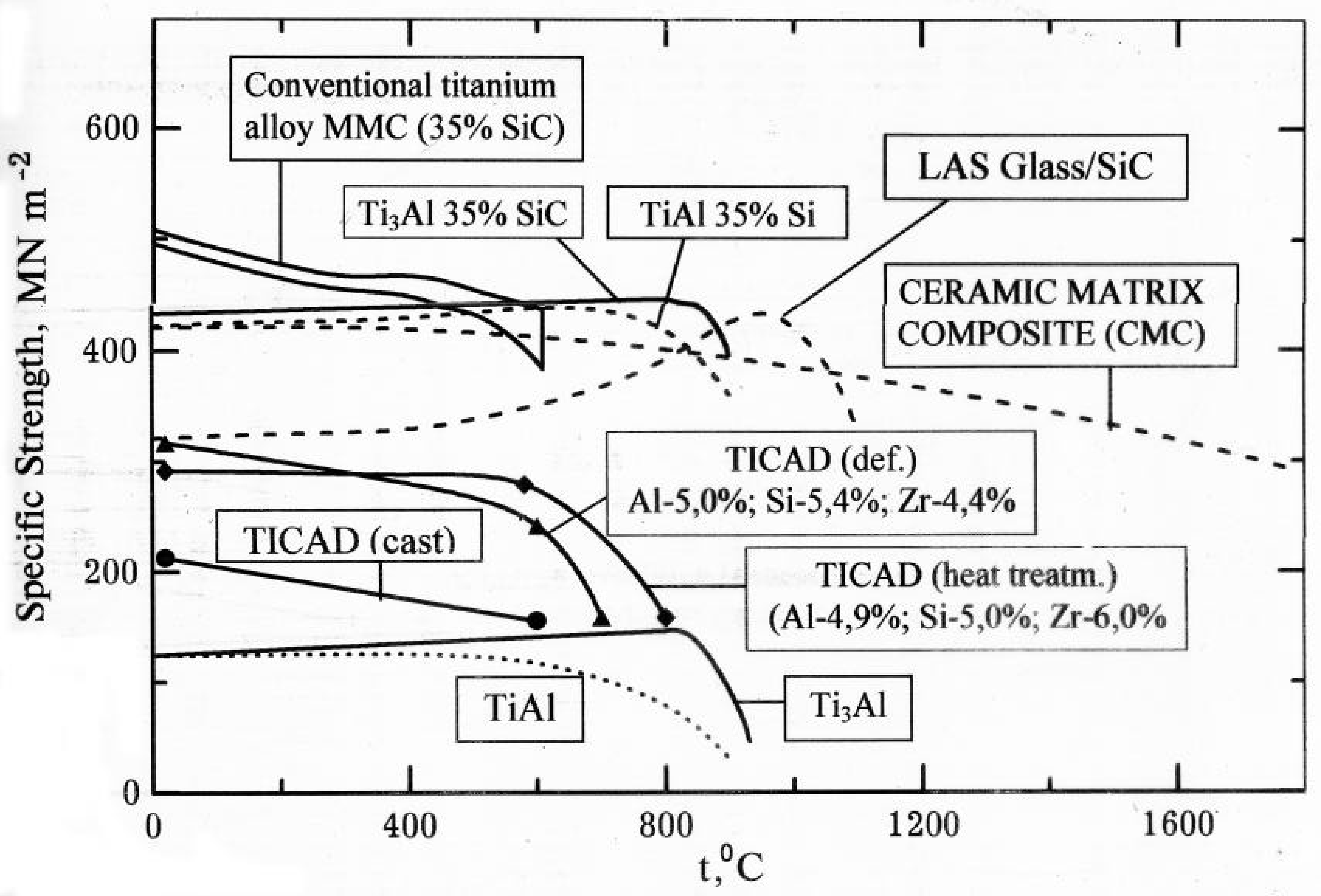
III – Ceramics

IV – Intremetallic composites and intermetallic

V – Ceramic composites

VI – Carbon / carbon composites


Structural weight change, %
25
20
15
10
5
0
20
40
60
80
100
Properties change, %
density
σ tension 0,2
modulus elasticity, E
σ compression 0,2


Conventional titanium alloy MMC (35% SiC)
Ti3Al 35% SiC
TiAl 35% Si
LAS Glass/SiC
CERAMIC MATRIX COMPOSITE (CMC)
TICAD (def.) Al-5,0%; Si-5,4%; Zr-4,4%
TICAD (cast)
TICAD (heat treatm.) (Al-4,9%; Si-5,0%; Zr-6,0%
TiAl
Ti3Al
Specific Strength, MN m -2
600
400
200
0
0
400
800
1200
1600
t,0C

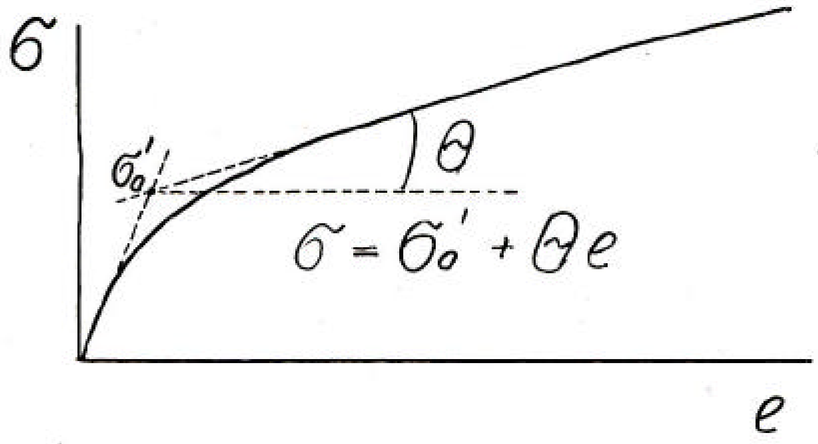
PART 1

Nanostructured materials produced via severe plastic deformation and other technologies

Unusual properties of nanomaterials

1. Reduced density (up to 10%)
2. 2. Reduced modulus of elasticity (up to 10%) and Debye temperature (in the case iron 240K instead 476K)
3. 3. Some severe deformed metals demonstrate good RT plasticity (Ti, Al, Cu)
4. 4. Increased solubility of interstitial elements
5. (Carbon in Iron up to 1.2% instead 0.06% at RT)

DEFORMATION HARDENING



$$s = s'_S + \Theta e$$

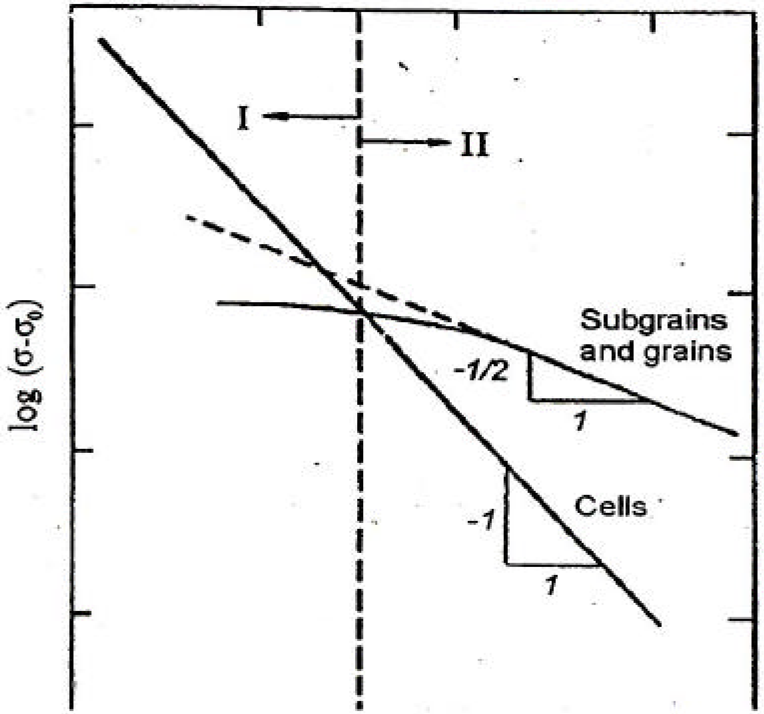
$$s = s_0 + kd^{-1}$$

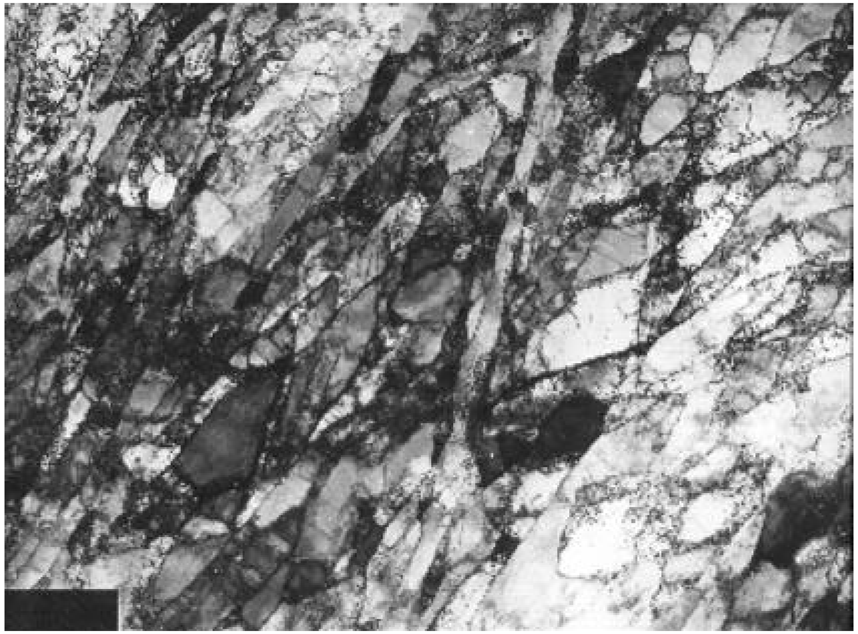
$$d(e) = \frac{k}{\Delta s + \Theta e} = \frac{d_0}{1 + ae}$$

Material	σ_{theor} **, MPa**	e_{ult}	d_{ult} **, ì m**
Mo	11000	25	0.02
Fe	7130	40	0.02

MECHANISMS OF STRAIN HARDENING

(*Thompson A.W.*)





Efficiency of various mechanisms of hardening dependence of substructural elements (schematic diagram):
I – hardening cells;
II – hardening by grains prevails.

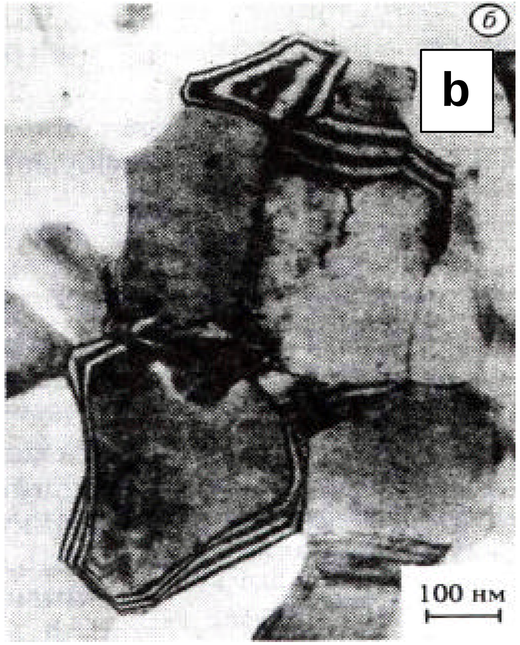
The critical sizes of structural elements (grains)

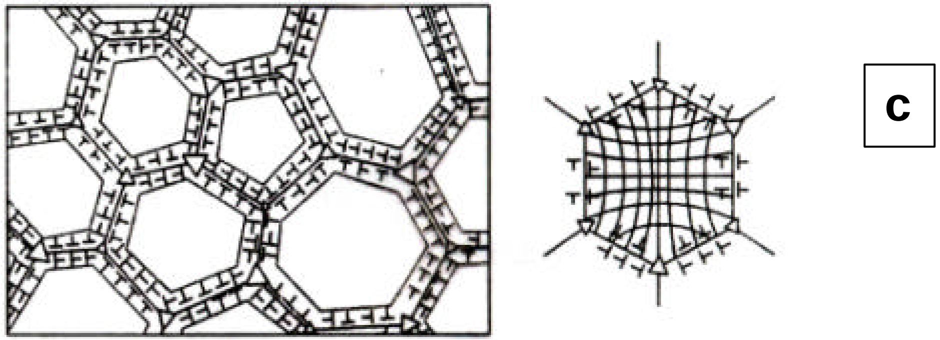
$$\Delta\sigma \sim d^{-0.5} \rightarrow \Delta\sigma \sim d^{-1}$$

$$0.4\ \mu m \leq d \leq 1\ \mu m$$

$$\sigma = \alpha Gb/L \rightarrow \sigma_{theor}$$

$$d \leq 0.02\ \mu m$$





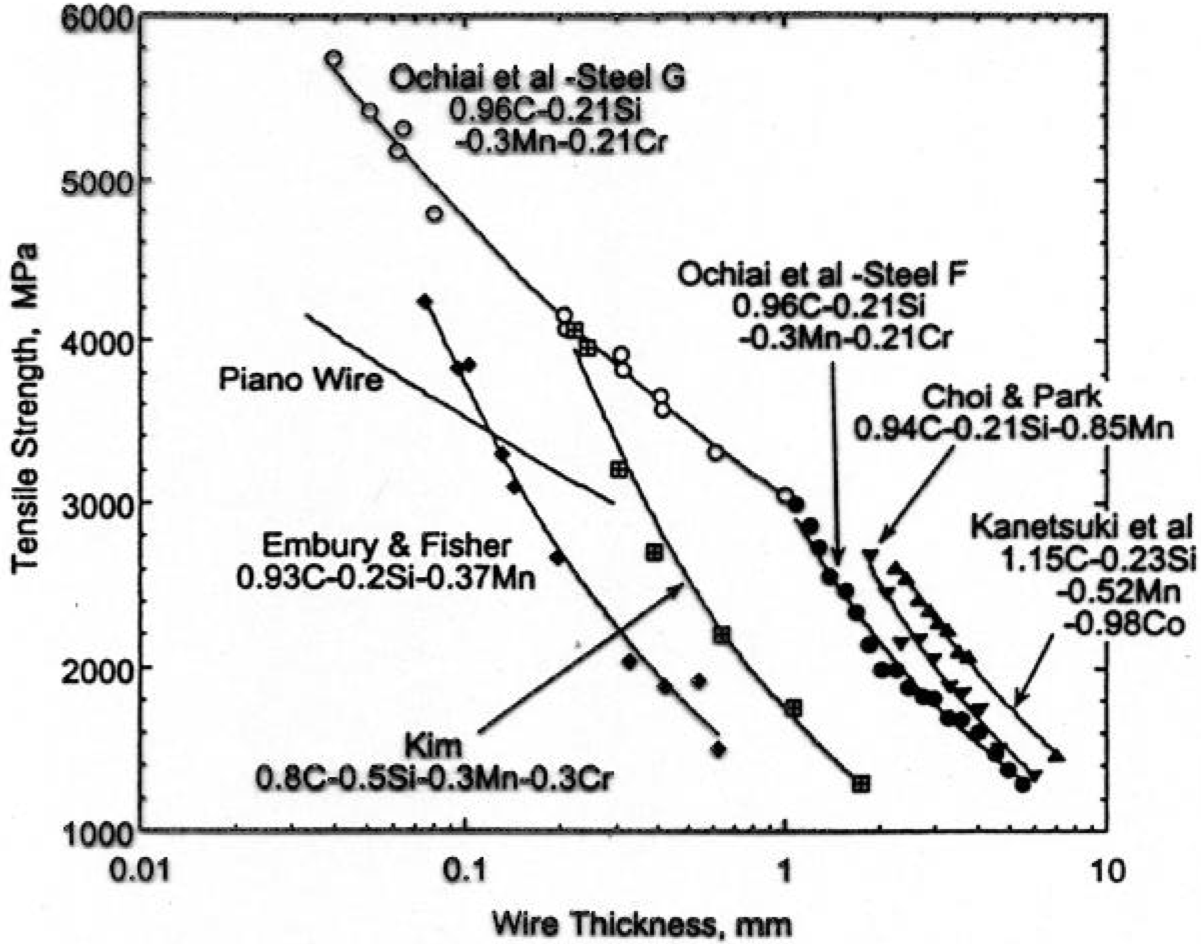
Grain boundary in the heavily deformed Al-4%Cu-0.5%Zr alloy:

(a) after deformation at e=7 and T=20 ^{0}C;
(b) after additional annealing at 160 ^{0}C for 1 h;
(c) schematic illustration of the GB in nanostructured state

Valiev R.Z.

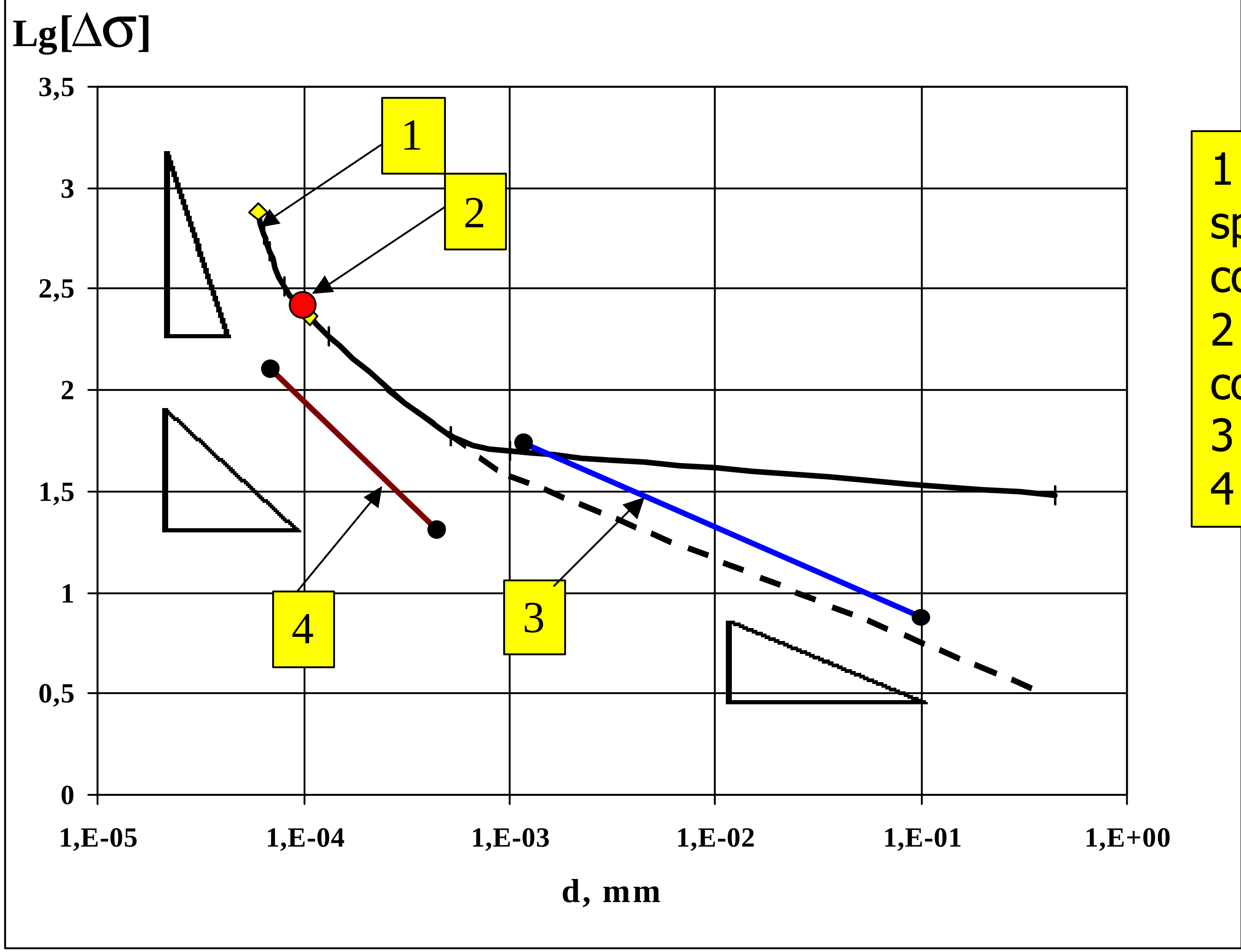
Grain boundary energy

- Low energy ($\gamma_b < 0.1 - 0.2\gamma_0$) – amorphous/crystalline interface, special boundaries.
- Middle energy ($\gamma_b < 1/3\ \gamma_0$) – ordered boundaries with random misorientation .
- High energy ($\gamma_b \rightarrow 2\gamma_0$) – non-equilibrium boundaries with disordered structure (boundaries produced during low temperature deformation).



Tensile strength as a function of wire diameter during wire drawing for eutectoid and hypereutectoid steels

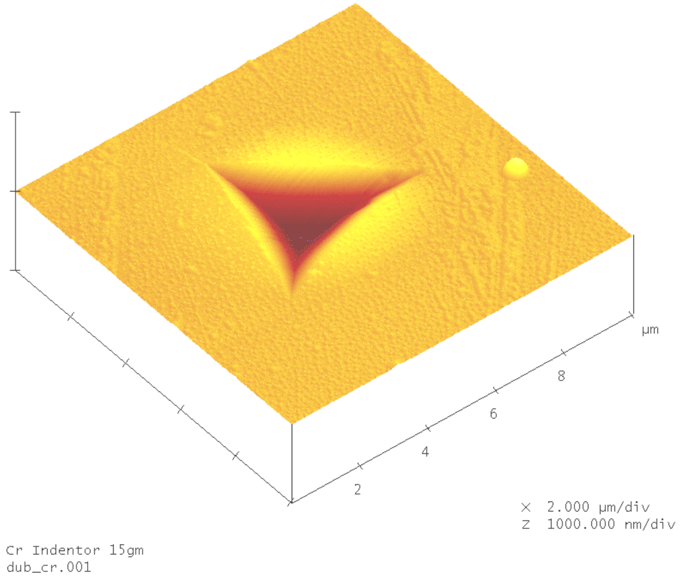
Chromium coatings produced by magnetron sputtering



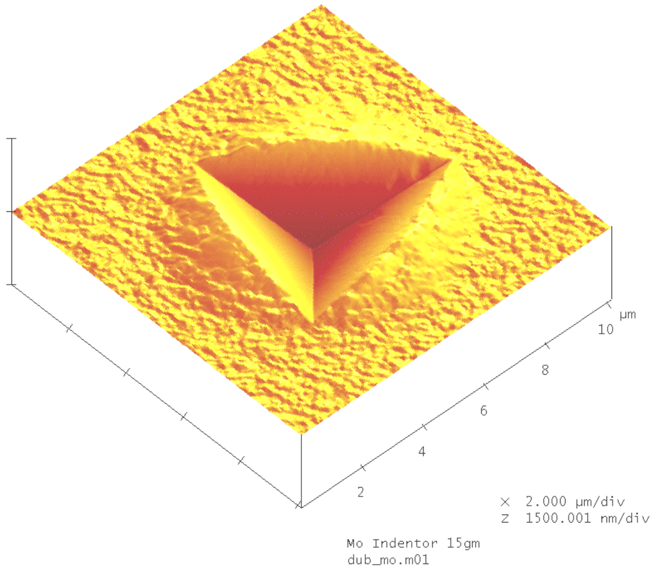
1 - magnetron sputtering of Cr coatings;
2 - ion-plasmic Cr coatings;
3 - (Fe-C);
4 - (Fe-0,49%Ti)

Chromium coating produced by magnetron sputtering (t=400nm)

AFM image of indentation made in the chromium and molybdenum produced by magnetron sputtering on silicon substrates



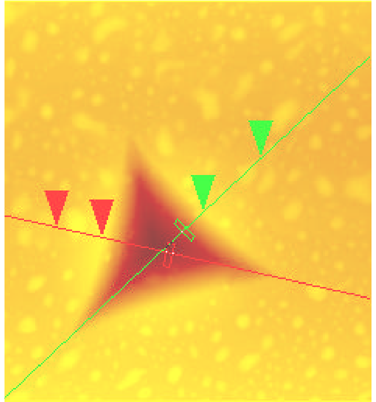
Cr

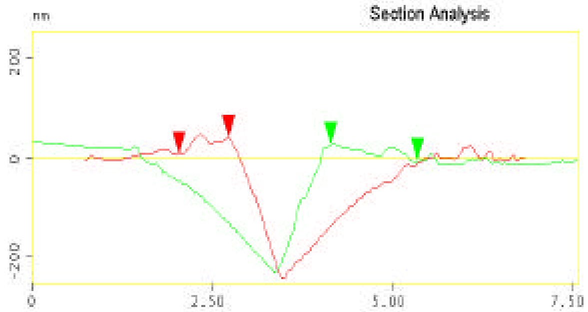


Mo

Cross-section of indentation in the chromium and molybdenum produced by magnetron sputtering on silicon substrates

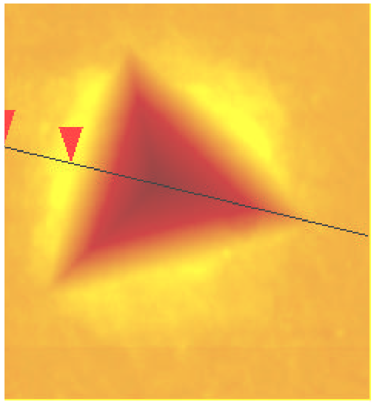
(AFM)

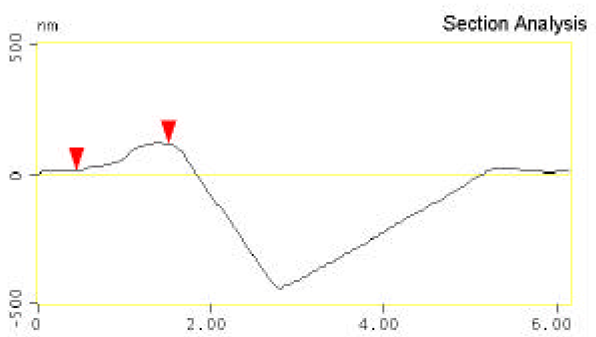




Cr

Indentor 5gm



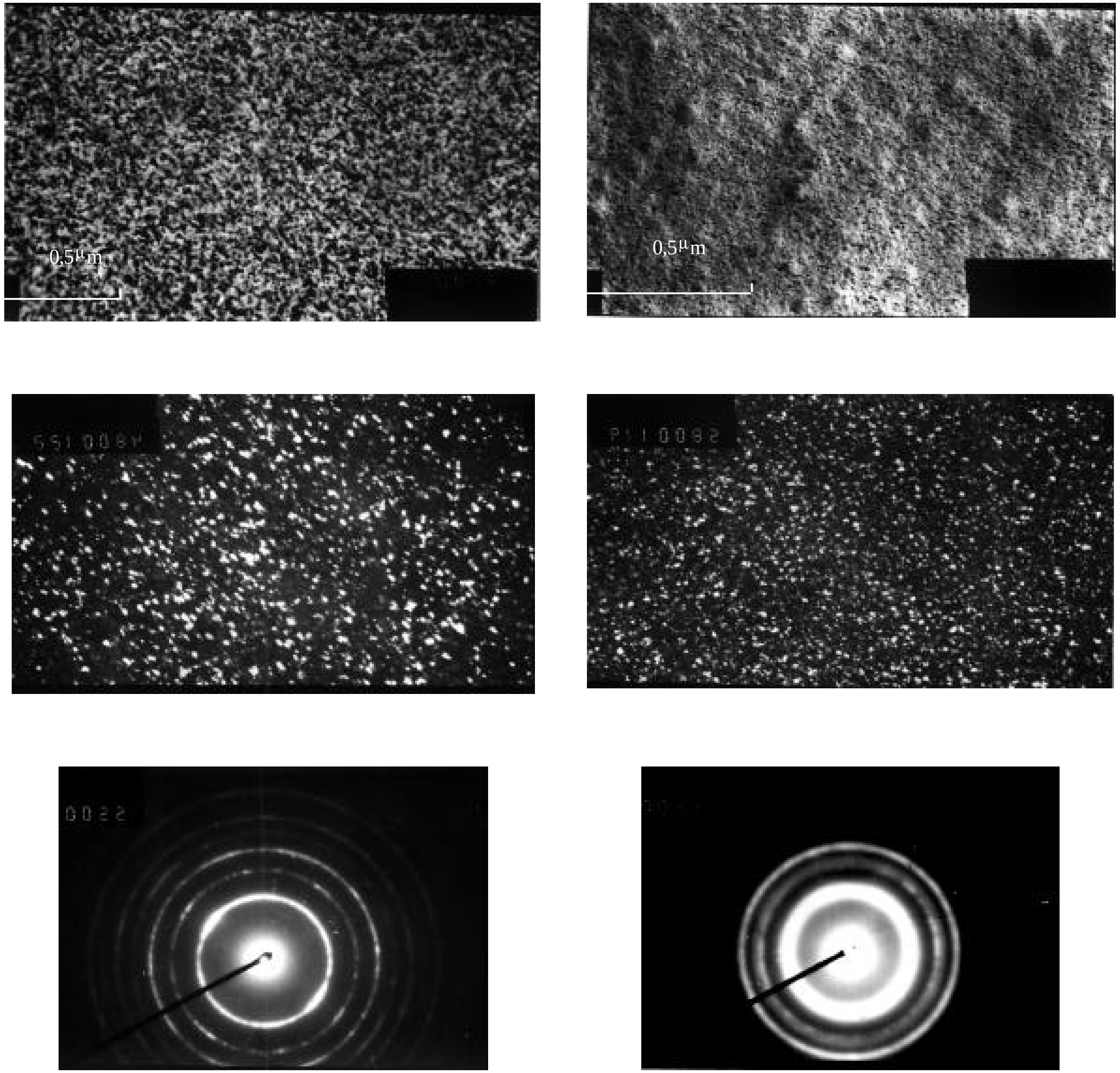


Mo

Indentor 5gm

	Load, gm	Indentation depth, nm	Height of the pile-up, nm
Cr	5	235,69	33
Cr	15	409,3	98,7
Mo	5	377	104
Mo	15	661	198

Cr Mo



Chromium and molybdenum produced by magnetron sputtering

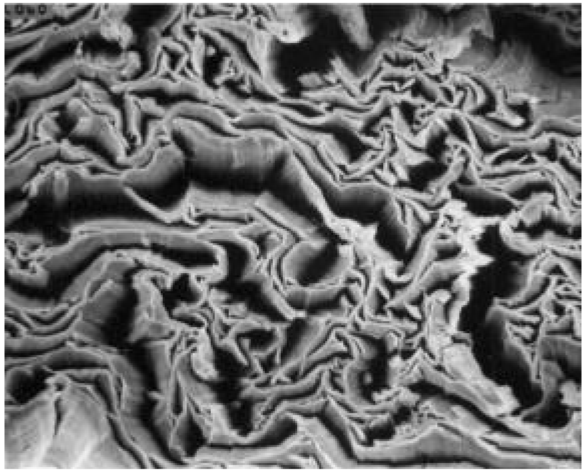
Boundary

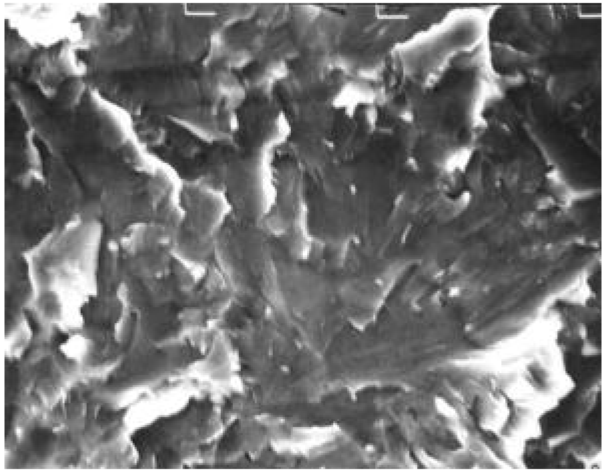
↓	↓
M-M-M-M=M-M-M-M	M-M-M-M=M-M-M-M
M-M-M-M=M-M-M-M	M-M-M-M=X-M-M-M
M-M-M-M=M-M-M-M	M-M-M-X=M-M-M-M
M-M-M-M=M-M-M-M	M-M-M-M=X-M-M-M
M-M-M-M=M-M-M-M	M-M-M-X=X-M-M-M
M-M-M-M=M-M-M-M	M-M-M-M=M-M-M-M
↑	↑

If E_{xx} > E_{MM} and E_{MX}>E_{MM} strength (hardness) increases.

If E_{xx} (E_{MX})< E_{MM} strength (hardness) decreases.

FRACTURE SURFACES OF HEAVILY DEFORMED Cr AND Mo





	$-^{D}H_{298}$		T melting, K
	Kilojoules/mole	Kilocalorie/mole	
Cr	397.75	95.0	2173
Cr_2O_3	1130.4	270.0	2538
Mo	659.42	157.5	2883
MoO_2	548	131	2200

"Useful" impurities (additives) concept

Theoretical strength can be achieved at d≈0.02 μm. Practically, in one-component systems, the “negative” Hall-Petch (or strength saturation) has been observed in many investigations at the nanoscale level of grain sizes. The main reason for such phenomenon is the increase of the "bad" material volume in nanostructured materials with decreasing the grain size.

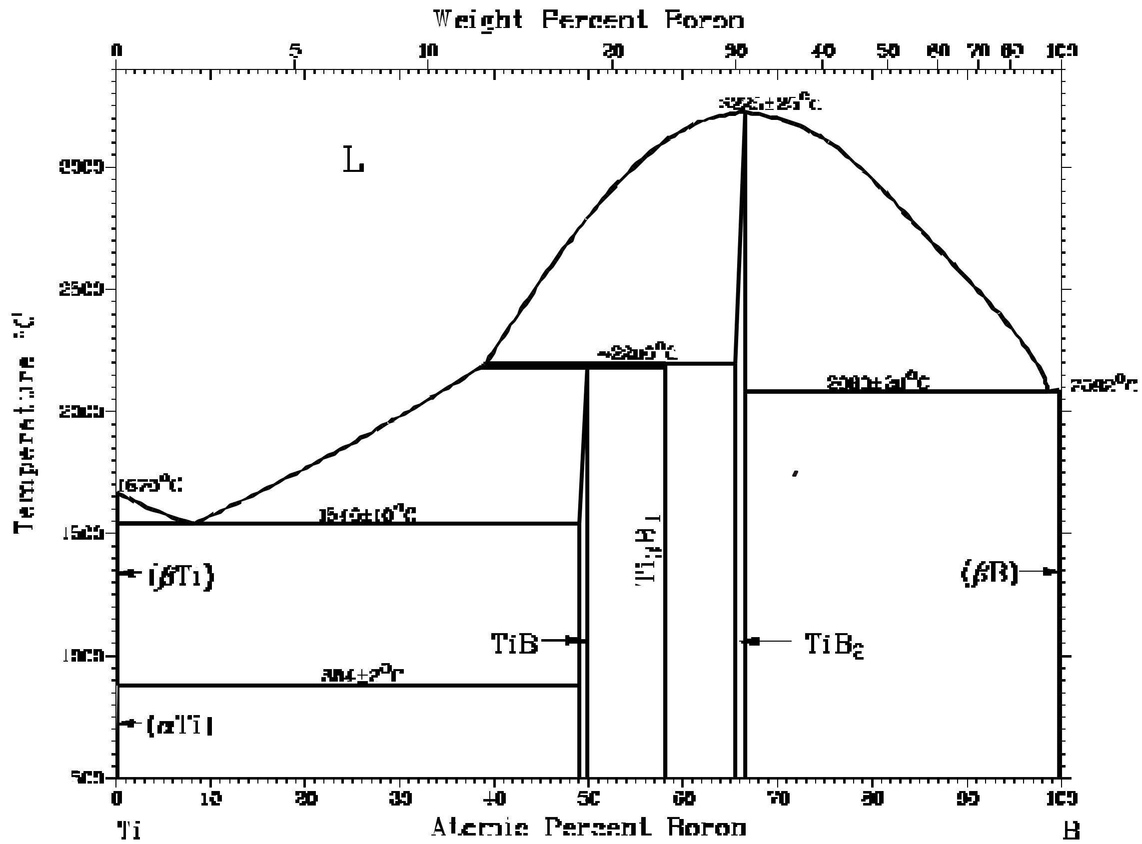
In multicomponent systems the possible **healing of the week points** in the grain boundaries structure can occur and this can lead to the extremely high strength (hardness). Using the **segregation of the useful impurities** or alloying elements, it is possible to realize the healing of weak places in the grain boundaries and to obtain the essential increase of mechanical properties as a result.

PART 2

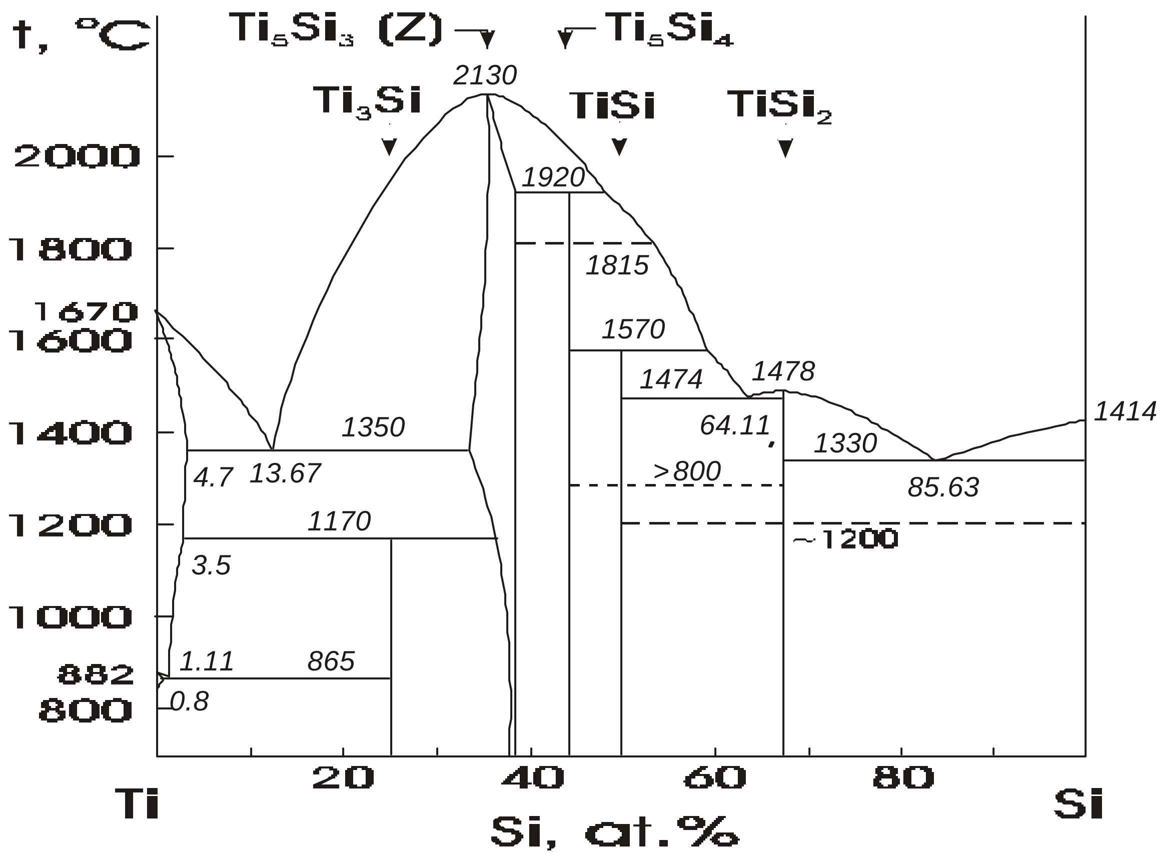
Advanced Ti – based materials

Properties of Ti alloys and Discontinuously-Reinforced Ti (DRTi) materials

	Ti-6Al-4V	Ti-6Al-4V + 3% TiB	Ticompl. alloyed + 5% TiB	Ti-6Al-4V +10(20)% (TiB+TiC)	TENTATIVE GOAL	ACHIEVED Ti-9.0Al-2.2Zr-1.6Si deformed
Modulus (GPa)	110-115	125	132	141/168	≥150%of matrix = 170	~135-140
YS (MPa)	840-1070	1007	1175	1406/ 1181	≥140% of matrix = 1400	-
UTS (MPa)	940-1180			1550/ 1215	≥140% of matrix = 1500	b 1180 a 1230
Strain (%)	7-20%	9.5	5.0	4.6/0.6	≥5%	b 0.8 – 1.6 a 3.8 – 6.1
K_{IC} (MPa.√m)	44-66 (α+β) 88-110 (β)	47			≥30	b 19.2 a 51.1
Max Oper. Temp	427°C (800°F)				≥600°C (~1100°F)	at 700 °C b 650 at 700 °C a 400

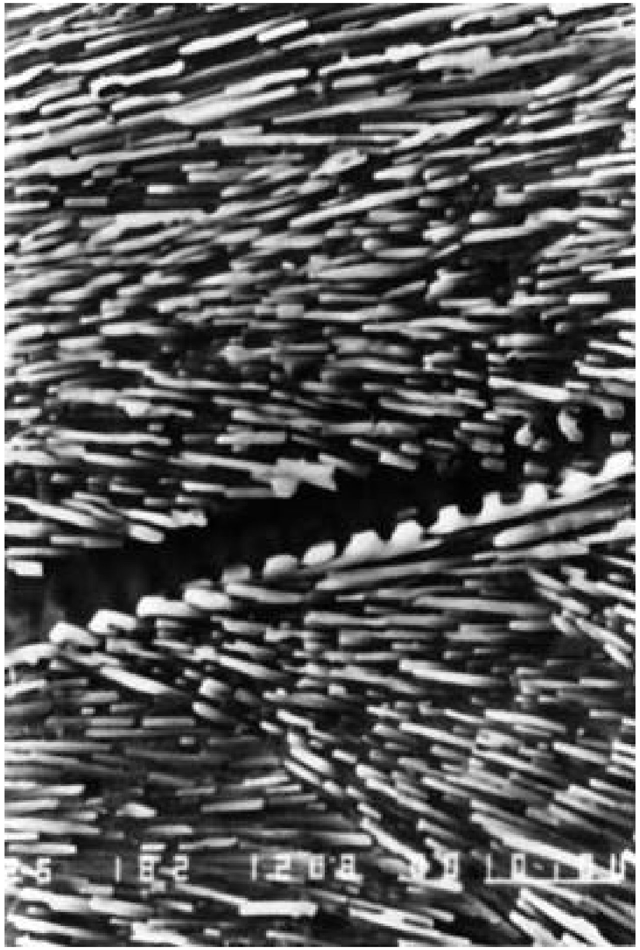


The Ti-B system from Massalski's handbook.

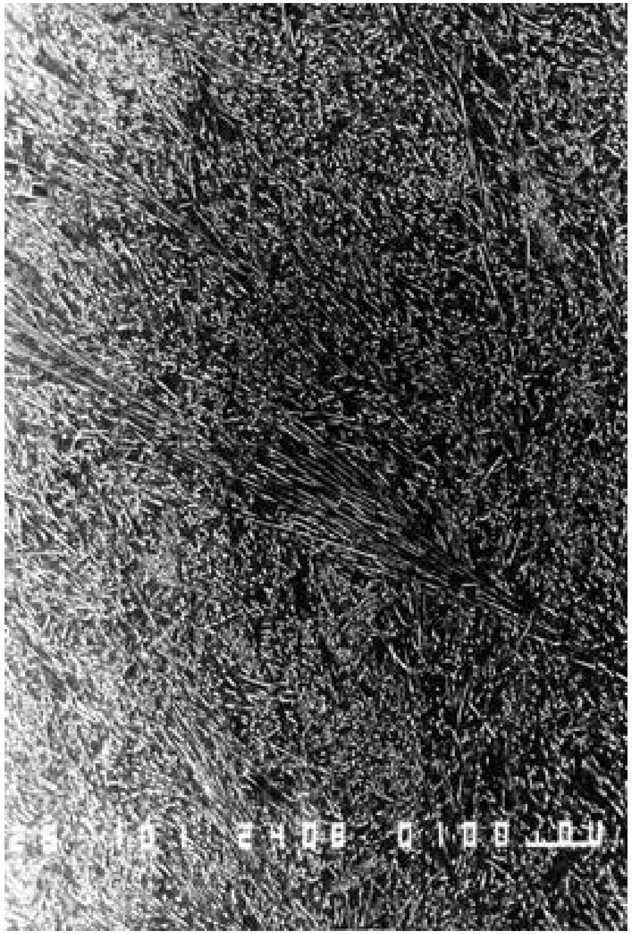


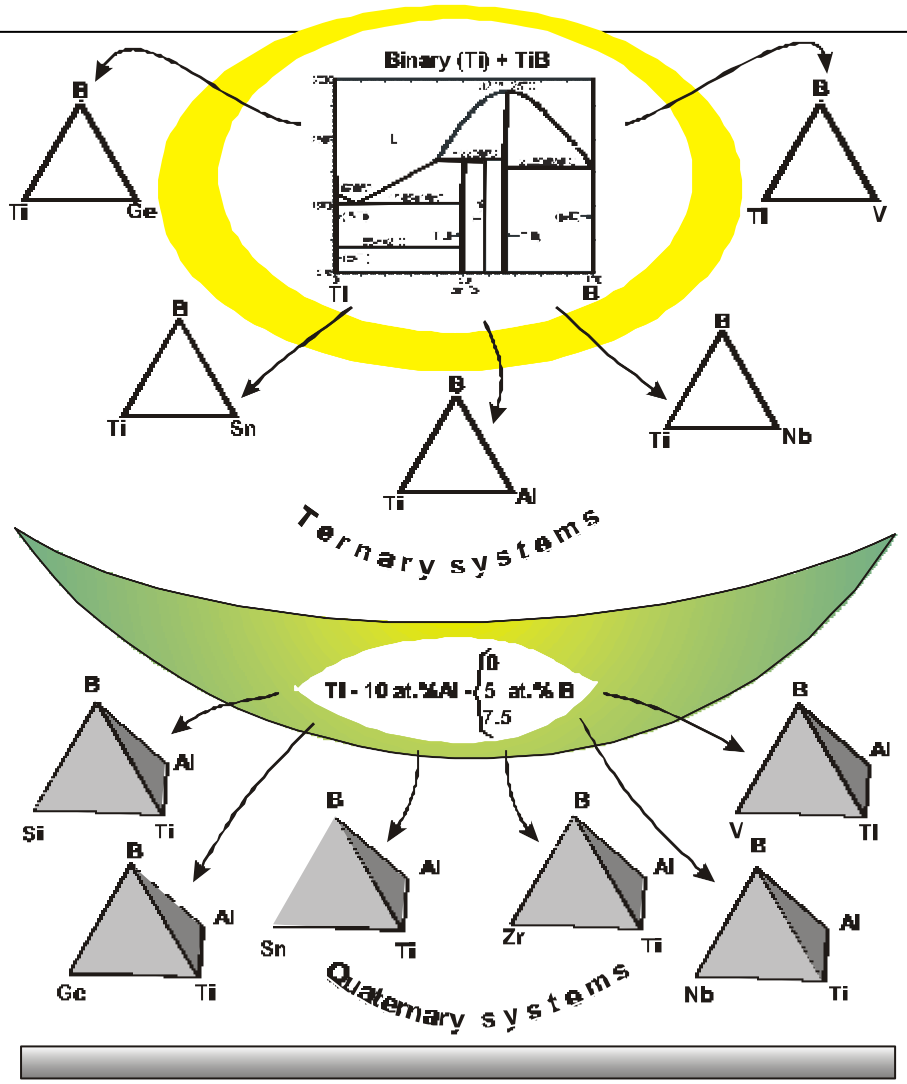
The Ti-Si system, Dr. Bulsnova's assessment.

Ti -8,5 Si (wt. %), DEEP ETCHING, SEM. UPERPROBE -733



Ti – 2.0 B (wt. %), STRUCTURE, SS

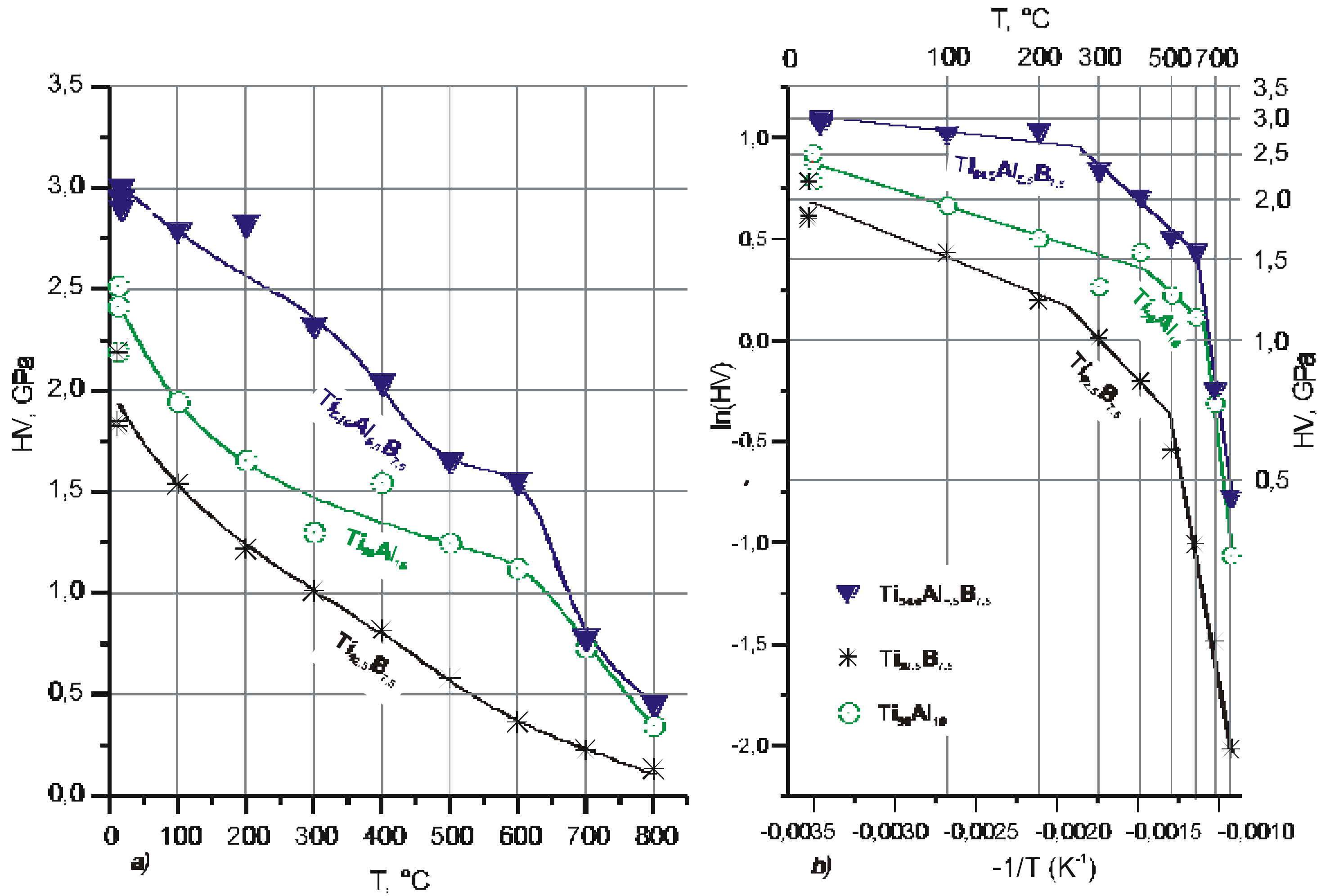




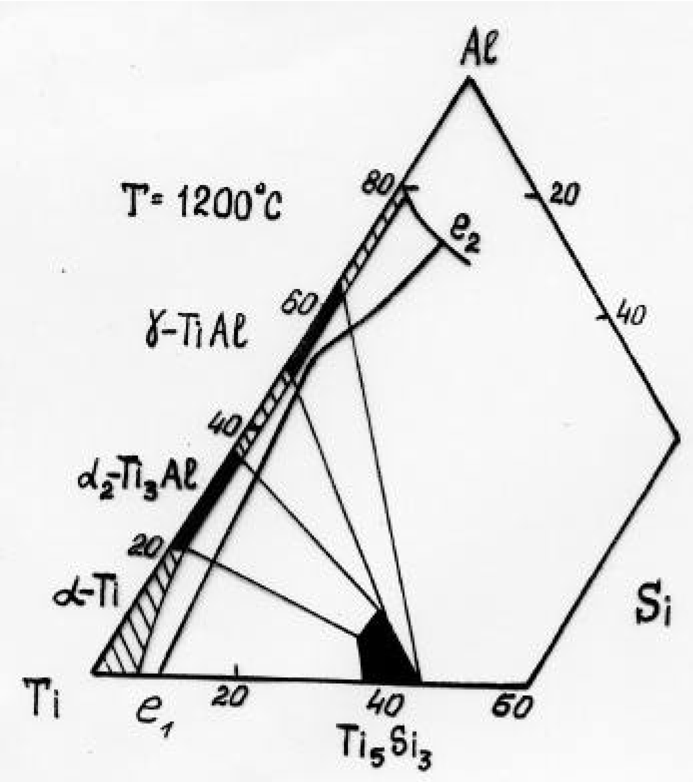
Multicomponent alloys:

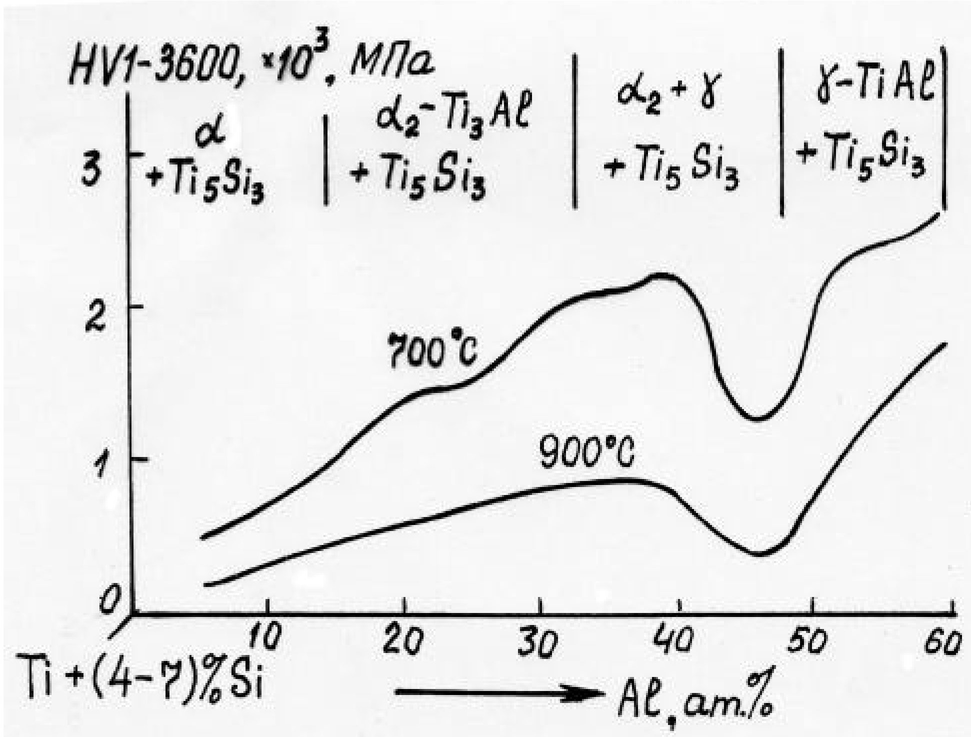
Ti-Al-Ge-Sn-(0;5;7.5)B; Ti-Al-Ge-Sn-Zr-(0;5;7.5)B;
Ti1100 + (TiB); IMI834 + (TiB)

Strategy of research work on alloying of the binary (Ti) + TiB eutectic alloy.

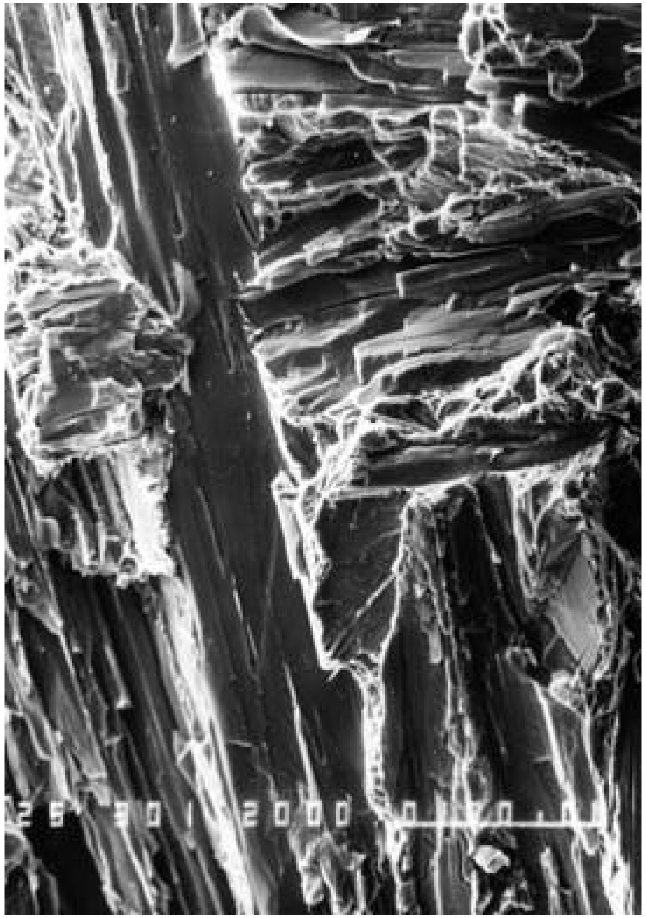


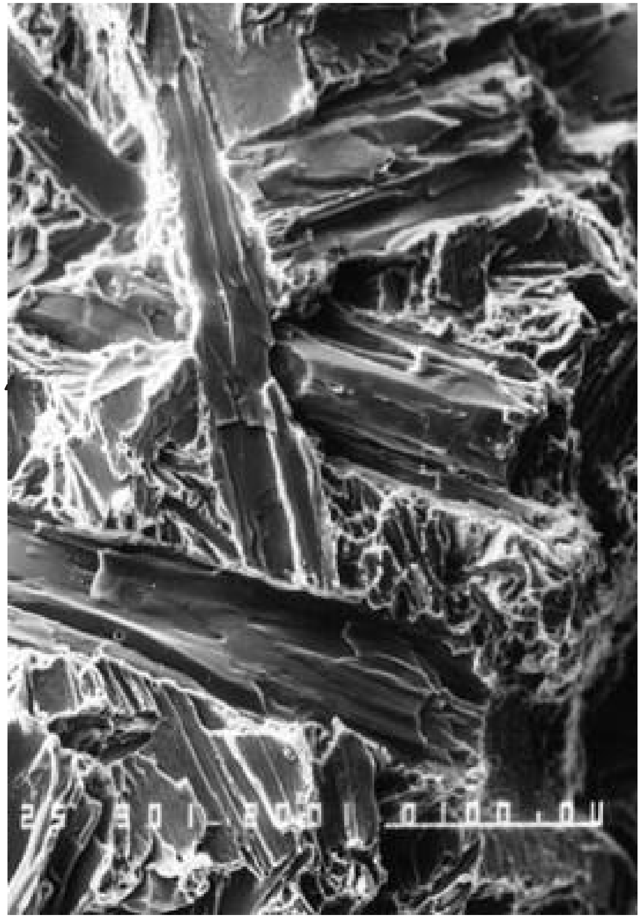
Contributions of alloying additives to the hardness of $Ti_{84}Al_{8.5}B_{7.5}$ alloy compared with the appropriate binaries, *HV vs T* (*a*) and *lg(HV) vs -(1/T* (*b*).


Al
T = 1200°C
80
20
e_2
60
40
γ-TiAl
40
$α_2$-Ti_3Al
20
α-Ti
Si
Ti
e_1
20
40
60
Ti_5Si_3

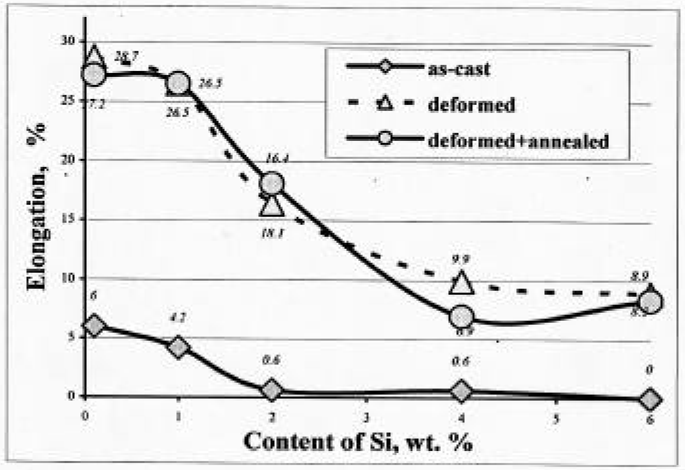

HV1-3600, ×10^3, МПа
α + Ti_5Si_3
$α_2$-Ti_3Al + Ti_5Si_3
$α_2$ + γ + Ti_5Si_3
γ-TiAl + Ti_5Si_3
3
2
1
0
700°C
900°C
10
20
30
40
50
60
Ti + (4-7)%Si
Al, am.%

FRACTURE MICROMECHANISMS OF AS-CAST Ti – 3.5 B, iod, 20^{0}C

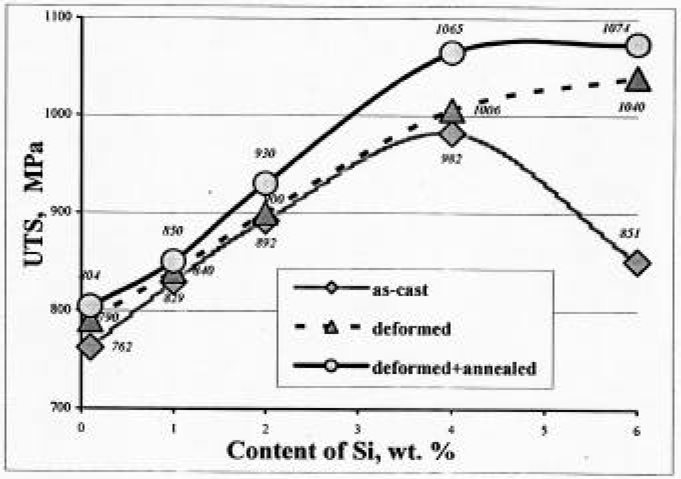


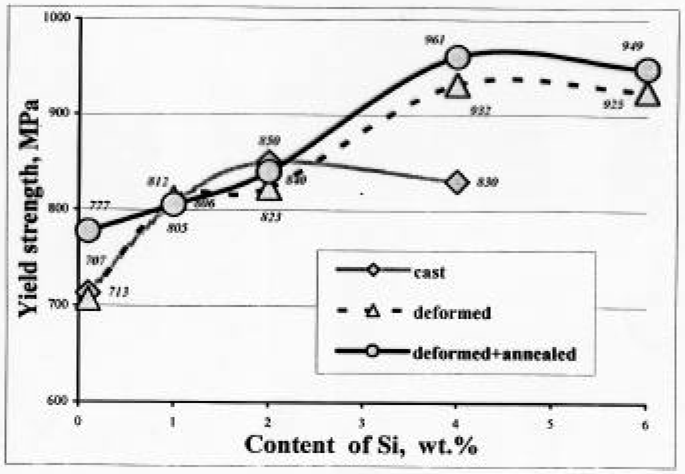


Binary Ti – Si system



Ultimate tensile strength (UTS), yield strength and plasticity (elongation, δ) of commercial titanium alloy BT1-0 vs. silicon content in it for as-cast, deformed (forged for 90 %) and forged + annealed at 800 °C for 2 hours states.





Properties of selected alloys after forging, ε > 60%

Alloy	RT strength, UTS, MPa	RT fracture toughness K_{1c}, MPa $m^{1/2}$	RT yield strength, s 0.2 MPa;	RT elongation, d%;	RT fracture micro-mechanism	Elasticity modulus, GPa
Ti-6.3Al-5Zr-1.8Si LM-863	1220		1120	5.4	void coales-cence	
	in process					
Ti-6.6Al-3.5Zr-1.3Si-1.1B LM-908	1530		1469	1.4	void coales-cence	158
	in process					
Ti-9.0Al-2.2Zr-1.6Si LM-905	1302			1.83	void coales-cence	~140
	b 1180 **a 1230**	**b 19.2** **a 51.1**		**b 0.8 – 1.6** **a 3.8 – 6.1**		
Ti-5.5Al-1.9B LM-903	1184		1140	6.24	void coales-cence	152
	in process					

Structure of as–cast (a) and as– forged (b) Ti – Al – Zr – Si - B

a X 400 SEI

b X 400 SEI

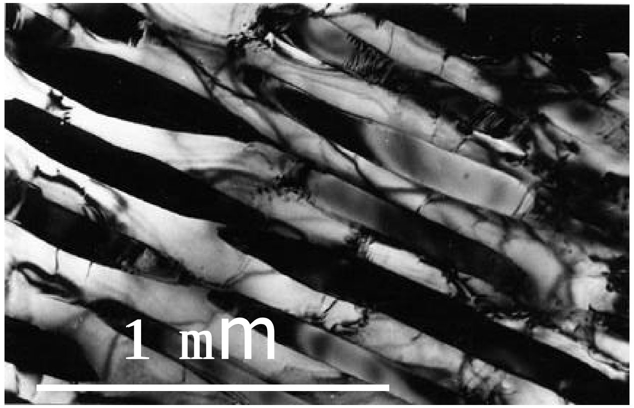
Ternary Ti-B system

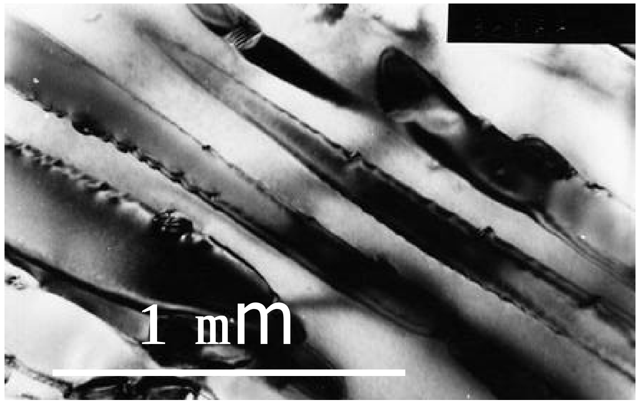
Tensile yield strength ($\sigma_{0.2}$), ultimate tensile strength (UTS), plasticity (elongation, δ) and elasticity modulus (E) of complex alloyed Ti-B alloys, deformed and annealed (800^{o}C, 2 hours), at room temperature. Produced with arc (AM) and electron beam melting (EBM) of BTI-O alloy.

Chemical composition	Melting	As-cast			Forged			
		UTS, MPa	$\sigma_{0.2}$, MPa	δ, %	UTS, MPa	$\sigma_{0.2}$, MPa	δ, %	E, GPa
Ti-3Al-1.2B (2B-57)	AM	1020	1000	1,2	1033	972	7.2	137-138
Ti-5.5Al -1.9B (LM-903) annealed 800 ^{o}C	EBM	-	-	-	1184	1140	6.24	151-152

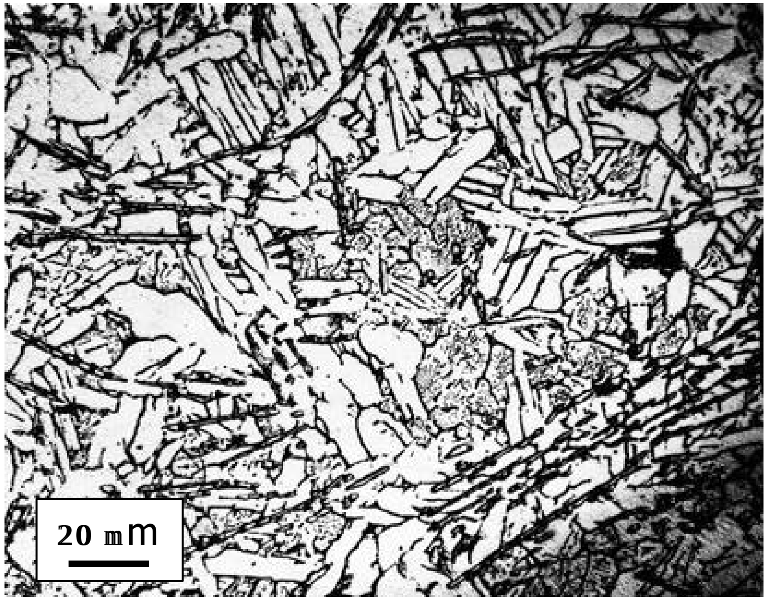
Ti – Al – Si – B

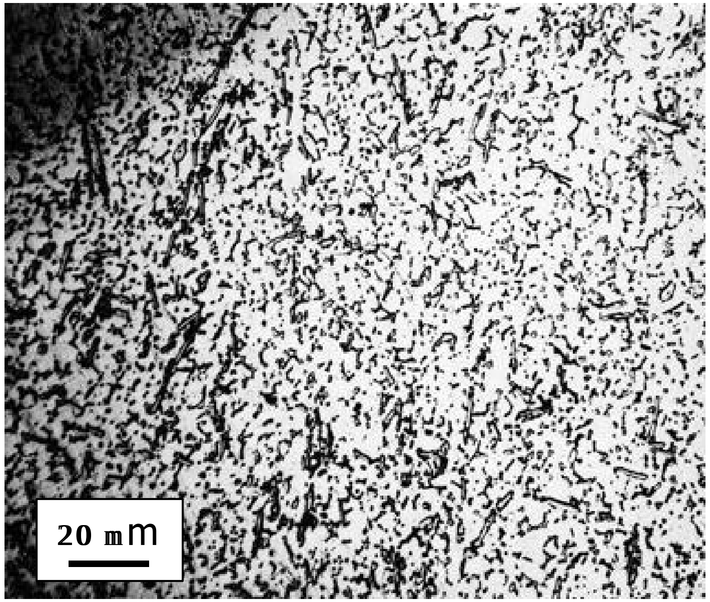
Ti – Si – B





Structure of as–cast and as–rolled alloys Ti – 4Al – 4Zr – 1Si – 2B





CONCLUSIONS

The following directions of R&D in the field of elaboration of materials with high specific strength are actual:

1. Further elaboration of different methods producing of nanostructured materials including gradient nanostructured materials
2. Grain boundary engineering of nanostructured materials including thermo-chemical treatment based on concept of "useful" additives
3. Clarifying of the mechanisms of plasticity in nanostructures. Achievement of a good combination of different mechanical properties (σ, δ, ψ, K_{1c}, fatigue properties, heat resistance etc.)
4. Phase equilibria investigations of multicomponent systems as base for producing of advanced materials strengthened by quasicrystals, intermetallics, creation in situ composites, nanocomposites, nanolaminates, amorphous structures etc.
5. Further development lightweight materials including porous materials with different volume and morphology of pores

As to Ti-based materials:

1. Ti-Si-X systems alloys are attractive for creation of heat resistant materials
2. Ti-B-X systems alloys are promising for achievement of high specific stiffness
3. Further investigations of Ti-B-Si-X alloys. Amorphisation, icosahedral phase production, search of new strengthening phases
4. Methods of obtaining of alloys with high boron content
5. Ti-Si-X systems alloys are a good matrix for producing MMM's